

Seasonal evolution of suncup roughness describes broadband albedo decay on alpine snow

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Abstract. We monitored the formation and seasonal evolution of suncup roughness over three snow ablation seasons at Weissfluhjoch, ~~Swiss Alps, in the Swiss Alps~~ using a terrestrial LiDAR scanner. ~~Suncup onset required two concurrent conditions, identified from~~ From high-temporal-resolution digital surface models ~~of surface roughness: sustained surface melting through most of the day,~~ we find that suncup onset required three concurrent conditions: sustained daytime surface melting,
5 above-freezing wet-bulb temperatures, and reduced wind speeds. Suncups formed in all three years, but their planar arrangement and ~~geometric properties varied substantially across seasons~~ geometry varied substantially, controlled by whether radiative or turbulent ~~heat-exchange conditions~~ dominated ablation. Comparing measured broadband albedo to flat-surface ~~simulations from TARTES~~ TARTES simulations forced by SNOWPACK-modelled snow properties, we find that ~~the combined effect of~~ suncup roughness and surface impurity loading ~~reduces albedo by 0.02~~ together reduce albedo by 0.03–0.15, depending on
10 illumination geometry and impurity load, consistent with previous ~~literature work~~. Isolating the two contributions is complicated by their co-evolution ~~during the ablation season~~: the same melt processes that ~~progressively~~ deepen suncups also drive surface enrichment and the spatial redistribution of impurities. ~~Resolving the two effects independently would in principle require equally fine-scale measurements of both roughness and impurity distribution. We,~~ which are uniformly distributed during early suncup formation but concentrate into the hollows as melt progresses. As a practical alternative, we identify a robust
15 logarithmic ~~correlation relationship~~ between broadband albedo and the aerodynamic roughness length ~~that simultaneously captures the radiative effects~~ z₀ that captures the combined radiative effect of roughness and impurities, regardless of their relative ~~contributions~~. During early suncup formation, impurities remained uniformly distributed. At later stages, meltwater scavenging concentrated impurities to the suncup hollows. As the rate of broadband albedo decay is strongest at the beginning contribution. Because broadband albedo decays fastest at the onset of suncup formation ~~and relaxes thereafter~~, we infer that
20 ~~the interaction between the multiple-reflection mechanism and the more uniform distribution of impurities~~ a uniform early impurity distribution is particularly effective ~~in accelerating albedo decay, beyond the effect of either factor alone~~. Given that C-band SAR backscatter is sensitive to the early development of surface roughness on wet snow, these findings encourage future work on the assimilation of surface roughness into snow energy balance models at accelerating albedo loss. Because z₀ evolves by one order of magnitude through ablation, yet is kept constant in most snow models, our results call for its explicit,

25 time-varying representation of z_0 in physics-based snow models, which would improve both the turbulent fluxes z_0 governs directly and, through its link to albedo, the roughness–impurity darkening.

1 Introduction

Snow is the most ~~reflecting~~ reflective natural surface on Earth, scattering up to 98% of incident solar radiation in its pristine state (Wiscombe and Warren, 1980). Therefore, even marginal decreases in albedo substantially increase the proportion of absorbed solar energy. Because seasonal snow can cover up to ~~the~~ 50% of the Northern Hemisphere each year (Armstrong and Brodzik, 2001), even small albedo reductions have large effects on the Earth’s energy budget (Flanner et al., 2011). Several factors determine albedo decreases in snow, and they often concur in a complex way: snow metamorphism reducing the specific surface area (SSA) of the grains (Wiscombe and Warren, 1980; Domine et al., 2006), the grain shape (Robledano et al., 2023; Libois et al., 2014, 2013), the presence of liquid water at the surface (Dumont et al., 2017), the incident angle (Warren, 1982), the concentration of light-absorbing particles (LAPs; Skiles et al. (2018)), and the presence of surface roughness features (Warren et al., 1998; Zhuravleva and Kokhanovsky, 2011). Surface roughness has received less attention than other albedo drivers, partly because it is ~~very~~ highly heterogeneous across spatial scales (Fassnacht et al., 2023), making it difficult to identify the scale most relevant to the ~~radiative footprint of the measuring sensor~~ sensor’s radiative footprint. Yet, since snow surfaces are rarely flat, roughness is ~~the primary physical cause of the divergence between intrinsic albedo (i.e., the bihemispherical reflectance of a substance, Schaepman-Strub et al. (2006)) and apparent~~ an important physical factor governing the effective albedo (i.e., the ratio of reflected to incident radiation ~~over a rough surface~~), which can differ substantially from the bihemispherical reflectance measured (or modeled) for a flat surface (Schaepman-Strub et al., 2006). In the context of surface energy balance, the ~~apparent~~ effective albedo is the physically meaningful quantity, ~~since pyranometer-based measurements inherently integrate the effects of surface roughness within~~ because it determines the net shortwave radiation absorbed by the rough snow surface. Pyranometer-based measurements capture effective albedo because they inherently integrate roughness effects into their radiative footprint (Bair et al., 2016, 2015).

In the accumulation phase, macroscopic surface roughness features such as sastrugi, ripples, and dunes often result from snow transport or ~~erosion by wind~~ wind erosion (Sommer et al., 2018; Amory et al., 2017; Filhol and Sturm, 2015). Many studies ~~showed~~ have shown systematic albedo decreases in the presence of such features (Corbett and Su, 2015; Leroux and Fily, 1998; Carroll, 1982), which can reach several meters in height (Warren et al., 1998). In the ablation phase, at ~~high-altitude~~ high-elevation, arid environments where snow ablation is driven by sublimation rather than melting, snow penitentes form (Betterton, 2001; Lliboutry, 1954). They appear as snow pillars pointing ~~towards the sun~~ toward the sun, potentially reaching several meters in height, and ~~cause apparent albedo to drop~~ can drop apparent albedo by up to 0.4 (Lhermitte et al., 2014; Corripio and Purves, 2005). Penitentes do not form in the Alps under current climatic conditions, where humidity is too high, and melting dominates over sublimation. However, ~~high-alpine~~ high-Alpine snowfields at mid-latitudes develop ~~their own characteristic ablation roughness~~ characteristic ablation roughness features in the form of ablation hollows, more commonly referred to as suncups. Suncups show up as a quasi-periodic natural pattern composed of round, concave dimples that can grow

vertically and laterally by ~~up to tenths of more than 10~~ centimeters, separated by rounded ridges (Betterton, 2001; Rhodes et al., 1987; Matthes, 1934). According to ~~Betterton (2001); Lliboutry (1954)~~ Betterton (2001) and Lliboutry (1954), suncups
60 are early forms of penitentes, sharing the same initial instability mechanism, ~~i.e.:~~ radiation clustering in concavities ~~creating~~
creates a positive feedback that deepens the hollows.

The albedo decay over a rough snow surface is controlled by two mechanisms that activate under different illumination conditions: (1) the effective-angle effect and (2) multiple reflections in the hollows (Warren et al., 1998). The effective-angle
refers to a simultaneous effect ~~effect refers to the simultaneous influence~~ of surface features facing both the sun and away
65 from the sun. The former receive solar radiation at a smaller incidence angle than the solar zenith angle, causing stronger absorption; the latter are either shadowed or ~~only illuminated~~ illuminated only at grazing angles and therefore contribute
~~marginally little~~ to the total reflected flux. The insolation-weighted albedo of a rough surface is therefore reduced with respect to that of a flat surface under equivalent illumination conditions (Kokhanovsky and Zege, 2004; Warren et al., 1998; Warren, 1982). This effect varies with the shape and orientation of the roughness features (Larue et al., 2020; Lhermitte et al., 2014)
70 and only activates in conditions of direct illumination and larger solar zenith angles (Warren et al., 1998). The ~~multiple reflections~~ multiple reflections effect activates because, on a rough surface, the probability of photons being trapped inside concavities rather than being scattered away is higher than it is for a flat surface. After each collision with the roughness walls, the probability ~~of light being that light is~~ absorbed rather than reflected increases. This causes a systematic increase in absorption, especially in conditions where reflection and absorption are balanced, i.e., for values of albedo close to 0.5 in
75 the near-infrared (NIR, ~~700-1100~~ 700-1400 nm) (Bair et al., 2022; Larue et al., 2020). This effect is active under both direct and diffuse illumination ~~conditions~~. Because it operates in the near-infrared and vanishes where snow albedo approaches 1, its broadband imprint is unlikely to be larger under the visible-dominated overcast spectrum than under a clear-sky beam.

As an alpine snowpack melts, its surface is simultaneously rugged by suncup growth and progressively darkened by the enrichment of LAPs such as black carbon or mineral dust. LAPs are fundamental drivers of albedo reductions (Warren and
80 Wiscombe, 1980) both directly, as they enhance solar energy absorption in the visible range (400-700 nm), and indirectly, as they accelerate near-surface SSA decrease that further decreases albedo (Skiles and Painter, 2019; Tuzet et al., 2017). Specifically, as the snow melts, black carbon and dust are retained at the snow surface because the scavenging ~~efficiency effect~~
of percolating meltwater is ~~less than 100%, causing surface concentrations to increase~~ generally inefficient (Doherty et al., 2013; Sterle et al., 2013; Conway et al., 1996), especially for particles of greater size like aeolian dust (Tuzet et al., 2017; Yang et al., 2015). This can increase surface
85 concentrations by up to a factor of 5 during extreme melt events, an effect referred to as melt amplification (Doherty et al., 2013; Conway et al., 1996). Moreover, in late spring, algal populations of *Sanguina nivaloides* can proliferate quickly and form red blooms near the snow surface (Stewart et al., 2021). Algae reduce the albedo of snow surfaces similarly to LAPs, but unlike LAPs, their proliferation depends on specific environmental conditions, and it is not a systematic feature of snowmelt. ~~In their recent work~~ Recently, Roussel et al. (2024) demonstrated that proliferation of *S. nivaloides* requires a snowmelt duration
90 exceeding 46 days and is unlikely when the ground beneath the snowpack is frozen. ~~The authors further suggest that nutrients supplied by Saharan dust~~ Nutrients supplied by aeolian dust deposition may also drive algal blooms.

Isolating the effect of suncups on albedo is therefore not straightforward, particularly as the environmental conditions governing suncup development, melt amplification, and algal proliferation vary between seasons, complicating the derivation of general conclusions. In experiments with artificially modified snow surface roughness, Larue et al. (2020) disentangled and quantified the effective-angle and ~~multiple-reflections~~multiple-reflections effects, introduced above. They found that roughness reduced albedo by up to 0.1 at 1000 nm, that both effects are amplified when SSA is low ($<10 \text{ m}^2 \text{ kg}^{-1}$), and that the effective-angle effect enhances rapidly at large solar zenith angles. Manninen et al. (2021) and Bair et al. (2022) validated the framework of Larue et al. (2020) on natural snow roughness: a surface that, in the case of suncups, would be almost impossible to replicate artificially. Importantly, Larue et al. (2020) did not account for the concomitant effect of LAPs. Manninen et al. (2021) monitored roughness, broadband albedo, and spectral reflectance in Finnish Lapland for a total of 3 months over two years. They showed ~~how-that~~ centimeter-scale surface roughness, comparable to that of suncups, decreased the broadband albedo by 0.1 during the late melting season, especially ~~for-at~~ smaller solar zenith angles and lower bulk albedo values. To date, the most temporally extensive study was carried out by Bair et al. (2022) in Sierra Nevada: the surface was tracked for roughly 100 days with a LiDAR system and field spectroradiometry to simultaneously track suncup growth, resolve grain size and impurity content, and quantify the resulting albedo reduction (0.05 in the broadband). Moreover, Bair et al. (2022) ~~found~~ identified a major challenge ~~associated-with-multispectrometry. Because-for-multispectral-sensors~~with multispectral sensors: because pixels containing mixed fractions of pristine and dirty snow are spectrally inseparable from pixels containing only dirty snow, ~~urface-surface~~ roughness effects on albedo cannot be separated from impurity effects, unless the snow is relatively dirty. Similar conclusions were reached by Warren (2013). With suncup roughness driving differential dirt ~~concentration-between~~ concentrations among hollows, ridges, and walls (Rhodes et al., 1987; Takahashi, 1978; Jahn and Kłapa, 1968; Richardson and Harper, 1957), a suncup field presents a spatially heterogeneous mix of clean and dirty snow at the sub-pixel scale, potentially rendering all pixels ~~as-mixed~~ for a multispectral sensor.

Spectral albedo measurements provide richer information than broadband, as they enable the attribution of surface albedo changes, i.e., the reflectivity of the snow surface, to snow microstructure (Libois et al., 2013), liquid water (Dumont et al., 2017), impurities (Tuzet et al., 2019; Skiles et al., 2018), or algae (Roussel et al., 2024; Painter et al., 2001). However, spectral measurements require expensive instrumentation and are particularly labor-intensive (e.g., Donahue et al. (2022)), making them impractical for unsupervised, continuous deployment at ~~high-alpine-sites; as-a-consequence~~high-elevation sites; consequently, they are carried out sporadically. Broadband pyranometers, conversely, are simpler, more robust, and better suited for long-term unattended deployment in harsh environments, enabling continuous monitoring at high temporal resolution across multiple melt seasons. This makes broadband measurements better suited for capturing inter-annual variability in surface conditions. Furthermore, ~~as-most physically based snowpack models use-broadband-albedo-as-a-target-variable, improving the-understanding-of-rely-on-broadband-albedo, so-clarifying~~ how surface roughness affects ~~broadband-albedo-has-direct-relevance-for-snowmelt-modelling. In-particular, Carletti-et-al.(2025b)-recently-showed-it-is-directly-relevant-to-snowmelt-modeling. Recent-work-shows~~ that Sentinel-1 backscatter is ~~especially-particularly~~ sensitive to the early development of surface roughness on wet snow (Carletti et al., 2025b; Marin et al., 2020); characterizing its relationship with broadband albedo ~~is therefore-essential-for-the-design-of-assimilation-schemes~~would therefore be valuable for future assimilation-scheme design.

Here, we present the first three-season survey of suncup roughness on ~~high-altitude~~ high-elevation alpine snow during the ablation phase. We ~~characterise~~ characterize the conditions governing suncup onset and the ~~inter-annual~~ interannual variability in planar arrangement and geometric properties as ~~a function~~ functions of measurable snow state variables and meteorological ~~forcing~~ forcings. We then compare broadband albedo measurements to smooth-surface TARTES simulations under pristine and impurity-loaded conditions, using scenarios of impurity content based on existing alpine surveys, and apply the effective albedo parametrization of Löwe and Helbig (2012) to account for suncup-induced albedo reductions. We address the challenge posed by the co-evolution of suncup growth and progressive impurity concentration and clustering at the snow surface, which complicates ~~the separation of~~ separating their individual contributions to albedo decay, and propose a practical way forward based on the empirical relationship between measured broadband albedo and aerodynamic roughness length. Together, these results motivate and assist the explicit representation of ablation-driven surface roughness in snow energy balance models.

2 Data and Methods

2.1 Surface ~~microtopographies and roughness indices~~ microtopography from terrestrial LiDAR

~~LiDAR-laser scanning~~ Terrestrial LiDAR is an established ~~effective technique to monitor~~ effective technique for monitoring surface roughness (Bair et al., 2022; Lacroix et al., 2008) and a wide variety of snow processes ~~in general~~ (e.g., Ruttner et al. (2025)). A fixed, automated, high-resolution 3D Terrestrial Laser Scanner (TLS; FARO® Focus3D S120) scanned a delimited area of about 300 m² in the immediate proximity of the Weissfluhjoch research station (2536 m a.s.l., Davos, Switzerland), at hourly resolution and over three snow seasons. The TLS occasionally required restarting or relocation, resulting in mostly minor data gaps, ~~the largest occurring~~ the largest occurred in 2023, when the TLS only became operational in April ~~and no acquisitions were~~ with no acquisitions made beforehand. ~~Moreover~~ Overall, less than 2% of the scans were discarded due to acquisition instabilities caused by wind gusts or heavy snowfall. Because the scanned area is large and contains obstacles such as instruments and fences, and because point density decreases with distance from the scanner due to ~~decreasing incidence angle~~ increasingly grazing incidence angles, the point clouds were reduced to a region of interest (ROI) of ~~~approximately~~ 10 x ~4 m. ~~The ROI is then projected to~~ x 5 m. During ablation, snow generally disappears earlier in the south-eastern part of ~~the domain; therefore, to track suncup evolution over a longer period, we defined a smaller 5 x 5 m sub-domain within the north-western area of the ROI. We then project the ROI onto~~ the horizontal plane. To remove points not belonging to the snow surface (be it snowflakes from snowfall or blowing snow, or random noise) which would disturb the interpolation, we applied the well-established cloth simulation filtering algorithm of Zhang et al. (2016), with a cloth resolution of 30 cm, a classification threshold of 10 cm, and maximum rigidity, as recommended for flat ~~terrain~~ terrains. On average, 1% of the points per scan were filtered out. ~~The~~ We then interpolated the filtered point clouds ~~were then interpolated~~ to a regular grid of 5 mm ~~resolution~~ grid using bilinear interpolation to produce digital surface models (DSMs). ~~Ultimately, the altitude trend was removed~~ Finally, we removed the slope trend using Gaussian filtering ~~, unraveling the~~ (e.g., Fassnacht et al. (2009)), revealing microtopographic reliefs and concavities. The result is a time series of microtopographic DSMs, suitable for ~~the estimation of~~ estimating surface roughness indices using ~~faster~~ raster-based approaches (Fassnacht et al., 2009).

2.2 Descriptors of snow surface roughness

We computed snow surface roughness descriptors across two complementary scales. Vertical ~~indices descriptors~~ characterize the amplitude of surface ~~reliefs; to represent it, we chose the root mean square of heights (RMSH) and relief; we represent them using a parameterization of~~ the aerodynamic roughness length (z_0), ~~computed with the raster-based version of Lettau (1969)~~. ~~The root mean square of heights measures the standard deviation of a surface's height deviations relative to a flat mean plane (Manninen, 2003, 1997). The aerodynamic roughness length is.~~ z_0 is defined as the theoretical height above a surface at which the mean wind speed logarithmic profile extrapolates to zero (Lettau, 1969). ~~Horizontal indices, on the other hand,~~ We estimated z_0 from our Gaussian-detrended LiDAR DSMs using the geometric method of Lettau (1969), adapting it to raster grids. First, we smoothed the interpolated DSMs from their native resolution of 5 mm to 1 cm, to reduce computational load and remove grain-scale roughness. Then, drawing conceptual inspiration from Neville et al. (2025), we identified roughness elements as individual obstacles. While Neville et al. (2025) identifies individual roughness elements using an innovative watershed segmentation approach, we chose a simplified method to reduce computational costs, given the need to process nearly 10'000 DSMs. We used the 75th percentile of the elevation distribution to classify cells as obstacles, and merged neighboring obstacle cells into single roughness elements. A percentile threshold, rather than a fixed height, provides a measure independent of the surface amplitude, which varies throughout the season. This threshold identifies individual suncups as obstacles and avoids aggressively merging multiple suncups. We also set a minimum threshold of 20 neighboring cells (i.e., 20 cm²) for an obstacle element to be identified. Physically, the resulting obstacles correspond to the suncup walls, which produce most of the drag. The hollows in between are assumed to be mostly sheltered from the wind and therefore do not enter the calculation. Then, for each obstacle i , we computed the maximum height h_i above the mean detrended surface, the horizontal footprint area S_i , and the vertical area $s_{i,wd}$ facing each cardinal wind direction $wd \in (N, E, S, W)$, where a cell counts as wind-facing if it is higher than its immediate upwind neighbor. For each wind direction, the aerodynamic roughness length of the whole ROI is:

$$z_{0,wd} = C_d \cdot \bar{h} \cdot \frac{\sum_i s_{i,wd}}{\sum_i S_i}, \text{ with } \bar{h} = \frac{1}{n} \sum_i h_i \quad (1)$$

Where $C_d = 0.5$ is Lettau's drag coefficient and n is the total number of obstacles. Unlike Neville et al. (2025), we summed the areas first, giving larger elements more relative weight. Each scan thus yielded four directional z_0 values, which we averaged to obtain the time series shown in Fig. 2a–c. The median spread of the four directional z_0 values over the totality of the scans is less than 3%, meaning that there is almost no directional z_0 anisotropy at our study plot.

Horizontal descriptors characterize the lateral scale of ~~the surface reliefs; to represent it, we chose surface relief. To represent this scale, we use~~ the correlation length (CL). ~~Correlation length, which~~ expresses the horizontal distance over which surface height fluctuations remain statistically correlated ~~, i. e., the scale beyond which two points on the surface can be considered~~

uncorrelated with respect to their elevation (Manninen, 2003, 1997). These metrics inform differently on the state of (Manninen, 2003; Huar

. We computed CL separately across (CL_x) and along (CL_y) the TLS beam direction. The TLS is facing north; therefore, the y-axis is along the dominant wind direction. We define the anisotropy between CL_x and CL_y :

$$a_{CL} = \frac{\max(CL_x, CL_y)}{\min(CL_x, CL_y)} \quad (2)$$

195 The ratio a_{CL} describes surface directionality: anisotropic, preferentially oriented reliefs exhibit large values, whereas $a_{CL} \simeq 1$ (i.e., $CL_x \simeq CL_y$) indicates isotropy. The vertical and horizontal descriptors provide complementary information about the snow surface. A sastrugi field, for example, is characterized by high horizontal and moderate-low vertical roughness indices: reliefs are often spatially extended and spaced far apart state. A ripple field exhibits large horizontal and moderate-to-low vertical descriptors: its reliefs are spatially extended, widely spaced, and strongly directional, giving large a_{CL} . Suncups, 200 conversely, show low horizontal and high vertical roughness indices, as smaller horizontal and larger vertical descriptors, since reliefs of similar amplitude arrange periodically over short distances with generally no preferential direction: the surface tends towards isotropy, giving $a_{CL} \rightarrow 1$.

Moreover, we computed raster-based descriptors of suncup formation and growth through image analysis of the DSMs, such as the number of features with a negative height, the mean planar extension, the mean suncup area, the suncup maximum 205 depth, and the 2D equivalent of the roughness coverage fraction η used in Larue et al. (2020). Unlike in Larue et al. (2020), the non-concave portions of our natural surfaces are not flat; therefore, ridges were incorporated into, which led us to include ridges in the calculation.

2.3 SNOWPACK simulations Simulation and validation of snowpack state variables

Snow metamorphism decreases albedo through changes in by altering snow density, liquid water content, and SSA. We 210 simulated the evolution of these snowpack properties with SNOWPACK (Bartelt and Lehning, 2002), a the 1D multi-layer snow physical model describing a complete ensemble of processes that impact, physics-based SNOWPACK model (Bartelt and Lehning, 2002). SNOWPACK describes the driving processes impacting the snow energy balance, such as metamorphism and microstructure (Vionnet et al., 2012; Lehning et al., 2002), phase changes, liquid water transport and preferential flow (Würzer et al., 2017; Wever et al., 2016, 2014), and turbulent kinetic exchanges at the surface (Schlögl et al., 2018), among others. We 215 forced applied the snow surface temperature as a Dirichlet upper boundary condition as long as while the snow surface was in sub-freezing conditions, and used calculated energy fluxes as Neumann boundary conditions during melt. SNOWPACK simulations were forced with quality-controlled measurements from advanced meteorological sensors at the research station and its immediate surroundings (Bavay and Theile, 2026). The SNOWPACK output includes energy fluxes and full multilayer 220 profiles of snow temperature, density, liquid water content, and optical grain size among others, at a sub-hourly and, among other properties. We analyzed surface energy fluxes at hourly resolution and multi-layer snow profiles at 3-hour resolution, respectively. Such information is combined with the nearest acquisition of surface roughness in time intervals (00, 03, ..., 21 UTC) to improve computational efficiency.

The ability of SNOWPACK to reproduce the SSA and density of individual layers at Weissfluhjoch was thoroughly investigated by Calonne et al. (2020) at Weissfluhjoch (Calonne et al., 2020). Over one winter season, the authors indicate overall SSA underestimations from report overall underestimations of SSA by SNOWPACK, with the amplitude magnitude of the deviations depending on the compared measurement technique measurement technique used for comparison. With respect to densities, Calonne et al. (2020) pointed out density, Calonne et al. (2020) found that SNOWPACK overestimates the densification rate of lower snowpack layers and, conversely, underestimates the density of surface layers evolving from fresh snow to rounded grains. The comparison between our SNOWPACK simulations and the detailed surface measurements from Carletti et al. (2025a) confirms the above observations (Fig. 4k–l,n–o).

2.4 TARTES flat-surface simulations of broadband albedo

Impurity concentration scenarios:

We used the Two-streAm Radiative TransfER in Snow (TARTES; Picard and Libois (2024)) to simulate the spectral albedo (350–2200nm) of a flat snowpack, with density and optical grain size prescribed by SNOWPACK. Because incident light is either absorbed or back-scattered-scattered away by snow grains within 10 to 20 cm from the snow surface (Kokhanovsky, 2022; Libois et al., 2013), we prescribed numerical layers 1 cm thick for the top 10 cm, and a single layer of weighed-averaged weighted-average properties below. For each layer, the we specified the impurity type and concentration of impurities has to be prescribed.

As impurity content measurements were unavailable at our site, we designed three-five scenarios (Tab. 1) building upon the existing monitoring campaigns in the Alps, assuming that LAPs absorption is only attributable to black carbon and dust (Tuzet et al., 2020), which systematically co-exist in the Central Swiss Alps (Gabbi et al., 2015), although at strongly varying ratios. Specifically, our dust dominates radiative forcing in dust-event years, while black carbon dominates otherwise (Réveillet et al., 2022). Therefore, we divided our scenarios into two families: mixed scenarios, in which black carbon and dust co-exist at comparable levels, and dominated scenarios, in which one species clearly outweighs the other.

Table 1. Impurity concentration scenarios. Black carbon ranges follow Kau et al. (2026); Tuzet et al. (2020); Gabbi et al. (2015) and are amplified according to Doherty et al. (2013). Dust ranges follow Di Mauro et al. (2019). The concentration of red snow algae, *S. Nivaloides*, are estimated from Roussel et al. (2024) and Chevroliier et al. (2023).

Scenario	Notation in Fig. 4	Black carbon [ng g^{-1}]	Dust [$\mu\text{g g}^{-1}$]	<i>S. nivaloides</i> [$\mu\text{g g}^{-1}$]
Pristine	$c_{\text{imp}}^{\text{pristine}}$	0	0	0
Mixed-low	$c_{\text{imp}}^{m-\text{low}}$	40	10	0
Mixed-medium	$c_{\text{imp}}^{m-\text{medium}}$	80	50	0
Mixed-high	$c_{\text{imp}}^{m-\text{high}}$	200	100	0
Dust-dominated	$c_{\text{imp}}^{\text{dust}}$	80	100	0
Black-carbon-dominated	$c_{\text{imp}}^{\text{BC}}$	200	10	0
Algal bloom	$c_{\text{imp}}^{\text{algae}}$	0	0	66

Our medium black carbon scenario matches the observed maxima in the two-year campaign of Tuzet et al. (2020) and is consistent with several previous assessments (see Tab. 1) (Kau et al., 2026; Gabbi et al., 2015; Doherty et al., 2013). Our high black carbon scenario reflects extreme melt events where the in which surface concentration can multiply through up to a factor of 5 via melt amplification (Doherty et al., 2013). Our dust scenarios are based upon the on measurements and simulations of Di Mauro et al. (2019), considering from Di Mauro et al. (2019), which considers Algeria as the main source area of Saharan dust (PM_{2.5}) reaching Europe. The two scenarios in which either black carbon or dust dominates (Réveillet et al., 2022) are based on the same literature mentioned above. TARTES computes the mass absorption efficiency of impurities assuming optical properties for, assuming the optical properties of black carbon (Bond and Bergstrom, 2006) and dust (Caponi et al., 2017).

The current version of TARTES does not implement the optical properties of red snow algae are not implemented in the current version of TARTES. Therefore, we incorporated them as a custom light-absorbing impurity using the empirical *in vivo* properties measured by Chevrollier et al. (2023). For the algal bloom scenario, we estimated a mass mixing ratio from the minimum cell concentration detectable by Sentinel-2 (~ 20000 cells/ml; Roussel et al. 2024), representing bloom intensities with a measurable impact on the surface reflectance; a cell dry mass of 10^{-12} kg/cell derived from the mean snow algal biovolume and dry density reported in Chevrollier et al. (2023), and the mean modelled snow surface density during the melt season (300 kg m^{-3}); yielding a mass mixing ratio of $66 \mu\text{g g}^{-1}$.

We ran TARTES simulations in diffuse (cloudy/under diffuse) (overcast-sky) and direct (clear-sky) conditions and compared them the results with measurements from a Kipp & Zonen CM21 broadband pyranometer. Using the formulation of Picard et al. (2020) to compute the ratio r_λ We discarded measurements with grazing solar zenith angles (below 25° and above 65°) to avoid errors arising from the pyranometer's cosine response (Grenfell et al., 1994). In the absence of a dedicated diffuse-radiation sensor, the diffuse fraction was obtained by decomposing the measured global radiation using the formulations of Reindl et al. (1990); Helbig et al. implemented in MeteIO (Bavay and Egger, 2014), the meteorological pre-processing library of SNOWPACK. Following Picard et al. (2020), we then computed the ratio r_λ between incoming diffuse and global horizontal irradiance, we and classified timesteps with $r_\lambda \leq 0.2$ as direct-dominated and $r_\lambda \geq 0.95$ as diffuse-dominated. The deliberately wide gap between thresholds likely the two thresholds excludes mixed illumination conditions, ensuring, so that each group represents a quasi-pure illumination condition. In absence of a separate diffuse radiation sensor, the diffuse fraction was obtained from decomposing measured global radiation using the formulations of Helbig et al. (2010); Tapakis et al. (2015); Reindl et al. (1990) implemented in MeteIO (Bavay and Egger, 2014), SNOWPACK's meteorological preprocessing library. Moreover, for

Modeled broadband albedo values for both illumination conditions are obtained by weighting the TARTES spectral albedo by modeled incident solar spectra, computed with libRadtran 2.0.6 (Emde et al., 2016): the direct-beam irradiance under clear sky for the direct class, and the global downwelling irradiance under overcast sky for the diffuse class. Spectra were generated for the neighboring Totalp site (46.837°N, 9.815°E; 2470 m a.s.l.) on 7 March 2024 at 12:00 UTC (solar zenith angle 52.3°) using the Kurucz solar source (Kurucz, 1994), a midlatitude-summer atmosphere (Anderson et al., 1986), the rural aerosol model of Shettle (1989) scaled via the Ångström relation ($\alpha = 1.491$, $\beta = 0.0482$). Overcast conditions were represented by a fully overcast water cloud (liquid water content 0.2 g m^{-3} , effective droplet radius $10 \mu\text{m}$) between 3000 and 4500 m a.s.l.. Both spectra were resampled to 1 nm between 350 and 2500 nm and normalised to unit integral before weighting.

280 To determine the effect of suncups on the apparent broadband albedo, we compare measured time series with TARTES simulations in diffuse and direct illumination conditions for all years (Fig. 4a–f). Because TARTES neglects the presence of liquid water, relying on pure-ice refractive indices, we evaluate the quality of the simulations in dry and wet conditions separately (Fig. 4g–i). Wet conditions are initiated when the daily average of the modeled LWC exceeded 1% in the top 30 cm (2022), or based on direct field measurements through 2023 and 2024 (Carletti et al., 2025a). Because suncups form on a wet
 285 snow surface (Carletti et al., 2025b), any misrepresentation of wet-snow metamorphism by SNOWPACK or TARTES must be ruled out for the earlier flat-surface stage. Despite SNOWPACK sometimes underestimating surface SSA and systematically underestimating density (Fig. 4k–l, ~~measurements with solar zenith angles exceeding 60° were excluded to avoid sensor’s cosine response errors (Grenfell et al., 1994). Modelled n–o~~), TARTES simulations forced by either SNOWPACK or measured surface properties show mostly negligible differences in broadband albedo (Fig. 1). This indicates that simulated albedo is insensitive to
 290 these input biases in the wet phase, before suncup development. We therefore attribute the deviation from measured broadband albedo primarily to TARTES not accounting for the optical effects of liquid water and wet-snow metamorphism on a flat surface. To do so, we define the index $\beta_{wet}^{c,smooth}$, which is the mean offset between TARTES simulations and broadband albedo measurements, computed separately for each year and illumination condition, over the wet-smooth phase. Therefore, for each year y , the wet-smooth window $\mathcal{W}_y^{smooth} = \{t : t_{wet} \leq t < t_{rough}\}$ defines the evaluation set $\mathcal{S}_y^{smooth}$ containing
 295 pairing broadband albedo values ~~for both illumination conditions are obtained by weighting the TARTES spectral albedo by modelled incident solar spectra for clear and overcast skies (Dadic et al., 2013)~~ $\alpha_{TARTES}(t)$ and $\alpha_{measured}(t)$. The offset is the mean difference over the evaluation set:

$$\beta_{wet}^{smooth}(y) = \frac{1}{|\mathcal{S}_y^{smooth}|} \sum_{t \in \mathcal{S}_y^{smooth}} (\alpha_{TARTES}(t) - \alpha_{measured}(t)) \quad (3)$$

We evaluate this separately for direct and diffuse illumination conditions. Consequently, and similarly, we define $\beta_{wet}^{c,rough}$
 300 as the additional offset that appears once the suncups develop:

$$\beta_{wet}^{rough}(y) = \frac{1}{|\mathcal{S}_y^{rough}|} \sum_{t \in \mathcal{S}_y^{rough}} (\alpha_{TARTES}(t) - \alpha_{measured}(t)) - \beta_{wet}^{smooth}(y) \quad (4)$$

mean raw offset over $\mathcal{W}_y^{rough}$

By subtracting $\beta_{wet}^{c,smooth}$ from albedo residuals in the rough phase, we assume that the systematic errors deriving from wet-snow representation in TARTES are accounted for to the first order, leaving a residual signal that we can attribute solely to the co-evolution of suncup roughness and impurity concentration.

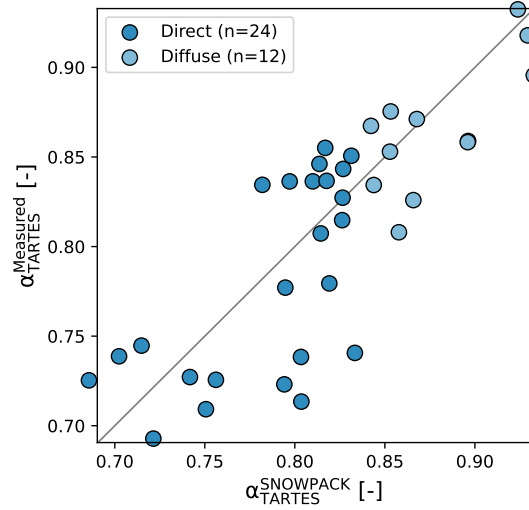


Figure 1. TARTES broadband albedo computed from SNOWPACK-modeled surface properties ($\alpha_{TARTES}^{SNOWPACK}$) against TARTES albedo derived from manual measurements ($\alpha_{TARTES}^{Measured}$, Carletti et al. (2025a)) under direct (opaque, $n=13$) and diffuse (transparent, $n=7$) illumination conditions. The grey line indicates the 1:1 reference. Each point represents one measured snow profile, paired with the co-located TARTES run driven by SNOWPACK, using timesteps within ± 1 h of profile acquisition. No manual measurements are available in 2022, so the comparison is restricted to 2023 and 2024.

305 2.5 Effective albedo parametrization

To (partially) account for the effect of suncup roughness on the domain-averaged broadband albedo, we applied the effective albedo parametrization presented in Löwe and Helbig (2012), originally formulated for subgrid topographic shading and terrain reflections in large-scale models, but fully applicable to smaller scales to the first order, provided the surface statistics are described by the same geometric parameters. These parameters are, in fact, the mean-squared slope μ and the sky-view factor ψ . According to these parameters, this approach modifies the flat-surface albedo computed by TARTES. To avoid propagating the wet-snow bias, this parametrization modifies the flat-surface albedo already corrected for $\beta_{wet}^{c,smooth}$ (Eq. 4). Specifically, the direct irradiance is attenuated by a shading factor that accounts for the fraction of the surface in shadow as a function of the solar zenith angle and μ , including partial shadowing at low sun elevations when suncup walls shade adjacent terrain. The diffuse irradiance is reduced in proportion to ψ , whereas the obstructed fraction $(1 - \psi)$ adds up the terrain-reflected radiation.

315 Both μ and ψ were derived from the LiDAR surface scans.

As the shading factor depends on the solar zenith angle and decreases significantly under diffuse illumination (cloudy/overcast sky), direct-dominated illumination conditions are where-those in which shading between suncup walls is the dominant roughness-induced albedo-reduction-albedo-reduction mechanism (Larue et al., 2020). Under an overcast sky, the remaining roughness-induced albedo reductions are instead governed by the limited sky view factor and single-terrain-single-terrain

320 reflections, both of which are included in the parameterization. Multiple reflections are not accounted for under either condition in the parametrization of Löwe and Helbig (2012). This practical compromise is motivated by the need for a quasi-analytical method that can be applied systematically across three seasons of hourly LiDAR roughness acquisitions, ~~where for which full 3D ray-tracing would result in extreme computational complexity~~ be computationally prohibitive. Neglecting multiple reflections omits the photon-trapping contribution to albedo reduction. Bair et al. (2022) quantified this effect in the field at 325 roughly 5% of the total roughness-driven albedo decay on average, but found it exceeds the 20% for late-ablation suncups: a regime our observations fully cover. Its omission therefore likely underestimates the modeled albedo reduction that increases with suncup growth.

3 Results

3.1 Conditions for suncup formation

330 Our time series highlight two distinct roughness regimes. The transition between regimes is marked by the onset of monotonically increasing vertical roughness ~~indices~~ index, occurring on May 11th 2022, May 22nd 2023, and June 3rd 2024 for the three seasons, respectively (Fig. 2a-ea-c). We refer to the period prior to these thresholds as the smooth (or textured) phase, and to the period after as the rough phase.

During the smooth phase, the horizontal roughness index ($\sigma_{\Delta CT} a_{CL}$) shows large variability, while ~~vertical roughness~~ indices ~~the vertical roughness index~~ (z_0 ~~and RMSH~~ remain) ~~remains~~ comparatively stable. In detail, $\sigma_{\Delta CT} a_{CL}$ peaks up to ~~250 mm~~ 4, whereas z_0 ~~and RMSH change~~ changes by no more than 4 mm above the 1 mm smooth baseline across all years (Fig. 2a-fa-f). Here, isolated peaks in $\sigma_{\Delta CT} a_{CL}$ are decoupled from any vertical roughness signal and are often correlated with wind gusts (Fig. 2d-f, m-op-r). This suggests that wind-driven (dry) snow redistribution processes ~~of~~, such as surface erosion or deposition ~~alter the horizontal structure of the snow surface, in agreement with previous findings from Amory et al. (2017)~~ , significantly alter the snow surface roughness. Zheng et al. (2026); Amory et al. (2017) reported similar findings, albeit in Antarctic snowfields, where sastrugi can form. During the rough phase, this pattern reverses. Vertical roughness ~~indices increase steeply and reach~~ increases steeply, reaching values one order of magnitude above the smooth baseline. Across all years, z_0 ~~and RMSH change~~ changes by up to 15 ~~and 30~~ mm. Conversely, ~~horizontal roughness flattens to a near-zero trend, with~~ $\sigma_{\Delta CT}$ ~~shrinking down to only 8 mm. the horizontal roughness signal becomes highly isotropic, with~~ a_{CL} shrinking towards 1. The 340 ~~absence of a wind signature in~~ $\sigma_{\Delta CT} a_{CL}$ during this phase suggests that suncup development, rather than wind redistribution, governs the evolution of surface roughness: ~~in this phase,~~ the surface is mostly a melt-refreeze crust, therefore rather insensitive to wind redistribution processes. In the following, we focus on the rough phase, which coincides with the snow ablation season (Fig. 2s-u) and where suncup growth is the dominant surface degradation mechanism at our site.

~~By~~ We define conditions for the onset of suncup growth by combining roughness time series with meteorological forcings and snowpack state variables, ~~we define a set of conditions for the onset of suncup growth.~~ The disappearance of cold content provides the first signal for roughness-prone conditions (Fig. 2g-ig-i). Once ~~it~~ the cold content reaches zero for the first time, the snowpack is isothermal and can ~~thereon then~~ melt and refreeze, initiating the first melt-related surface reliefs such as

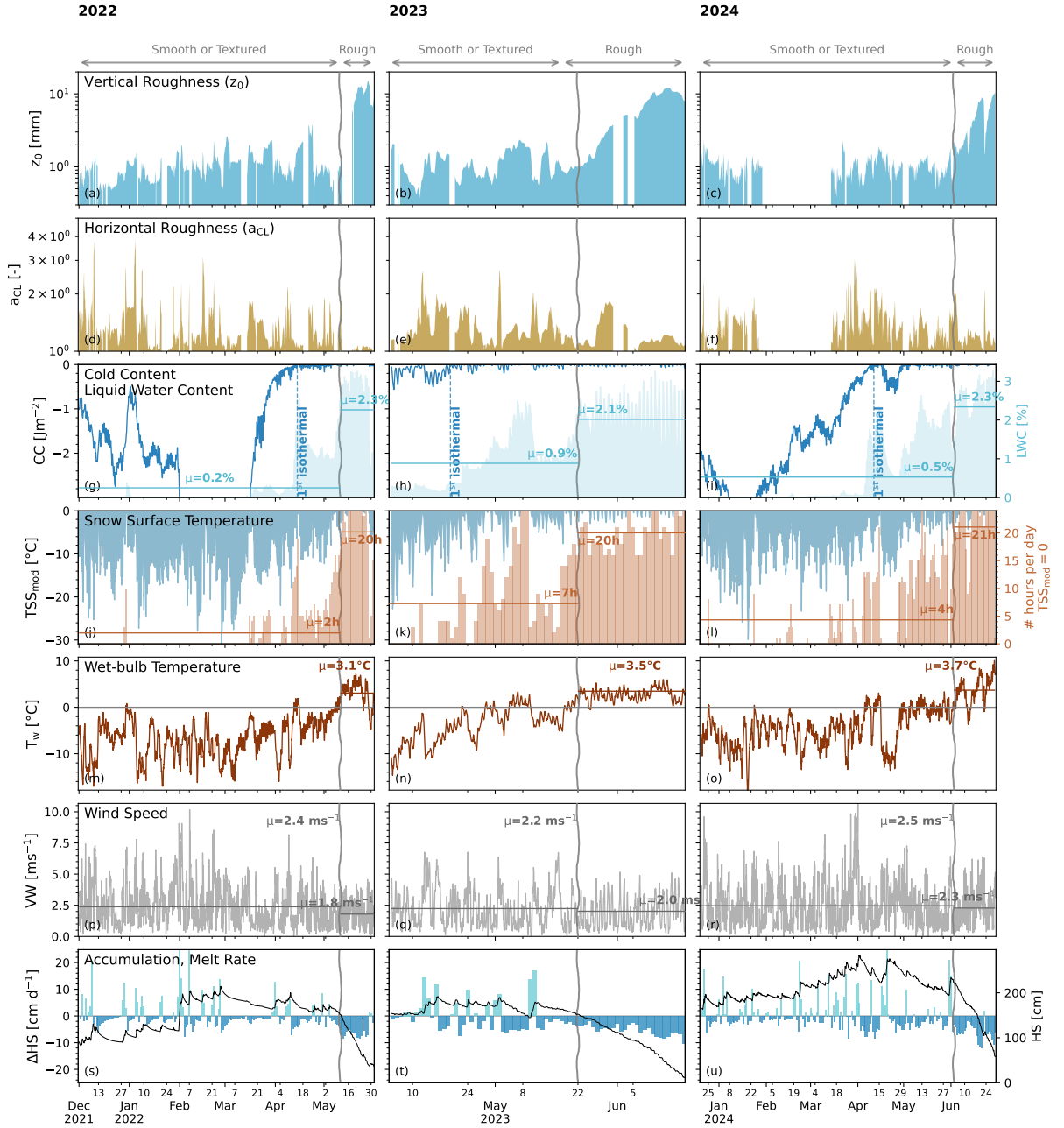


Figure 2. 2022 through 2024: (a-e-a-c) Vertical roughness indices, expressed as z_0 and RMSH (12-h average); (d-f-d-f) Horizontal roughness index, expressed as the standard deviation of the difference anisotropy ratio between CL in both directions $\sigma_{\Delta CL}$, correlation lengths a_{CL} (12-h average); (g-i-g-i) SNOWPACK-simulated cold content (dark blue, 3-h average) and average snowpack total liquid water content (light blue, 3-h average); (j-l-j-l) SNOWPACK-simulated snow surface temperature (blue, 3-h average) and the amount count of isothermal surface occurrences per day (light red); (m-o-m-o) Wet-bulb temperature as formulated by Stull (2011) (3-h moving average of measured-); (p-r-p-r) Measured wind speeds (3-h average); (s-u-s-u) measured snow depths (black, 3-h average) with daily accumulation and melt rates (light and dark blue, respectively).

melt-refreeze crusts and ice layers. ~~Then, the snowpack undergoes~~ After several melt-refreeze cycles, ~~and~~ the wetting front propagates until the bottom of the snowpack, with increasing average liquid water content (LWC, Fig. 2g-i). The average daily snow surface temperature (TSS) progressively increases, together with the number of isothermal surface hours per day (Fig. 2j-l). Across all years, the transition from ~~smooth to a~~ smooth to a rough regime consistently occurs when TSS remains at 0°C for approximately 20 hours /per day, with an average snowpack LWC of around 2%. This suggests that the persistence of melt-prone conditions, rather than their episodic occurrence, is the key threshold for suncup growth. Moreover, in all years, the suncup growth onset ~~coincides with~~ closely coincides with wet-bulb temperatures consistently above zero (with average values of around 3°C over the entire period – Fig. 2m-o) and reduced wind speeds with respect relative to the smooth phase, ~~likely attributable to~~ (Fig. 2s-u). The warming reflects the seasonal shift in thermal conditions. With above-freezing air temperatures and high wind speeds, more heat is likely delivered to the ~~suncups' ridges rather than~~ suncup ridges than to the hollows, ~~therefore~~ reducing the deepening process. Together, these indicators mark favorable conditions for the onset of suncup growth: (1) a snowpack that has reached an isothermal state, (2) near-continuous daily surface melt, ~~and~~ (3) close to constantly positive wet-bulb temperatures, and (4) reduced wind speeds. As noted above, the smooth phase corresponds predominantly to the accumulation period, whereas the rough phase coincides with snowpack ablation and higher melt rates (Fig. 2p-rs-u).

3.2 ~~Suncup dynamics across years~~ Interannual variability of suncup geometry and its meteorological drivers

We observe suncups growing throughout the rough phase in all three years. Suncup growth was consistently observed across all ablation seasons on our study plot (Fig. 3a-e). Approximately a-c, with 170 to 200 suncups formed every year over a 5x5 m survey sub-domain. The webcam forming each season. Webcam and LiDAR acquisitions in (Fig. 3a-f-a-f) show that the 2D equivalent of the roughness coverage fraction η used in Larue et al. (2020) approaches approached 100% under natural conditions across all three seasons. The: the portions of the sub-domain not occupied by suncup hollows are, in fact, structured into ridges, leaving little to no flat reference area. This means that, under natural conditions area. Consequently, η alone cannot describe suncup development under natural conditions, motivating the use of suncup area and maximum depth as additional descriptors.

During the initial two weeks of each rough phase, suncup growth is driven primarily by an increase in suncup number, after which We define the suncup growth window as the interval between the onset of the rough phase and the attainment of maximum depth. Its initial phase is marked by a steady increase in the number of suncups; subsequently, individual features begin to merge, and further growth is characterized by proceeds through merging and deepening. Spring snowfall events periodically interrupted interrupt this progression, temporarily suspending suncup growth and growth by producing abrupt decreases in depth and increases in size. Suncup growth is equivalent diameter. Tab. 2 summarizes the suncup growth descriptors, the duration of the growth window, and the concurring meteorological and radiative conditions for each season.

Suncup growth was most pronounced in 2022, where depth and size reached peak values of approximately 30 mm and 10 cm, respectively, and depth growth rate was also considerably faster which recorded the highest average depth of 7 cm (at least 2 cm greater than in the other seasons), coinciding with the narrowest mean suncup areas (Fig. 3g,j,m). This period was characterized by strong shortwave radiation gains Deepening was also fastest that year (0.4 cm d⁻¹), compressed into a 17-day growth window.

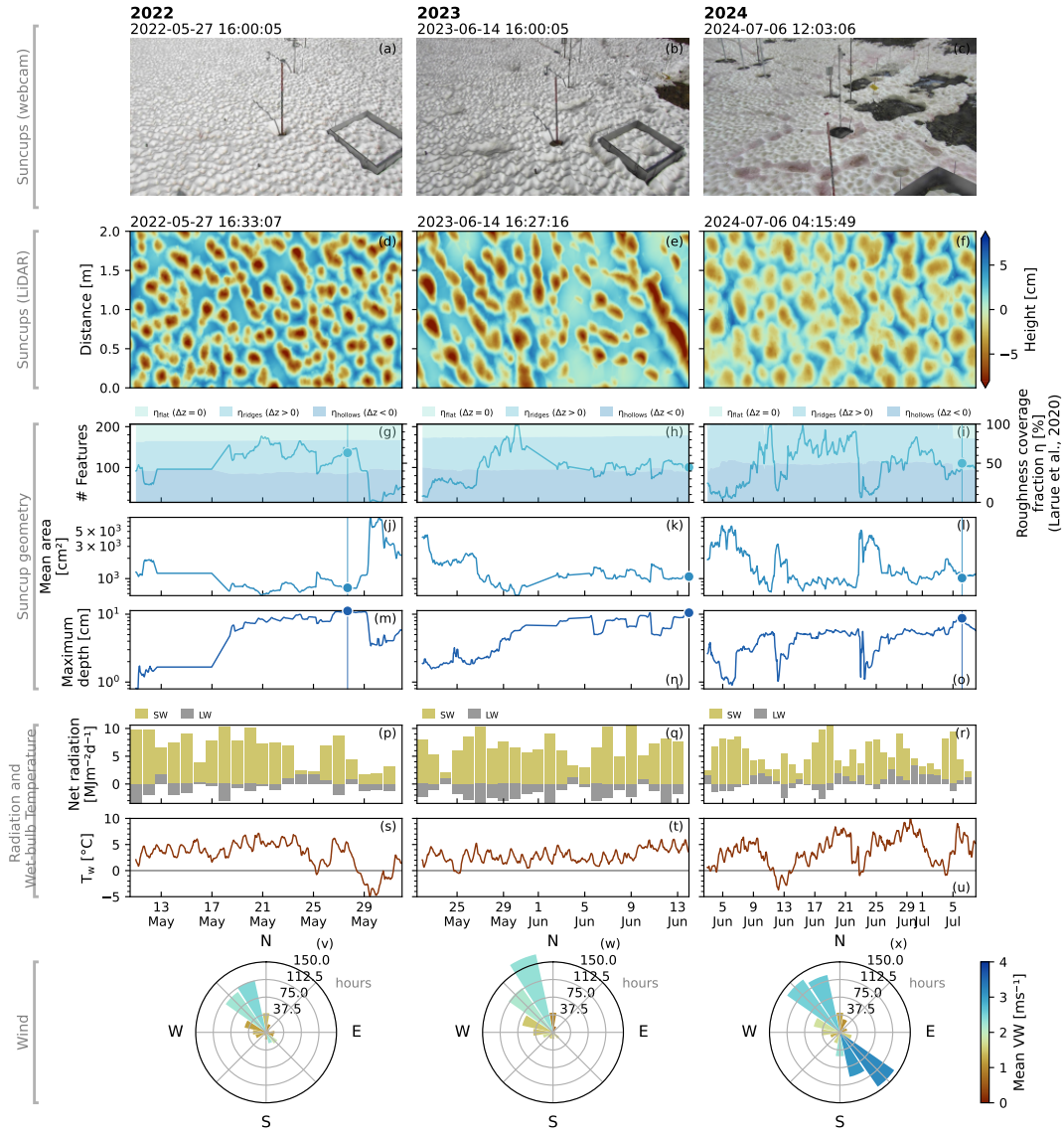


Figure 3. 2022 through 2024: (a-ea-c) Suncups, as seen from the webcam acquisitions next in close proximity to the field of view of the LiDAR scanner; (d-fd-f) Suncups, as seen from processed DSMs from LiDAR point clouds acquired at the same time of as the webcam snapshots; (g-i-g-i) Number of suncup features (blue line) and cover fractions (shaded areas) computed as the 2D equivalent of Larue et al. (2020) (3-h average). Specifically, η_{ridges} , $\eta_{hollows}$ and η_{flat} denote the areal proportion of each surface type within the control area ($\eta_{ridges} + \eta_{hollows} + \eta_{flat} = 1$) and are classified by deviation from mean elevation: ridges ($\Delta z > 0$), hollows ($\Delta z < 0$) and flat ($\Delta z = 0$); (j-l-j-l) Suncup mean equivalent diameter area; (m-o-m-o) Suncup maximum depth. The round point and the vertical lines in (g-o) mark the moment of webcam and LiDAR acquisitions in (a-f), corresponding to the timestamp of maximum suncup depth; (p-r-p-r) Cumulative daily net radiation, shortwave (yellow) and longwave (grey). (s-u-s-u) Relative humidity (dark yellow, 3-h average) and wet-bulb temperature (brown, 3-h average) as formulated by Stull (2011). (v-x-v-x) Wind speeds and directions. Every hourly time series is smoothed with a 3-h moving average.

Table 2. Suncup geometry, meteorological, and radiative conditions averaged over the suncup growth window for all seasons (2022 through 2024). When $(t_{D_{max}})$ is indicated, quantities are evaluated at the date of deepest acquisition; otherwise, they are averaged over the growth window of duration d_g . Wind direction, constancy, and directional variability are computed from speed-weighted vectors following Singer (1967).

Variable	Notation	Unit	2022	2023	2024
Growth window duration	d_g	[d]	17	23	33
Date of deepest acquisition	$t_{D_{max}}$	[-]	May 27 th	June 14 th	July 06 th
Number of suncups at $t_{D_{max}}$	$n_s(t_{D_{max}})$	[-]	133	97	108
Suncup average area at $t_{D_{max}}$	$\mu_A \pm \sigma_A(t_{D_{max}})$	[cm ²]	740 $\pm$ 591	1119 $\pm$ 1982	1043 $\pm$ 1185
Suncup average depth at $t_{D_{max}}$	$\mu_D \pm \sigma_D(t_{D_{max}})$	[cm]	7.3 $\pm$ 2.1	5.1 $\pm$ 2.4	3.8 $\pm$ 1.4
Suncup maximum depth	D_{max}	[cm]	11.4	10.9	8.8
Suncup deepening rate	$r_d = \frac{\mu_D(t_{D_{max}})}{d_g}$	[cm d ⁻¹]	0.4	0.2	0.1
Net shortwave radiation	$\overline{SW}_{net}$	[MJ m ⁻² d ⁻¹]	+7.1	+6.6	+5.7
Net longwave radiation	$\overline{LW}_{net}$	[MJ m ⁻² d ⁻¹]	-0.4	-1.7	+0.4
Wet-bulb temperature	$\overline{T}_w$	[°C]	+4.0	+2.8	+3.7
Wind speed	$\overline{VW}$	[m s ⁻¹]	1.7	1.8	2.3
Wind hours	n_w	[h]	398	545	796
Speed-weighted average wind direction	$\overline{\theta}_w = \text{atan2}(\sum_{i=1}^n VW_i \sin \theta_i, \sum_{i=1}^n VW_i \cos \theta_i)$	[°]	320 (NW)	317 (NW)	Bimodal (NW/SE)
Wind constancy (Singer, 1967)	$\overline{C}_w = \frac{\sqrt{(\sum_{i=1}^n VW_i \cos \theta_i)^2 + (\sum_{i=1}^n VW_i \sin \theta_i)^2}}{\sum_{i=1}^n VW_i} \in [0, 1]$	[-]	0.5	0.7	0.05

5 and longwave losses, low relative humidity, 15 days shorter than in 2023 and low wind speeds 2024, respectively. Despite being the shortest window, it combined extremely favorable radiative and thermal conditions. The net shortwave gains were the highest (+7.1 MJ m⁻² d⁻¹; 7% and 20% above 2023 and 2024 – Fig. 3p–r), and the wet-bulb temperature the warmest (+4.0 °C – Fig. 3s), and therefore the overall most melt-permissive. Winds were the weakest (1.7 m s⁻¹), showing decent constancy ($\overline{C}_w=0.5$, Singer (1967)) and relatively low directional variability ($\sigma_{\theta_w} = \pm 69^\circ$) around a mean direction from the NW (Fig. 3p–x). Features were v. This combination of favorable radiative and thermal conditions produced deep, small, circular, and evenly distributed suncups (Fig. 3d), consistent with the most favorable radiative and thermal conditions observed across the three years a.d).

395 In 2023, suncups developed at a slower pace, likely due to more persistent winds promoting turbulent heat exchange, and slightly lower net shortwave radiation in the initial phase compared to 2022. Nevertheless, favorable radiative conditions and dry air persisted, allowing suncups to reach considerable depths of 10 cm despite the slower growth rate (reached comparable maximum depths (11 cm) but were on average 2 cm shallower and 50% wider than in 2022, developing over a longer 23-day window (Fig. 3h,k,n). Radiative conditions remained favorable (+6.6 MJ m⁻² d⁻¹ net shortwave), yet this season carried the largest net longwave loss (-1.7 MJ m⁻² d⁻¹ – Fig. 3n,q,t). The persistent directional wind component also drove asymmetric ablation, resulting in q) with the overall coolest wet-bulb temperature (+2.8 °C – Fig. 3t) which, whilst still favoring melt, did so least of the three seasons. Despite average wind speeds and directions being comparable to 2022, in 2023 wind showed overall greatest constancy ($\overline{C}_w=0.7$, Singer (1967)) and lowest directional variability ($\sigma_{\theta_w} = \pm 52^\circ$) around the NW direction (Fig. 3w). This produced notably larger, elongated features oriented along the prevailing NW wind direction, which remained consistent across the season ($\sigma = 51^\circ$) (Fig. 3e,w). In (Fig. 3b,e), consistent with the large size variability of that season, where the standard deviation of suncup area ($\sigma_A=1982$ cm²) approached twice the mean ($\mu_A=1119$ cm²).

405 Radiative conditions in 2024, conditions were the least favorable overall: substantially lower shortwave gains, high longwave gains due to, with the overall lowest net shortwave gains (+5.7 MJ m⁻² d⁻¹), and the highest net longwave gain from frequent cloud cover, humid air, and high but highly variable wind speeds (+0.4 MJ m⁻² d⁻¹ – Fig. 3r). However, thermal conditions were still favorable: the wet-bulb temperature was the second-highest and exceeded 2023 by nearly 1 degree (Fig. 3u). Winds were the strongest (2.3 m s⁻¹) but also the most variable ($\overline{C}_w=0.05$) around a bimodal NW/SE regime ((Fig. 3r,u,x). On average, suncups in 2024 were 30 Suncups were 25% shallower than in 2022, with maximum depths reduced by 3 cm (Fig. 3o,n–o). The high directional variability of wind ($\sigma = 142^\circ$) highest directional variability ($\sigma_{\theta_w} = \pm 118^\circ$) precluded the development of a preferred morphological axis despite the greatest total turbulent energy input across all three years, resulting in features less elongated overall cumulative wind forcing, producing similarly wide but less elongated suncups than in 2023 (Fig. 3f). These observations suggest that suncup growth b–c,e–f,k–l).

420 Together, these results indicate that suncup deepening rate and depth are primarily governed by were most closely associated with the radiative energy balance and modulated by humidity and wind speed, while suncup with melt-permissive (warm, humid) near-surface conditions. On the other hand, orientation and elongation are controlled by prevailing wind direction were most closely associated with wind speed and directional constancy. All quantitative indices are summarized in Tab. 2.

3.3 ~~TARTES broadband albedo sensitivity to suncup growth~~ Suncup roughness and impurity loadings signatures in the broadband albedo decay of melting snow

~~To determine the effect of suncups on the apparent broadband albedo, we compare measured time series with TARTES simulations in~~ Under smooth, dry conditions, TARTES overestimates and slightly underestimates measured albedo under
425 ~~diffuse and direct illumination conditions for all years (Fig. 4a-f). We evaluate the quality of the simulations in dry and wet conditions separately, respectively, with biases β_{dry}^{smooth} +0.04 and -0.01 (Fig. 4g-i), with wet conditions initiating when the daily average of the modelled LWC exceeded 1% on the top 30 cm (2022), or based on direct field measurements through 2023 and 2024 (Carletti et al., 2025b). In smooth, dry conditions, the root mean squared error (RMSE) is 0.04 and the bias is on average -0.02 (diffuse) and -0.005 (direct); meaning that TARTES tends to slightly underestimate measured albedo~~
430 ~~on average, with random errors attributable to minor forcing and model uncertainty~~ a-c,d-f), which may reflect inaccuracies in the input snowpack and model limitations. As the snow wets and SSA decreases, but prior to suncup development, the overestimation of albedo in TARTES increases. The RMSE doubles up to roughly 0.08, with the bias turning strongly positive and contributing on average 70 and 50% of the RMSE in direct and diffuse conditions, respectively. We interpret this as the signal of wetting and growth, TARTES overestimates albedo under all illumination conditions, with average biases across
435 years β_{wet}^{smooth} = +0.06 (diffuse) and +0.04 (direct). Despite SNOWPACK systematically underestimating the density of the uppermost layer and, occasionally, its SSA (Fig. 4j-o), this doesn't seem to introduce important biases in SNOWPACK-forced simulations with respect to measurement-forced ones (Fig. 1). Therefore, we attribute β_{wet}^{smooth} to the misrepresentation of wet-snow metamorphism on a smooth surface ($\beta_{wet,smooth}$) flat surface in TARTES.

~~With~~ At the onset of suncup growth, we further partition the contributions to albedo reduction ~~, and take into account the~~
440 ~~presence of and account for~~ impurities and algae on a wet, heavily metamorphosed snow. We quantify the suncup signature by
~~subtracting $\beta_{wet,smooth}$, β_{wet}^{rough} by subtracting β_{wet}^{smooth} from the residual between measured and TARTES broadband albedo (Eq. 3, Fig. 4m). On p). Assuming pristine snow, suncups generate albedo decreases of 0.05-0.12 and 0.09-0.15 0.04-0.07 and 0.08-0.1 for direct and diffuse conditions, respectively.~~

~~When accounting for low to medium impurity contents, the suncup signal becomes less important. Albedo decreases~~
445 ~~shrink down to 0.02-0.1 and 0.04-0.13 for~~ The consistently larger diffuse signature (Fig. 4q), evident across all scenarios, reflects the visible-weighting of the overcast spectrum (Fig. 4r; see below). When assuming mixed, low-to-medium impurity scenarios (or the black-carbon-dominated scenario, which reduces albedo comparably), suncup signatures decrease to 0.01-0.06 and 0.05-0.09 under direct and diffuse conditions, respectively. This suggests that suncup roughness and impurities jointly contribute to the observed albedo deficit that TARTES cannot reproduce from optical properties alone. On the other hand, the
450 ~~suncup signal persists across most scenarios at the end of the season when assuming a flat surface. When assuming mixed-high scenarios (or the dust-dominated scenario, which reduces albedo comparably) and algal bloom scenarios, β_{wet}^{rough} tends to, and often falls below, zero under direct illumination conditions (Fig. 4a-f)p). These impurity scenarios cancel the suncup signature, suggesting that an even very high (assumed) impurity levels alone cannot explain the measured albedo decay. It is only for extremely high impurity contents or algal bloom that the suncup signal partially decouples from the impurity signal. In such~~

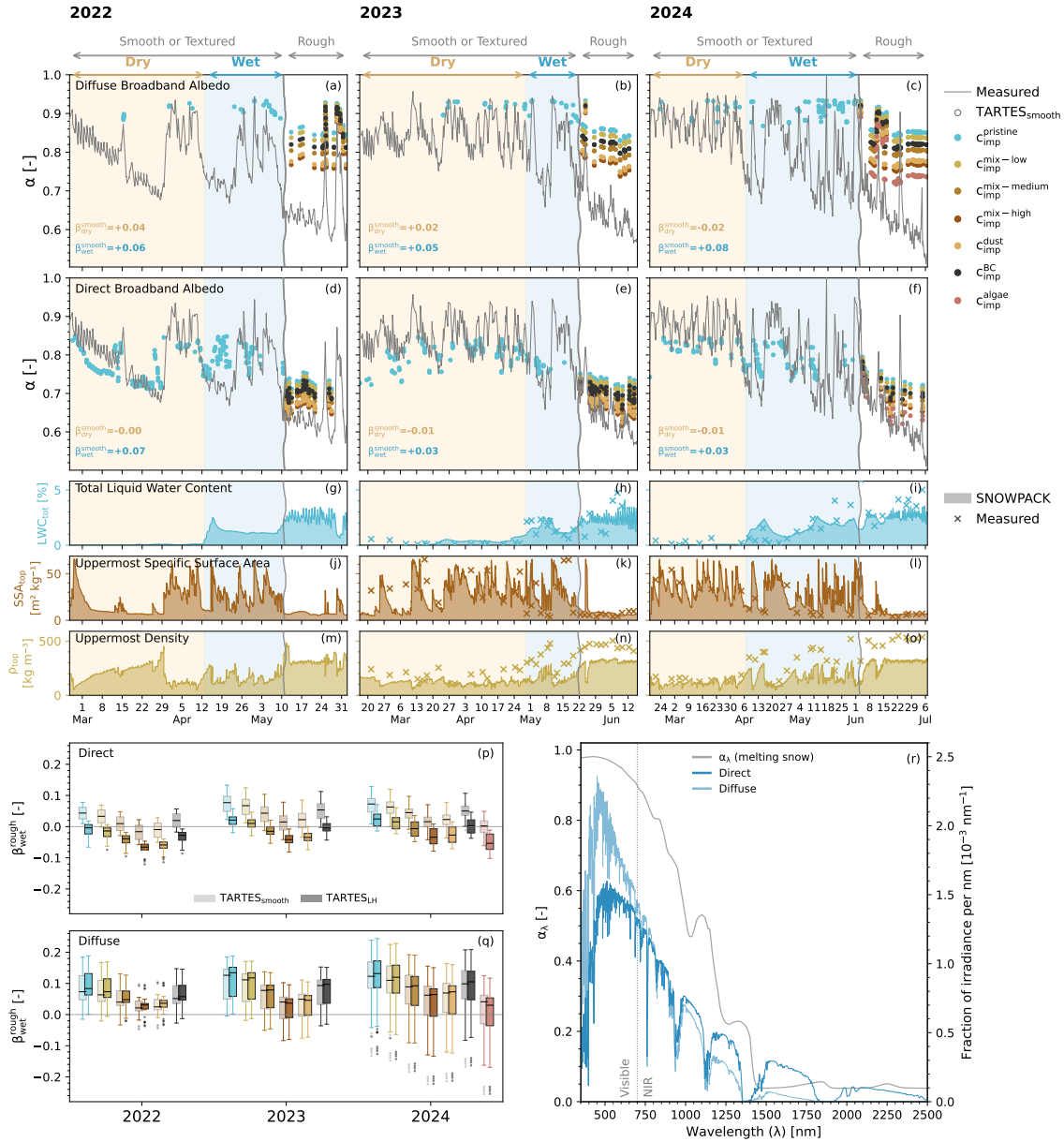


Figure 4. 2022 through 2024: (a-e-a-c) Measured and TARTES flat-surface broadband albedo for pristine and impurity-loaded snow under diffuse illumination conditions; and (d-f-d-f) Measured and TARTES flat-surface broadband albedo for pristine and impurity-loaded snow under direct illumination conditions; (g-g-i) SNOWPACK-modelled total liquid water content (LWC, 3-h averaged); (j-j-l) SNOWPACK-modelled uppermost specific surface area (SSA, 3-h averaged) over the top 30/10 cm; (j-m-o) SNOWPACK-modelled specific surface area uppermost density (SSA ρ , 3-h averaged) averaged over the top 10 cm. All SNOWPACK simulations in (m-g-o) are compared to manual measurements from Carletti et al. (2025a) (cross marks); (p-q) Residual roughness signatures in $\beta_{rough/wet}$ under direct and diffuse illumination for pristine and impurity-loaded scenarios, comparing flat-surface TARTES simulations (TARTES_{smooth}, TARTES_{smooth}; transparent boxes) and TARTES corrected with the effective-albedo parametrization of Löwe and Helbig (2012) (TARTES_{LH}; opaque boxes); (r) Fraction of irradiance per nm for the clear-sky direct (dark blue) and overcast diffuse (light blue) libRadtran solar spectra used as weighting functions, and TARTES spectral albedo of pristine, wet-metamorphosed snow (SSA=5 m² kg⁻¹, ρ =450 kg m⁻³) at 52° under diffuse conditions.

455 ~~cases, the suncup signal either only slightly persists or disappears~~ combined effect of suncups and impurities is comparable to that of the hypothesized impurity content on a flat surface.

β_{wet}^{rough} is, on average, twice as large under diffuse as under direct illumination (Fig. 4p–q). This asymmetry cannot be attributed to suncup roughness alone. At the visible-NIR boundary, the two insolation weights intersect and cross (Fig. 4r): the diffuse spectrum over-weights in the visible, the direct over-weights in the NIR. However, suncup mechanisms do not
460 favor diffuse illumination: the effective-angle effect activates only under direct illumination, and the multiple-reflections effect activates in the NIR, where the diffuse spectrum carries less weight (Fig. 4m). ~~Considering all impurity contents in the rough regime, the bias explains the 76% of the RMSE on average, meaning that errors are non-random, and likely attributable to processes that are not represented in the model. The hypothesized algal cell concentration in r).~~ Moreover, in the highly metamorphosed rough phase, the NIR spectral albedo lies well below the ≈ 0.5 balance value that maximizes photon trapping
465 (Larue et al., 2020), further limiting its contribution. Therefore, suncup mechanisms cannot produce a larger diffuse signature. The asymmetry instead matches a visible-dominated absorption signature: because the diffuse weight is concentrated in the visible, where LAPs and algae have their strongest influence, any impurity component of the residual is preferentially amplified under diffuse conditions. This explains why the diffuse β_{wet}^{rough} decreases as the hypothesized impurity concentration increases (and approaches 0 in the 2024 ~~brings albedo residuals below zero for direct illumination conditions, whereas albedo residuals~~
470 ~~converge to zero for diffuse conditions~~ algal bloom scenario), and why it requires higher assumed concentrations to approach zero than the direct residual does. Rather than suncup roughness, the larger diffuse residual likely reflects unaccounted-for impurity darkening.

The effective albedo parametrization of Löwe and Helbig (2012) ($TARTES_{LH}$) further supports this interpretation, as it lowers the residuals relative to the flat-surface assumption ($TARTES_{smooth}$) predominantly under direct illumination
475 conditions, when both suncup mechanisms are active. Under diffuse illumination, it only marginally reduces the spread of residuals or converges towards the flat-surface results (Fig. 4m)q), as expected if the diffuse residual is governed by visible-range impurity darkening that a roughness parametrization cannot capture. We note, however, that we cannot attribute the diffuse residual to impurities with full confidence. Under overcast, smooth-wet conditions, TARTES flat-surface albedos exceed the measurements substantially and decrease little through the season, unlike under clear skies, where they track the
480 seasonal decline. Therefore, part of the residual may reflect flat-albedo bias, inaccuracies in the direct–diffuse partitioning r_A or spectral radiation input, or the influence of the surrounding terrain, rather than impurity loading alone.

~~The~~ Under direct illumination, the effective albedo parametrization of Löwe and Helbig (2012) ~~successfully reduces the residuals between measured broadband albedo and flat-surface TARTES simulations. The~~ brings residuals close to, or slightly below zero across all years and for all hypothesized scenarios, with β_{wet}^{rough} being -0.02 on average. The mixed, low-to-medium
485 ~~concentration range is the most probable (or black-carbon-dominated) hypothesized concentrations seem the most likely~~ at our site, and the residuals being closest to zero across all three years support this hypothesis. High impurity and algal bloom scenarios are, on the other hand, likely on the extreme side, and the fact that residuals fall below zero in such cases seems to support the hypothesis. As expected, under diffuse illumination, the parametrization either only marginally reduces the spread of residuals or converges towards the flat-surface results failing to fully capture the suncup signature, in contrast to

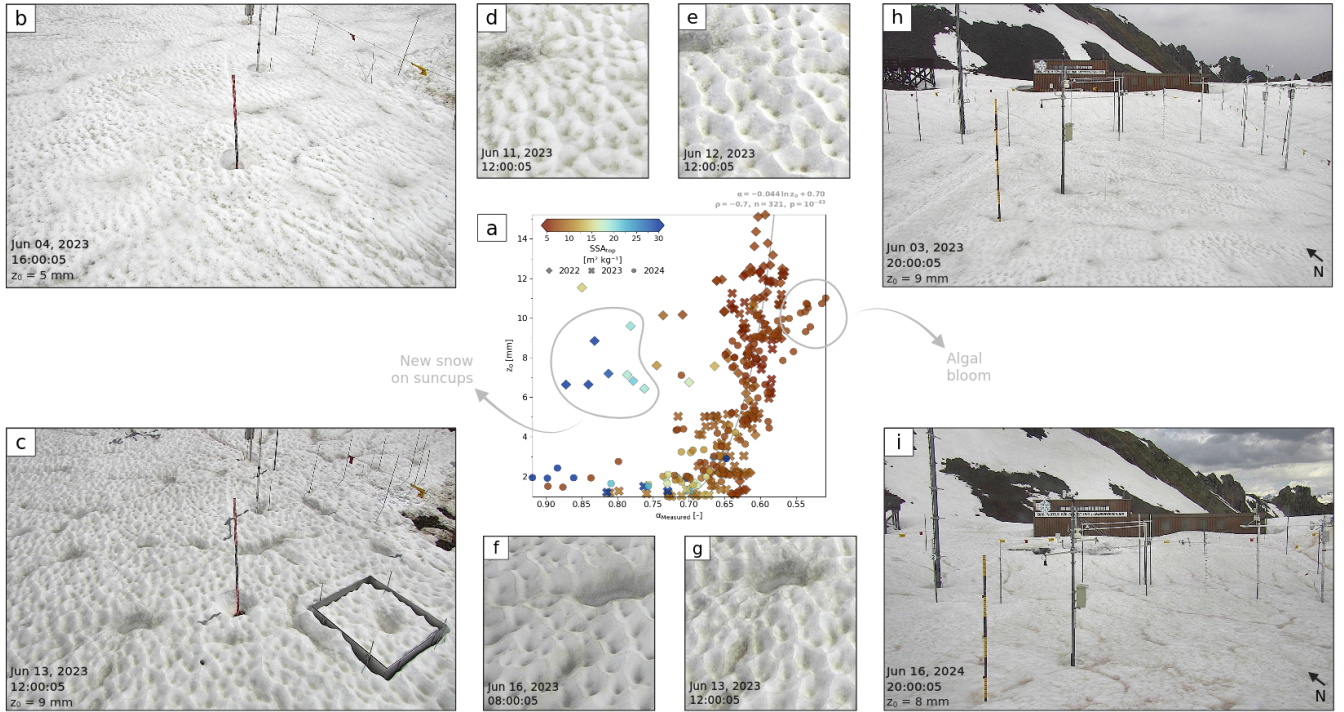


Figure 5. (a) KDE-averaged logarithmic correlation between measured broadband albedo $\alpha_{Measured}$ and aerodynamic roughness length z_0 across all years ($\alpha = -0.04 \cdot \ln(z_0) + 0.71$; $\alpha = -0.044 \cdot \ln(z_0) + 0.70$; $n = 301$; $n = 321$; $\rho_s = -0.7$; $p = 10^{-40}$; $p = 10^{-43}$). The hourly data is resampled in-to a 3-h 3h average. Outliers identify-represent either thin new snow layers on the top of already developed suncups, or exceptionally high surface impurities, such as the 2024 algal bloom. (b) Webcam acquisition of early-stage suncups (June 04th, 2023; $z_0 = 5$ mm). (c) Webcam acquisition of late-stage suncups (June 13th, 2023; $z_0 = 9$ mm). (d-e) Detailed look at the differential distribution of impurities at suncups' hollows. (f-g) Detailed look at the differential distribution of impurities at suncups' ridges and walls. (h) Webcam acquisition (June 03rd, 2023; $z_0 = 9$ mm; diffuse illumination). Winds over the preceding week predominantly from the NW (speed-weighted mean direction 305°, prevailing for 77% of the total hours). (i) Webcam acquisition (June 16th, 2024; $z_0 = 8$ mm; diffuse illumination). Winds over the preceding week were predominantly from the SE (speed-weighted mean direction 147°, prevailing for 70% of the total hours).

490 its performance under direct illumination with the lowest $\beta_{wet}^{rough} = 0.009$ across all years. The mixed-high, dust-dominated, and algal-bloom scenarios yield residuals that fall systematically below zero ($\beta_{wet}^{rough} = -0.04$ on average). Because β_{wet}^{rough} is averaged over the entire rough period, this suggests these high impurity concentrations are unrealistic as a whole-phase average, though plausible for the late ablation stage, when surface impurities have become most concentrated.

3.4 Impurity redistribution and suncup growth as interplaying controls on broadband albedo decay

495 Fig. ??a shows that during During the rough phase, the measured broadband albedo exhibits a strong logarithmic correlation with the aerodynamic roughness length z_0 ($\rho_s = -0.7$, $p = 10^{-40}$, Fig. 5a). Two categories of events deviate from this

relationship: spring ~~new snow-new snow~~ layers depositing on pre-existing suncups, which ~~progressively-abruptly~~ increase SSA and raise albedo ~~above-outside~~ the fitted trend, and impurity loadings of exceptionally high magnitude, such as the 2024 algal bloom. The logarithmic fit ~~further-reveals-also shows~~ that the rate of albedo decay is steepest at low z_0 and progressively
500 relaxes as z_0 approaches values characteristic of deep suncups.

~~Two webcam acquisitions illustrating early-stage~~ The shape of the correlation between z_0 and the broadband albedo decay suggests a possible link between the evolution of suncup roughness and impurity loading. Webcam acquisitions from our study plot (Fig. ~~??b~~) and late-stage 5) point to a spatial redistribution of impurities as suncups deepen. Over early-stage suncups (Fig. ~~??e~~) suggest a plausible mechanism underlying this behavior. At early stages, visible impurities are distributed relatively
505 homogeneously across the snow surface. At late stages 5b), impurities appear homogeneously distributed. At later-stage suncups (Fig. 5c), despite likely higher total concentrations, impurities ~~are preferentially concentrated-appear preferentially located~~ in the hollows (Fig. 5d-e) and, to a lesser extent, at the ridges (Fig. ~~??d,e5f-g~~), leaving ~~a greater proportion of the exposed snow surface comparatively clean~~ the exposed surface apparently cleaner than in the early-stage situation. This redistribution ~~pattern suggests that the~~ appears to relocate impurities within the suncup topography rather than remove them from the surface. The
510 coupling between suncup growth and impurity loading ~~is most effective in driving albedo decay~~ may therefore be most effective during the early-stage ~~suncup phase. As suncups deepen-, meltwater scavenges phase,~~ when impurities are more uniformly distributed; as suncups deepen and meltwater concentrates impurities into the hollows, ~~likely attenuating the LAPs contribution to albedo decay~~ the roughness contribution may grow, while the ~~roughness effect becomes dominant~~. Taken together, these observations indicate that ~~darkening effect of LAPs, though spatially reorganized, is not necessarily reduced.~~

515 Aeolian debris transport also appears to contribute to surface darkening. Fig. 5h (Jun 03rd, 2023; z_0 ~~serves as a robust proxy for the combined albedo decay attributable to surface microtopography and impurity redistribution, integrating both effects regardless of their relative contributions at any given stage~~=8.7 mm) corresponds to a week in which winds blew predominantly from the NW, with a speed-weighted average direction of 305° prevailing for 77% of the total hours. Dark, rock-like debris is visible on the upwind section of the early-stage suncups. The NW sector of the research field is enclosed by steep rock faces
520 where snow generally disappears well before it does on the field itself, which sits in a slight local terrain depression that allows snow to persist longer. The surface darkening is therefore consistent with rock debris mobilized from the surrounding slopes. Conversely, Fig. 5i (June 17th, 2024; z_0 =8.3 mm) corresponds to a week of predominantly SE winds, with a speed-weighted average direction of 147° prevailing for 70% of the total hours. Although the suncup roughness is nearly identical to that of the previous year, the upwind dark debris is markedly less apparent. Unlike the NW sector, the SE side of the research field opens
525 onto the valley and is not overlooked by steep rock faces, consistent with a reduced local debris supply.

4 Discussion

~~Over three seasons of~~ Three seasons of high-resolution LiDAR monitoring of ~~a snow surface, we have identified an evolving snow surface allowed us to identify~~ a smooth regime, characterized by dynamic horizontal ~~roughness indices and relatively stable vertical roughness indices~~ anisotropy and a relatively stable aerodynamic roughness length (z_0), and a rough regime,

characterized by ~~sharp increases in vertical roughness indices and steady horizontal roughness indices~~ an order-of-magnitude increase in z_0 and the disappearance of horizontal anisotropy. These results confirm the ~~findings-conclusions~~ of Fassnacht et al. (2023, 2009), ~~who drew similar conclusions from which were supported by~~ only six observations ~~across-over~~ a single season. Our time series show that wind is the primary driver of ~~horizontal roughness anisotropy~~ during the smooth regime (Fig. 2d-f, p-r): ~~wind~~. Wind gusts coincide with ~~sudden increases in horizontal roughness indices, while vertical roughness indices remain mainly unchanged~~. This suggests that ~~peaks in anisotropy, while z_0 remains unchanged~~ (Fig. 2d-f, p-r). This contrasts ~~with~~ wind-driven ~~erosion and redistribution (producing features such as sastrugi and ripples) reorganize the snow surface laterally, extending the horizontal coherence of surface elements, without building comparable vertical reliefs. This confirms previous findings of Amory et al. (2017). The onset of the rough regime is marked by the formation of suncups~~ environments such as Antarctica (Amory et al., 2017), where sastrugi fields develop pronounced vertical relief and can raise z_0 by an order of magnitude (Zheng et al., 2026). At our alpine latitude and ~~altitude, we found that the conditions enabling suncup growth are the predominance of energy regimes allowing surface melting at lower elevation, suncup growth favored conditions that combined surface melt with low~~ wind speeds. ~~These observations confirm that suncups lose mass through melting across their entire~~ This is consistent with the mechanism described by Lliboutry (1954), in which ablation occurs across the entire suncup surface, including hollows, walls, and ridges, ~~as described by Lliboutry (1954), and that their formation is driven by solar radiation (Matthes, 1934; Post and LaChapelle, 2000). Moreover, the fact that suncup initiation~~. The onset of suncup growth coincides with the daily preponderance of isothermal surface temperatures and above-freezing wet-bulb temperatures. This carries an important implication: ~~As this threshold is easily detectable from~~: because these thresholds are easily detectable by both standard field sensors and snow simulations, it provides they provide a simple diagnostic ~~to detect~~ for detecting the onset of suncups, ~~opening~~. This opens the way for surface energy balance schemes to explicitly account for the transition from a flat to a ~~rough surface regime during the ablation phase~~ rough-surface regime during ablation.

Our data show that the geometric arrangement of suncups varied substantially across years. ~~In~~ Across all three years, suncup depth and growth rate followed the radiative energy balance, whereas the shift from the clear, calm conditions of 2022 and 2023, clear-sky conditions likely favored radiation-driven suncup growth. Suncups reached shallower depths in to the overcast, windy conditions of 2024 illustrates how turbulent exchange displaces radiation as the dominant ablation mode. The contrast with 2022 marks 2023, likely due to more persistent winds delivering more turbulent energy to the ridges, and as an intermediate season: shallower suncups, which deepened more slowly, co-occurred with lower net shortwave ~~radiation gains in the early formation phase. In 2024, overcast and windy conditions suggest a shift toward turbulent-dominated ablation, resulting in the shallowest suncups across all three years. Our observations are in agreement with the formation theories formulated by Matthes (1934); Lliboutry (1954); Mitchell and Tiedje (2010). Nevertheless, gains and the largest longwave losses, leaving less~~ energy for melt, consistent with the radiation-driven growth formulation of Mitchell and Tiedje (2010); Post and LaChapelle (2000); Llibou. The 2024 is an interesting case: suncups formed despite unfavorable radiative conditions. Although our data cannot confirm it, we offer the following hypothesis based on the framework of case is interesting because suncups formed under the overall least melt-permissive radiative regime across all years: frequent cloud cover suppressed shortwave input, and strong, variable winds favored turbulent over radiative ablation. This outcome is not predicted by the radiation-driven theory alone, unless we

565 consider the framework proposed by Rhodes et al. (1987). According to Rhodes et al. (1987), when ~~ablation is dominated~~
~~by~~ turbulent heat exchange dominates, impurities act as thermal insulators ~~for in~~ snow, slowing melt ~~where they are and~~
~~allowing reliefs locally and allowing hollows~~ to deepen elsewhere. ~~The threshold for this mechanism has been formalized in~~
~~terms of dirt layer~~ This mechanism was then described as a function of the dirt layer thickness (Tiedje et al., 2006; Betterton,
2001), though a quantitative threshold in terms of impurity type or concentration ~~remains unestablished. Exceptionally intense~~
570 ~~Saharan dust intrusions affected Switzerland in 2024~~ (Pons et al., 2025; Cuevas-Agulló et al., 2024), which, combined has
not been established. The exceptional 2024 Saharan dust deposition events (Pons et al., 2025; Cuevas-Agulló et al., 2024),
together with prolonged melt ~~duration and an and~~ unfrozen soil (Carletti et al., 2025b) ~~likely promoted~~, likely created favorable
conditions for the algal bloom visible in Fig. 3c (Roussel et al., 2024). ~~Therefore, in 2024, the combination of dust and algal~~
~~loading may have provided sufficient surface impurity concentration to trigger the turbulent formation regime described by~~
575 ~~Rhodes et al. (1987), enabling suncup development despite radiative conditions that would otherwise have caused their decay.~~
~~We note, however, that,~~ which could have enhanced the surface concentrations to a sufficient amount to sustain suncup growth
despite otherwise unfavorable conditions. This interpretation comes with two caveats. First, Rhodes et al. (1987) assume
impurities ~~to be concentrated on ridges via the normal trajectory, whereas algae grow in situ across~~ concentrate on ridges,
whereas the algae covered the entire suncup surface, ~~introducing uncertainty about whether their insulation feedback was~~
580 ~~fully active in 2024. This spatial distribution differs from the idealized scenario underlying;~~ it is therefore unclear whether
the insulation feedback ~~theory proposed by Rhodes et al. (1987). Whether~~ operated as formulated. Second, our data cannot
separate whether the algal bloom was ~~a necessary condition for suncup formation in 2024~~ necessary for suncup growth, or
merely ~~an enhancer of a transition primarily driven by meteorological forcing, cannot be determined from our observations~~
~~alone~~ enhanced a transition already driven by meteorology. Interestingly, under turbulent conditions, Fassnacht et al. (2009)
585 observed entirely smoothed-out suncups over "red" snow, and reduced suncup amplitude following the deposition of coarse
aeolian debris (Fassnacht et al., 2010), suggesting that not only concentration, but also distribution and grain size of impurities
may influence how suncup roughness evolves on snow.

~~We compared deviations of modelled broadband albedo from measurements against a baseline period where the snow surface~~
~~was wet but suncups had not yet developed. This baseline accounts for two systematic biases inherent to TARTES~~ To isolate
590 the albedo signal attributable to the co-evolution of suncup roughness and impurities, we first account for biases unrelated
to surface morphology. These could arise at two points in the modeling chain: the surface properties from SNOWPACK and
the albedo TARTES computes from them. SNOWPACK errors do not propagate into systematic biases in TARTES albedo
(Fig. 1). Instead, TARTES shows two systematic biases, both under wet conditions. First, liquid water ~~in snow triggers~~
~~grain size growth through wet snow metamorphism and grain clustering (Brun, 1989). Optically~~ drives grain size growth
595 through wet snow metamorphism and clustering (Brun, 1989); optically, clustered grains behave as larger grains, increasing
absorption ~~and reducing albedo in comparison to dry snow~~. Second, TARTES ~~relies on~~ uses ice refractive indices ~~neglecting the~~
~~presence of liquid water. Although small, and neglects liquid water;~~ in the NIR ~~regime there is an increase in,~~ the imaginary
part of the refractive index ~~from ice to liquid water (Green et al., 2006; Warren, 1982; O'Brien et al., 1981), which causes~~
~~enhanced absorptions (Donahue et al., 2022; Dumont et al., 2017). Because TARTES does not account for the presence of~~

liquid water in snow, the above neglected processes cause systematic overestimation of albedo during wet conditions that is slightly higher for water than for ice (Green et al., 2006; Warren, 1982; O'Brien et al., 1981): this omission suppresses absorption further (Donahue et al., 2022; Dumont et al., 2017). The net result is a systematic albedo overestimation under wet conditions, independent of surface roughness. Similar observations were made by Manninen et al. (2021). By subtracting the bias for wet, smooth conditions from albedo residuals in (Fig. 4d–f), consistent with Manninen et al. (2021). We remove this bias empirically. Using a baseline period when the surface was wet, but suncups had not yet developed, we subtract the wet-smooth bias from the albedo residuals of the rough phase, we assume that these systematic errors are accounted for. This corrects the wet-condition error to the first order, leaving a signal that, in conditions of pristine snow, we can attribute to suncups and dirt accumulation alone residual attributable to the co-evolution of suncup roughness and impurity concentration.

Based on this and across all years, suncups Suncup roughness and impurities cause broadband albedo decreases of 0.020.03–0.15 0.1 (Fig. 4mp), in agreement with the results of Manninen et al. (2021) and slightly higher than the controlled experiments of Larue et al. (2020). Moreover, the albedo reduction is drastically accentuated in all years for values of SSA lower than The reduction is sharply accentuated below SSA of $10 \text{ m}^2 \text{ kg}^{-1}$ (Fig. 4j–lj–l), as prescribed in Larue et al. (2020). These consistencies have two important implications. First, they provide by Larue et al. (2020). This provides independent field validation of previous experimental results: the albedo reductions documented by Larue et al. (2020) under artificially created roughness, and interpreted through Larue et al. (2020) obtained under artificial roughness and a ray-tracing radiative transfer model, model translate almost directly to natural suncup morphology observed over multiple melt seasons on Alpine snow. Second, it shows two apparent counterintuitive results that require suncups over multiple alpine ablation seasons. Two of our results, however, warrant discussion.

The first concerns the comparison with the study of Manninen et al. (2021), set in the Finnish tundra. The albedo reductions caused by deep Alpine suncups seem comparable to those caused by is that deep alpine suncups reduce albedo comparably to the shallower roughness features typical of tundra environments that Manninen et al. (2021) describe. Initially, this may indicate of the Finnish tundra (Manninen et al., 2021), which would suggest roughness coverage fraction, rather than feature depth, as the primary driver of for albedo reduction. The study of Manninen et al. (2021) was conducted at 20° higher latitude than the Alps, where the sun elevation is systematically lower, i.e., solar zenith angles are larger at any time of day. Within the theoretical framework of Larue et al. (2020), this first apparent contradiction is partially resolved: the authors demonstrate that an increase in suncup roughness coverage (at constant depths) causes significant albedo reductions, and that this is further partially reconciles this: increasing coverage at fixed depth reduces albedo, and the reduction is amplified at large solar zenith angles through the effective-angle effect. In other words, the tundra roughness features of Manninen et al. (2021) may benefit from a stronger Manninen et al. (2021) conducted experiments at 20° higher latitudes than the Alps, so the systematically larger solar zenith angles may provide an effective-angle contribution that may partially compensate for their shallower geometry, bringing their net albedo reduction into agreement with the deeper but differently illuminated alpine suncups compensate for shallower geometry. However, the possibility that coverage fraction is the dominant control deserves further investigation our data cannot resolve whether coverage fraction dominates over suncup depth: this aspect requires dedicated experiments.

The second ~~apparent contradiction concerns the illumination regime dependence of the roughness and impurity signal~~. The
 635 ~~gap between measured and modelled albedo attributable to suncups and impurities is that the roughness-plus-impurity signal~~
 is systematically larger under diffuse than ~~under direct illumination~~. This seems to conflict with Warren et al. (1998), as direct
~~illumination activates both multiple reflections and direct illumination (Fig. 4p). This cannot originate from suncup geometry;~~
 the effective-angle effect ~~, whereas under diffuse illumination multiple reflections operates alone. Therefore, a stronger signal~~
~~under diffuse conditions may seem counterintuitive at first. This result can be explained by several concurring factors. First,~~
 640 ~~under direct illumination TARTES reduces albedo with increasing solar zenith angle, as oblique incidence enhances forward~~
~~scattering; under diffuse illumination, angular effects are averaged into a single fixed hemispherically integrated value, leaving~~
~~the model insensitive to any further geometry-driven albedo reduction. Second, our $\theta_s < 60^\circ$ filter excludes the large solar~~
~~zenith angle regime where the effective-angle effect is strongest (Larue et al., 2020), dampening the detectable roughness~~
~~signal requires direct illumination, and multiple reflections is most effective in the NIR (Larue et al., 2020), where the diffuse~~
 645 ~~spectrum carries little weight (Fig. 4r); in the metamorphosed rough phase, NIR albedo also falls well below the ≈ 0.5~~
~~value that maximizes photon trapping (Larue et al., 2020). The asymmetry, instead, reflects a visible-dominated absorption~~
~~signature: the diffuse weight is concentrated in the visible, where LAPs and algae dominate, so any impurity component of~~
~~the residual is preferentially amplified under diffuse conditions. This is corroborated by the $TARTES_{LH}$ parametrization~~
~~(Löwe and Helbig, 2012), which lowers residuals mainly under direct illumination~~. Third, ~~although suncups show preferential~~
 650 ~~orientation along the main wind direction in one season (where both roughness mechanisms are active) but barely affects~~
~~the diffuse spread (Fig. 3e), individual suncups maintain an isotropic periodic structure, reducing the relative importance of~~
~~effective-angle effects (Painter and Dozier, 2004; Warren et al., 1998). Fourth, under diffuse illumination radiation arrives from~~
~~the full sky hemisphere, meaning a geometrically larger fraction of photons enter suncups at oblique angles, i.e., the condition~~
~~that maximizes internal reflections before escape. Thus, even though total incoming global radiation is substantially lower~~
 655 ~~under overcast conditions, the fraction of intercepted photons undergoing multiple reflections may be larger under diffuse~~
~~illumination. Bair et al. (2022) and Warren et al. (1998) both indicate that intermediate values of snow albedo, characteristic~~
~~of rough ablation phases, are dominated by the multiple reflections effect. Moreover, Larue et al. (2020) quantified a strong~~
~~multiple reflection effect precisely for the SSA ranges modelled by SNOWPACK across all our observed rough seasons.~~
~~However 4p–q), as expected if the diffuse residual is impurity darkening that a roughness parametrization cannot capture.~~
 660 ~~The larger diffuse residual is therefore more likely diagnostic of unaccounted impurities, rather than stronger roughness~~
~~effects. Nevertheless, natural suncups differ significantly from the artificial configurations likely do maximize the roughness~~
~~mechanisms that operate. Unlike the artificial fields of Larue et al. (2020), where uncarved areas remained flat and coverage~~
~~fractions approached flat areas remained and coverage peaked near 60% at maximum. Natural suncup fields, being, natural~~
~~suncups are structured into ridges or hollows, leave little to and hollows with essentially no flat surface, so coverage fractions~~
 665 ~~approach pushing coverage toward 100%, suggesting that the multiple reflection mechanism likely operates at its theoretical~~
~~maximum under natural conditions. Multiple reflection effects may be particularly relevant in alpine suncup roughness regimes,~~
~~where overcast conditions driven by frontal systems, föhn events, and orographic cloudiness are substantially more frequent~~

than in the predominantly clear-sky environment of the Sierra Nevada studied by Bair et al. (2022), though this remains a hypothesis that our data cannot directly confirm.

670 The dependence of the suncup signal on the illumination regime is further supported by the contrasting performance of the Löwe and Helbig (2012) effective albedo parametrization under direct and diffuse conditions. Despite being originally formulated to account for subgrid topographic shading, terrain reflections and limited sky view in large-scale models, this approach can be applied to smaller suncup geometries showing similar roughness feature characteristics. Under direct illumination, the shading factor and mean-squared slope capture the effective angle effect very well, successfully reducing model residuals
675 across all years. Under diffuse illumination, however, the shading factor vanishes by definition and the only remaining roughness correction is the redistribution of irradiance between sky and terrain fractions through the sky-view factor. This single exchange does not capture subsequent multiple reflections, causing the parametrization to converge toward flat-surface TARTES values and leaving the multiple reflections effect under diffuse conditions unaccounted for. This is particularly relevant in the presence of LAPs, where each subsequent reflection carries an increased probability of absorption and multiple reflections toward their
680 theoretical maximum. Bair et al. (2022) and Warren et al. (1998) both find that the intermediate albedos characteristic of rough ablation phases are dominated by multiple reflections.

The systematic co-existence of enhanced LAPs concentration and suncup growth has been addressed by our study, but remains a clear limitation of our modeling approach. The presence and evolution of impurities is not accounted for in SNOWPACK, which therefore co-evolution of suncups and impurities remains a modeling limitation. SNOWPACK does not account for
685 surface impurities, so it neglects the enhanced SSA decrease derived from LAP-accelerated decrease in SSA from LAPs-accelerated metamorphism (Skiles and Painter, 2019; Tuzet et al., 2017). Since we had no measurements of impurity content at our site, the scenarios we defined rely on literature values available for LAPs concentrations on seasonal Alpine snow. Specifically, our medium black carbon concentration matches the highest value measured in the two-seasons campaign of Tuzet et al. (2020), and is consistent with previous assessments in the Alps and beyond (Kau et al., 2026; Gabbi et al., 2015; Doherty et al., 2013; Painter et al.,
690 . These campaigns included the melting season, when impurities that are not scavenged through percolating meltwater accumulate at the surface through melt amplification. This process can increase surface impurity concentrations by up to a factor of 5 (Doherty et al., 2013). This motivated our high black carbon scenario threshold, which is 5 times the low scenario. Dust carries greater uncertainty due to its even scarcer monitoring (Tuzet et al., 2020). We based our thresholds on the measurements and simulations of Di Mauro et al. (2019), despite Without on-site measurements, our impurity scenarios rely on values whose
695 transferability is uncertain, even though the literature supports them. Dust is the most uncertain: monitoring is scarce (Tuzet et al., 2020), and the large-scale distribution assessment of Dumont et al. (2023) showing that dust deposition is strongly skewed towards shows deposition skewed toward the western Alps, likely making the high dust scenario making our mixed-high and dust-dominated scenarios likely unrealistic for our eastern alpine site. For the algal bloom scenario, we adopted the optical properties measured by Chevrollier et al. (2023) and the minimum bloom concentration detectable by Sentinel-2 from Roussel et al. (2024). These
700 assumptions carry uncertainties that we are unable to quantify: algal bloom scenario, the optical properties of Chevrollier et al. (2023) were estimated in an Arctic environment, where pigment content measured in the Arctic, where pigmentation, cell size and packaging effects of the same species may differ; and the, and packaging may differ, and the Sentinel-2 detection

threshold of Roussel et al. (2024) ~~is likely an overestimate of~~ likely overestimates the minimum bloom concentration, ~~especially given their finding that algal blooms seem more intense in the western rather than in the eastern Alps. Moreover, for all impurity types,~~. We must also assume the mass absorption ~~efficiency must be assumed known, introducing further uncertainties (e.g., Tuzet et al. (2019))~~ efficiencies for each impurity type (Tuzet et al., 2019). Despite these ~~limitations, the uncertainties, our mixed-low and mixed-medium~~ black carbon concentrations ~~in our low and medium scenarios bracket the entire elemental carbon range reported by~~ bracket the full elemental carbon range of Manninen et al. (2021), and the ~~corresponding resulting~~ roughness-induced albedo reductions ~~are consistent with their findings~~ match theirs, with a slight low bias attributable to the simultaneous presence of dust in our scenarios.

The ~~measurements of Tuzet et al. (2017) show that surface LAPs concentrations follow a trend fully consistent with~~ progressive surface LAP enrichment monitored by Tuzet et al. (2017) reflects the suncup growth ~~documented in this study. However, they also reveal no consistent inter-annual trend and , in agreement with Dumont et al. (2017), reveal significant scatter between measurement techniques . This suggests that increased measurement frequency alone would not straightforwardly~~ resolve the suncups LAPs disentanglement problem. A further complication arises from the fact that suncups favor differential LAPs concentration we observed, but, in contrast, it shows no consistent interannual trend and varies significantly across measurement techniques (Dumont et al., 2017). Disentanglement therefore would not depend solely on increasing LAP measurement frequency. Geometry brings further complications: because suncup growth drives differential LAP accumulation between hollows and ridges (Rhodes et al., 1987), meaning that a rigorous partitioning of their respective partitioning their contributions to albedo decay would require ~~tracking both suncup geometry and LAPs~~ co-registered tracking of surface topography and LAP distribution at the same fine spatial resolution. In the absence of tools LiDAR scanners like ours can resolve the spatiotemporal evolution of surface reflectance and have been deployed for this purpose (Walter et al., 2023), but they record backscattered intensity at a single wavelength in a fixed directional geometry and are rarely radiometrically calibrated. They yield, at best, a relative single-wavelength directional reflectance rather than the hemispherically and spectrally integrated quantity that albedo represents. Resolving the suncup LAP problem would thus require instrumentation capable of tracking surface LAPs evolution spatially and temporally and including their high-resolution vertical distribution in LAP evolution not only in space, time, and vertical distribution within the surface snow ~~(whether through distributed measurements or coupled models), but also across wavelengths. Even then, spectral resolution alone may not fully separate the two sources; until then, this remains a fundamental obstacle to overcome in future for future work.~~

The robust logarithmic relationship ~~we identified~~ between broadband albedo and aerodynamic roughness length z_0 (Fig. ??5a) provides a physically informed proxy that ~~helps address several open questions raised in this discussion~~ addresses several questions raised above. First, the partial decoupling of albedo decay from suncup growth during the ~~pronounced algal bloom of 2024 suggests that in previous 2024 algal bloom implies that in other~~ years, impurity concentrations either ~~followed tracked~~ suncup growth closely enough to preserve the correlation , or remained too low to ~~produce a detectable independent effect on~~ independently darken albedo. Second, the logarithmic ~~form of the correlation implies that albedo decays more rapidly at lower values of aerodynamic roughness length. The webcam imagery in Fig. ??b,c shows that, despite surface impurity concentrations likely being lower early in the ablation phase, impurities appear more evenly distributed across the surface of early-stage~~

suncups. Later in the ablation phase, higher concentrations are progressively scavenged ~~shape~~ (faster albedo decay at smaller z_0) is consistent with how impurities redistribute over the season. Early in ablation, impurities are lower in concentration but evenly spread across shallow suncups (Fig. 5b–c); later, they concentrate into the deepest sections of each suncup, with hollows, leaving only a small fraction persisting on the ridges (Fig. 225d,e). We propose that an even distribution of impurities over early-stage suncups produces a comparatively stronger effect on albedo decay: with the multiple-reflection-effect operating at its maximum efficiency and the uniform distribution of absorbing particles, the probability of absorption spread evenly over the surface, absorbing particles raise the absorption probability at each reflection further increases. As the season progresses, albedo decay dampens likely because impurities, although present at higher concentrations, are scavenged into very localized sections of the suncups and become less homogeneously distributed. It is therefore possible that their radiative effect is dampened, whereas later redistribution into localized hollows makes the loading spatially heterogeneous, possibly dampening its radiative effect despite higher bulk concentrations. This interpretation would provide another explanation on why the albedo reduction observed by Manninen et al. (2012) would also explain why Manninen et al. (2021) measured comparable albedo reductions over shallower tundra suncups is comparable to that measured over our deeper alpine suncups, and it would support the hypothesis that coverage fraction has, supporting coverage fraction over feature depth as a stronger control on albedo decay than feature depth. This interpretation offers a physical explanation of the albedo decay intensity as the result of the interplay between frames albedo decay as the interplay of roughness and impurities. However, our results alone can only suggest this without providing direct proof. The findings of Bair et al. (2022) highlight a fundamental measurement difficulty: spectroradiometry cannot distinguish the radiative effects of suncups from those of impurities in heterogeneous, but our data cannot isolate the two contributions to confirm it. Bair et al. (2022) identify why this is challenging even with spectral information: in snow composed of mixed pristine and dirty fractions. Since this appears to be the dominant condition for suncup surfaces, it indirectly supports the use of our roughness proxy as an integrative measure of both effects, the darkening from roughness and from impurities remains difficult to separate, and our webcam imagery (Fig. 5) shows the two are coupled from the earliest stages of ablation. Under these conditions, z_0 serves as a robust proxy for the combined albedo decay due to surface microtopography and impurity loading, integrating both regardless of their relative contributions at any ablation stage.

These findings open concrete possibilities for improved remote sensing of snow surface properties and their representation in energy balance models. First, within the radiative footprint of a broadband pyranometer, suncup coverage is considerably easier to monitor than impurity concentration, and extremely more homogeneous spatially than the combined variability of multiple impurity types that are increasingly scavenged and redistributed and more spatially homogeneous than impurity concentration. The identified correlation may therefore offer a practical approach to the LAPs quantification problem at the pyranometer footprint scale, and could be incorporated into snow energy balance models to simultaneously correct reflected shortwave radiation to account for both surface roughness for surface roughness and impurity effects at the pyranometer radiative scale. Second, the hypothesis that the coupling between suncup growth and impurity loading is most effective in driving albedo decay during the early-stage suncup phase would have suncup roughness is not only an optical property governing albedo but also an aerodynamic one, with direct implications for remote sensing in the ablation season. Because ablation-season energy balance. Sanow et al. (2024) showed that varying the aerodynamic roughness length in SNOWPACK substantially changes

cumulative sublimation, sensible heat, and snow water equivalent. Although dynamic z_0 was implemented in SNOWPACK to study the seasonal effect of wind (Amory et al., 2017), it is almost universally kept constant during ablation, site-specific at best. Our results call for a way forward: because C-band radar backscatter over wet snow is highly sensitive to the early development of suncup roughness (Carletti et al., 2025b), these results highlight the potential value of assimilating surface roughness observations into snow energy balance models. Early suncup development (Carletti et al., 2025b; Marin et al., 2020), a SAR-derived, time-varying z_0 could replace this constant in the turbulent-flux scheme, and, in models that parameterize albedo from grain size and age, omitting roughness and impurity darkening, similar empirical and site-specific z_0 -albedo relationships offer a way to introduce that missing decay. A single, remotely observable roughness signal could thus constrain both the radiative and turbulent components of the surface energy balance during the phase when each evolves fastest.

5 Conclusions

We monitored the formation and seasonal evolution of suncup roughness over three ablation seasons at a high-altitude alpine site—the high-elevation alpine site of Weissfluhjoch. Suncup onset required a combination of sustained surface melting and low-, above-zero wet-bulb temperatures, and reduced wind speeds. We identify the number of daily isothermal surface hours per day together with the transition to a positive wet-bulb temperature as a physically based indicator of suncup initiation, which is readily onset indicator, measurable with standard station instrumentation and could be used in energy balance models, that models could use to flag the transition shift from flat- to rough-surface conditions. Across Suncups formed in all three years, suncups consistently formed but with markedly different planar arrangements and geometry but with substantially different arrangements and geometries, which we explain through attribute to meteorological forcing and the formation regimes described in previous experimental work. However, whether suncups would have formed under turbulent-dominated conditions without the extreme impurity loadings of the 2024 algal bloom remains an open question. Comparing TARTES flat-surface simulations to against broadband albedo measurements, we quantify the combined albedo decay attributable to from suncups and surface impurities at 0.02–0.15, consistent with previous studies. Disentangling 0.1. Separating the two contributions is complicated by the fact that difficult: suncup growth and impurity surface enrichment follow similar seasonal trends, and by the and reinforce one another, generating extreme fine-scale heterogeneity of impurity distribution induced by suncup growth. A correct separation of the two effects. A clean separation would require simultaneous mapping of suncup geometry and impurity concentration at the same fine spatial scale. As a practical alternative, we identify a robust logarithmic correlation between measured relationship between broadband albedo and the aerodynamic roughness length. Since roughness z_0 , which captures the coupled roughness-impurity effect through a single variable that is considerably easier to monitor than fine-scale impurity content, this relationship could serve to correct reflected shortwave radiation in physical snow models, accounting for roughness and impurity effects simultaneously. The logarithmic form of the relationship also implies that albedo reduction is most intense at early stages of suncup development. We interpret this as the result of impurities being homogeneously distributed across the early-stage suncups before progressive melt scavenging concentrates them in localized sections, likely dampening their overall radiative effect. We hypothesize that the combination of early-stage

roughness and evenly distributed impurities is more efficient at reducing albedo than either factor acting alone. The . This carries two implications for snow energy-balance modeling. First, z_0 evolves strongly through the ablation season and governs both the turbulent and, via its link to albedo, the radiative surface fluxes; treating it as constant, as nearly all models do, misrepresents the energy balance at its most rapid rate of change. Snow cover models should therefore adopt a time-dependent z_0 for the ablation season. A time-varying z_0 could be derived from weather station measurements, starting from the onset indicators. Alternatively, because C-band radar backscatter over wet snow is particularly sensitive to roughness at these early stages. If the co-occurrence of suncup initiation and impurity loading is indeed the dominant control on broadband albedo reduction, it represents a physically meaningful and remotely observable quantity that could be assimilated into energy balance snow models, directly addressing the need to account for surface roughness in snowpack energy balance computations highly sensitive to early suncup roughness, time-dependent z_0 could be retrieved from SAR data. Such a z_0 would replace the constant used in the turbulent-flux scheme and, in models that parameterize rather than observe albedo, additionally inform the radiative term through the z_0 -albedo relationship.

. LiDAR roughness measurements are available on EnviDat: <https://doi.org/10.16904/envidat.761>. The quality-controlled meteorological forcings for SNOWPACK simulations are available on Zenodo: <https://zenodo.org/records/22304449>.

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