



Scenario-based wind drifted snow indication maps for site-specific operational avalanche forecasting in Iceland

Pia Ruttner^{1,2,3,*}, Stephanie Alice Matti^{4,*}, Andreas Wieser³, and Yves Bühler^{1,2}

*These authors contributed equally to this work.

¹WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, 7260, Switzerland

²Climate Change, Extremes, and Natural Hazards in Alpine Regions Research Center CERC, Davos Dorf, 7260, Switzerland

³Institute of Geodesy and Photogrammetry, ETH Zurich, Zurich, 8092, Switzerland

⁴Icelandic Meteorological Office, Avalanche Research Center, Ísafjörður, 400, Iceland

Correspondence: Pia Ruttner (pia.ruttner@slf.ch) and Stephanie Alice Matti (stephaniema@vedur.is)

Abstract.

Wind speed and direction strongly influence avalanche conditions in Iceland, where wind-transported snow can rapidly accumulate in avalanche starting zones. However, operational tools for predicting the spatial distribution and magnitude of wind-driven snow accumulation remain limited. This study investigates whether the terrain-based wind shelter index can support the development of scenario-based wind-driven snow accumulation indication maps for site-specific avalanche forecasting. We analysed terrestrial laser scanning measurements from two study sites near Ísafjörður in the Westfjords of Iceland and selected five wind-driven snow events from the 2025–2026 winter season for detailed analysis. We first compared snow thickness and its changes derived from terrestrial laser scanning with continuous point measurements from an in-situ SM4 snow-depth sensor. We then calculated the wind shelter index for the observed wind conditions and fitted linear relationships between the index and measured snow-thickness changes. The fitted relationships varied among events, highlighting the influence of precipitation, wind speed, initial snow conditions, and the chronology of meteorological conditions. Based on these findings, we developed preliminary indication maps of relative wind-driven snow accumulation patterns for different wind directions. The maps can help identify potentially critical starting zones and situations in which small changes in wind direction lead to substantial changes in terrain shelter. The results demonstrate the potential of the wind shelter index as a transparent and computationally efficient basis for scenario mapping. However, the current maps should be considered a proof of concept rather than quantitative predictions of snow depth or avalanche occurrence. Further development should incorporate wind speed, precipitation, event duration, and snow availability and proceed in close collaboration with operational forecasters to evaluate the practical value of the maps.

1 Introduction

On 28 March 2026, at about 5:00 UTC, a large avalanche released in the Skápgil gully on Grænafell (580 m.a.s.l.) approximately 5 km west of Reyðarfjörður in the East Fjords of Iceland. The avalanche crossed the main road serving several towns in the area, depositing debris over a 60 to 70 m road section. The middle section of the slope has an inclination of approximately



35 degrees, with a steeper cliff band upslope and a road crossing the avalanche path below. Avalanche risk is known to build up quickly on Grænafell, especially in storms with snowfall, and NE to NNE winds. The Icelandic Meteorological Office IMO provides the road authority with site specific avalanche forecasts for approximately 85 km on seven different sections of road across the country including beneath Grænafell. When the avalanche occurred on 28 March, the prevailing wind direction had been from the NW, a direction that forecasters did not typically associate with increased avalanche danger. Consequently, the road forecast remained at the lowest level, indicating that the probability of avalanche release was estimated to be below 10 per cent and that, in the event of a release, the avalanche was considered unlikely to reach the road. In the aftermath of the avalanche, the forecasting team and other stakeholders in the area identified the need to understand better how snow depth builds up in different wind directions, especially those that have not typically been associated with recent or frequent avalanches.

Wind transport distributes snow heterogeneously across mountainous terrain, with local topography affecting patterns of erosion and deposition. In particular, preferential deposition on leeward slopes can contribute substantially to total snow depth (Mott et al., 2010). When wind-transported snow is deposited together with, or shortly after, fresh snowfall, rapid loading can promote the formation of cohesive wind slabs and cornices and thereby can create favourable conditions for avalanche release (Schweizer et al., 2003; Hancock et al., 2020). These processes are particularly relevant in Iceland, which has a maritime, direct action avalanche regime in which avalanche activity is strongly influenced by wind speed and direction. In many Icelandic regions, flat-topped mountains provide large source areas from which snow can be transported into the steep slopes below (Björnsson, 1980; Decaulne, 2007). In the Westfjords, major avalanche periods have been associated with persistent winds from the N to NE and snowfall during the days preceding avalanche activity (Jóhannesson and Jónsson, 1996; Nawri, 2013). The catastrophic avalanches that occurred in the Westfjords villages of Flateyri and Súðavík in 1995, which killed 34 people, both involved strong winds over 20 m s^{-1} ranging from N to E directions in the 24 hours before the avalanches (Egilsson, 1996). In the case of Flateyri, wind gusts were up to speeds of 74 m s^{-1} ; while in the case of Súðavík there was an important reversal of wind direction from strong SW to strong NE winds in the 48 hours beforehand (Hættumatsnefnd Ísafjarðarbæjar, 2004). The combination of preceding snowfall, high wind speeds and subsequent avalanches suggests that redistribution of available snow can be more important for avalanche release than intense precipitation at the time of release (Haraldsdóttir et al., 2004). Therefore, wind loading, depending heavily on the wind direction, is one of the most important parameters in avalanche forecasting in the Westfjords.

Operational avalanche forecasting requires information on meteorological and snow conditions across the forecast region. Automatic weather stations commonly record wind speed, wind direction, temperature, and snow depth (Lehning et al., 1999). However, station networks are often sparse, and conditions vary substantially across complex terrain, meaning that individual stations may represent only a limited area (Grünwald and Lehning, 2015). Wind-driven snow transport is particularly difficult to measure operationally. Acoustic and optical sensors can detect airborne snow particles and provide estimates of drifting-snow flux (Schmidt, 1977; Sato et al., 1993; Chritin et al., 1999; Aksamit et al., 2026), but the operational use of such instruments remains limited. Assumptions about windblown snow in release and erosion areas are also key inputs in numerical simulations of avalanches (Glaus et al., 2026). For large-scale modelling in Switzerland, very basic lump-sum values are applied to account



for windblown snow (Bühler et al., 2022). As a result, forecasting approaches frequently rely on meteorological proxies or model-based estimates. For example, Haraldsdóttir et al. (2004) used wind speed as an indicator of drifting-snow activity, while Lehning and Fierz (2008) developed a station-based wind-drift index using SNOWPACK (Bartelt and Lehning, 2002) to estimate the potential amount of additional snow resulting from wind redistribution. More complex snow-cover models can simulate the spatial and temporal evolution of snowpack conditions. There have been attempts to apply an early version of the SAFRAN-Crocus model chain (Durand et al., 1999) in Iceland, but transferring such models to Icelandic conditions remains challenging because they were originally developed and calibrated primarily for Alpine environments. The model applied in the study did not explicitly represent wind-driven snow redistribution, which is a particularly important process in Icelandic snow climates (Haraldsdóttir et al., 2001).

Numerous models account for wind-driven snow redistribution by incorporating simulated wind fields into spatial estimates of snow-depth distribution, often with the aim of reproducing seasonal patterns across large domains (Vionnet et al., 2021; Dujardin and Lehning, 2022; Daudt et al., 2023; Quéno et al., 2024; Saigger et al., 2026). Other approaches include wind-related variables in models predicting avalanche danger levels (Dkengne Sielenou et al., 2021; Pérez-Guillén et al., 2022; Sharma et al., 2023). While these models capture important effects of wind on snow distribution and avalanche danger, they are not necessarily designed to reproduce snow redistribution for individual meteorological events at the scale of an individual avalanche release area.

Maps can be developed to indicate terrain where wind-transported snow may accumulate under specific wind conditions. Such maps have, for example, been developed for the Niseko region of Japan (Komatsu and Nishimura, 2022). However, their comprehensive validation remains challenging because measurements of wind-driven snow accumulation with both high spatial and temporal resolution are scarce. Ground-, drone-, airplane- and satellite based snow depth distribution mapping evolved during the past decade, producing high spatial resolution and high accuracy maps, sometimes also before and after major snowfalls (Eberhard et al., 2021; Ruttner et al., 2026). However, the available observations are often restricted to individual case studies or a small number of events and therefore cover only a limited range of meteorological conditions. Available observations are often restricted to individual case studies, including a small number of events and therefore cover only a limited range of meteorological conditions.

The wind shelter index, developed by Winstral et al. (2002), is a terrain parameter that characterizes whether a location is sheltered from or exposed to wind from a specified direction. Previous studies have used the wind shelter index to explain spatial variations in snow depth and to derive quantitative relationships between terrain shelter and snow accumulation (Schirmer et al., 2011; Schön et al., 2015, 2018; Ruttner et al., 2026). Wind shelter and other topographic indices have also been incorporated into statistical and machine-learning models of snow-depth distribution (Revuelto et al., 2020; Meloche et al., 2022; Liljestrand et al., 2025; Störmer et al., 2025; Pan et al., 2026) or for hazard mapping and infrastructure planning (Prokop and Procter, 2016).

Although Haraldsdóttir et al. (2004) investigated the role of wind-driven snow in Icelandic avalanche forecasting, recent applications of spatially distributed snow-redistribution models in Iceland remain limited. This study assesses whether a terrain-derived wind shelter index can be scaled to measured snow-depth changes and be used to generate scenario-based wind-driven snow accumulation indication maps. We calibrate and evaluate this relationship using measurements from individual



snowstorm events near Ísafjörður, Iceland. The resulting maps show potential accumulation patterns along the main avalanche paths for which the Icelandic Meteorological Office conducts site-specific avalanche forecasting. They are intended to support operational forecasting, forecaster training, and numerical avalanche simulations rather than to provide deterministic predictions of snow depth or avalanche occurrence.

2 Data

2.1 Field sites

The study sites are sections of the Kirkjubólshlíð and Seljalandshlíð slopes in Skutulsfjörður fjord where Ísafjörður, the regional capital of the Westfjords of Iceland is located (see Fig. 1). These two avalanche path sections represent some of the main avalanche risks for people and infrastructure in the fjord based on the avalanche hazards assessments conducted for the area (Arnalds et al., 2007; Jóhannesson and Gíslason, 2012).

The Kirkjubólshlíð slope is located on the southeastern side of Skutulsfjörður. This study focuses on the southern section of Inner Kirkjubólshlíð, specifically on three west-facing avalanche paths above the waste processing facility Funi (collectively **Funi** hereafter). The mountain edge is at approximately 700 m.a.s.l., above which is a plateau that acts as a large snow catchment area. The uppermost 100–300 m of Funi are steep at approximately 40 degrees or more; the slope decreases to approximately 30 degrees at 100 m.a.s.l. The main release areas on Funi are deep, rocky west-facing gullies in the steep upper section of the slope; however, avalanches have also occurred on the open slopes between gullies (Arnalds et al., 2007). The main infrastructure below the slope include the road and waste collection facility (Arnalds et al., 2007). A deflection dam was built in 2002 to protect the main building at Funi from avalanches, but this does not cover the surrounding yard and container area. Several avalanches that would have reached the building have been deflected successfully by the dam, including in 1999, 2004, 2005 and 2007 (Arnalds et al., 2007). However, large avalanches or those with a fluidised front still present a risk to the main building (Arnalds et al., 2007).

The Seljalandshlíð slope of Eyrafjall mountain is on the inner northern section of Skutulsfjörður. The slope is intersected by several steep and deep gullies, which are the most common avalanche release areas on the slope. This study focuses on the 700 m section of south-east-facing slope between Karlságil and Stakkaneshryggur avalanche paths (**KaS** hereafter). Eyrafjall has a relatively flat plateau similar to Kirkjubólshlíð, which is up to 700 m wide above KaS with an elevation of approximately 700 m.a.s.l. In the northern section of KaS, above Stakkagil, there is a large shelf on Eyrafjall at about 400–460 m.a.s.l., called Gleiðarhjalli. The upper release areas of KaS are approximately 40–45 degrees; the slope decreases to about 30 degrees at 160 m.a.s.l (Jóhannesson and Gíslason, 2012). Of the avalanche paths on Seljalandshlíð, Steiniðjugil is the most dangerous. Historically avalanches from Steiniðjugil have reached Seljalandsvegur, the main road to the cross-country ski area. The Icelandic Meteorological Office (IMO) records indicate that several avalanches have also crossed the lower Skutulfjarðabraut—the main access road into Ísafjörður—and fallen into the sea. Several commercial buildings in the area are also at considerable risk from avalanches in the same gully. There are no longer any residential buildings in the area.

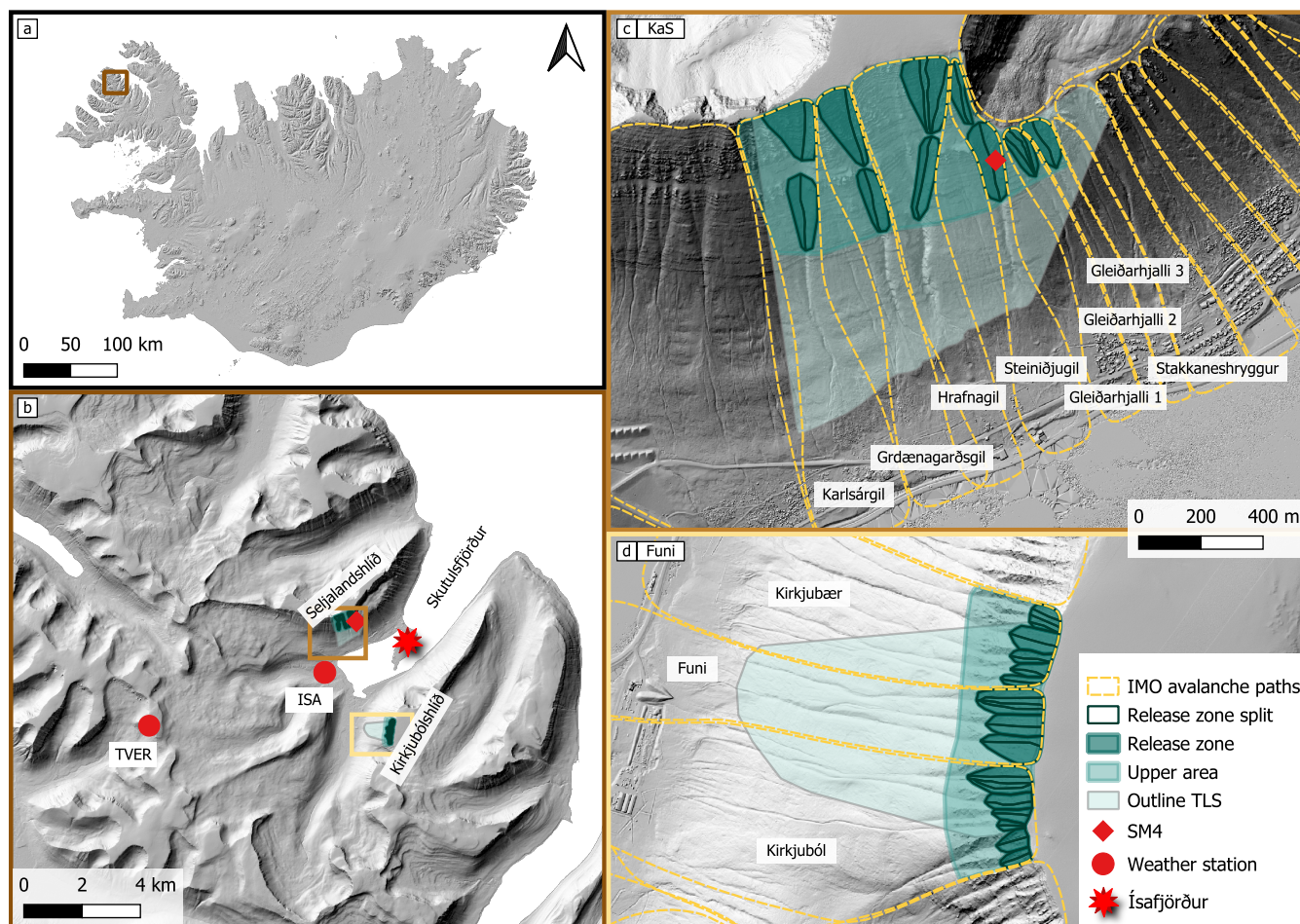


Figure 1. Overview of the study area (a) location of Skutulsfjörður in Iceland, (b) Skutulsfjörður, and the locations of Ísafjörður, the weather stations Þverfjall (TVER) and Tungudalur (ISA), and SM4 (c) and (d) maps of the field sites KaS (Karlsá að Stakkanesi) and Funi, with the outlines of the avalanche paths, release zones and approximate area monitored with the Terrestrial Laser Scanner (TLS). The background hillshade for (a) and (b) was derived from the DSM of the Icelandic Environmental Agency, and for (c) and (d) from the NERC-ARF-DAN dataset (see Sec. 2.2).



125 This study focuses on snow accumulation under windy conditions in the avalanche release areas at these two field sites, Funi and KaS. The upper sections of the IMO-defined avalanche paths were used as starting points for identifying these release areas. The release areas were then manually constrained to individual gullies using the terrain model. Gullies and large release zones can span entire bowl-features, which differ significantly in terms of wind exposure. As a result, these release zones were further divided laterally based on the main aspects of the sides of each gully (see Fig. 1).

130 **2.2 Terrain model**

The snow-free digital surface model (DSM) for the main study site (Skutulsfjörður) used in this research was based on aerial photography and lidar data collected on 12 August 2013 by the UK Natural Environment Research Council's Airborne Research Facility Data Analysis Node (NERC-ARF-DAN) (Conway, 2014). The DSM has a horizontal resolution of 1 m by 1 m, in the Icelandic national coordinate system ISN93. For areas outside the field site of Skutulsfjörður, the 2 m by 2 m DSM available
 135 through the Icelandic Environmental Agency was used (Natural Science Institute of Iceland - ÍslandsDEM, v.1.0).

2.3 Snow thickness (DS) based on terrestrial laser scanning

We conducted laser scans using a Riegl VZ6000 long-range terrestrial laser scanner (TLS) that has a maximum range of 6 km and operates at a wavelength of 1064 nm, which is suitable for scanning snow and ice (Prokop, 2008). The TLS was deployed on fixed metal tripods anchored to a large rock for scans of Funi (66.045, -23.154, 5 m.a.s.l), and to a concrete mount on
 140 stable ground for scans of KaS (66.059, -23.166, 3 m.a.s.l). The positions were selected to provide maximum coverage of the release areas, with minimised shadowing. We chose the scan parameters to maximise the resolution while keeping the scan time to approximately 20 to 30 minutes to minimise potential interference by wind and snow. The scans were processed using primarily manufacturer-specific software into 1 m by 1 m horizontal resolution DSMs, in the Icelandic national coordinate system ISN93.

145 We aimed to obtain TLS scans of Funi and KaS immediately before and after winter storms with significant snowfall during the 2025–2026 winter, as weather conditions allowed. Maps of snow depth change (ΔHS) were calculated as the vertical difference between the DSM before and after, and due to the mostly very steep terrain, corrected by the local slope angle to produce maps of the change in snow thickness (ΔDS).

2.4 Snow thickness based on in-situ measurements

150 The IMO measures snow thickness and temperature gradients within the snowpack using a SM4 device, which comprises a point laser and a thermistor string at approximately 20 cm intervals (Ingólfsson and Grímsdóttir, 2008). The SM4 is installed at a single location within Steiniðjugil on the KaS slope (66.076, -23.159, 420 m.a.s.l). The measurements from the SM4 are available every 10 minutes. While the TLS provides high spatial resolution and relatively low temporal resolution, the SM4 data are only available for a single point in the field but at a much higher temporal resolution. The data from this single point
 155 are not representative of the entire study area.



The thermistor string is positioned vertically on a mast to measure snow height (HS), while the laser sensor is tilted orthogonal to the terrain to give snow thickness (DS), the perpendicular equivalent of snow depth. The distance to the snow-free ground was estimated using the mean distance in the periods from 27 December 2025 to 8 January 2026 and 24 January 2026 to 7 February 2026, when there was no snow on this section of the KaS slope. The SM4 laser measurements were subtracted from the mean distance to the ground to give DS. Small gaps in the SM4 data during the studied events were filled using linear interpolation. A size 3 avalanche (IMO identification number 61415) released in the area measured by the SM4 on 17 March 2026, and is clearly visible as a sudden drop in DS in the SM4 laser data (see Figs. 2 and 3). The focus of this research was on the change in snow thickness due to wind drift. As a result, the last measurement before the avalanche occurred was taken as a rough estimate for the end of the corresponding event. The SM4-derived ΔDS is shown for the studied events in Fig. 3 and for the entire winter season in Fig. 2. In the results (Sec. 4.1, Fig. 9) we have clearly marked which calculated values include curated values, and which values are directly derived from the measurements.

2.5 Meteorological data

The Þverfjall (TVER) automatic weather station (66.044, -23.307, 741 m.a.s.l) is located in the upper section of a high flat-topped mountain south-west of Skutulsfjörður, and is frequently used by avalanche forecasters at the IMO as an indicator of the prevailing mountain weather in the northern Westfjords region. The station records measurements every 10 minutes including: air temperature and humidity at 2 m above the ground; and wind speed and wind direction at 10 m above the ground (see Figs. 2 and 3). The station does not measure precipitation or snow height. Precipitation is measured at the Tungudalur automatic weather station (ISA) (66.060, 23.184, 4 m.a.s.l) located within Skutulsfjörður.

The prevailing wind direction is the most important driver of where additional snow is deposited and eroded during events with significant wind. The wind direction used in this study is based on the prevailing mountain wind as measured at the station TVER. However, on a given slope, wind patterns are deflected by the mountain slopes and other local terrain. In this study, we experimented with downscaling wind direction using the diagnostic wind model WindNinja (Forthofer et al., 2014) to calculate wind fields at 100 m resolution, based on the 10 m DSM model.

2.6 Avalanche events

Information about avalanche events that occurred in the field sites during the 2025 to 2026 winter was obtained from the Avalanche Database maintained by the IMO (see Appendix Tab. A1). During this period, IMO reported 10 avalanches in the Funi field site and 12 in KaS (see Fig. 2). There were two periods during which several relatively small avalanches occurred overnight on 5–6 February and 3–4 March. In the avalanche cycle from 13 to 17 March, there were 10 avalanches in the field sites including a size 3 avalanche in Steiniðjugil that went over the road and broke several trees. From late March until mid-April, avalanches occurred more sporadically; during this time there were two large size 3 avalanches that released in the Funi avalanche path, one of which went over the avalanche defence wedge. The outlines of the starting zone and runouts of these avalanches, as well as other smaller avalanches identified on the TLS scans, were masked out manually from the TLS data to reduce the influence of snow redistributed through avalanche processes.

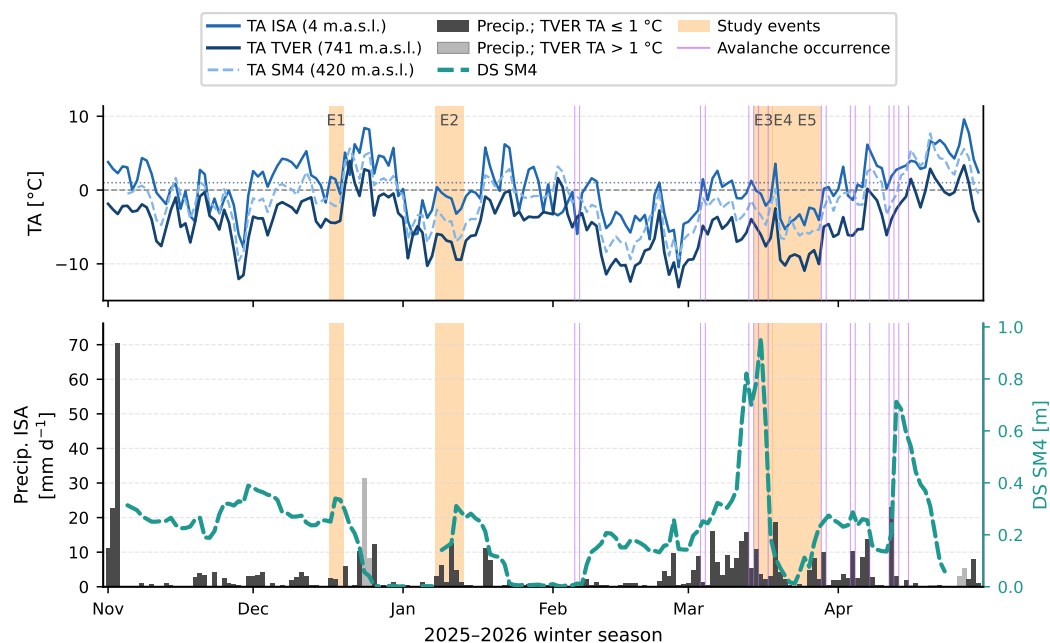


Figure 2. Overview of the winter season at the stations TVER and ISA and the SM4 sensor, showing the air temperature (TA), the precipitation (Precip.) recorded at the ISA station, and the snow thickness measured by SM4. The orange areas mark the study event times, and purple lines the recorded avalanche occurrences.

2.7 Selected study events

- 190 The 2025–2026 winter in the Westfjords was characterised by unusually low snowfall until the beginning of March, followed by large storms and corresponding avalanche cycles from March to April 2026. Only 6 of the 22 avalanches for the winter in the IMO avalanche database occurred in the period before the E3 start scan on 14 March 2026. From 23 to 26 December 2025, approximately 60 mm precipitation fell as rain during warm conditions in Ísafjörður leading to the widespread melting of most of the existing snow cover.
- 195 In total, 29 scans were acquired during the winter as part of this study, of which 15 were ultimately used (see Appendix Tab. A2). High quality scans with the Riegl VZ6000 TLS require good visibility (no fog and no or very little precipitation), which is not always the case immediately before and after major storms. The events used for this research were selected based on: a) availability of high quality scans; b) consistent weather conditions; c) scans not dominated by redistribution of snow by avalanches; and d) a relatively clearly confined duration. Snowfall rendered some scans unusable including those of Funi on
- 200 14 March, Steiniðjugil on 16 March and both sites on 30 March 2026. In addition, scans taken in April were dominated by redistribution of snow through large avalanche events and were therefore unsuitable for this analysis. Scans were not possible before and after a smaller storm event in late February due to limited personnel availability. Based on these criteria and circumstances, five events were selected, hereafter referred to as E1–E5 (see Tab. 1).



Table 1. Summary of meteorological parameters for selected events at TVER (except Precip. at ISA), with accumulated precipitation (Precip.), wind direction (DW), average wind speed (VW), average (and maximum) gust wind speed ($VW_{gust,max}$), and minimum and maximum air temperature (TA).

Event	Period	Duration [d]	Precip. [mm]	DW	VW [ms ⁻¹]	$VW_{gust,max}$ [ms ⁻¹]	TA _{max} [°C]	TA _{min} [°C]	Notes
E1	16–19 Dec 2025 17:00–15:00 UTC	3	5	NE–N	14.1	20.0 (34.5)	-3.5	-5.3	Consistent NE wind direction, constrained temporally
E2	7–13 Jan 2026 15:00–13:00 UTC	6	28	N/NE→ E	11.1	17.0 (30.0)	-5.4	-10.7	More varied wind directions, considerable snow accumulation
E3	14–18 Mar 2026 15:00–11:00 UTC	4	20	NNE	18.0	23.9 (43.6)	-5.6	-8.5	Consistent wind direction; Funi scan missing—not usable due to snowfall
E4	18–22 Mar 2026 11:00–16:00 UTC	4	25	SW	11.0	19.6 (40.7)	1.3	-12.0	Different wind direction from the other events
E5	22–28 Mar 2026 16:00–10:00 UTC	6	10	NE	11.1	14.7 (42.7)	-5.0	-14.4	Less constrained temporally, consistent wind direction during strong winds

For all events, except E4, the wind was generally in a NE wind direction. By comparison, E4 was characterised by strong winds from a SW direction. E3 to E5 were consecutive, taken on calm days between avalanche cycles. These calm periods also correlated with a significant change in wind direction from NE to SW and back to NE. This reversal of the wind direction is particularly interesting given the focus of this study. Such a shift from strong SW winds to strong N/NNE winds at TVER was also observed in the 2 days before the catastrophic avalanche in Súðavík on 16 January 1995, only 7 km SE of Funi (Hættumatsnefnd Ísafjarðarbæjar, 2004). E1 had relatively low accumulated snowfall compared with the other events, E2 was a longer stand-alone event with relatively low wind speeds and almost 30 mm of accumulated precipitation. Meanwhile, E3 had much higher wind speeds from the same direction with significant snowfall. Figure 3 presents an overview of the meteorological and SM4 snow thickness data for each event.

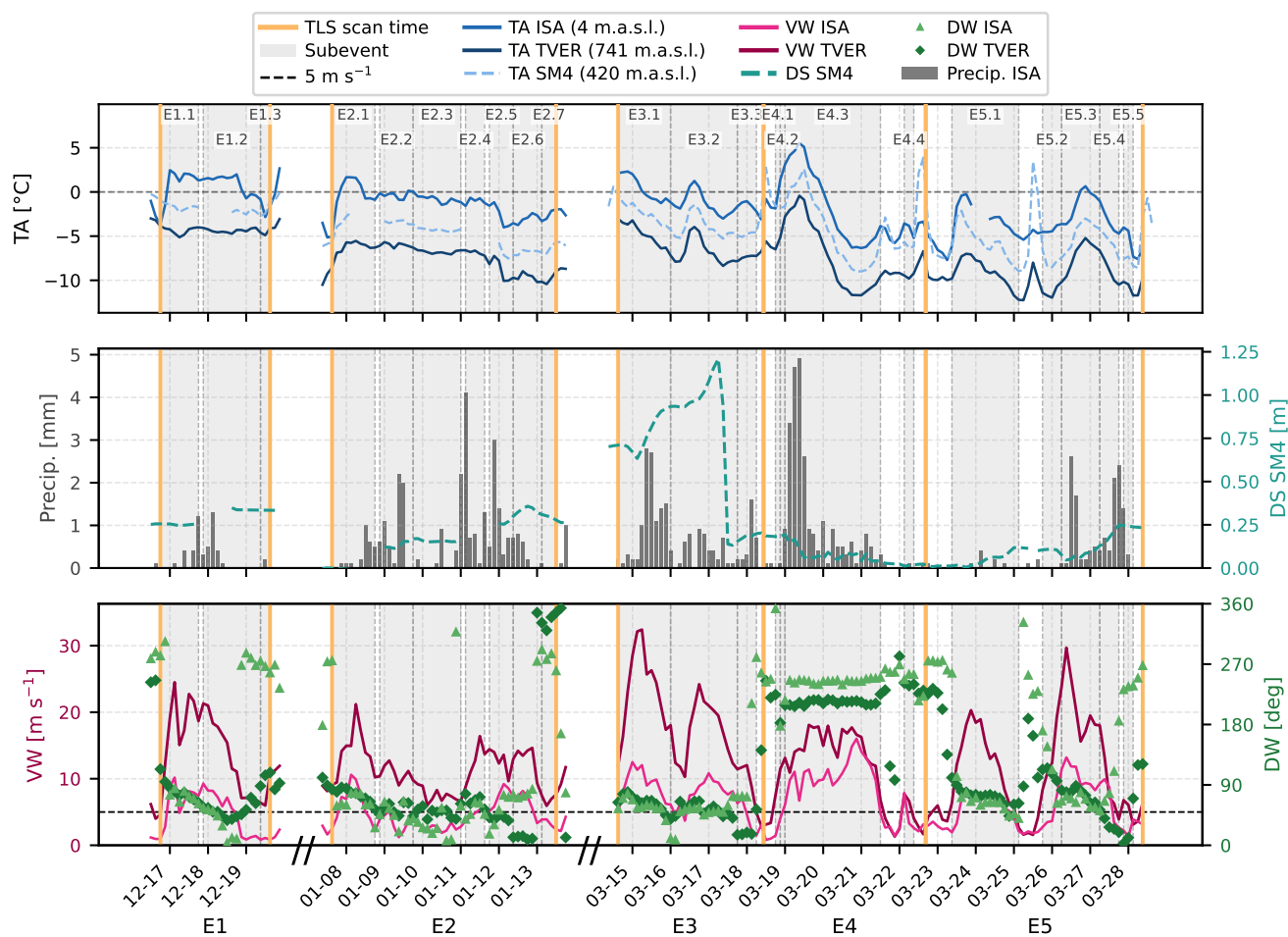


Figure 3. Overview of the meteorological conditions, TLS scan times and separation into sub-events. The top row shows the air temperature (TA) of the weather stations ISA and TVER and at the SM4 sensor. The middle row shows the accumulated precipitation, measured at the weather station ISA and the lidar-derived snow thickness DS. The last row gives information on the wind speeds (VW) and wind directions (DW), measured at the weather stations ISA and TVER.



3 Methodology

3.1 Sub-event classification

215 The events delineated by before and after laser scans were further divided into sub-events, primarily based on the consistency of the wind direction as measured at TVER. The wind shelter index is driven by wind direction, which shifted significantly during the multi-day events used in this study. A minimum wind speed threshold of 5 m s^{-1} was applied to exclude wind speeds that are generally considered too low to initiate snow drift (Li and Pomeroy, 1997), and are often characterised by highly changeable directions. The classification of a sub-event started with the first valid observation; the next observation was
 220 then added if the standard deviation of the wind direction in the current sub-event remained below a threshold of 10 degrees. When five consecutive observations did not meet this threshold, a new sub-event was established. Sub-event classification was further constrained by requiring a minimum sub-event duration of 2 hours. These criteria were introduced to prevent excessive splitting especially at the onset of a sub-event. Additionally, a temporal gap between observations of 2 hours or more triggered the initiation of a new sub-event. Two neighbouring sub-events were merged if the difference in the circular mean
 225 wind direction was below 20 degrees, and the circular standard deviation of the combined sub-events was below 15 degrees. All thresholds were chosen empirically.

3.2 Wind shelter index

The wind shelter index (S_x), as developed by Winstral et al. (2002), aims to indicate which areas of a terrain are sheltered or exposed for a given wind direction. The maximum angle between a terrain point $\mathbf{X}_j(x_j, y_j, z_j)$ and all terrain points
 230 $\mathbf{X}_d(x_d, y_d, z_d)$ located along the azimuth defined by the wind direction A within a maximum search distance D is determined by:

$$S_{x_j}^{A,D} = \max \left[\arctan \left(\frac{z_d - z_j}{\sqrt{(x_d - x_j)^2 + (y_d - y_j)^2}} \right) \right], \quad (1)$$

Restricting the analysis to a single wind direction makes the index strongly dependent on terrain features aligned with that azimuth and neglects small temporal variations in wind direction. Therefore, the wind shelter index $S_{x_j}^{A,D}$ is expanded by
 235 considering a number of azimuths n_A around the azimuth of a given wind direction A , where n_A is determined by the range of azimuths from A_1 to A_2 , and a defined step size (Winstral et al., 2002):

$$\overline{S_{x_j}^D} |_{A_1}^{A_2} = \frac{1}{n_A} \sum_{A=A_1}^{A_2} S_{x_j}^{A,D}, \quad (2)$$

The wind shelter index ($\overline{S_{x_j}^D}$, for simplicity referred to as S_x hereafter) was calculated separately for each sub-event using. For each sub-event, the mean wind direction was defined as A , A_1 and A_2 from the standard deviation of wind directions per
 240 sub-event, and the step size was set to 5 degrees. To compare S_x with the event-scale measured ΔDS , the sub-event values were combined using a weighted mean based on accumulated precipitation and squared mean wind speed, considering only wind speeds above 5 m s^{-1} .



We tested the assumption that the correlation between snow depth distribution and S_x improves at higher wind speeds using a larger search distance D . For each event, we calculated the S_x with varying search distances D and performed Spearman
 245 rank correlation tests on the correlation between TLS snow thickness in release areas, and the search distance-adjusted S_x . No clear correlation was found between mean wind speed and optimal search distance for the studied events. Instead, the optimal search distance D of all evaluated events was averaged, resulting in 15 m, which is consistent in magnitude with values used in previous studies (Schön et al., 2015; Ruttner et al., 2026).

3.3 Scaling to snow depths

250 ΔDS based on TLS data was used to determine scaling parameters to convert the calculated wind shelter index S_x to snow thickness. We defined the modelled ΔDS_{S_x} as

$$\Delta DS_{S_x} = a * S_x + b \quad (3)$$

where a is the regression slope [m deg^{-1}] and b is the intercept [m], derived separately for each event. Table 2 gives an overview of a and b per event.

255 For the reconstruction of the events with available TLS data, we computed the event-specific linear fit based on the mean measured ΔDS and S_x for each split release zone. To ensure that the fit was based only on areas covered by both datasets, we restricted the S_x map to the spatial extent of the TLS measurements. We additionally excluded areas from the TLS measurements that were influenced by avalanches.

3.4 DS and ΔDS at sub-event-scale with SM4 data

260 The SM4 and TLS measurements were validated against each other at the same location and time by comparing both absolute snow thickness (DS) and event-scale snow-thickness change (ΔDS). TLS data was only available for the start and end of each multi-day storm event when weather conditions were suitable for scanning. However, it is useful to understand snow-depth variations at a sub-event level to better understand the effects of changes in wind direction, wind speed, precipitation and temperature. The SM4 data was used to evaluate the wind shelter scaling approach developed in this study at sub-event level.
 265 The SM4 laser sensor is mounted at an angle, as a result, the snow-thickness measurement is located upslope of the GNSS coordinates recorded at the pole base. We therefore estimated the measurement location by shifting the GNSS location of SM4 2 m upslope and averaged the TLS and scaled values within a 2 m radius around this point.

3.5 Wind drifted snow indication maps

Experimental wind-driven snow indication maps were developed for sites where the IMO avalanche forecasting team conducts
 270 site-specific forecasts. Such maps could provide a useful forecasting tool by incorporating wind speed, wind direction, event duration, and accumulated precipitation. These parameters could be entered manually by a forecaster or obtained automatically from meteorological observations to estimate wind-driven snow accumulation. As a proof of concept, however, we developed a preliminary set of indication maps based solely on the wind shelter index. The maps do not predict actual snow thickness but



instead can be interpreted as indication of the relative spatial distribution of wind-driven snow across the slope based on wind direction and terrain. Their purpose is to highlight which avalanche starting zones are more likely to accumulate snow under different wind directions, particularly those not typically associated with avalanche activity at the site.

We generated the indication maps by calculating the S_x for wind directions taken at 45 degree intervals. For each main wind direction, S_x was averaged over a 15 degree sector. The selected directions were intended to represent a range of contrasting wind scenarios rather than all possible wind directions. Averaging S_x over a sector also reduces the sensitivity of the index to individual terrain features aligned with a specific azimuth and better represents natural variability in wind direction. The resulting maps provide a first estimate of which release zones are more likely to accumulate wind-drifted snow under different wind directions. We additionally developed polar plots for selected critical locations within these release zones to identify the wind directions associated with the greatest potential accumulation and to highlight changes in wind direction that may be particularly relevant for avalanche forecasting.

4 Results

The TLS-derived changes in snow thickness (ΔDS) for the five events at both study sites are presented in Figure 4. Although E1, E2, E3, and E5 had similar wind directions, the events showed different spatial distributions and ΔDS magnitudes. For E3, the mean ΔDS for KaS was relatively low at 0.06 m, but there were strong spatial variations with a standard deviation of 0.54 m. E3 also had the highest mean wind speeds of 18 m s^{-1} and wind gusts of up to 44 m s^{-1} (measured at TVER), which resulted in large accumulations in some areas such as gullies, but negative ΔDS in other areas such as ridges. The negative ΔDS data points also indicated that there must have been some erodible snow layer before the start of the event.

Events E3–E5 were consecutive, with TLS surveys conducted during calm periods between the events (Fig. 3). E4 differed from the other events because it was characterized by predominantly SW winds, yielding negative mean ΔDS at both study sites. During E5, the wind was predominantly from the E and showed comparatively little directional variability for most of the event and relatively little precipitation was recorded at ISA. Both study sites showed positive mean ΔDS , but the spatial variability was comparatively large.

Although all events (except E4) had broadly similar wind directions, the pairwise correlations between the measured ΔDS were generally low (Fig. 5). The strongest relationship was observed between E3 and E4, and was negative correlating to an overall reversal of wind direction from NE to SW.

A comparison of the TLS measurements with SM4 data (Fig. 6.) showed good overall agreement, with a root mean squared error (RMSE) of 0.29 m for DS and 0.20 m for ΔDS . A positive bias was observed for absolute DS, with TLS generally yielding higher values than the SM4 measurements. The standard deviation of TLS measurements within the evaluated area was generally lower for ΔDS than for absolute DS, indicating that snow-thickness changes were more spatially uniform than the underlying snow cover.

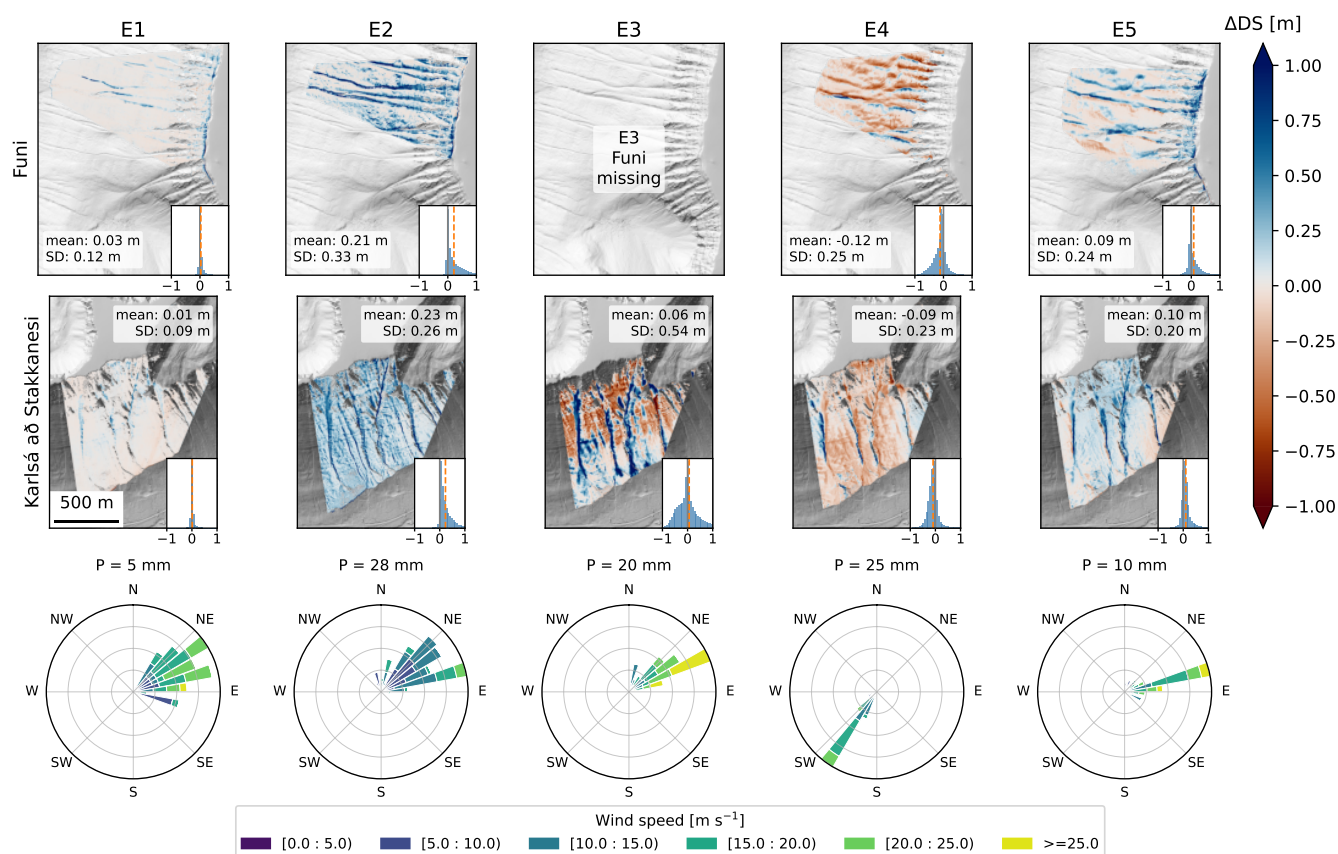


Figure 4. Measured changes of snow thickness (ΔDS) for all events on both sites. The insets show the corresponding histogram, with the grey line indicating 0.0 and the dashed orange line the mean. The bottom row shows the windroses for the corresponding events, stating the accumulated precipitation (P), measured at the weather station ISA.

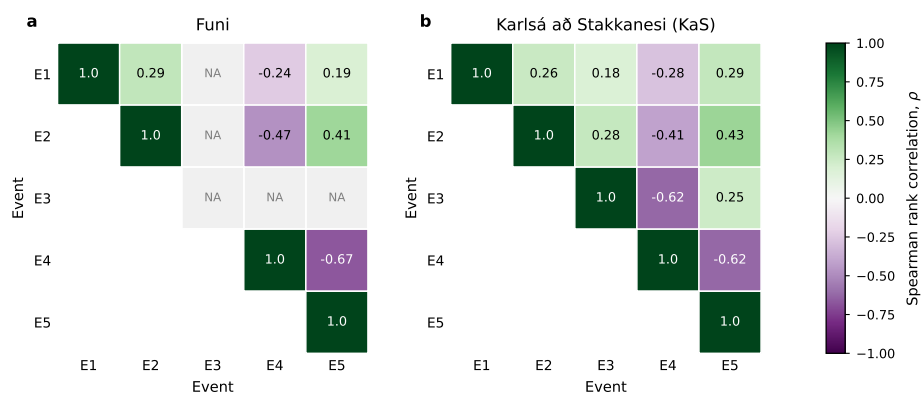


Figure 5. Correlations of measured ΔDS between events

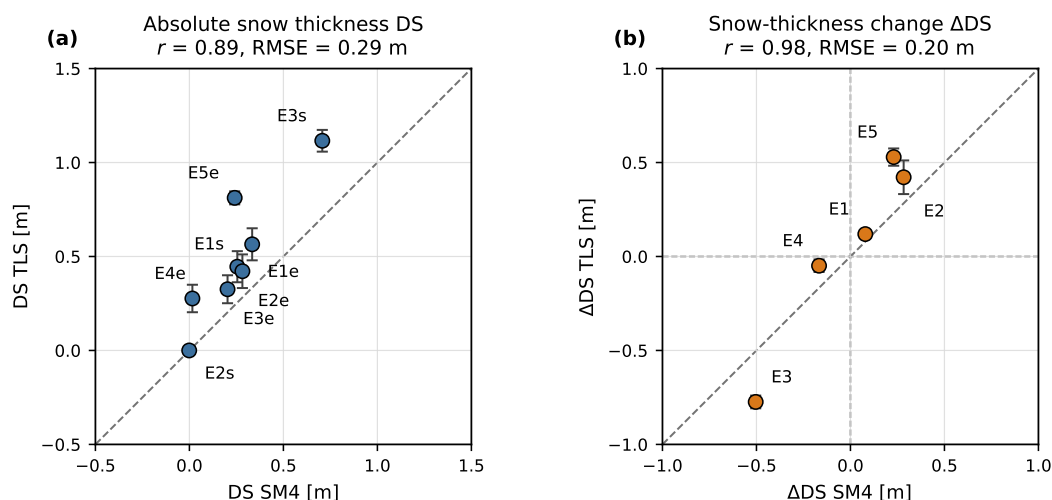


Figure 6. Comparison of (a) DS and (b) ΔDS derived from the TLS measurements and the SM4 sensor. The vertical error-bars show the standard deviation of the TLS measurements in the evaluation footprint (circle of 2 m radius upslope of the SM4 location).

305 4.1 Modelling snow depth distribution

The S_x was calculated for each sub-event and subsequently compiled for each event (exemplified and explained using the sub-event S_x maps of E1 in Fig. 7). These initial maps provide an indication of the expected spatial pattern of snow redistribution based on the static terrain and wind direction but do not provide information about overall magnitude of snow accumulation, which is mainly affected by the total erodible snow layer, wind speed and event duration. Consequently, events with similar
 310 wind directions, such as E1, E2, and E3, produced comparable S_x patterns despite substantial differences in TLS measured snow thickness.

During the E1 sub-events, the mean wind direction ranged from 50 degrees to 103 degrees (see Fig. 7). On Funi, these wind directions generally led to airflow from the high plateau down the slope. As a result, the slope was predominantly sheltered for all three sub-events with little variation. By contrast, on the generally east-west orientated KaS slope, the difference in the
 315 sheltering between sub-events 1.1 to 1.3 was more pronounced. During E1.1, the 78 degrees wind direction was approximately parallel to the slope, resulting in shelter for deep gullies and exposure on the slopes between the gullies. By contrast, the 50 degrees wind direction during E1.2 led to airflow from the ridge down the slope leading to greater overall sheltering.

The linear relationship between the measured ΔDS and S_x was evaluated using the more spatially constrained split release zones (see Fig. 8). The parameter values obtained from the linear fit for the split release zones and some statistics are
 320 presented in Tab. 2. Measurements from the Funi and KaS sites were analysed together due to their spatial proximity and similar meteorological conditions. Differences in terrain and aspect between the two sites were accounted for through the corresponding differences in S_x values.

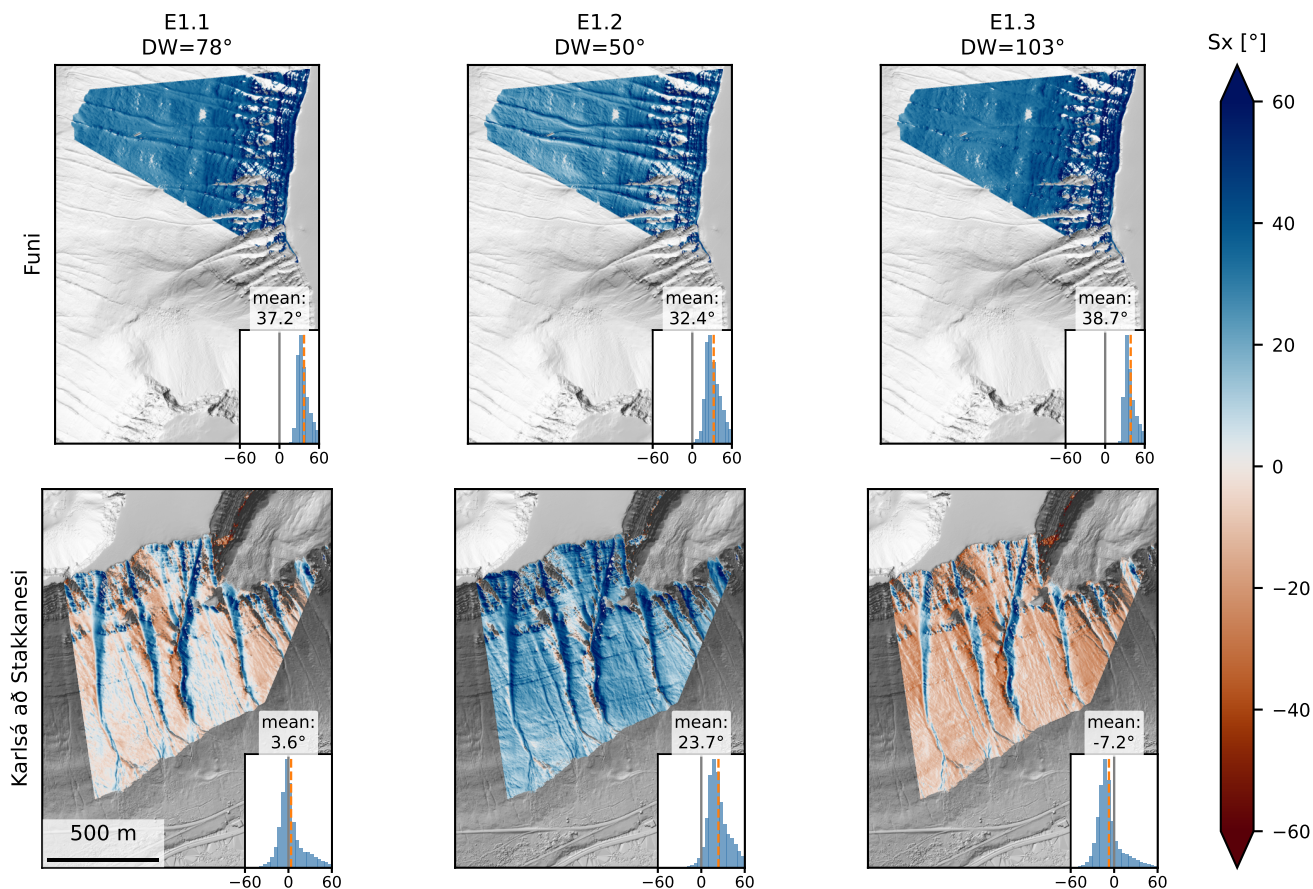


Figure 7. Calculated S_x on the sub-events of E1 (the mean wind direction DW is stated for each sub-event), masked by the pixels available from the TLS measurements

Table 2. Linear regression parameters and goodness-of-fit statistics relating mean weighted shelter index (S_x) to mean measured snow depth change (ΔDS) across split release zones.

Event	a [mdeg ⁻¹]	b [m]	R^2	RMSE [m]
E1	0.0025	-0.01	0.15	0.09
E2	0.0040	0.14	0.18	0.10
E3	0.0147	-0.25	0.45	0.25
E4	0.0046	-0.08	0.13	0.21
E5	0.0048	0.05	0.35	0.12
Global	0.0060	-0.03	0.38	0.18

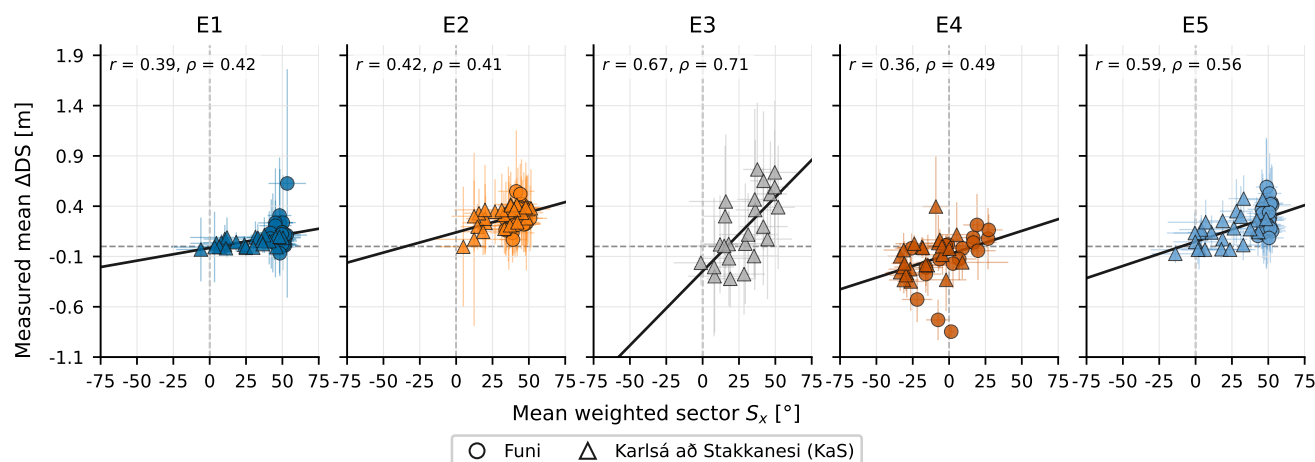


Figure 8. Event-specific linear fit of mean measured ΔDS and calculated S_x on split zone level (including error bars for standard deviation), with scores for Pearson r and Spearman ρ correlations.

4.2 Model evaluation

Figure 9 compares the scaled S_x estimates with the SM4-derived ΔDS at the sub-event scale. Agreement varied considerably among sub-events. The model reproduced the direction and approximate magnitude of the pronounced accumulation during E3.1 and the erosion during E4.3, although it overestimated the magnitude of erosion in E4.3. Larger discrepancies occurred during E3.2 and several E5 sub-events: the model underestimated the measured accumulation during E3.2, E5.1, and E5.4, while overestimating it during E5.3. For E1 and E2, the measured and modelled changes were generally small and predominantly positive, but the model tended to underestimate the reviewed SM4 values. Overall, the model captured some of the main accumulation and erosion signals but did not consistently reproduce the magnitude of ΔDS across all sub-events.

Figures 10 and 11 show the measured and modelled mean ΔDS together with the corresponding residuals for split zones at the event level. Overall, the residuals were small, generally on the order of 0.1 m, and the model reproduced the main spatial patterns of snow enrichment and depletion well. The largest discrepancies between measured and modelled ΔDS was during E3.

4.3 Indication maps

The first wind-driven snow indication maps were produced using only the wind shelter index S_x . The index was calculated for a series of wind directions to show the relative spatial patterns of terrain shelter and exposure (Figs. 12 and 13). The indication maps show clear differences in terrain shelter among wind directions and between the two study sites, reflecting their different terrain orientations: the KaS slope is oriented approximately E–W, whereas Funi has a more N–S-oriented terrain structure. At KaS, the release zones are predominantly sheltered under NW–N winds, whereas SE to S winds result in greater exposure.

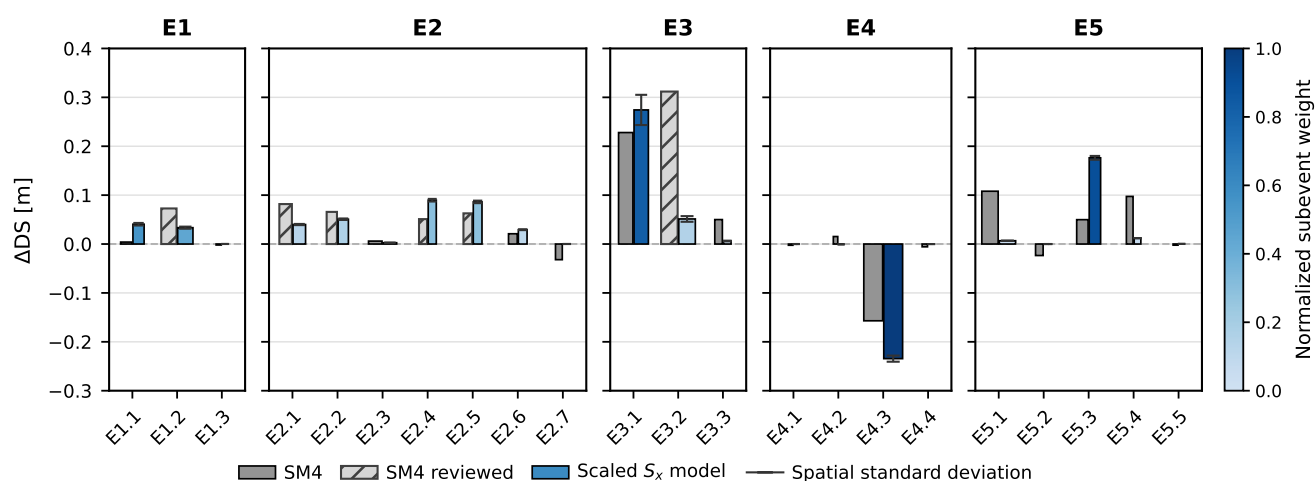


Figure 9. Comparison of modelled ΔDS using S_x and measured ΔDS from the SM4. The hashed bars indicate that the SM4 data for the sub-events was reviewed manually. The width of the bars indicate the length of the sub-event, and the colour the normalized weight.

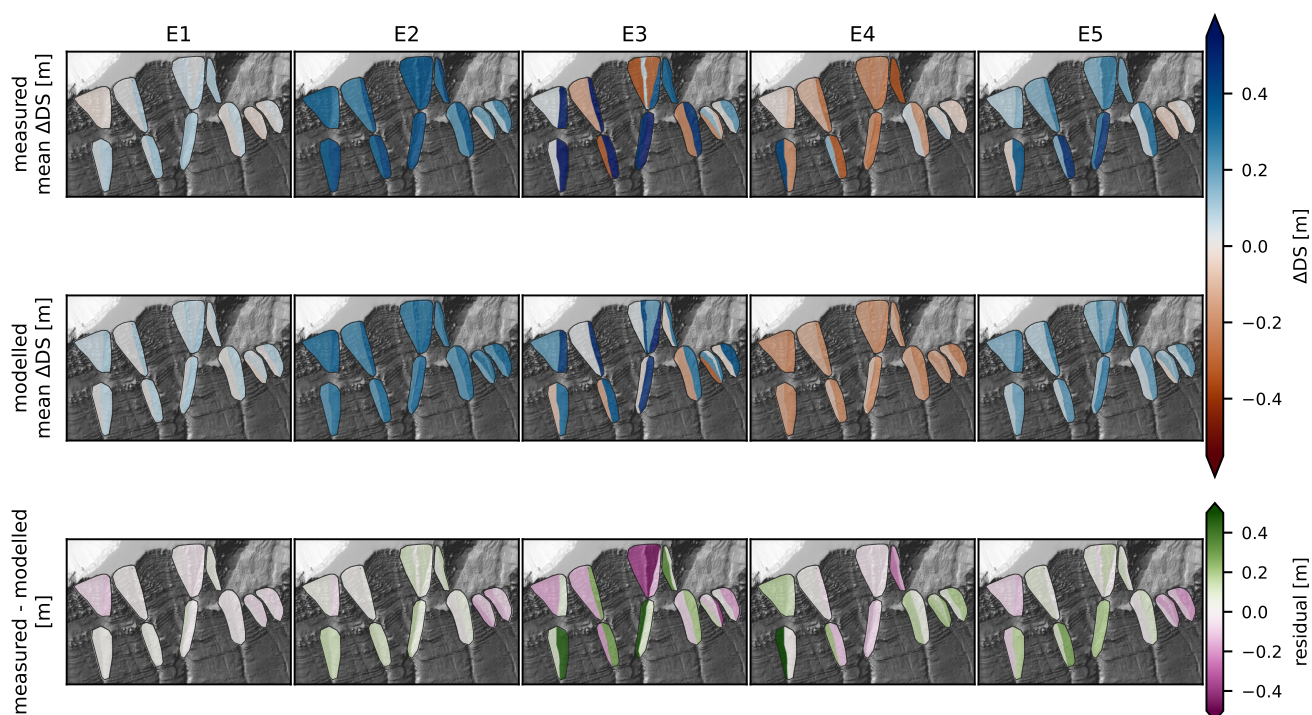


Figure 10. Comparison of modelled ΔDS using S_x , measured ΔDS and the difference between both for split release zone for the KaS site.

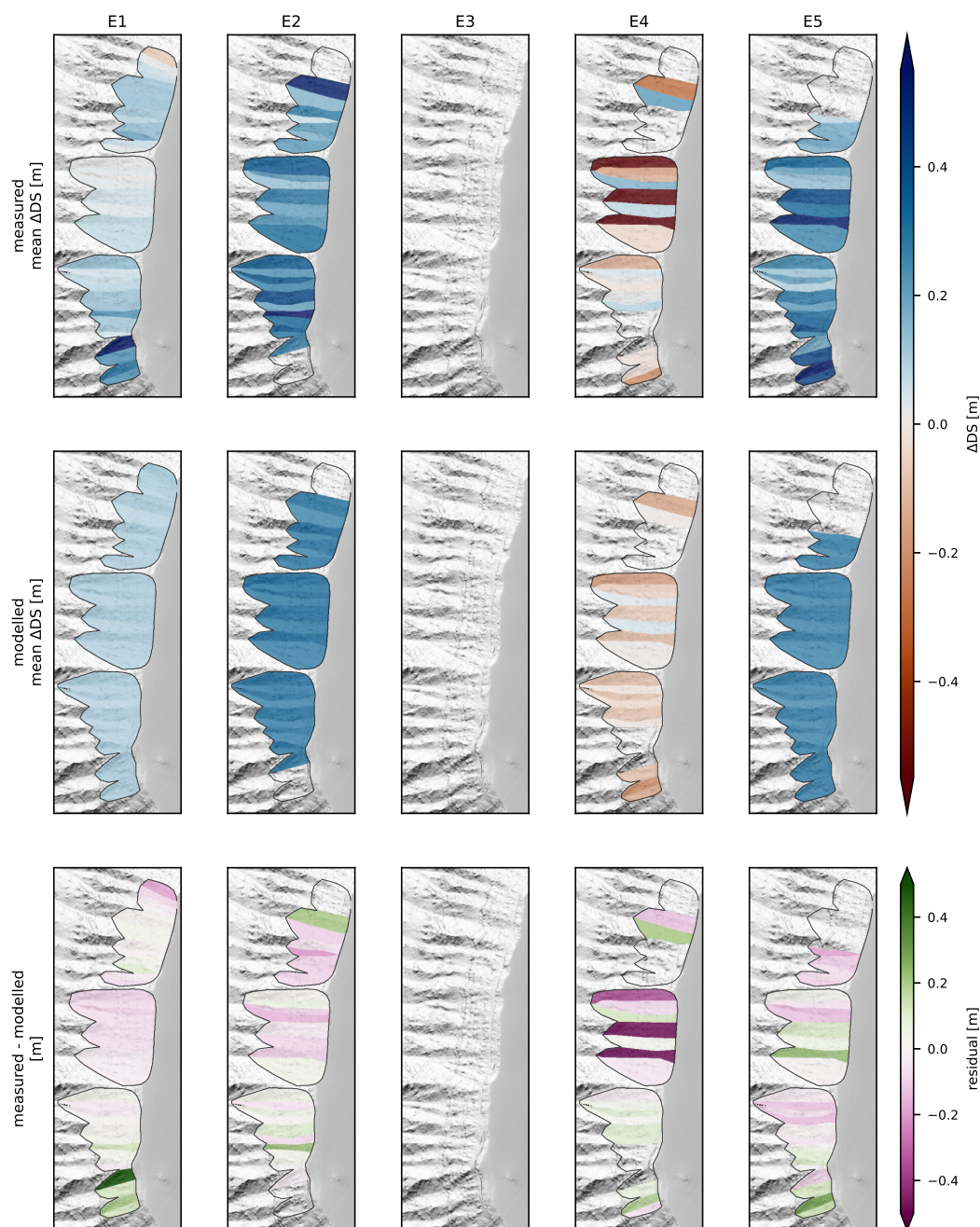


Figure 11. Comparison of modelled ΔDS using Sx and measured ΔDS on a split release zone and main event level for the Funi test site.

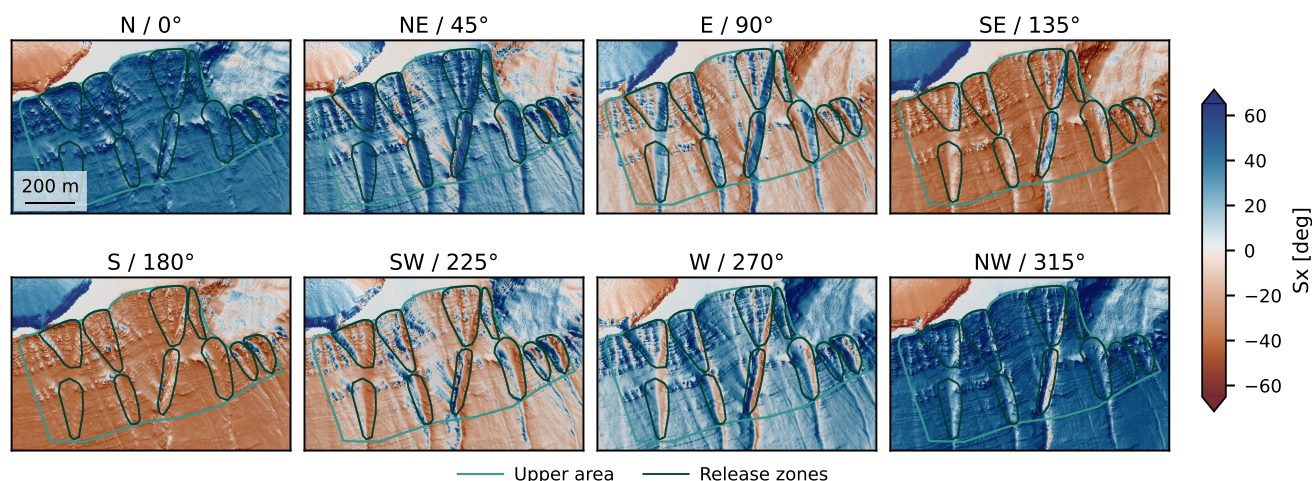


Figure 12. Wind-driven snow indication maps showing the wind shelter index for the upper KaS study area under a selection of wind directions. The outlined areas indicate the upper study area and the avalanche release zones; positive values represent sheltered terrain and negative values represent exposed terrain.

At Funi, the release zones are most strongly sheltered under E and SE winds, while W and NW winds produce the greatest exposure. When the wind is rather aligned with the main ridge orientation, smaller terrain features become more important, with individual gullies showing sheltered and exposed sides at the local scale.

Figure 14 presents a polar plot for a location on Grænafell associated with the avalanche of 28 March 2026. The evaluated location shows the strongest terrain shelter under NE winds, while N and E winds also produce favourable conditions for wind-driven snow accumulation. Although NW winds are less commonly associated with major winter storms at this site, they may redistribute available snow into the gully, particularly when erodible snow is present. A shift towards NW winds may therefore maintain or increase loading in the starting zone, even after the main snowfall period.

5 Discussion

5.1 Characteristics of snowfall events and data acquisition

The differences between E1, E2, E3 and E5 (Fig. 4) demonstrate that prevailing wind directions do not necessarily produce similar ΔDS . The events differ in terms of wind speed, accumulated precipitation, duration, and initial snow-cover conditions, all of which affect the amount of snow that is available for transport. In particular, the combination of strong winds and large spatial variability during E3 suggests more extensive redistribution than during E1 and E2. The negative ΔDS in E3 suggests that an erodible snow layer was already present at the beginning of the event. The consecutive sequence of E3–E5 was particularly informative because snow deposited during one event was likely available for redistribution in an opposing

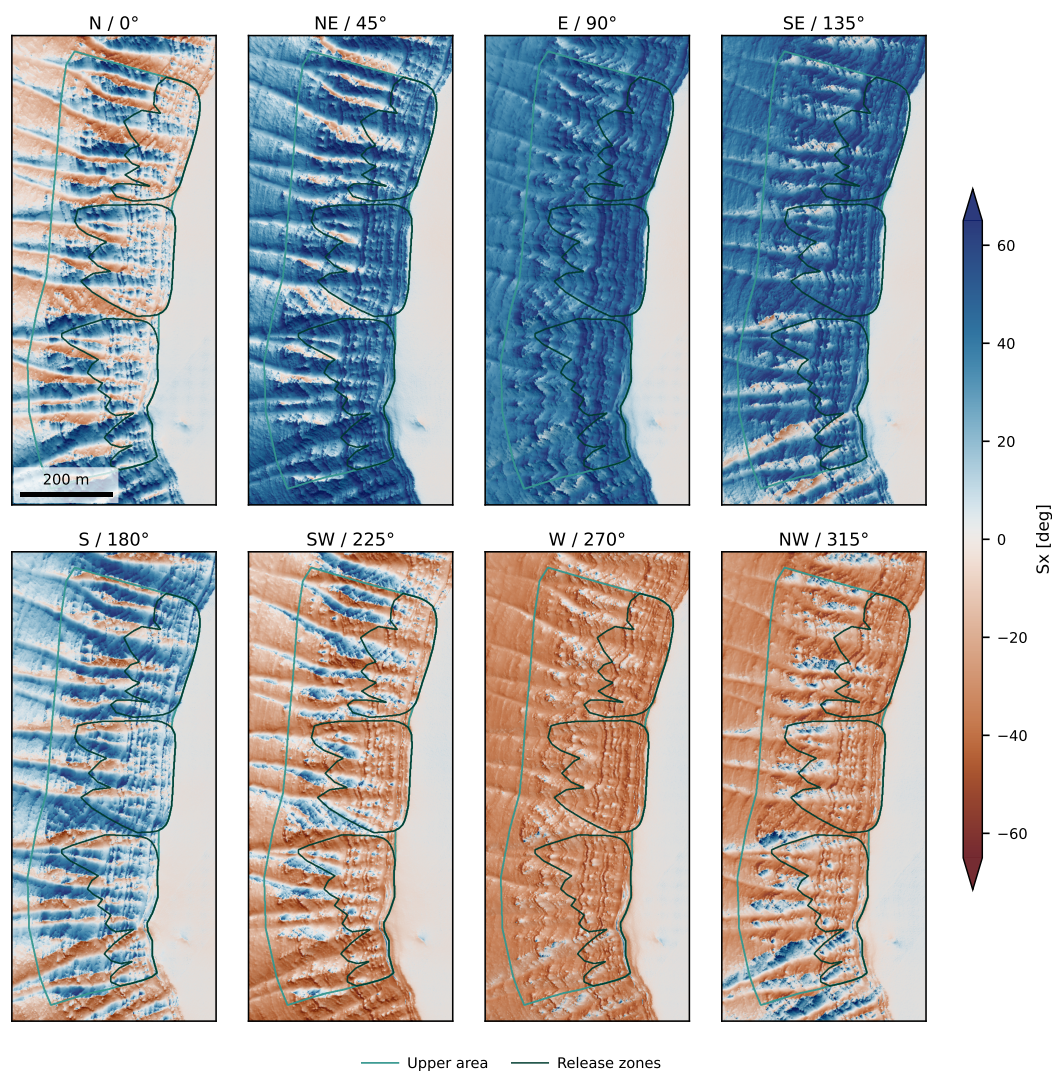


Figure 13. Wind-driven snow indication maps showing the wind shelter index for the upper Funi study area under a selection of wind directions. The outlined areas indicate the upper study area and the avalanche release zones; positive values represent sheltered terrain and negative values represent exposed terrain.

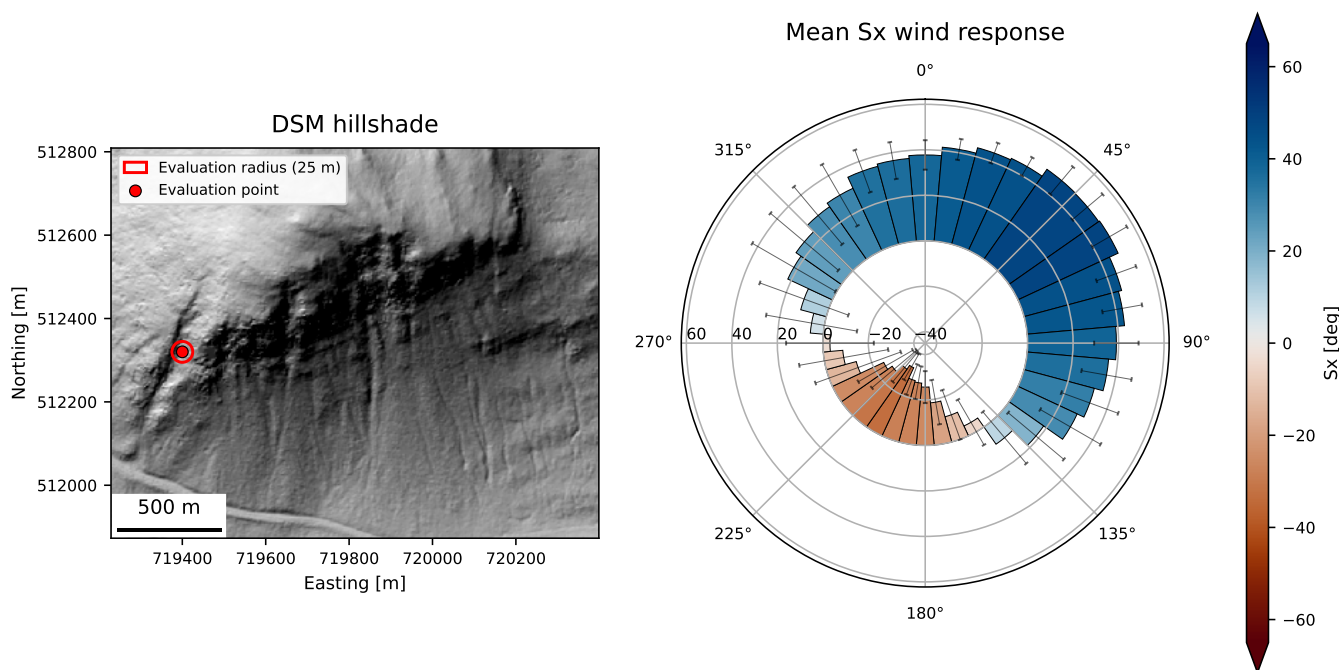


Figure 14. Directional response of the wind shelter index at a location on Grænafell associated with the avalanche of 28 March 2026. The left panel shows the evaluated area, and the right panel shows the mean wind shelter index and its spatial variability across wind directions.

direction during the subsequent event. During E4, the wind direction reversed from NE to SW, exposing the study sites to a markedly different loading pattern. The negative mean ΔDS in E4 suggests that large sections of both sites were dominated by erosion. The strong negative correlations of E4 to E3 and E5 may therefore indicate a partial reversal of the spatial pattern, with snow removed from areas in which it had previously accumulated and vice versa.

The generally low Spearman correlation based on a pixel-based analysis of events with similar prevailing wind directions (see Fig. 5) indicate that the event-dominant wind direction alone cannot explain the observed patterns of ΔDS . The chronology of wind and snowfall conditions plays an important role. In this context, the consecutive measurement sequence for E3–E5 is particularly informative, as it allows the snow-cover conditions preceding E4 and E5 to be inferred from the previous event. By contrast, E1 and E2 occurred after periods with little and presumably predominantly frozen snow, limiting the amount of erodible snow initially available for redistribution.

Based on the dominant ENE shifting towards northerly wind directions during E5 (see windrose in Fig. 4), most of the Funi site was expected to be wind sheltered. However, the TLS measurements showed noticeable erosion in the middle and lower parts of the slope. During the final sub-event, the wind direction shifted towards the north (see Fig. 3), and the corresponding Sx pattern (Appendix Fig. A1) agreed more closely with the measured ΔDS in Fig. 4. This suggests that earlier accumulation may have been redistributed and the older snow layer may have been partially eroded towards the end of the event, highlighting the importance of meteorological chronology. Alternatively, terrain-induced flow deflection may have caused local



wind directions at Funi to differ from those measured at TVER. Without slope-scale wind observations, the relative dominance of these processes cannot be determined.

375 The comparison between TLS and SM4 measurements is also subject to uncertainty. An avalanche occurred during E3 and passed over the SM4 installation. The reference distance to the ground was estimated from snow-free periods in January and February; however, a greater sensor-to-ground distance was measured after the winter season in May. This difference suggests that either the sensor installation or the ground surface may have shifted during the winter. As the SM4 installation appeared stable over the individual measurement events, changes in snow thickness are expected to be less affected than absolute snow-
 380 thickness measurements. The TLS-derived snow thickness changes also contained several sources of uncertainty. The SM4 sensor was located approximately 2 km from the TLS position, where scanning geometry and atmospheric effects may influence measurement accuracy. Voordendag et al. (2023) studied several sources of TLS uncertainty and reported point errors ranging from a few centimetres near the scanner to approximately 0.66 m at a distance of 4 km. The agreement between the TLS and SM4 measurements should therefore be interpreted in relation to the uncertainties of both measurement systems.

385 5.2 Sx and wind directions

The calculation of Sx requires a representative wind direction. In this study, the event-based maps used the domain-average wind direction per sub-event measured at TVER, consistent with the information available in operational forecasting. However, wind can be deflected by complex topography, and the direction measured at TVER differs from the exact local wind direction at the study sites. This limitation is particularly relevant when the wind is directed along a slope or ridgeline, where small
 390 directional changes can result in substantially different patterns of terrain exposure and shelter. To assess the sensitivity of Sx to the prescribed wind direction, Sx was calculated for all possible directions and correlated with the measured ΔDS (Fig. 15). At Funi, the direction producing the highest correlation was consistently shifted northward relative to the measured event direction for all events from generally NE directions. However, for E4, which was predominantly from a SW direction, the highest correlation was shifted further south. This systematic shift may be affected by the orientation of the slope and the main
 395 fjord, which likely deflects the local flow relative to the wind observed at TVER. No similarly consistent deviation was found at KaS. Overall, however, selecting the direction with the highest correlation resulted in only small improvements compared to using the measured wind direction at TVER. This suggests that uncertainty in wind direction explains only part of the mismatch between Sx and the observed ΔDS . Wind speed, precipitation, snow availability, event duration and event chronology are all factors influencing the measured patterns.

400 As a plausible alternative to using TVER for the prevailing wind direction, WindNinja (Forthofer et al., 2014) was used to downscale the domain-average wind field to a spatial resolution of 100 m (used version: 3.12.2, solver: conservation of mass, wind input: domain average using TVER station). The resulting values with downscaled wind directions slightly improved correlations for most events, but performed less well for some of the more sensitive along-slope wind conditions. Although terrain-based downscaling could improve the representation of local shelter and exposure, the simulated wind fields are difficult
 405 to validate without slope-scale wind measurements. Consequently, the results do not demonstrate a consistent advantage over

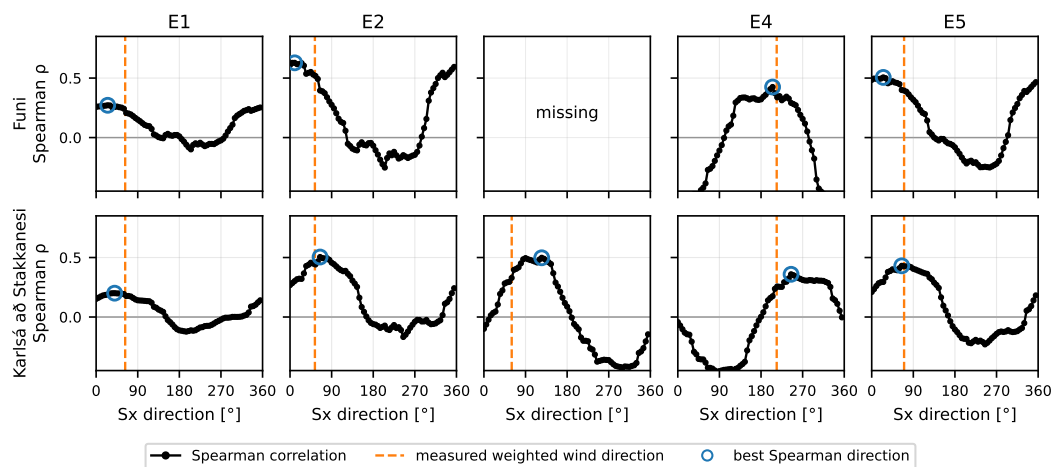


Figure 15. Spearman correlation between modelled S_x and measured ΔDS (pixel-wise) for all tested input wind directions and events at Funi and KaS (Karlsá að Stakkanesi). The dashed orange lines indicate the measured event-based wind directions at TVER, and the blue circles indicate the directions producing the highest correlations.

the simpler use of the TVER prevailing wind direction. Wind downscaling nevertheless remains a promising direction for future work.

5.3 Scaling S_x to snow depths

Deriving a quantitative relationship between S_x and snow depth remains challenging. Ruttner et al. (2026) scaled S_x by redistributing the observed precipitation while preserving the average mass balance. However, this approach is sensitive to the ratio of sheltered to exposed cells and can therefore produce biased estimates when applied to small domains. Similar to the present study, Schön et al. (2015) used a linear regression but found that large deposition amounts were generally underestimated. A nonlinear power relationship was subsequently proposed by Schön et al. (2018). In this study, we tested this nonlinear power relationship but obtained better agreement with the measurements using linear scaling. Although the pixel-wise relationship between S_x and ΔDS was only moderate, the correlations improved when the release areas were divided into smaller subzones and the measured and modelled values were averaged within each subzone. This suggests that spatial aggregation reduces the influence of small-scale variability that cannot be represented in the S_x .

The fitted relationship nevertheless varies among events because S_x describes terrain shelter but does not take into account the amount of snow available for transport or the intensity of redistribution, which is also dependent on wind speeds and duration. The event-specific fitting captures the combined influence of these factors empirically, without explicitly representing the underlying physical processes. For example, the fitted relationship is substantially flatter for E1 than for E3, while E2, which had the largest accumulated precipitation, had the largest positive intercept (see Fig. 8). These differences suggest that the intercept may partly represent event-wide accumulation, whereas the gradient reflects the strength and spatial variability



of wind redistribution. The gradient may depend not only on wind speed but also on wind direction relative to the slope:
425 strong cross-slope winds may produce greater spatial variability than similarly strong winds directed along the slope. Previous
studies have combined precipitation and wind speed in transport proxies, including formulations proportional to precipitation
multiplied by the fourth power of wind speed (Pomeroy, 1988; Davis et al., 1999; Hendrikx et al., 2005). We therefore explored
different combinations of precipitation and wind speed, using exponents ranging from a linear relationship to the fourth-power
430 formulation reported in the literature. These combinations were compared with several metrics derived from the snow-depth
measurements. The strongest relationships were found between mean absolute ΔDS and combinations of precipitation and
wind speed, with Spearman correlation coefficients of up to 0.9. However, these findings are based on very few events and
should be regarded as preliminary results rather than evidence of a robust meteorological scaling relationship.

The event-specific relationships were derived directly from the measured ΔDS and modelled S_x values for each sub-event.
Such measurements are not available when generating indication maps for other locations or unobserved events, and the event-
435 specific relationships are therefore not operationally transferable.

5.4 Purpose and interpretation of wind drift indication maps

The current wind-drifted snow indication maps do not explicitly account for variations in precipitation, wind speed, event
duration or snow availability and should therefore not be interpreted as quantitative predictions of snow accumulation. Experienced
forecasters are generally familiar with the release areas and gullies that are sheltered or exposed under prevailing wind
440 directions. Nevertheless, the maps provide a consistent and rapid overview of potential accumulation areas and may support
training, knowledge transfer and numerical simulations. They may be particularly useful for unusual wind directions or in
remote areas with which a forecaster is less familiar, helping to identify locations that warrant closer assessment. The approach
can also be used by summarizing the response of a specific release point across all wind directions as a polar plot (Fig. 14). Such
a representation highlights small changes in wind direction that cause pronounced transitions between exposure and shelter.
445 Looking at Græafell for example, small variations in NE or SW winds produce relatively minor changes in shelter, whereas
changes in winds around SE or W result in much greater directional sensitivity. This information could help forecasters identify
situations in which uncertainty or short-term variation in wind direction is particularly relevant. The maps should be viewed
as scenario-based indication and educational products that complement, rather than replace, local observations and expert
judgement.

6 Conclusion and outlook

This study investigated whether the wind shelter index S_x can be used to produce scenario-based maps of wind-driven snow
accumulation for avalanche forecasting and training in Iceland, where the amount of windblown snow is a key component
of avalanche risk. We used TLS measurements from two study sites near Ísafjörður, covering five major snow-redistribution
events during the 2025–2026 winter season. These measurements were complemented by continuous point measurements from
455 an SM4 snow thickness sensor.



The pixel-wise correlations between S_x and measured snow thickness change were moderate. However, the relationships improved when the release areas were aggregated into smaller subzones and the values were averaged within each zone. We used a linear relationship to scale S_x to snow thickness change. Downscaling the wind direction produced small improvements for most events, but did not consistently perform better than directly using the prevailing wind direction measured at the weather station. Overall, S_x provided useful insights and indications of relative accumulation patterns. However, the wind-drifted snow indication maps were only based on the terrain, wind direction and wind shelter index. They should be interpreted as an experimental tool through which the wind shelter index can help inform forecasters rather than predictions of accurate snow depths or potential avalanche occurrence.

The next step to improve the value of the generated indication maps is to incorporate wind speed and the amount of precipitation so that the maps respond to different meteorological scenarios. The approach should also be tested in further regions in Iceland, regions with similar conditions such as Svalbard, and other mountain ranges in differing snow climates. High-temporal-resolution lidar measurements from avalanche release areas in Switzerland could provide a useful dataset, although the more variable Alpine terrain and different snow conditions will require adaptations. Further development should be carried out in close collaboration with avalanche forecasters to ensure that the maps include the information and functions needed in practice. On the longer term, the approach could support an interactive tool in which users adjust wind direction, wind speed, and precipitation to generate scenario-based maps for critical areas across a forecasting region. The resulting maps could also provide input for avalanche simulations, large-scale hazard mapping, and scenario-based probability maps.

. *Code availability:* The data used in this study will be published on ENVIDAT on the acceptance of the paper

. *Author contribution:* Study design: PR and SAM, data acquisition: PR and SAM, data processing: PR, with inputs from SAM and AW.
Manuscript: PR and SAM, with contributions from all co-authors.

. *Competing interests:* The contact author has declared that none of the authors has any competing interests.

. *Acknowledgements:* The authors want to thank IMO and the University of Iceland for the loan of the laser scanner and Jóhannes Konráð Andrésson, Örn Ingólfsson and Magni Hreinn Jónsson for the support of fieldwork and installations, as well as Tómas Jóhannesson and Jón Kristinn Helgason for discussions around the setup and data processing. This research was funded by the Swiss National Science Foundation SNSF within the project "Avalanche Safety for Roads" (Nr. 207519).

AI-assisted tools were used to support language editing, clarity, and code development. All outputs were reviewed and verified by the authors, who take full responsibility for the final manuscript.



Appendix A: Appendix

Table A1. Summary of avalanches in the study area during winter 2025–2026.

ID	Path	Date	Size	Type	Notes
61105	Kirkjuból	5–6 Feb 2026	2	Dry slab	
61104	Kirkjubær	5–6 Feb 2026	1	Dry slab	
61249	Steiniðjugil	3–4 Mar 2026	1	Dry slab	
61244	Gleiðarhjalli1	3–4 Mar 2026	1.5	Dry slab	
61245	Gleiðarhjalli2	3–4 Mar 2026	1	Dry slab	
61312	Kirkjuból	13 Mar 2026	2	Dry slab	Crown in the high cliffs
61847	Steiniðjugil	14 Mar 2026	1.5	Dry slab	Source in the lower outer part of the ravine
61356	Gleiðarhjalli1	14–15 Mar 2026	2	Dry slab	
61370	Funi	14–15 Mar 2026	1.5	Dry slab	
61358	Kirkjubær	14–15 Mar 2026	2.5	Dry slab	
61369	Kirkjuból	14–15 Mar 2026	2.5	Dry slab	
61350	Steiniðjugil	15 Mar 2026	2	Dry slab	Three avalanches on Seljalandshlíð
61351	Hrafnagil	15 Mar 2026	2	Dry slab	
61394	Grænagarðsgil	15 Mar 2026	2	Dry slab	
61415	Steiniðjugil	17 Mar 2026	3	Dry slab	Detected on SM4. Closed the Grænagarðsstíg road, several trees broken
61589	Funi	28–29 Mar 2026	3	Dry slab	Struck the avalanche barrier and snow overtopping
61623	Funi	3 Apr 2026	2	Dry slab	
61645	Karlsárgil	4 Apr 2026	1	Dry slab	
61721	Hrafnagil	7 Apr 2026	2	Dry slab	Cornice collapse on NE-aspect of gully
61065	Funi	11–12 Apr 2026	1	Dry loose	
61784	Steiniðjugil	13 Apr 2026	1.5	Dry slab	
61804	Funi	15 Apr 2026	3	Dry slab	240 m wide, stopped 100 m from the defence wedge



Table A2. Overview of TLS scans acquired at the KaS and Funi study sites during winter 2025–2026.

Date	KaS	Funi	Notes
19 Nov 2025	x	x	
26 Nov 2025	x	x	
16 Dec 2025	X	X	
19 Dec 2025	X	X	
7 Jan 2026	X	X	
13 Jan 2026	X	X	
5 Feb 2026	x	x	
2 Mar 2026	x	x	
14 Mar 2026	X	x	KaS: small part of the upper slope missing. Funi: snowfall during acquisition; most of the slope missing.
16 Mar 2026	x	–	KaS: snowfall during acquisition; approximately half of the scan missing, but the KaS avalanche path is mostly visible.
18 Mar 2026	X	X	Funi: upper part of the slope cut off.
22 Mar 2026	X	X	
28 Mar 2026	X	X	Funi: part of the upper slope missing, possibly due to sunlight.
30 Mar 2026	–	x	Funi: heavy snowfall during acquisition; most of the upper slope missing.
4 Apr 2026	–	x	
16 Apr 2026	x	x	

An “x” indicates that a TLS scan was acquired, **X** that the scan data was used in the study, and “–” that no scan was available.

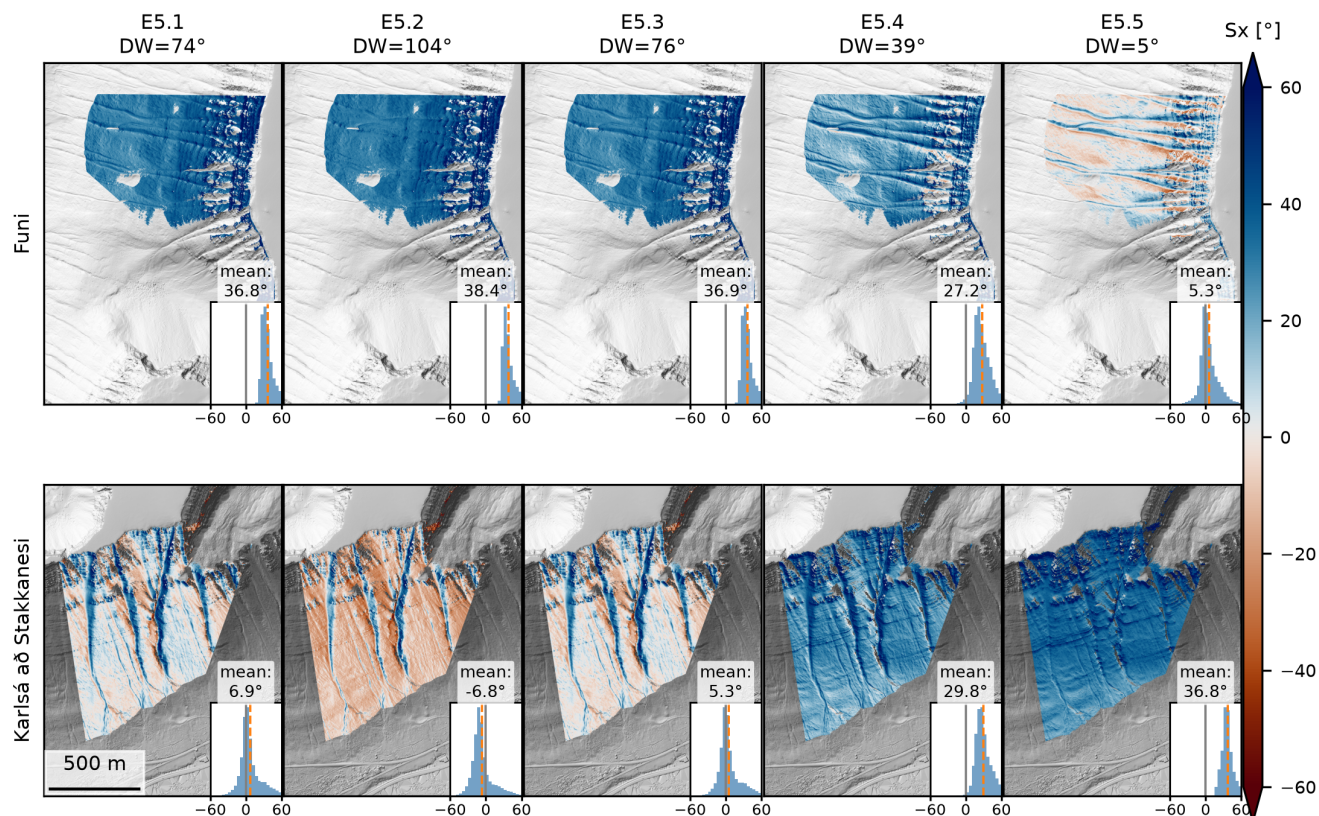


Figure A1. Calculated Sx on the sub-events of E5, masked by the pixels available from the TLS measurements



References

- 485 Aksamit, N., Nemoto, M., and Ito, Y.: Measurement and tracking of blowing and falling snow particles using an automotive 1550 nm LiDAR, *Cold Regions Science and Technology*, 251, 105 073, <https://doi.org/10.1016/j.coldregions.2026.105073>, 2026.
- Arnalds, P., Sauermoser, S., Sigurðsson, H., Jóhannesson, T., and Þórður, A.: Hættumat fyrir Innri-Kirkjubólshlíð, final, Icelandic Meteorological Office, <https://www.vedur.is/media/vedurstofan/utgafa/greinargerdir/2007/07011.pdf>, 2007.
- Bartelt, P. and Lehning, M.: A physical SNOWPACK model for the Swiss avalanche warning: Part I: numerical model, *Cold Regions Science and Technology*, 35, 123–145, [https://doi.org/10.1016/S0165-232X\(02\)00074-5](https://doi.org/10.1016/S0165-232X(02)00074-5), 2002.
- 490 Björnsson, H.: Avalanche Activity in Iceland, Climatic Conditions, and Terrain Features, *Journal of Glaciology*, 26, 13–23, <https://doi.org/10.3189/S0022143000201007>, 1980.
- Bühler, Y., Bebi, P., Christen, M., Margreth, S., Stoffel, L., Stoffel, A., Marty, C., Schmucki, G., Caviezel, A., Kühne, R., Wohlwend, S., and Bartelt, P.: Automated avalanche hazard indication mapping on a statewide scale, *Natural Hazards and Earth System Sciences*, 22, 1825–1843, <https://doi.org/10.5194/nhess-22-1825-2022>, 2022.
- 495 Chritin, V., Bolognesi, R., and Gubler, H.: FlowCapt: a new acoustic sensor to measure snowdrift and wind velocity for avalanche forecasting, *Cold Regions Science and Technology*, 30, 125–133, [https://doi.org/10.1016/S0165-232X\(99\)00012-9](https://doi.org/10.1016/S0165-232X(99)00012-9), 1999.
- Conway, S.: A study of the hazard and geomorphic change caused by debris flows in Iceland, final, NERC Geophysical Equipment Facility, <https://gef.nerc.ac.uk/reports/977/>, 2014.
- 500 Daudt, R. C., Wulf, H., Hafner, E. D., Bühler, Y., Schindler, K., and Wegner, J. D.: Snow depth estimation at country-scale with high spatial and temporal resolution, *ISPRS Journal of Photogrammetry and Remote Sensing*, 197, 105–121, <https://doi.org/10.1016/j.isprsjprs.2023.01.017>, 2023.
- Davis, R. E., Elder, K., Howlett, D., and Bouzaglou, E.: Relating storm and weather factors to dry slab avalanche activity at Alta, Utah, and Mammoth Mountain, California, using classification and regression trees, *Cold Regions Science and Technology*, 30, 79–89, [https://doi.org/10.1016/S0165-232X\(99\)00032-4](https://doi.org/10.1016/S0165-232X(99)00032-4), 1999.
- 505 Decaulne, A.: Snow-avalanche and debris-flow hazards in the fjords of north-western Iceland, mitigation and prevention, *Natural Hazards*, 41, 81–98, <https://doi.org/10.1007/s11069-006-9025-x>, 2007.
- Dkengne Sielenou, P., Viallon-Galinier, L., Hagenmuller, P., Naveau, P., Morin, S., Dumont, M., Verfaillie, D., and Eckert, N.: Combining random forests and class-balancing to discriminate between three classes of avalanche activity in the French Alps, *Cold Regions Science and Technology*, 187, 103 276, <https://doi.org/10.1016/j.coldregions.2021.103276>, 2021.
- 510 Dujardin, J. and Lehning, M.: Wind-Topo: Downscaling near-surface wind fields to high-resolution topography in highly complex terrain with deep learning, *Quarterly Journal of the Royal Meteorological Society*, 148, 1368–1388, <https://doi.org/10.1002/qj.4265>, 2022.
- Durand, Y., Giraud, G., Brun, E., Mérindol, L., and Martin, E.: A computer-based system simulating snowpack structures as a tool for regional avalanche forecasting, *Journal of Glaciology*, 45, 469–484, <https://doi.org/10.3189/S0022143000001337>, 1999.
- Eberhard, L. A., Sirguey, P., Miller, A., Marty, M., Schindler, K., Stoffel, A., and Bühler, Y.: Intercomparison of photogrammetric platforms for spatially continuous snow depth mapping, *The Cryosphere*, 15, 69–94, <https://doi.org/10.5194/tc-15-69-2021>, 2021.
- Egilsson, J. G.: Two Destructive Avalanches in Iceland, *Proceedings of the 1996 International Snow Science Workshop*, Banff, Canada, pp. 264–267, <https://arc.lib.montana.edu/snow-science/item.php?id=1453>, 1996.



- Forthofer, J. M., Butler, B. W., and Wagenbrenner, N. S.: A comparison of three approaches for simulating fine-scale surface winds in support of wildland fire management. Part I. Model formulation and comparison against measurements, *International Journal of Wildland Fire*, 23, 969–981, <https://doi.org/10.1071/WF12089>, 2014.
- Glaus, J., Kleinn, J., Stoffel, L., Ruttner, P., Wikstrom Jones, K., Gaume, J., and Bühler, Y.: Probabilistic avalanche runout modelling for daily risk management of traffic routes, *EGUsphere*, pp. 1–29, <https://doi.org/10.5194/egusphere-2026-999>, 2026.
- Grünewald, T. and Lehning, M.: Are flat-field snow depth measurements representative? A comparison of selected index sites with areal snow depth measurements at the small catchment scale, *Hydrological Processes*, 29, 1717–1728, <https://doi.org/10.1002/hyp.10295>, 2015.
- Hancock, H., Eckerstorfer, M., Prokop, A., and Hendrikx, J.: Quantifying seasonal cornice dynamics using a terrestrial laser scanner in Svalbard, Norway, *Natural Hazards and Earth System Sciences*, 20, 603–623, <https://doi.org/10.5194/nhess-20-603-2020>, 2020.
- Haraldsdóttir, S. H., Ólafsson, H., Durand, Y., Mérindol, L., and Giraud, G.: SAFRAN-Crocus snow simulations in an unstable and windy climate, *Annals of Glaciology*, 32, 339–344, <https://doi.org/10.3189/172756401781819120>, 2001.
- Haraldsdóttir, S. H., Ólafsson, H., Durand, Y., Giraud, G., and Mérindol, L.: A system for prediction of avalanche hazard in the windy climate of Iceland, *Annals of Glaciology*, 38, 319–324, <https://doi.org/10.3189/172756404781815293>, 2004.
- Hendrikx, J., Owens, I., Carran, W., and Carran, A.: Avalanche activity in an extreme maritime climate: The application of classification trees for forecasting, *Cold Regions Science and Technology*, 43, 104–116, <https://doi.org/10.1016/j.coldregions.2005.05.006>, 2005.
- Hættumatsnefnd Ísafjarðarbæjar: Mat á hættu vegna ofanflóða á Flateyri, Tech. rep., https://www.vedur.is/gogn/snjoflod/haettumat/fl_nefnd.pdf, 2004.
- Ingólfsson, and Grímsdóttir, H.: The SM4 snowpack temperature and snow depth sensor, in: *International Snow Science Workshop (ISSW) Proceedings 2008*, Whistler, United States, p. 1, 2008.
- Jóhannesson, T. and Gíslason, E.: Endurskoðun á ofanflóðahættumati fyrir innanverðan Gleiðarhjalla á Ísafirði, final, Icelandic Meteorological Office, https://www.vedur.is/media/vedurstofan/utgafa/skyrslur/2012/2012_002.pdf, 2012.
- Jóhannesson, T. and Jónsson, T.: Weather in Vestfirðir before and during several avalanche cycles in the period 1949 to 1995, *Veðurstofa Íslands Internal Report VÍ-G96015-ÚR15*, Reykjavík, <https://www.vedur.is/media/vedurstofan/utgafa/greinargerdir/1996/96015.pdf>, 1996.
- Komatsu, A. and Nishimura, K.: Calculation of Snowdrift Distribution over Complex Topography to Improve the Accuracy of Snow Avalanche Warning Systems, *SOLA*, 18, 71–75, <https://doi.org/10.2151/sola.2022-012>, 2022.
- Lehning, M. and Fierz, C.: Assessment of snow transport in avalanche terrain, *Cold Regions Science and Technology*, 51, 240–252, <https://doi.org/10.1016/j.coldregions.2007.05.012>, 2008.
- Lehning, M., Bartelt, P., Brown, B., Russi, T., Stöckli, U., and Zimmerli, M.: snowpack model calculations for avalanche warning based upon a new network of weather and snow stations, *Cold Regions Science and Technology*, 30, 145–157, [https://doi.org/10.1016/S0165-232X\(99\)00022-1](https://doi.org/10.1016/S0165-232X(99)00022-1), 1999.
- Li, L. and Pomeroy, J. W.: Estimates of Threshold Wind Speeds for Snow Transport Using Meteorological Data, *Journal of Applied Meteorology and Climatology*, 36, 205–213, [https://doi.org/10.1175/1520-0450\(1997\)036<0205:EOTWSF>2.0.CO;2](https://doi.org/10.1175/1520-0450(1997)036<0205:EOTWSF>2.0.CO;2), 1997.
- Liljestrand, D., Johnson, R., Neilson, B., Strong, P., and Cotter, E.: Leveraging snow probe data, lidar, and machine learning for snow depth estimation in complex-terrain environments, *The Cryosphere*, 19, 3123–3138, <https://doi.org/10.5194/tc-19-3123-2025>, 2025.
- Meloche, J., Langlois, A., Rutter, N., McLennan, D., Royer, A., Billecocq, P., and Ponomarenko, S.: High-resolution snow depth prediction using Random Forest algorithm with topographic parameters: A case study in the Greiner watershed, Nunavut, *Hydrological Processes*, 36, e14 546, <https://doi.org/10.1002/hyp.14546>, 2022.



- Mott, R., Schirmer, M., Bavay, M., Grünewald, T., and Lehning, M.: Understanding snow-transport processes shaping the mountain snow-cover, *The Cryosphere*, 4, 545–559, <https://doi.org/10.5194/tc-4-545-2010>, 2010.
- Nawri, N.: Large-scale atmospheric conditions associated with major avalanche cycles and cold season weather hazards in Iceland, final, Icelandic Meteorological Office, https://www.vedur.is/media/vedurstofan/utgafa/skyrslur/2013/VI_2013_004.pdf, 2013.
- 560 Pan, C. G., Johnston, J., Jacobs, J. M., and O’Neel, S.: Mapping daily snow depth with machine learning and airborne lidar across two contrasting snowpacks, *The Cryosphere*, 20, 3759–3781, <https://doi.org/10.5194/tc-20-3759-2026>, 2026.
- Pomeroy, J. W.: Pomeroy_John_Williard_sec_1988, Doctoral Dissertation, University of Saskatchewan, 1988.
- Prokop, A.: Assessing the applicability of terrestrial laser scanning for spatial snow depth measurements, *Cold Regions Science and Technology*, 54, 155–163, <https://doi.org/10.1016/j.coldregions.2008.07.002>, 2008.
- 565 Prokop, A. and Procter, E. S.: A new methodology for planning snow drift fences in alpine terrain, *Cold Regions Science and Technology*, 132, 33–43, <https://doi.org/10.1016/j.coldregions.2016.09.010>, 2016.
- Pérez-Guillén, C., Techel, F., Hendrick, M., Volpi, M., van Herwijnen, A., Olevski, T., Obozinski, G., Pérez-Cruz, F., and Schweizer, J.: Data-driven automated predictions of the avalanche danger level for dry-snow conditions in Switzerland, *Natural Hazards and Earth System Sciences*, 22, 2031–2056, <https://doi.org/10.5194/nhess-22-2031-2022>, 2022.
- 570 Quéno, L., Mott, R., Morin, P., Cluzet, B., Mazzotti, G., and Jonas, T.: Snow redistribution in an intermediate-complexity snow hydrology modelling framework, *The Cryosphere*, 18, 3533–3557, <https://doi.org/10.5194/tc-18-3533-2024>, 2024.
- Revuelto, J., Billecocq, P., Tuzet, F., Cluzet, B., Lamare, M., Larue, F., and Dumont, M.: Random forests as a tool to understand the snow depth distribution and its evolution in mountain areas, *Hydrol. Process.*, 34, 5384–5401, <https://doi.org/10.1002/hyp.13951>, 2020.
- 575 Ruttner, P., Helbig, N., Voordendag, A., Wieser, A., and Bühler, Y.: Comparing high spatial and temporal resolution snow depth measurements and modelling results in an avalanche release area, *The Cryosphere*, 20, 4185–4208, <https://doi.org/10.5194/tc-20-4185-2026>, 2026.
- Saigger, M., Goger, B., and Mölg, T.: SNOWstorm (v1.0) – a deep-learning based model for near-surface winds and drifting snow in mountain environments, *Geoscientific Model Development*, 19, 6497–6516, <https://doi.org/10.5194/gmd-19-6497-2026>, 2026.
- 580 Sato, T., Kimura, T., Ishimaru, T., and Maruyama, T.: Field test of a new snow-particle counter (SPC) system, *Annals of Glaciology*, 18, 149–154, <https://doi.org/10.3189/S0260305500011411>, 1993.
- Schirmer, M., Wirz, V., Clifton, A., and Lehning, M.: Persistence in intra-annual snow depth distribution: 1. Measurements and topographic control, *Water Resources Research*, 47, <https://doi.org/10.1029/2010WR009426>, 2011.
- Schmidt, R. A.: A System that Measures Blowing Snow, Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, google-Books-ID: 7_OHnPhvFiAC, 1977.
- 585 Schweizer, J., Bruce Jamieson, J., and Schneebeli, M.: Snow avalanche formation, *Reviews of Geophysics*, 41, <https://doi.org/10.1029/2002RG000123>, 2003.
- Schön, P., Prokop, A., Vionnet, V., Guyomarc’h, G., Naaim-Bouvet, F., and Heiser, M.: Improving a terrain-based parameter for the assessment of snow depths with TLS data in the Col du Lac Blanc area, *Cold Regions Science and Technology*, 114, 15–26, <https://doi.org/10.1016/j.coldregions.2015.02.005>, 2015.
- 590 Schön, P., Naaim-Bouvet, F., Vionnet, V., and Prokop, A.: Merging a terrain-based parameter with blowing snow fluxes for assessing snow redistribution in alpine terrain, *Cold Regions Science and Technology*, 155, 161–173, <https://doi.org/10.1016/j.coldregions.2018.08.002>, 2018.



- Sharma, V., Kumar, S., and Sushil, R.: A neural network model for automated prediction of avalanche danger level, *Natural Hazards and Earth System Sciences*, 23, 2523–2530, <https://doi.org/10.5194/nhess-23-2523-2023>, 2023.
- Störmer, A., Kumpula, T., Villoslada, M., Korpelainen, P., Schumacher, H., and Burkhard, B.: Comparing high-resolution snow mapping approaches in palsa mires: UAS lidar vs. modelling, *The Cryosphere*, 19, 3949–3970, <https://doi.org/10.5194/tc-19-3949-2025>, 2025.
- Vionnet, V., Marsh, C. B., Menounos, B., Gascoin, S., Wayand, N. E., Shea, J., Mukherjee, K., and Pomeroy, J. W.: Multi-scale snowdrift-permitting modelling of mountain snowpack, *The Cryosphere*, 15, 743–769, <https://doi.org/10.5194/tc-15-743-2021>, 2021.
- Voordendag, A., Goger, B., Klug, C., Prinz, R., Rutzinger, M., Sauter, T., and Kaser, G.: Uncertainty assessment of a permanent long-range terrestrial laser scanning system for the quantification of snow dynamics on Hintereisferner (Austria), *Frontiers in Earth Science*, 11, <https://www.frontiersin.org/articles/10.3389/feart.2023.1085416>, 2023.
- Winstral, A., Elder, K., and Davis, R. E.: Spatial Snow Modeling of Wind-Redistributed Snow Using Terrain-Based Parameters, *Journal of Hydrometeorology*, 3, 524–538, [https://doi.org/10.1175/1525-7541\(2002\)003<0524:SSMOWR>2.0.CO;2](https://doi.org/10.1175/1525-7541(2002)003<0524:SSMOWR>2.0.CO;2), 2002.