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Saharan dust exacerbates the sensitivity of Alpine glaciers to climate change

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Abstract

Glacier albedo is a key driver of snow and ice melt through the absorption of solar radiation. The albedo strongly depends on the amount of light-absorbing particles deposited on the surface. In the European Alps, Saharan dust particles are frequently deposited and highly contribute to lower snow albedo. However, the role of dust in the currently accelerated melt of Alpine glaciers remains unknown. Here, we show that dust promotes the accelerated wastage of Alpine glaciers in the context of climate change. Using process-based surface mass balance modeling and 60-year-long simulations, we demonstrate that dust increases the current sensitivity of Alpine glaciers to air temperature by 11 %, even in the absence of increasing dust deposition. The magnitude of the impact of dust is controlled by the snow and ice-albedo feedbacks, as well as the exposure of old firn layers. Such feedbacks are amplified by the current warming leading to longer exposure of darker surfaces to solar radiation. Dust thus induces increasingly negative mass balances not because of higher deposition fluxes but because of longer exposure. Our study hence emphasizes the crucial role of indirect positive feedbacks at play in the current accelerated decline of Alpine glaciers.

White, as the shade of snow that covers the glacier ice and protects it from solar radiation. The whiteness of pure snow limits the absorption of solar radiation up to nearly 10 % of the incoming energy (Gardner, Sharp, 2010). Knowing that absorbed solar radiation is the dominant energy-balance component controlling glacier melt in the European Alps (Pellicciotti et al., 2005; Sicart et al., 2008; Thibert et al., 2018) and is inherently modulated by the glacier's "colour", more rigorously defined as the albedo (Warren, 1982, 1984), this protective white snow cover delays the melting. Thus, Alpine glaciers accumulate mass until May-June, which precisely coincides with the timing of the maximum mineral dust deposition that can turn the surface orange (Collaud Coen et al., 2004; Israelevich et al., 2012; Varga et al., 2014; Flentje et al., 2015), as it was the case during the extreme melt event of the year 2022 (Cremona et al., 2023; Berthier et al., 2023). This dust originating from the Saharan desert is transported northward over the Mediterranean Sea and deposited on the Alpine glaciers (Moulin et al., 1998; Baladima, 2021; Dumont et al., 2023). Only a few grams per square meter of dust on the surface is sufficient to significantly decrease the snow albedo by more than 0.2 (Skiles, Painter, 2017). The simultaneous timing of the maximum dust deposition and the peak of snow accumulation is critical, allowing dust to have an almost immediate radiative effect on melt under the highest incoming shortwave (SW) radiation of the year (Rottler et al., 2019). As melt progresses, the transition from snow to ice provokes the abrupt acceleration of Alpine glacier melt in summer. The exposure of ice, which presents a lower albedo than all types of snow (Gardner, Sharp, 2010), compensates for the decline in incoming shortwave radiation and leads to the highest melt rate of the year (GLACIOCLIM, GLAMOS, see Data Availability).

Under the constraints of climate change, mountain glaciers are retreating increasingly rapidly, especially in the European Alps where glaciers are losing mass at one of the fastest rates worldwide (Hugonnet et al., 2021; Zemp et al., 2025). In the meantime, field or satellite observations from local to glacier scale reveal that Alpine glaciers are darkening (Oerlemans et al., 2009; Naegeli et al., 2019; Di Mauro, Fugazza, 2022), *i.e.*, present a decreasing trend in minimum, annual, or summer albedo. The prolonged exposure of bare ice over larger areas enhances melting in the ablation area of glaciers (Hartl et al., 2025). On snow, the presence of light-absorbing particles (LAPs) is also suspected to contribute to the current glacier darkening (Di Mauro, Fugazza, 2022; Menounos et al., 2025), in particular mineral dust (dust) and black carbon (BC) that are the particles dominating the decrease in snow albedo (Skiles et al., 2018). The influence of dust on the surface mass balance (SMB) of Alpine glaciers has been quantified locally, showing punctual impacts as high as 20 % of surface melt (Gabbi et al., 2015; Roussel et al., 2025). However, the question of how much, and through which processes, the albedo decrease due to LAPs contributes to the recent acceleration of Alpine glacier melt remains open.

Here, we analyse the long-term role of LAPs in glacier darkening and melt acceleration in the European Alps over the period 1970-2022. To do so, we simulate SMB for Alpine glaciers explicitly accounting for LAPs deposition and impacts (see Methods). Simulations are evaluated against SMB point measurements and satellite observations of transient snowline elevation, showing good agreement (see Methods).

Darkening processes vary within the glacier

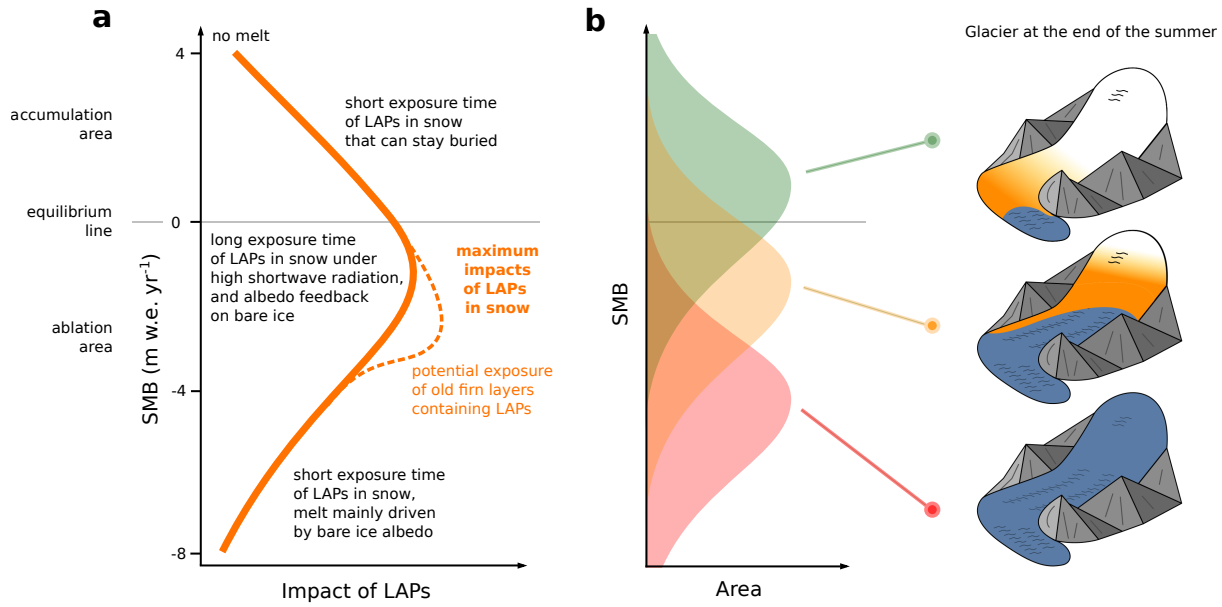


Figure 1: (a) Schematic summary of the dust and BC impact on glacier melt, and (b-c) implications for future mass balance.

The magnitude of the impact of LAPs in snow on Alpine glaciers SMB is driven by the efficiency of several physical processes (Fig. 1a). First, the progressive exposure of LAPs at the snow surface, combined with increasing snow grain size, decreases snow albedo and accelerates snow melt (*e.g.*, Dumont et al. (2014); Skiles, Painter (2017, 2019); Tuzet et al. (2020)), ultimately leading to an earlier snow melt-out. This process is called the LAPs snow-albedo feedback. This feedback is limited for positive SMB at the highest elevations where LAPs remain buried and are only exposed to sun light for a short period of time until subsequent snowfalls cover them again. Second, in the ablation areas where SMB is negative, once the surface becomes snow-free, melt is further enhanced by the exposure of bare ice which has a lower albedo than snow. This process is referred to as the ice-albedo feedback (Stephens et al., 2015). Here we only account for the effect of LAPs in snow, not in ice where LAPs are more likely scavenged by melt water. In the lowest part of the ablation area where the snowpack melts quickly and bare ice is exposed over most of the summer, LAPs snow-albedo feedback and ice-albedo feedback are less important compared to areas where snow persists longer and LAPs are exposed longer. In brief, LAPs exert a direct effect on snow by accelerating its melting and advancing the snow melt-out date, followed by an indirect effect through earlier ice exposure which further enhances melt. Third, in the context of climate change, glacier-wide SMB are increasingly negative, leading to a rise in the equilibrium line altitude (ELA), reducing the accumulation area and exposing old layers of firn containing LAPs especially

near the ELA (Gabbi et al., 2015; Roussel et al., 2025). During particularly extreme years (*e.g.*, 2022), Alpine glaciers exhibited almost no accumulation zone (Cremona et al., 2023; Six et al., 2023; Berthier et al., 2023), which can further enhance the exposure of LAPs.

The relative contribution of these three physical processes varies depending on the location on the glacier, and results in maximal impacts for negative SMB close to the ELA, due to long exposures of LAPs. When the glacier-wide SMB are negative and aligned on these maximal impacts (middle orange distribution in Fig. 1b), the impact of LAPs at the glacier-scale is increased compared to positive glacier-wide SMB, for which most of the LAPs would stay buried at the highest elevations (upper green distribution in Fig. 1b). Thus, the presence of LAPs enhances the sensitivity of glacier melt for moderately negative mass balance.

To quantify the spatio-temporal variability of LAP impacts, we perform gridded simulations of the glacier surface mass balance at 250 m resolution explicitly representing the three processes above. We use the detailed snowpack model SURFEX/ISBA-Crocus (Lafaysse et al., 2025), forced by meteorological inputs from the SAFRAN and COSMO reanalysis (Vernay et al., 2022; Mott et al., 2023). We account for the two dominant types of LAPs, dust and BC, for which deposition fluxes are taken from the CNRM-ALADIN regional climate model (Nabat et al., 2020). It must be noted that accurately quantifying the effect of one type of LAPs requires accounting for the other types of LAPs in the model (*e.g.*, Réveillet et al. (2022); Roussel et al. (2025)). We hereafter quantify the total impact of an LAP type, termed $\Delta\mathrm{SMB}_{\mathrm{LAP}}$ by evaluating the difference in SMB between (i) the simulations without the radiative effect of the given LAP type, and (ii) the simulations including the radiative effect of all LAPs, *i.e.*, dust and BC (see Methods).

Dust amplifies the sensitivity of glacier melt to temperature change

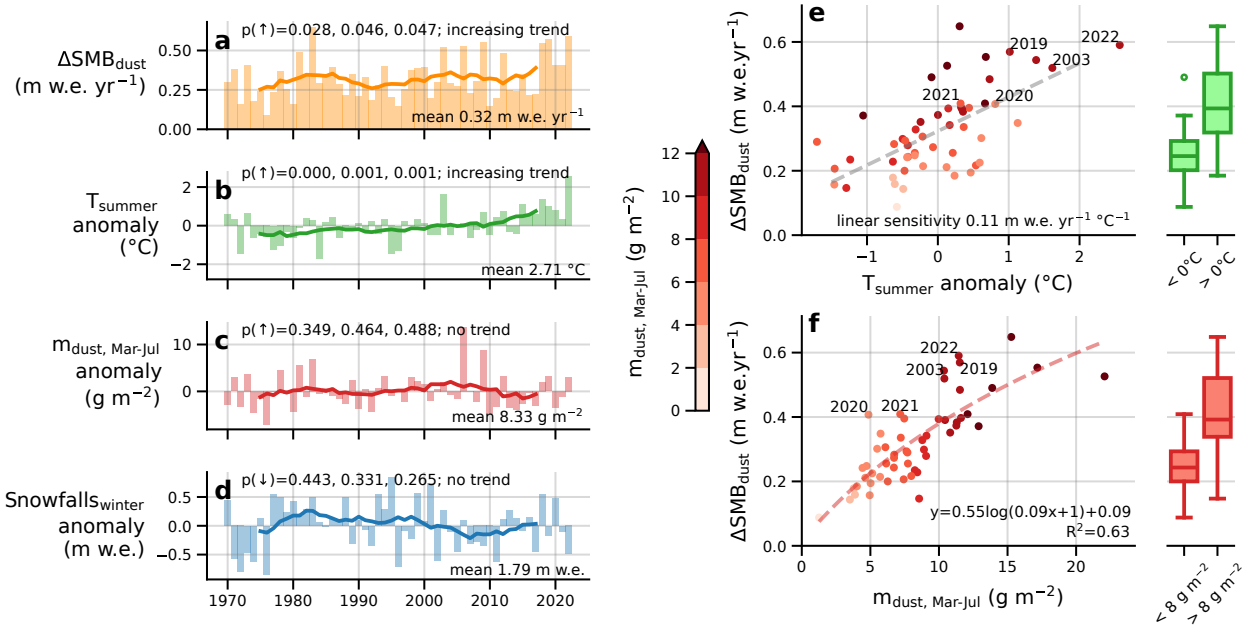


Figure 2: Dust impact and meteorological variables on the glacier of Argentière, France, over the 1970-2022 period. (a) Impact of dust on the SMB anomaly. (b) Summer air temperature anomaly from May to September. (c) Dust deposition between March and July. (d) Winter snowfalls from October to April. Lines are the 11-year running means. The three p-values correspond to Pearson, Spearman, and Kendal tests to either increasing of decreasing trends. Trend is assumed if all p-values are under 0.05. (e) Summer air temperature anomaly vs. dust impact on the SMB, and associated boxplots of the dust impact values divided into two bins. (f) Dust deposition between March and July vs. dust impact on the SMB, logarithmic regression, and associated boxplots of the dust impact values divided into two bins.

Over the period 1970-2022, simulation results show that the mean impact of dust on the annual SMB of Argentière is 0.32 meter water equivalent per year (m w.e. yr^{-1}). This can be seen as the background effect, *i.e.*, under normal annual dust deposition and temperature. The associated standard deviation of 0.13 m w.e. yr^{-1} however demonstrates the large inter-annual variability of the effect of dust on the annual SMB. Over this 50-year period between 1970 and 2022, the impact of dust on the SMB is growing at Argentière (Fig. 2a), as well as the mean summer air temperature increasing by 1.3 °C (Fig. 2b), while the impact of BC does not show this increasing trend (Supp. Fig. 5h). This section will thus focus solely on the effect of dust. Recent years including some of the warmest summers such as 2003, 2019, or 2022 (1σ away from the mean), present an abnormally high impact of dust on the SMB (Fig. 2e-f). For these specific years, the impact of dust on SMB almost doubles, presenting a positive anomaly of up to 0.25 m w.e. yr^{-1}, corresponding to an increase of 1.5 standard deviations with respect to the mean. Based on a linear regression, the sensitivity of SMB to summer temperature increases from 0.84 to 0.94 m w.e. yr^{-1} °C^{-1} when accounting for dust depositions (Supp. Fig. 5i).

In other words, the presence of dust amplifies the sensitivity of Argentière SMB by 11 % to the mean summer air temperature.

While dust affects the long-term sensitivity of Argentière to summer air temperature, the pronounced inter-annual variability in dust deposition strongly modulates the annual impact of dust (Fig. 2f). This inter-annual variability in dust deposition explains more than 50 % of the dust impact variability. Considering the dust deposition only on a restricted period of the year (from 1st March to 31th July, when the radiative impact of dust deposition is the highest) reinforces the correlation between this deposited mass and the impact on the SMB (Supp. Fig. 5a-d). We find that a variation of 5 g m^{-2} of dust (the order of magnitude for an intense dust deposition event, *e.g.*, Dumont et al. (2023)) over this spring/early-summer period of the year, provokes a change of 0.1 m w.e. yr^{-1} in the glacier-wide SMB.

In the current context of climate change, the European Alps have warmed up with an annual air temperature increase of around 0.3°C per decade since 1970 (Dumont et al. (2025), Fig. 2c), and this warming is more pronounced in spring and summer (Rottler et al., 2019). No clear trend in total annual precipitations is observed in the European Alps over the recent period (Bozzoli et al. (2024); Dumont et al. (2025), Fig. 2d), nor in dust deposition fluxes (Fig. 2e, Supp. Fig. 3a). Thus, the increase in sensitivity of glacier SMB to air temperature due to dust cannot be explained by higher deposition fluxes. However, rising air temperature together with conditions favouring glacier melt (Rottler et al., 2019; Philipona et al., 2023) contribute to increasingly negative glacier-wide SMB (Zemp et al., 2025). Another consequence is that the transient snowlines of Alpine glaciers are progressively rising (Hu et al., 2020), leading to more frequent exposure of old firn layers in summer (Supp. Fig. 5g). These intertwined effects amplify the effect of dust (as detailed below and in Fig. 1). Therefore, dust exacerbates the present sensitivity of Alpine glaciers to climate change.

An important conclusion is that a significant increase in LAP deposition fluxes is not required to enhance the impact of LAPs on the SMB. A longer time exposure driven by ongoing warming is sufficient. Previous studies have shown that an increase in LAP deposition fluxes can cause a decrease in SMB (*e.g.* Painter et al. (2013)). Without contradicting this argument, we demonstrate that atmospheric warming also increases the impact of LAPs in snow and hence contributes to a decrease in glacier-wide SMB.

A common pattern of impact for all glaciers

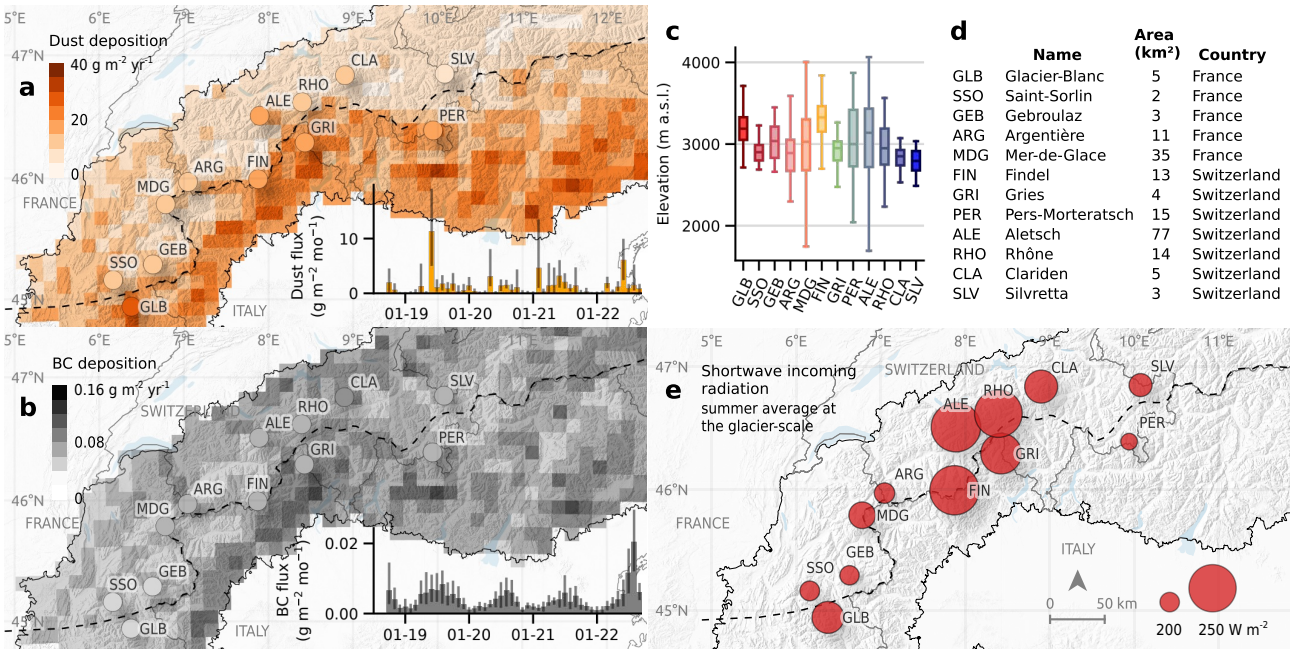


Figure 3: (a) Dust and (b) BC deposition fluxes from ALADIN over the period 2019-2022. Insets show the temporal evolution of the means (colored bars) and the minimum and maximum deposition fluxes (black lines) over the 12 glaciers across the European Alps. The dotted line separates northern from southern Alps (Auer et al., 2007). (c) Elevations of the gridded simulation points on the 12 glaciers (d) Name, area, country of each glacier. (e) Glacier-wide mean incoming summer SW radiation over the period 2019-2022 according to SAFRAN and COSMO inputs (see Methods).

The increasing sensitivity of glacier melt due to dust deposition is caused by the physical processes that involve LAPs described in the first section. We investigate the spatial variability of these processes across the European Alps using simulated glacier SMB over the 2019-2022 period for 12 monitored glaciers in different regions of the European Alps, spanning a wide range of topographies and thus experiencing different meteorological forcing and LAPs deposition fluxes (Figure 3).

Results show that LAP-induced impacts on SMB exhibit similar patterns within each glacier, including Argentière (Figure 4). The key zone where the impact of LAPs is maximal is located in the ablation area below the ELA (annual SMB between -4 and 0 m w.e. yr^{-1}). These maximum impacts range from 0.4 to 1.5 m w.e. yr^{-1} for dust (from 5 to 40 % of the annual summer melt) and 0.1-0.9 m w.e. yr^{-1} for BC (from 3 to 25 % of the annual summer melt) depending on the glacier. Over all glaciers, we find that a variation of 5 g m^{-2} of the annual dust deposition provokes a variation of 0.16 m w.e. yr^{-1} on this key zone. For the year 2022, characterized by very negative mass balance, we quantify the impact of dust in old firn layers by removing all dust content in snow and firn from the previous years (see Methods). In 2022, results show that

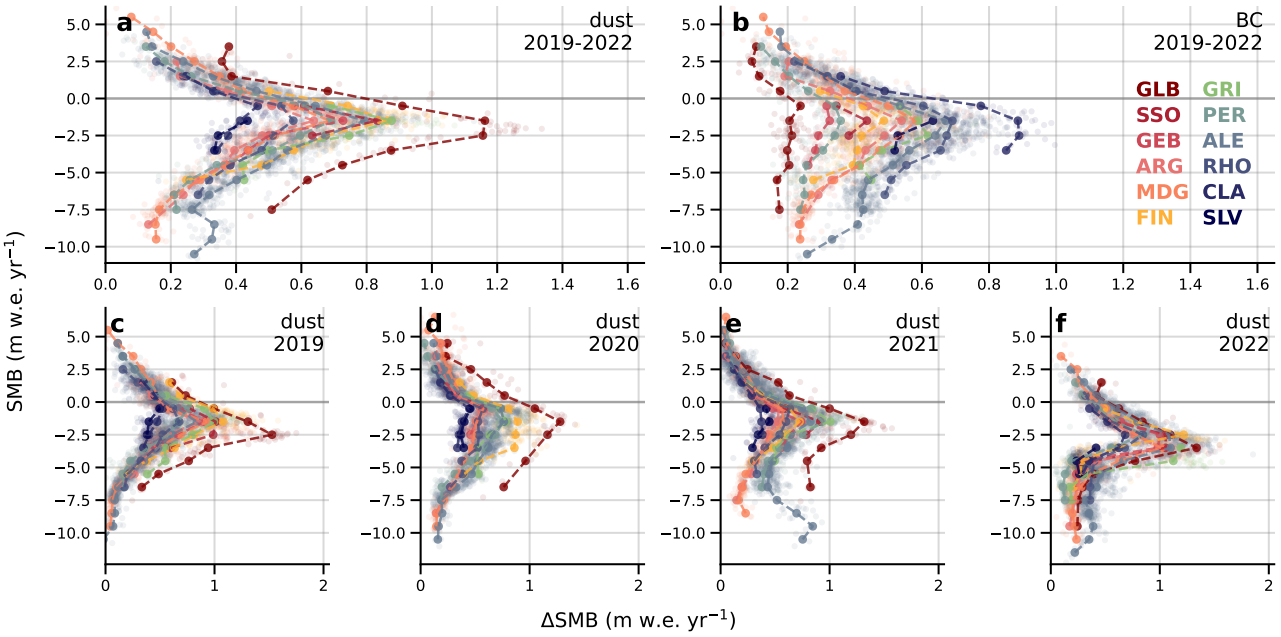


Figure 4: Annual impacts of (a) dust and (b) BC on the surface mass balance of the investigated glaciers, specified according to mean annual mass balance 2019-2022. Bins of 1 m w.e. yr^{-1} are plotted if they contain at least three grid cells. (c-f) Impact of dust on the surface mass balance of individual years.

dust stored in the old layers of firn accounted on average for 4 to 24 % of the simulated annual glacier-wide dust impact depending on the glacier, and 13 to 37 % when restricted to areas where old firn layers were exposed. A lower impact of LAPs is found in the accumulation area (SMB > 0 m w.e. yr^{-1}), as well as in the lowest part of the ablation area (SMB < -4 m w.e. yr^{-1}). Interestingly, for negative SMB, the decrease in LAPs impact with decreasing SMB is more pronounced for dust than for BC, (Fig. 4a,b), likely due to the recurrent winter deposition of BC, whereas dust deposition events are scarce during winter (Supp. Fig. 3b,d).

In summary, our four-year analysis across 12 Alpine glaciers reveals a consistent pattern in the impact of LAPs, with the strongest effects occurring in the ablation area close to the ELA. This demonstrates once more that when SMB distributions are shifting towards increasingly negative values, the impact of LAPs is amplified. Hence, this explains why the sensitivity of these glaciers to rising air temperature is enhanced by the presence of dust, even in the absence of an increasing trend in dust deposition.

The contrasted signature of dust and black carbon on Alpine glaciers

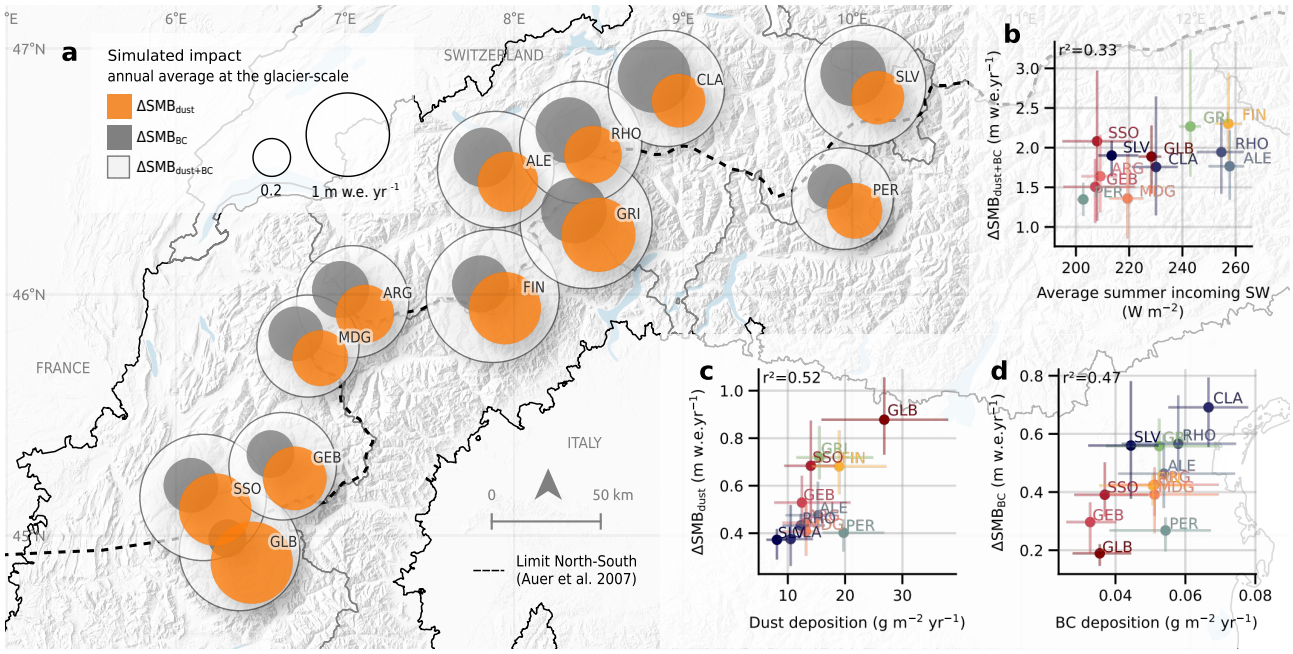


Figure 5: (a) Average glacier-scale surface mass balance impact for dust, BC, and dust + BC combined, over the period 2019-2022. The dotted line separates northern from southern Alps (Auer et al., 2007). (b) Annual dust impact on the surface mass balance vs. dust deposition flux. (c) Annual BC impact on the surface mass balance vs. BC deposition flux. (d) Annual impact of dust + BC combined on the surface mass balance vs. incoming summer SW radiation, over the period 2019-2022 at the glacier-scale. Lines in the scatter plots show the annual minimum and maximum.

Compared to other glaciers, the combined effect of dust and BC is weaker on the north-facing glacier of Argentière (Fig. 5a). While LAPs directly lower snow albedo and enhance absorbed SW radiation, the glacier topography, characterized among other factors by its slope, aspect, and sky view factor, modulates the incoming, and therefore, the absorbed SW radiation (Fig. 3d-e). Higher SW inputs amplify the effect of LAPs (Fig. 5b). For instance, the combined impact of dust and BC reaches 1.6-3.0 m w.e. yr^{-1} on Findel or Gries that both receive higher incoming SW radiation compared to the other studied glaciers (Fig. 3d). In contrast, for north-facing glaciers located in deep valleys such as Argentière or Gébroulaz, the combined impact of dust and BC is lower (0.5-1.7 m w.e. yr^{-1}).

Results also show that the marked spatial patterns in dust and BC deposition drives their respective impacts (Fig. 3a-b, Fig. 5a,c-d). The effect of dust on the melt of Alpine glaciers prevails over BC on the southern part of the European Alps (Fig. 5a). From 2019 to 2022, the simulated impact of dust reaches 0.6-1.2 m w.e. yr^{-1} for glaciers such as Glacier-Blanc, Findel or Gries (Fig. 5a), which is respectively equivalent to 21, 19, 17 % of the annual melt (including snow and ice-melt) for each glacier. Comparatively, BC accounts for 0.25-0.55 m w.e. yr^{-1} on these glaciers located in the South of France or near the Swiss-Italian border. Using a linear

regression over the 12 selected glaciers, the sensitivity of the annual SMB to the dust deposition fluxes is 0.024 m w.e. g^{-1} m^2 for dust and 0.010 m w.e. mg^{-1} m^2 for BC, meaning that an annual addition of 5 g m^{-2} of dust would decrease the annual SMB of 0.12 m w.e. yr^{-1}. We note that the sensitivity to dust deposition is comparable to that found for the long-term simulation on the glacier of Argentière.

Furthermore, despite the pronounced inter-annual variability in dust deposition (*e.g.*, 8.3 ± 3.7 g m^{-2} for mean and standard deviation of dust deposited over the period 1970-2022 at Argentière), the spatial pattern of dust deposition, featuring a strong north-south spatial gradient (Fig. 3a), has been stable over the last 70 years (Supp. Fig. 3a). Dust deposition occurs mostly by wet deposition (*e.g.*, Vincent et al. (2016)), and deposition events are mainly associated with weather regimes including a southern flow (Baladima, 2021), explaining the preferential deposition on the southern part of the European Alps. Since the amount of deposited LAPs drives its impact (*e.g.*, Fig. 5c), this spatial contrast can be seen as a recurring radiative forcing, possibly influencing the long-term altitude of the equilibrium lines in the southern and northern parts of the European Alps differently, and ultimately affecting the present extent of Alpine glaciers (Rabatel et al., 2005).

Implications for the current and future state of Alpine glaciers

All in all, the orange color of dust, which appears on the glacier surface as the transition between the whiteness of snow and the blue-grayish color of ice, acts as a leverage effect on the melting of Alpine glaciers with rising air temperature. In the present climate, glacier-wide SMB are negative in the European Alps (middle orange distribution in Fig. 1b). Given that dust increases the sensitivity of SMB to temperature by 11 % over the period 1970-2022, lower temperature and positive glacier-wide SMB (upper green distribution in Fig. 1b) would reduce the effect of dust in snow on average. In this case, LAPs would only be active on the lowest part of the glacier, and most of the LAPs at intermediate and top elevations would stay buried.

Since air temperature is projected to continue to increase in the future until net greenhouse gas emissions reach zero (Dumont et al., 2025), one could argue that the effect of LAPs in snow will continue to grow leading to increasingly negative glacier-wide SMB in the future (lower red distribution in Fig. 1b). However, it is likely that the amplification of the sensitivity of glacier SMB to air temperature due to dust is reaching a maximum nowadays in the absence of future trends of dust deposition. Indeed, with the projected increase in ELA, the share of bare ice surfaces will increase at the expense of snow and firn surfaces, hence leading to less active LAPs in snow due to a snowpack vanishing quickly for most elevations. For this reason, we hypothesize the existence of a present peak of dust impact on glacier mass balance.

Method

Studied glaciers

We selected 12 glaciers in the European Alps either located in France or in Switzerland. These glaciers are closely monitored (by the GLACIOCLIM observatory for the French glaciers, and by the programme Glacier Monitoring Switzerland (GLAMOS) for the Swiss glaciers, see Data Availability), regularly distributed over the European Alps, with diverse topographic characteristics listed in Supp. Table 1. Constant glacier outlines referring to the year 2015 are used from Paul et al. (2020) for French glaciers and from the Swiss Glacier Inventory 2016 (Linsbauer et al., 2021) for Swiss glaciers, except for the long-term simulation over the period 1970-2022 on the glacier of Argentière. In the latter case, we use a linear interpolation between outlines (i) from year 1967 with the associated outlines from Gardent et al. (2014) and (ii) the recent outlines from Paul et al. (2020).

Mass balance and surface reflectance data

Point SMB measurements for winter accumulation and summer ablation are provided by the French and Swiss monitoring programmes (see Data Availability). The number of point SMB measurements for each glacier is listed in Supp. Table 2. For the long-term simulation on Argentière, we also use the glacier-wide SMB provided by the GLACIOCLIM observatory. The cumulative glacier-wide SMB is computed as the sum of the successive annual glacier-wide SMB.

We use Sentinel-2 bottom-of-atmosphere reflectances from Theia (see Data Availability). The Sentinel-2 tiles associated to every glacier are listed in Supp. Table 2. For each glacier, 4 to 5 cloud-free images are selected each year. Then, we derive a surface type, a mean snowline elevation and a snow albedo from each Sentinel-2 image, and a broadband ice albedo for each glacier, as detailed in Roussel et al. (2025). In short, the surface type is derived using an approach based on thresholds on the Sentinel-2 bands B3, B4, and B11, and a cloud mask. The mean snowline elevation is computed as the limit in elevation where the area of snow exceeds that of ice (Roussel et al. (2025), Appendix Fig. B2). Snow albedo is estimated using the method of Liang et al. (2003).

Meteorological data

For French glaciers, air temperature and specific humidity at 2 m, wind speed and direction, rainfall and snowfall rate, longwave incoming radiation, shortwave direct and diffuse radiations, are provided at hourly time steps by the SAFRAN reanalysis (Vernay et al., 2022). SAFRAN provides hourly meteorological data at the mountain massif scale (around 1,000 km^2) with a 300 m vertical resolution interpolated at each simulation point using its exact elevation following (Revuelto et al., 2018). Moreover, direct shortwave radiation is masked out using an

illumination mask at 5° resolution computed for each simulation point.

For Swiss glaciers, meteorological forcing data at 250 m horizontal resolution were provided by SLF's Operational Snow Hydrological Service (OSHD) (Mott et al., 2023). The dataset provided by OSHD is based on the COSMO analysis (1 km resolution), and downscaled to model resolution using a combination of statistical (*e.g.*, for wind speed) and dynamical (*e.g.*, for shortwave radiation) approaches described in Mott et al. (2023). Moreover, precipitation fields are corrected by assimilation of snow depth station data by an optimal interpolation scheme (Magnusson et al., 2014).

Light-absorbing particles deposition data

Dust and BC hourly deposition fluxes are obtained from a hindcast simulation of the CNRM-ALADIN63 regional climate model (Nabat et al., 2020) spanning the 1959-2022 period, driven by the ERA5 reanalysis (Hersbach et al., 2020). ALADIN includes a prognostic aerosol scheme, called TACTIC (Tropospheric Aerosols for Climate In CNRM), originally coming from Morcrette et al. (2009) and used in global and regional climate models Michou et al. (2015, 2020). The domain of the model used here includes the Saharan desert with a southern limit roughly corresponding to +15°N (Nabat et al., 2020). The emissions of dust are computed by the model as a function of surface wind and soil characteristics (Nabat et al., 2020). Then, mineral dust is a prognostic variable of the model subject to atmospheric processes (transport and deposition). Anthropogenic and biomass burning emissions (including BC) are based on monthly inventories varying from year to year, namely the CEDS v2021-04-21 dataset for historical anthropogenic emissions (O'Rourke et al., 2021) up to 2019, extended up to 2022 following the study of Lamboll et al. (2021), and the GFED4.1s dataset (Randerson et al., 2017) for biomass burning emissions. The horizontal grid resolution of ALADIN is 12.5 km. For a given glacier, outputs of the closest grid point are used for all simulation points as in Roussel et al. (2025). ALADIN wet and dry depositions are redistributed with respect to the SAFRAN or COSMO precipitations as in Réveillet et al. (2022) or Roussel et al. (2025), *i.e.*, wet depositions when precipitations are strictly positive, dry depositions otherwise. LAP deposition fluxes from ALADIN have been compared with in situ measurements in Tuzet et al. (2020) and their impacts on the snow melt-out date have been evaluated in Réveillet et al. (2022) using MODIS snow products.

Forcing corrections

Air temperature of both SAFRAN and COSMO dataset is adjusted to account for the decoupling of glacier temperature from their surroundings (Shaw et al., 2023, 2024, 2025). We use here the same correction method as in Roussel et al. (2025), including a correction above 276.65 K with a temperature sensitivity of 0.76 (K/K). The amount of solid precipitations is adjusted distinctly for each glacier using the same method as in Roussel et al. (2025) over the period 2019-2022. This adjustment of solid precipitation for the long-term simulation

on Argentière is also calibrated on the period 2019-2022. Incoming longwave radiation LW from both datasets depicts large discrepancies compared to the LW measurements from the AWS localized on a lateral moraine of Argentière (see Roussel et al. (2025) for its precise location), with biases of +1.3 W m^{-2} for the SAFRAN dataset and -9.4 W m^{-2} for the COSMO dataset on the period 01/09/2021-01/08/2022. To harmonize the two datasets with the observations, we minimize the function $|\mathrm{LW_{AWS}} - (\mathrm{LW} + \alpha\sigma \mathrm{T}^4 + \beta)|$ at the AWS for each dataset using non-linear least squares over the period 01/09/2021-01/08/2022, where T is the 2 m air temperature of each dataset, σ is the Stefan–Boltzmann constant (5.67×10^8 W m^{-2} K^{-4}), α (-) and β (W m^{-2}) are the parameters to be optimized. Results yields (α, β) = (-0.353, 114.8 W m^{-2}) for the SAFRAN dataset, and (α, β) = (0.075, -15.4 W m^{-2}) for the COSMO dataset. The correction $\mathrm{LW_{corrected}} = \mathrm{LW} + \alpha\sigma \mathrm{T}^4 + \beta$ is applied to all glaciers.

Surface mass balance model

We perform gridded simulations of SMB at 250 m horizontal resolution within glacier outlines as in Roussel et al. (2025), using as inputs the meteorological data detailed above. We use the detailed snowpack model SURFEX/ISBA-Crocus (Lafaysse et al., 2025), which has already been used to simulate glacier SMB, (*e.g.*, Gerbaux et al. (2005); Dumont et al. (2012b); Réveillet et al. (2018)). Crocus simulates the evolution of the snow cover, with a time-step of 15 minutes, representing different processes including thermal diffusion, phase change, water flow, snow metamorphism and compaction. Snow optical properties (single scattering albedo and absorption cross section for each snow layer) are calculated from prognostic variables of the model (surface specific area, density, layer thickness). No ice flow dynamic is accounted for in the model, LAPs are therefore not transported to lower locations. In Crocus, the snowpack is discretized as a one dimensional column with up to 50 layers, each of them having its own snow/ice properties and LAPs concentrations. An initial state of the glacier is prescribed at each simulation point, with a vertical column of several ice layers with a density of 917 kg m^{-3} as in Gerbaux et al. (2005); Dumont et al. (2012b); Vionnet et al. (2019). The resulting height H_0 of the total column is initially set to an arbitrary value of 165 m w.e., with a temperature of 0 °C. For the long-term simulations on Argentière during which a higher amount of ice is melted, the initial height of ice H_0 is set to up to 825 m w.e. for the lowest elevations of Argentière. The roughness length of snow z_0 is set to 0.1 mm, and the roughness length of ice is set to $10 \times z_0$. This ratio between snow and ice roughness length is kept constant for the entire study and for all the 12 glaciers. These values of roughness length are inside the usual ranges described in Cuffey, Paterson (2010). Ice albedo is used when the density of the surface layer is higher than 850 kg m^{-3}. Ice albedo is constant in space and time for each glacier, inferred from Sentinel-2 images using the same method as in Roussel et al. (2025) (values listed in Supp. Table 2). Crocus outputs are collected every 6 hours for all simulation points. We derived the simulated surface type from the mean density of the top 5.0 cm: ice if this density is higher than 850 kg m^{-3} (Cuffey, Paterson, 2010), else snow.

Compared to Roussel et al. (2025), additional modifications of the Crocus model are incorporated in this

study. LAPs located at a snow depth deeper than 10.0 m w.e. and inside a snow layer older than 5 years are deleted from the simulation, which allows the model to keep a detailed vertical discretization near the surface in case snow accumulates from year to year on long time duration. Moreover, the basal heat flux at the base of the entire snow/ice column is set to 0 W m^{-2} to ensure we consider only surface melt.

Simulation setup and metrics

Gridded simulations included two phases. First, the spin-up over the period 2008-2018. Since COSMO data are only available for the period 2016-2023, we repeatedly used the inputs of the hydrological year 2020 to force the SMB model during the spin-up phase for the 12 glaciers. The glacier-wide SMB of the year 2020 ranks as a representative year compared to the period 2008-2017 for all glaciers except for Glacier-Blanc (Supp. Table 2). For the case of long-term simulations on Argentière, the spin-up period is 1959-1970. Initially, a column of temperate ice is prescribed for all simulations, and the spin-up aims to initialize the LAPs contents in old firn in the accumulation area and as well as the temperature profile of the ice column. Second, the simulations are done on the period of interest: 2019-2022 for all simulations, except 1970-2022 for the long-term simulation on Argentière.

We remind that LAPs only have a radiative effect in snow and firn in the present study, not in ice, as in Roussel et al. (2025). For each simulation point, we run 4 simulations including the radiative impact on the SMB of both dust and BC (*i.e.*, all LAPs), dust, BC, and without both dust and BC (*i.e.*, without LAPs). As a result, the three different impacts on the SMB (i) ΔSMB_{dust}; (ii) ΔSMB_{BC}; (iii) $\Delta SMB_{dust+BC}$ (m w.e. yr^{-1}) are the differences in SMB between the simulations (i) with BC vs. all LAPs; (ii) with dust vs. all LAPs; (iii) without any LAPs vs. all LAPs, respectively. To quantify the role of the different feedbacks involved, we also calculate the effect of LAPs restricted to the period of simulation with only snow or firn at the surface, hence not accounting for the ice-albedo feedback. This method shows similar patterns of impacts on the SMB (Supp. Fig. 4).

Finally, we run additional simulations, used in section , in which we remove all the dust content in snow and firn stored before 01/10/2021. The difference in dust impact simulated in this set-up and the one simulated in the normal set-up described above is used to assess the impact of dust in old layers of firn from previous years during the hydrological year 2022.

Evaluation results

Evaluations of the simulated SMB over the period 2019-2022 including the radiative impact of dust and BC are presented in Supp. Fig. 1-2. Point winter accumulation measurements (Supp. Fig. 1a, 2a) using stakes are used to calibrate solid precipitation, thus they are not part of the evaluation data. Simulated point summer ablations show mean absolute errors between -1.1 and 0.6 m w.e. yr^{-1} against stake measurements of summer ablation

depending on the glacier (Supp. Fig. 1b,2b and Table 3), indicating that the model tends to overestimate the summer SMB. The corresponding root mean square errors range from 0.56 to 1.3 m w.e. yr^{-1} depending on the glacier. Since our simulation framework uses only the observed winter accumulation from stakes measurements to correct the inputs, these results are in line with methods that use a limited amount of data to be calibrated. For instance,Réveillet et al. (2017) used different models with the calibration of glacier-specific parameters (*e.g.*, degree-day or temperature-index models) to retrieve the SMB of 4 monitored French glaciers, and obtained root mean square errors between 0.51 and 0.94 m w.e. yr^{-1} depending on the model and the glacier. Relying on model calibration using snow-covered area fraction observations and long-term mean mass balance, Cremona et al. (2025) obtained mean absolute errors ranging from 0.17 to 0.51 m w.e. on the annual mass balance of Swiss glaciers over the period 2015-2023. Finally, Kneib et al. (2024) retrieved distributed SMB from stereo images and ice thickness measurements, obtaining root mean square errors between 0.5 and 1.0 m w.e. yr^{-1} over the period 2012-2021 against stake measurements of annual SMB at Argentière.

The simulated mean transient snowline elevations against the observed mean transient snowline retrieved using Sentinel-2 (Supp. Fig. 1e,2e) show mean errors between -20 and 120 m depending on the glacier (root mean square error between 100 and 200 m). The comparison between the modelled snow albedo and the observed albedo retrieved from Sentinel-2 images yields mean biases between -0.07 and 0.09 depending on the glacier, and root mean square errors between 0.05 and 0.14, demonstrating the ability of the model to reproduce the snow albedo with lower values (*e.g.*, < 0.5) for some of the glaciers exposed to the high fluxes of dust deposition (*e.g.*, Mer-de-Glace, Saint-Sorlin, Gebroulaz, Glacier-Blanc, Gries). These root mean square values correspond, for example, to those obtained between satellite and in-situ observations (Dumont et al., 2012a). However, this comparison has to be taken with cautious since the observed albedo is derived using the method of Liang et al. (2003). This method exhibits several limitations. First, it does not account for the anisotropy of light reflected by snow and ice (*e.g.*, Dumont et al. (2010)). Second, the uncertainties of the reflectance retrievals in complex terrain may be too high to estimate the accuracy of the simulated albedo (*e.g.*, Cluzet et al. (2020)). All in all, the evaluation of the simulations on different variables, namely summer melt, mean snowline elevation and albedo, using both satellite data and in situ measurements, demonstrate the robustness of the simulated SMB.

Concerning the evaluations of the long-term simulations over Argentière, Pearson's r^2 between glacier-wide simulated and observed SMB over the period 1976-2022 is 0.76 (Supp. Fig. 5e). Global variations of the cumulative SMB are well captured (orange curve vs. black dots in Supp. Fig. 5f), except in the 90s where the model shows a positive bias, *i.e.*, lower glacier-wide SMB in the observations. The simulations without the radiative effect of dust (blue curve in Supp. Fig. 5f) do not capture the variations of the observations. In addition, simulations without dust show a difference in cumulative SMB of +21 m w.e. yr^{-1} compared to the observations over the period 1976-2022, while the simulations accounting for the effect of dust show a difference of +4 m w.e. yr^{-1}.

Limitations

This study highlights the evolution of the dust impact on SMB over the last 60 years and the varying role of LAPs, depending on the glacier location and topography. Uncertainties on the deposition fluxes and impacts of LAPs have been previously quantified on Argentière (Roussel et al., 2025) showing that (i) the role of avalanches, which is not taken into account, may reduce the impact at specific locations where gravitational redistribution occurs; (ii) a variation of ± 20 % of LAP deposition fluxes induces a variation of 15 % on their impact; (iii) this variation of 15 % of the impact corresponds to the same order of magnitude than the meteorological uncertainty; (iv) an increase in the modelled scavenging efficiency of BC increases the impact of dust and decreases the impact of BC. While affecting the absolute impact of each type of LAP, such uncertainties do not modify the main conclusions of this study, since this study focuses on relative differences between simulations, as in Réveillet et al. (2022).

For long-term simulations, Argentière is selected because (i) it is a historical monitoring site with several decades of SMB measurements, (ii) its dust and BC impacts are close to the median of the 12 studied glaciers (Fig. 4), and (iii) its SMB is broadly representative of the European Alps, with a mean value of -0.8 m w.e. yr^{-1} since 1976 (GLACIOCLIM), compared to -0.6 m w.e. yr^{-1} reported for the entire central European region (WGMS, Dussaillant et al. (2025)). For these long-term simulations, we use varying outlines with time to account for the shrinking of the glacier (see Methods). This has only a small effect on the results compared to using constant outlines (the sensitivity of SMB to summer temperature increases from 0.85 to 0.96 m w.e. yr^{-1} $°C^{-1}$ when accounting for dust with constant outlines, compared to an increase from 0.84 to 0.94 using changing outlines). In addition, the progressive decrease in BC emissions and depositions (Supp. Fig. 3c, Supp. Fig. 5h) could have been a possible reason to justify the increase in dust impact as explained in Roussel et al. (2025). However the relationship between BC deposition and the impact of dust on the SMB is weak. The median-Q25-Q75 of dust impact are 0.34 [0.23, 0.41] m w.e. yr^{-1} for the lowest annual BC deposition, and 0.28 [0.21, 0.37] m w.e. yr^{-1} for the highest BC deposition (Supp. Fig. 5i), suggesting that the role of BC deposition decrease in not prevailing.

1 Code and Data Availability

Sentinel-2 products are distributed by Theia (https://geodes-portal.cnes.fr). The point SMB data are obtained from the GLACIOCLIM observatory (https://glacioclim.osug.fr/) and from the GLAMOS programme (https://doi.org/10.18750/massbalance.point.2023.r2023). SAFRAN meteorological forcings are distributed at https://doi.org/10.25326/37#v2024.1. The SRTM DEM are available at http://srtm.csi.cgiar.org,lastaccess01/06/2025. The corrected forcings and results files used in this study are available at https://doi.org/10.5281/zenodo.20645194; https://doi.org/10.5281/zenodo.20644814; https://doi.org/10.5281/zenodo.20698807; https://doi.org/10.5281/zenodo.20700129. Code used for this study is available at https://doi.org/10.5281/zenodo.20699381.

2 Competing interests

The authors declare that they have no conflict of interest.

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