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Shared climatic shift, divergent avalanche responses: topographic filtering across avalanche path types in the Krkonoše Mountains, Central Europe

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Abstract. Snow avalanches respond to changes in snow climate, but responses may vary with local topography. We analysed 797 avalanche events on 55 morphometrically classified paths in the Krkonoše Mountains, Czechia (1978/79–2019/20). Using a regional-to-local framework, we combined multivariate analysis of avalanche-day climate with a terrain-based path typology and mixed-effects models of path activity and avalanche geometry. Avalanche-day conditions shifted towards warmer and sunnier states ($p < 0.001$), with climatic variability concentrated along fewer dimensions. This shift was broadly consistent across five path types (interaction $p = 0.938$), whereas changes in path activity ($p < 0.001$), avalanche area ($p = 0.004$) and width ($p < 0.001$) varied by type. Large cirque paths showed the strongest reductions in activity and avalanche extent, whereas narrow incised gullies retained persistent activity and longitudinal extent despite substantial narrowing. Trends in the largest avalanches remained uncertain; tree cover increased less within paths than in their surroundings (1953–2024). These findings are consistent with topographic setting acting as a spatial filter of a broadly shared shift in avalanche-day climate. They highlight the importance of considering both recorded activity and event geometry when interpreting long-term avalanche changes and identifying priorities for path-specific monitoring.

1 Introduction

Mountain cryospheres are undergoing rapid change as atmospheric warming alters the quantity, duration and timing of seasonal snowfall, as well as its physical state. In the European Alps, for example, snow depth, snow cover duration and snowfall have all declined significantly in recent decades, particularly at lower elevations and during seasons close to the freezing point (Matiu et al., 2021; Bozzoli et al., 2024). Similar changes are evident in the mid-elevation mountains of Central Europe. Mountain regions, including the Krkonoše Mountains, have warmed considerably, with more frequent warm extremes and fewer cold extremes, mainly due to warming within prevailing circulation types rather than changes in their frequency (Tichopád et al., 2026). In the western Sudetes, the duration of snow cover has shortened due to rising air temperatures, increased sunshine hours, a declining proportion of solid precipitation, and changes in atmospheric circulation (Urban et al., 2023). Snow water equivalent and snow depth have also declined, while snowmelt has advanced in many

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Central European mountain catchments (Blahušiaková et al., 2020; Urban, 2024). Precipitation trends in the Sudetes are more seasonally differentiated, with increasing winter totals and decreasing spring totals (Ojrzyńska et al., 2026). These changes reflect a broader reorganisation of the climatic conditions that control snow accumulation, persistence, and melt. This could have significant consequences for mid-elevation ranges near the transition between persistent and intermittent seasonal snow.

Snow avalanches are an indicator of changes in the snow climate. Apart from topographic predispositions, their occurrence and magnitude are influenced by various climatic factors, such as snowfall, temperature, wind-driven snow redistribution, snow depth, solar radiation, liquid-water input and snow stratigraphy (Schweizer et al., 2003; Castebrunet et al., 2012; Eckert et al., 2024). Therefore, climate-driven avalanche change is not expected to follow a single trajectory or pattern of change. Recent studies indicate a decrease in dry-snow avalanche activity in many regions, as well as changes in the timing and relative importance of wet-snow avalanches. These responses also show a strong dependence on elevation (Eckert et al., 2024; Mayer et al., 2024; Reuter et al., 2025). In the low- to mid-elevation Vosges Mountains, for example, historical warming has been linked to a significant reduction in avalanche frequency and magnitude, a shorter avalanche season, and a shift in avalanche-prone terrain towards higher elevations (Giacona et al., 2021). Long-term evidence from the French Alps also suggests that large avalanche cycles may decline more slowly than mean annual activity (Doussot et al., 2026). Mid-elevation mountain ranges may therefore be particularly sensitive environments in which changes in seasonal snow conditions result in altered avalanche regimes.

However, regional climatic change need not produce spatially uniform avalanche responses. Snow accumulation in complex mountain terrain is strongly influenced by topography and wind (Lehning et al., 2008). Wind-driven processes link exposed snow-source areas with areas of preferential deposition, such as leeward slopes, gullies and cirques. This produces pronounced spatial contrasts in snow depth, snowpack structure and stability, even under similar regional weather conditions (Mott et al., 2018). Therefore, topographic setting may act as a spatial filter of regional climatic change; shifts in temperature, snowfall, wind or radiation may have different consequences depending on elevation, aspect, solar exposure, source-area configuration and topographic confinement. Long-term avalanche studies have mainly documented spatial contrasts among regions, mountain massifs and elevation bands (Laternser and Schneebeli, 2002; Castebrunet et al., 2012; Eckert et al., 2013; Giacona et al., 2021). However, it is less clear whether long-term changes in avalanche activity and dimensions can be systematically related to the topography of individual avalanche paths, including their morphology and position within wind-driven snow transport systems. Addressing this question requires a terrain-based classification that is independent of observed avalanche activity, which is particularly relevant given that avalanche hazard assessment, habitat conservation and protected area management often operate at the scale of individual paths.

Avalanches are also a recurrent form of ecological disturbance. By damaging woody vegetation and disrupting succession processes, they help maintain open, heterogeneous habitats within subalpine forests and treeline ecotones. This can influence plant diversity and species composition (Rixen et al., 2007; Bebi et al., 2009). Their ecological role may become increasingly important as mountain vegetation responds to warming. European high-mountain plant communities are already

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exhibiting increased vegetation cover, thermophilisation, and a shift from cold-adapted, low-growing species towards taller ones (Steinbauer et al., 2022). Meanwhile, treeline and shrubline dynamics are still strongly influenced by moisture availability, species interactions, topography, and disturbance (Lu et al., 2025). In the High Sudetes, the limited extent of naturally treeless subalpine habitats makes them particularly vulnerable to forest expansion (Zeidler et al., 2023). In addition, vegetation records demonstrate that land-use abandonment, conservation management and avalanche disturbance can collectively influence long-term subalpine vegetation change (Klinkovská et al., 2023). Therefore, declining or spatially contracting avalanche disturbance could interact with broader climatic and land-use-driven vegetation change by relaxing one of the local constraints on woody establishment.

These interactions are particularly relevant in the Krkonoše Mountains. Despite their moderate elevation, the area's broad summit plateaus, persistent winds and deeply incised glacial cirques favour substantial wind-driven snow redistribution. This forms a classical anemo-orographic system, in which topography, wind, snow accumulation and avalanches are closely coupled (Jeník, 1961). Avalanche activity overlaps with the treeline ecotone and the spatially restricted Arctic–Alpine tundra of the summit region. Avalanches can locally lower the treeline (Kociánová and Spusta, 2000; Treml and Migoń, 2015), while the summit region contains exceptional Central European tundra habitats, which are naturally devoid of trees and are home to cold-adapted biota with affinities to boreal and subarctic environments (Soukupová et al., 2026). Changes in avalanche disturbance are therefore relevant not only to avalanche hazard, but also to the persistence of open habitats within a protected mountain landscape.

The Krkonoše Mountains provide an unusually long, path-resolved avalanche record for a Central European mid-elevation range, supporting avalanche inventories, terrain analyses and studies of long-term avalanche change (Blahut et al., 2017; Součková et al., 2022). Součková et al. (2022) documented contrasting trends in wet- and slab-avalanche activity and identified their principal meteorological drivers. The authors also highlighted the need for finer-scale analyses linking snow and weather conditions to individual avalanche sectors. Building on this research, we address a complementary question: whether a shared shift in the multivariate climatic conditions of recorded natural avalanche days is accompanied by different changes in avalanche activity and event geometry across morphometrically distinct path types.

Here, we address this issue by employing a two-level regional-to-local framework. At the mountain-range scale (Layer A), we examine long-term changes in the climatic conditions associated with recorded natural avalanches. At the avalanche-path scale (Layer B and its components B1–B3), we derive an independent morphometric typology and examine whether the climatic shift was shared across all path types (B1) and whether there were differences in recorded path activity (B2) and in avalanche magnitude and geometry (B3). As the climatic analyses only include days with recorded natural avalanches, they characterise avalanche-day conditions rather than changes in avalanche probability relative to all winter days, which reflects the observational nature of the record. We also examine large avalanche events and changes in tree cover to provide context related to hazards and ecology. We address three research questions: (1) How did the multivariate space of natural avalanche-day climatic conditions evolve over four decades, and did its variability become more concentrated along fewer dominant gradients? (2) Was this climatic shift shared across morphometrically distinct avalanche path types? (3) Did

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changes in recorded path activity, avalanche magnitude, and geometry differ among path types, and how were these changes distributed spatially? While a regional climatic shift is an established backdrop, its differentiated expression across morphometrically distinct path types is not self-evident and forms the central empirical question of this study.

2 Materials and methods

2.1 Study area and data

The Krkonoše Mountains (Karkonosze in Poland) are the highest part of the Sudetes, reaching 1603 m a.s.l. at Sněžka (Fig. 1). The Variscan fault-block massif combines broad summit plateaus with deeply incised valleys; glacial cirques and trough valleys along the plateau margins contain most present-day avalanche paths (Engel, 1997; Engel et al., 2010; Blahut et al., 2017). A detailed description of the range and its avalanche environment is provided by Součková et al. (2022).

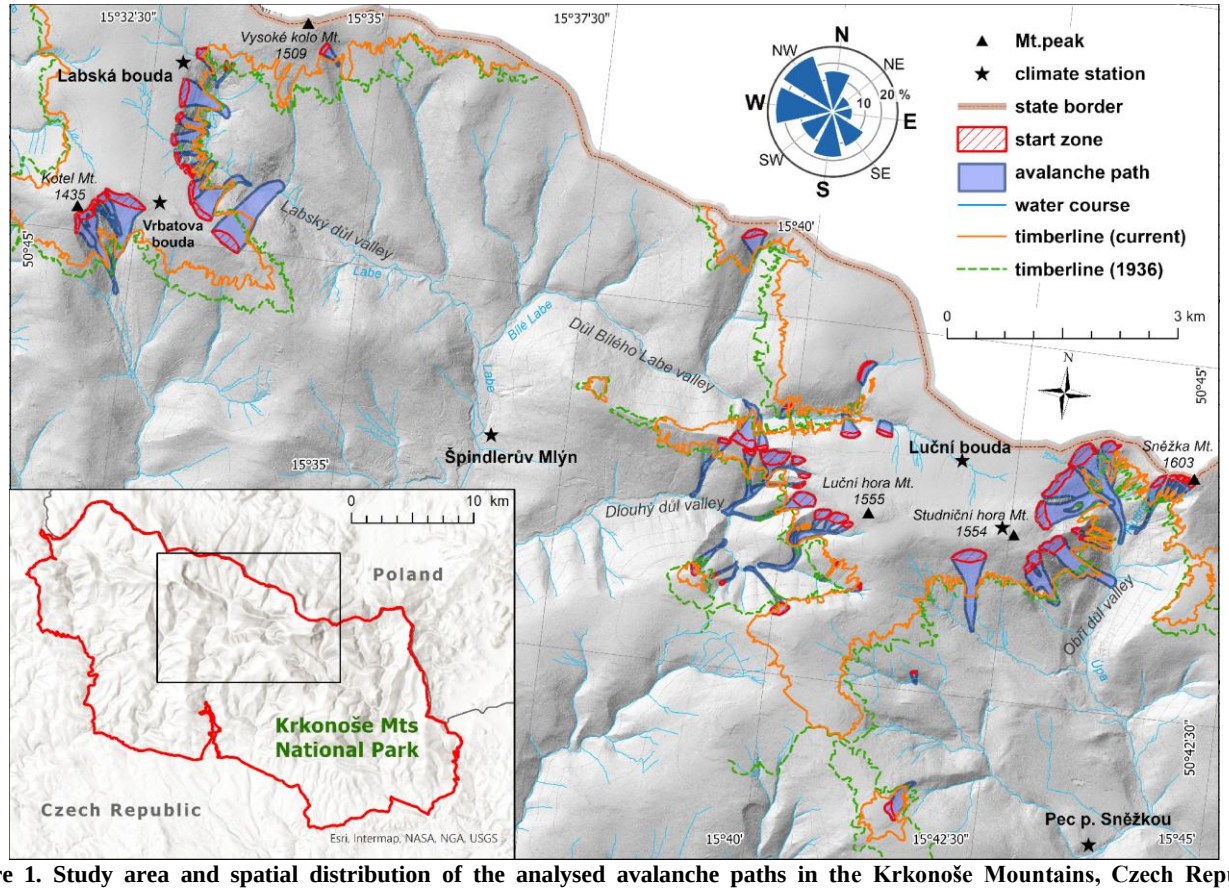


Figure 1. Study area and spatial distribution of the analysed avalanche paths in the Krkonoše Mountains, Czech Republic. Current and 1936 timberline/treeline after Treml et al. (2020); wind rose: mean annual frequency (%) of eight wind directions at the Labská bouda station, 1979–2020 (no data for 1995–2002; Czech Hydrometeorological Institute); avalanche paths and start (release) zones provided by the Krkonoše Mts. National Park Administration; shaded relief derived from the digital terrain model, water courses, contour lines and the national park boundary: Krkonoše Mts. National Park Administration; state borders: ArcČR 500 (© ARCDATA PRAHA, ZÚ, ČSÚ); inset basemap: World Hillshade (Esri, Intermap, NASA, NGA, USGS | Powered by Esri),

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Snow is transported from the summit deflation plateaus by north-westerly winds and accumulates on steep leeward slopes and in glacial cirques (Spusta et al., 2003; Blahut et al., 2017). This supports substantial avalanche activity despite the moderate elevation. Most release zones are located within the upper montane to alpine belt and have an average slope of around 31° (Blahut et al., 2017; Součková et al., 2022). The treeline, which is formed mainly by the Norway spruce (*Picea abies*) at around 1250–1450 m a.s.l., is locally depressed due to wind, snow accumulation, historical land use and avalanches. Many avalanche release zones and tracks occur within or just above the treeline ecotone, where spruce growth is influenced by temperature and nutrient availability, and which is already responding to warming (Treml and Chuman, 2015; Treml and Migoń, 2015; Tumajer et al., 2021; Kuželová et al., 2025). The summit region lies within Krkonoše Mts. National Park and the transboundary Krkonoše/Karkonosze UNESCO Biosphere Reserve. The area's international scientific significance is further reflected in long-term ecological monitoring programmes, including LTER, GLORIA and INTERACT (LTER-CZ, n.d.).

Avalanche and meteorological data. Avalanches in the Czech part of the Krkonoše Mountains have been documented since the early 1960s by the Krkonoše Mts. National Park Administration and the Mountain Rescue Service. These records have been compiled in successive avalanche cadastres and studies (Vrba and Spusta, 1975, 1991; Spusta and Kociánová, 1998; Spusta et al., 2003, 2006, 2019; Juras et al., 2013; Blahut et al., 2017; Součková et al., 2022). We analysed path-resolved records from the 42 winter seasons (1978/79–2019/20) for which climatic data and consistent avalanche attributes were available, assigning events to the winter that spanned two calendar years. Of the 822 recorded events, we excluded 10 mechanically triggered avalanches and five events with an uncertain trigger, leaving 807 natural avalanches.

Avalanche events were analysed to determine their magnitude and geometry. Climatic analyses used unique avalanche days to avoid repeatedly counting identical weather conditions. Avalanche area, estimated in the historical records using a trapezoidal approximation based on crown width, avalanche width and length, was used as the primary measure of event magnitude. This measure captures variation in both lateral and longitudinal avalanche dimensions but does not represent the precisely mapped area affected by an event. Width, length, crown height and deposit height were analysed as secondary responses: avalanche width (as distinct from the crown width) and length characterised the lateral and longitudinal extents, respectively, and crown height (the thickness of the released snow at the crown) and deposit height (the depth of the deposit) served as additional dimensional descriptors. In this context, avalanche magnitude refers to the recorded area and dimensions of the event rather than the volume of released snow or the destructive energy involved.

Nine climatic variables were used: three describing antecedent conditions and six describing conditions on the avalanche day. The antecedent variables covered the three days before the avalanche: the change in air temperature over these days (3-day temperature change, °C), the sum of new snow (3-day new snow, cm) and the maximum wind speed (3-day wind, m s^{-1}). The same-day variables were sunshine duration (h), mean air temperature (mean of the daily maximum and minimum, °C), diurnal temperature range (daily maximum minus minimum, °C), total snow depth (cm), relative humidity (%) and wind

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speed on the avalanche day (daily wind, m s^{-1}). All variables were taken from the Labská bouda station of the Czech Hydrometeorological Institute, as in Součková et al. (2022); the Luční bouda station and other nearby stations were used for validation. The Labská bouda record was interrupted between October 1999 and October 2002, so values for these winters were reconstructed using weather graphs and data from the lower Špindlerův Mlýn station (Spusta et al., 2003). The 1999/00–2001/02 winters were therefore excluded from the climatic analyses, as in Součková et al. (2022), but were included in the analyses of path activity, avalanche magnitude and geometry. The potential influence of the replacement of the wind and humidity sensors at Labská bouda in 2002 and 2010 was examined in sensitivity analyses.

Avalanche-path morphometry. Avalanche-path and release-zone polygons and a 0.5 m digital terrain model (2012) were provided by the Krkonoše Mts. National Park Administration. The topographic setting of the paths was characterised by thirteen terrain variables describing their form (mean release zone and path slope, maximum cross-profile depth, curvature, path area, vertical drop, and mean shape index) and position (release zone elevation, northness, eastness, mean and range of the topographic position index, and annual solar radiation). The position relative to the deflation plateaus and main snow transport pathways was not measured directly, but is partly reflected in the aspect, elevation, and topographic position. The variable definitions, units, derivation methods and data sources are provided in Table S1.

Tree-cover data. The tree cover within and around the avalanche paths was mapped using two orthophoto sources: a historical orthophoto from 1953 with a resolution of 0.5 m and a 2024 orthophoto with a resolution of 0.125 m, both of which were provided by the Czech Office for Surveying, Mapping and Cadastre (ČÚZK) via a Web Map Service. In both time periods, mature trees (including individual crowns and closed stands) were manually vectorised within avalanche paths and their immediate surroundings; only tree-covered patches of 3 m^2 or larger were mapped. Dwarf pine (*Pinus mugo*) and young trees were excluded, while forest stands that had been disturbed or cleared were classified as forest in both periods to avoid attributing non-avalanche disturbance to avalanche effects.

2.2 Analytical framework and regional climatic shift

The analysis adopted a two-level, regional-to-local framework. Layer A examined changes in climatic conditions on avalanche days across the mountain range. Layer B then assessed whether these changes were accompanied by different responses among morphometrically defined avalanche path types. The 42 winter seasons were divided into four periods: P1 (1978/79–1988/89), P2 (1989/90–1998/99), P3 (1999/00–2008/09) and P4 (2009/10–2019/20). Period was treated as a categorical variable to allow for non-linear changes over time.

The avalanche record comprised 390 unique natural avalanche days, of which 382 had complete observations for all nine climatic variables. After excluding 47 days from the 1999/00–2001/02 winters, 335 avalanche days remained for Layer A (83 in P1, 85 in P2, 94 in P3 and 73 in P4).

The nine climatic variables were z-standardised and summarised using a correlation-based principal component analysis (PCA; Jolliffe and Cadima, 2016) of all 335 avalanche days. This approach has previously been used to characterise

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combinations of correlated snow and weather variables in avalanche–climate studies (Peitzsch et al., 2021). This pooled PCA provided a common multivariate climatic space in which the four periods could be compared directly.

The first principal component (PC1) was oriented so that positive scores represented warmer, sunnier, and drier climatic conditions on avalanche days. Each period was characterised by its centroid, which was defined as the mean PC1 and PC2 scores of its avalanche days. Uncertainty in the PC1 centroids was estimated using 95 % confidence intervals obtained from 2,000 block-bootstrap resamples of complete winter seasons.

However, a shift in period centroids does not necessarily imply a change in the multivariate variability of avalanche-day climatic conditions. Therefore, separate PCAs were performed for each period to quantify the proportion of variance explained by PC1, and by PC1 and PC2 combined. The relative concentration of climatic variability along fewer dominant dimensions was assessed using effective dimensionality (Bretherton et al., 1999):

$$D_{eff} = \frac{\left(\sum_{i=1}^{p} \lambda_i\right)^2}{\sum_{i=1}^{p} \lambda_i{}^2}, \quad (1)$$

where λ_i denotes the eigenvalues of a period-specific correlation matrix and $p = 9$. Lower D_{eff} indicates stronger concentration of total climatic variability along fewer dominant multivariate dimensions.

The stability of the dominant climatic gradient was assessed by calculating the cosine similarity between the period-specific and pooled PC1 eigenvectors. Additionally, period-specific Pearson correlation matrices were examined to describe changes in the relationships between the climatic variables. Uncertainty in effective dimensionality and PC1 variance was estimated using whole-winter block bootstrapping. One-sided permutation tests were used to evaluate differences between P1 and P4 in PC1 centroids, effective dimensionality and PC1 variance share in the hypothesised direction (a positive PC1 shift, lower effective dimensionality and a higher PC1 variance share), permuting complete winters between the two periods (2,000 permutations).

2.3 Morphometric typology and path-specific responses

The morphometric typology of the 55 avalanche paths was derived from terrain variables alone, independently of the subsequent analysis of avalanche activity and event dimensions. The thirteen z-standardised terrain variables were reduced using principal component analysis (PCA), retaining components with eigenvalues greater than one (Kaiser, 1960), and subjected to orthogonal Varimax rotation without Kaiser normalisation (Kaiser, 1958). This approach simplifies the structure of components in multivariate environmental data (Richman, 1986), and comparable PCA-based geomorphometric classifications have been applied to mid-elevation relief in the Sudetes (Szymanowski et al., 2019). As the components were employed for dimensionality reduction (Kaiser–Meyer–Olkin measure = 0.51; Bartlett's test, $p < 0.001$), they were not interpreted as latent geomorphic factors.

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The standardised rotated component scores were classified using hierarchical agglomerative clustering with Ward's minimum-variance update (Ward.D2) applied to Manhattan distances to reduce the influence of extreme individual component scores. As Ward's criterion is formally defined for Euclidean distances, this combination does not strictly minimise within-cluster variance, and is therefore referred to as Ward-type clustering (Murtagh and Legendre, 2014). Clustering was performed using the hclust function in R, and the dendextend package was used for dendrogram analysis (Galili, 2015). As terrain variation is largely continuous, several partitions may be defensible. Solutions with two to ten clusters were compared using fusion distances, cluster size, and geomorphic interpretability. This was supported by complementary cluster-validation criteria, such as pseudo-F, pseudo-t^2, the cubic clustering criterion, silhouette width, and the gap statistic (Caliński and Harabasz, 1974; Tibshirani et al., 2001). The five-cluster solution (C1–C5) was retained for Layer B and all Layer B models were additionally fitted using the four-cluster solution to assess robustness (see Table S2). Of the 807 natural avalanche events, 797 (98.8 %) were assigned to the 55 classified paths; the remaining 10 events were recorded on five paths not included in the morphometric typology.

Layer B comprised three analyses: (B1) avalanche-day climatic conditions associated with active path types; (B2) recorded path activity across winter seasons; and (B3) the magnitude and geometry of individual avalanche events. In all models, 'Period' and 'Cluster' were categorical fixed effects, and the 'Period × Cluster' interaction tested whether temporal changes differed among path types. Mixed-effects models were employed to address the grouped and repeated nature of the observations, with random intercepts defined based on the analytical unit of each model (Bolker et al., 2009; Zuur et al., 2009).

B1 – Avalanche-day climatic conditions. The PC1 scores derived from the pooled PCA in Layer A were assigned to the morphometric path types active on each avalanche day. Each active path type contributed one observation per day, resulting in 436 cluster-days from 333 unique avalanche days. The remaining two Layer A days involved only unclassified paths. The PC1 scores were analysed using a linear mixed-effects model with a season-based random intercept, fitted with lme4 (Bates et al., 2015). As observations from different path types on the same date shared the same climatic conditions, the B1 results were also evaluated using date-based weights and a subset of days with only one active path type, as well as whole-winter block-bootstrap confidence intervals (see Table S3).

B2 – Path activity. Recorded path activity was represented by a binary response indicating whether at least one natural avalanche occurred on a given path during a winter season. The analysis included 55 paths across 42 winters (2,310 path-winters), including inactive path-winters as zeros. Temporal changes were assessed using a binomial mixed-effects model with Path and Season random intercepts, cross-checked using glmmTMB (Brooks et al., 2017).

B3 – Avalanche magnitude and geometry. Individual natural avalanche events were analysed using linear mixed-effects models of log-transformed avalanche area, width, length, crown height and deposit height. Models included crossed Path, Season and Date random intercepts to account for repeated observations within paths and winters and for multiple avalanches recorded on the same date.

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Period × Cluster interactions were evaluated using Wald tests for B1 and B2 and likelihood-ratio tests for B3, with the latter comparing models fitted by maximum likelihood. B3 ratios between P4 and P1 were obtained from models fitted by restricted maximum likelihood. Changes between P1 and P4 are reported as differences in PC1 scores (B1), odds ratios for recorded path activity (B2), and back-transformed ratios of avalanche dimensions (B3), with 95 % confidence intervals. Detailed model specifications and sensitivity analyses are provided in Supplementary Methods.

2.4 Large avalanches, tree-cover change and robustness

Two additional analyses extended Layer B. Large avalanche events were examined to assess temporal changes across event-size thresholds, while tree-cover change within and around avalanche paths was evaluated over a longer period (1953–2024) to provide ecological context. The latter analysis was intended to provide an initial indication of whether changes in avalanche activity may be associated with long-term tree-cover change and the persistence of open avalanche corridors. Neither analysis was intended to establish causal ecological effects or quantify avalanche hazard.

Large avalanche events were defined using both absolute and path-relative area thresholds. Absolute thresholds corresponded to the 75th (5.0 ha) and 90th (8.1 ha) percentiles of recorded avalanche area. Path-relative thresholds identified events occupying at least 0.5 times or at least the entire mapped path area (the latter hereafter referred to as path-overrunning events). Winter counts were analysed using negative-binomial models, while the proportions of large events among recorded natural avalanches were evaluated using binomial mixed-effects models (Supplementary Methods).

Tree cover was calculated using sf (Pebesma, 2018) as the proportion of area occupied by mapped mature-tree polygons within each avalanche path and in two surrounding zones, 0–25 m and 25–50 m beyond all mapped paths, for 1953 and 2024. Changes between the two horizons were tested using linear mixed-effects models with Year × Cluster fixed effects and a Path random intercept. Path-level tree-cover change was compared with changes in the surrounding zones using paired Wilcoxon tests, and its association with changes in recorded path activity and avalanche dimensions was assessed using Spearman correlations.

Sensitivity analyses addressed the principal sources of methodological uncertainty: inhomogeneities in meteorological measurements (Layer A), repeated climatic observations across path types (B1), alternative morphometric classifications (Layer B), changes in the recording precision of avalanche dimensions (B3), and avalanche paths entering the record after P1 (Supplementary Methods; Tables S2–S5).

Terrain variables, spatial analyses and maps were prepared in ArcGIS Pro. Statistical analyses and figures were produced in R 4.6.1 (R Core Team, 2026), including ggplot2 (Wickham, 2016).

3 Results

3.1 Long-term changes in avalanche-day climatic conditions (Layer A)

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The pooled PCA identified one dominant climatic gradient (PC1), contrasting warm, sunny and dry avalanche days with snowier, windier and more humid conditions (Fig. 2). Avalanche days shifted progressively along this gradient towards warmer and sunnier conditions: each period was positioned further along PC1 than the previous one, from clearly negative scores in P1 (−0.66) to clearly positive scores in P4 (+0.95; one-sided permutation test, $p < 0.001$; Fig. 3a; Table 1), while changes along PC2 were minor. Individual climatic variables exhibited heterogeneous temporal changes, with warming and increasing sunshine particularly apparent (Fig. S1).

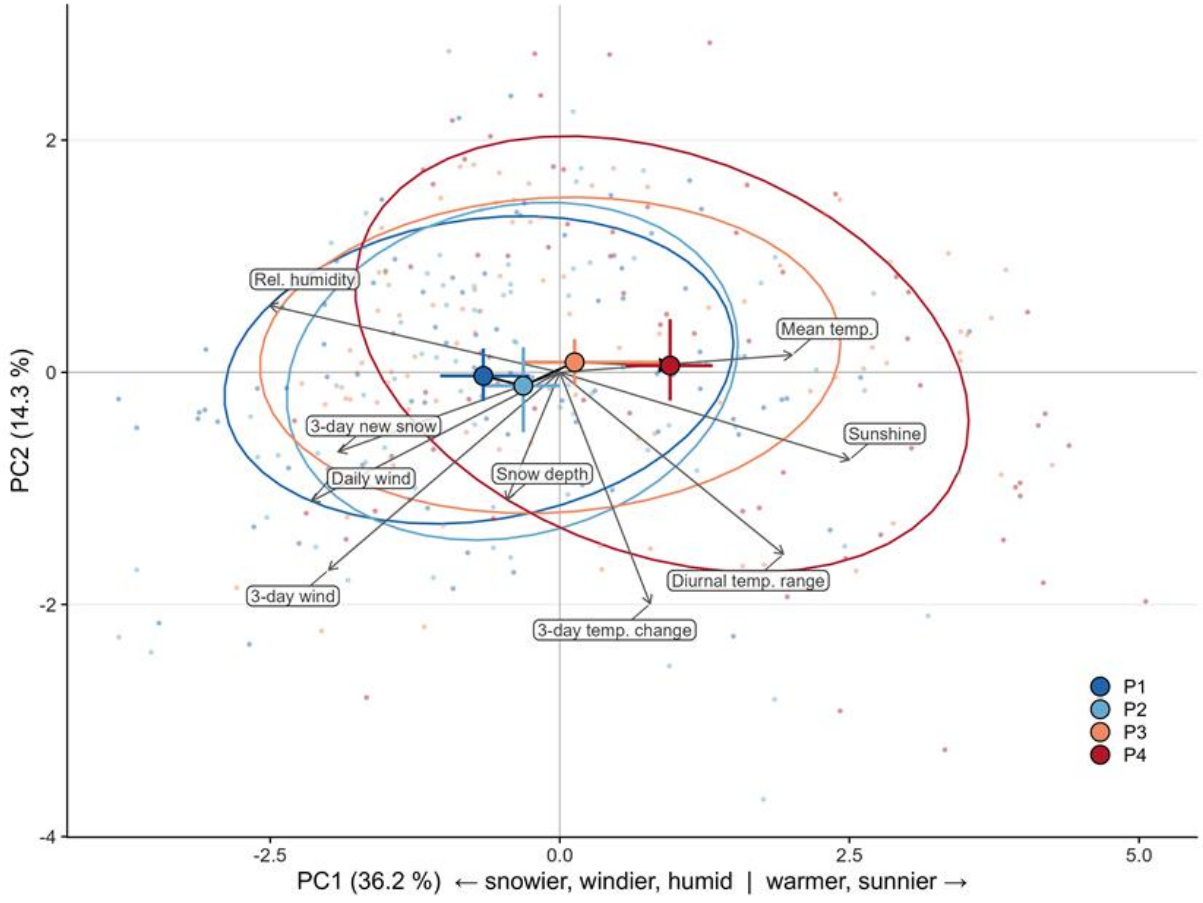


Figure 2. Avalanche days of the four periods in the pooled climatic PCA space. Ellipses enclose about 68 % of the days of each period; centroids are shown with 95 % whole-winter bootstrap confidence intervals.

At the same time, the multivariate variability of avalanche-day climatic conditions became more concentrated along fewer dominant dimensions: the share of variance explained by PC1 and PC2 increased from 48.8 % in P1 to 58.1 % in P4, and effective dimensionality declined from 5.74 to 4.51 (one-sided permutation test, $p = 0.025$; Fig. 3b, c; Table 1). Unlike the progressive shift of the climatic centroids, the decline in effective dimensionality was uneven, occurring mainly between P2 (5.47) and P3 (4.32), followed by a slight increase in P4 (4.51). The orientation of the dominant climatic gradient remained

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largely stable (cosine similarity with pooled PC1, 0.955–0.994), although several secondary relationships among the climatic variables changed between P1 and P4 (Fig. S2). These results were robust to excluding the wind and humidity variables affected by sensor changes and to including the 1999/00–2001/02 winters (Table S3).

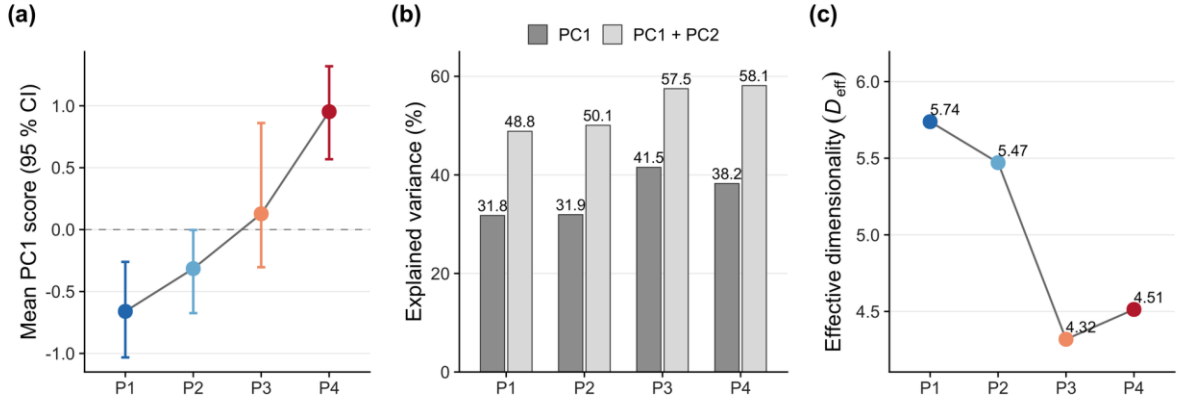


Figure 3. Shift and concentration of avalanche-day climate: (a) period centroids on PC1 with 95 % whole-winter bootstrap confidence intervals (positive = warmer and sunnier); (b) variance explained by PC1 and by PC1 + PC2; (c) effective dimensionality.

Table 1. Climatic structure of natural avalanche days in the four periods.

Period	Winter seasons	n	PC1 centroid [95 % CI]	PC2 centroid	PC1 var. (%)	PC1+PC2 var. (%)	D_eff	cos (PC1, pooled)
P1	1978/79–1988/89	83	−0.66 [−1.03, −0.26]	−0.03	31.8	48.8	5.74	0.955
P2	1989/90–1998/99	85	−0.31 [−0.67, 0.00]	−0.12	31.9	50.1	5.47	0.991
P3	1999/00–2008/09*	94	0.13 [−0.30, 0.86]	0.09	41.5	57.5	4.32	0.994
P4	2009/10–2019/20	73	0.95 [0.57, 1.32]	0.06	38.2	58.1	4.51	0.990

Note: n = avalanche days with complete data; centroids from the pooled PCA with 95 % whole-winter bootstrap intervals, other columns from period-specific PCAs. P1 vs. P4 one-sided permutation tests: centroid shift $p < 0.001$, D_eff $p = 0.025$, PC1 variance $p = 0.083$. * Without the 1999/00–2001/02 winters (Table S3).

3.2 Morphometric differentiation of avalanche paths (Layer B)

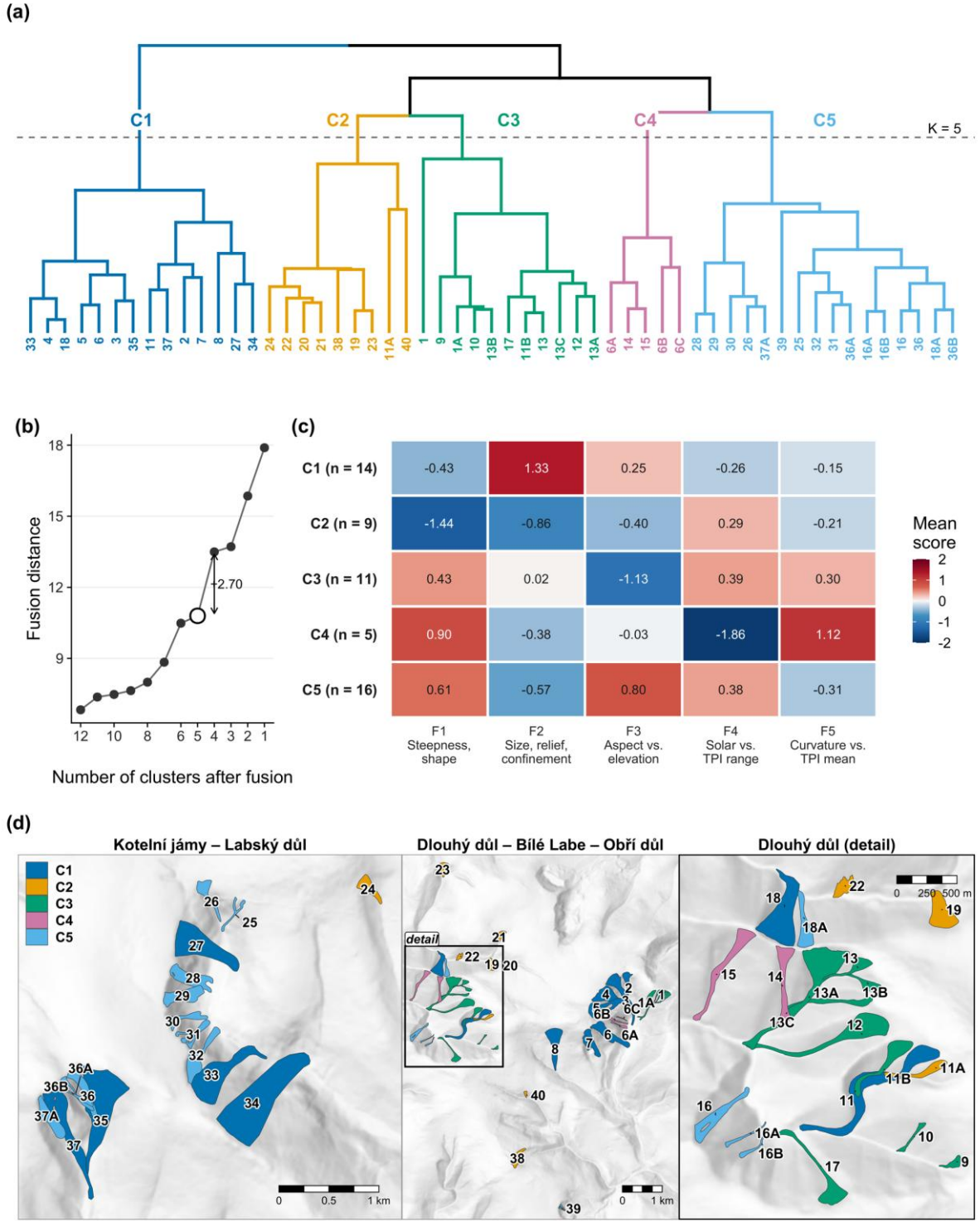
The 13 morphometric variables were reduced to five rotated dimensions (70.4 % of the variance) describing path steepness and shape, size and confinement, orientation and elevation, solar exposure, and local topographic position (Fig. 4c; Fig. S3). Five path types were retained (Fig. 4a, b). Cluster-validation criteria indicated weakly separated, gradient-like morphometric variation without a unique optimal partition; the gap statistic favoured a single group. The five-cluster solution was selected based on fusion distances, local maxima in pseudo-F and silhouette width, and geomorphic interpretability. It therefore

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represents an interpretable stratification of continuous terrain variation rather than sharply defined natural classes. Alternative rotation and distance specifications showed substantial, although incomplete, agreement (adjusted Rand index 0.69–0.72), while merging C2 and C3 (K = 4) left the Layer B results essentially unchanged (Table S2).

The types differ mainly in size, confinement and orientation (Fig. 4c, d). C1 (14 paths) comprises large, east- to south-east-facing paths of the main glacial cirques below the deflation plateaus; C2 (9) gentle valley-head paths in cirque-like hollows that were not markedly reshaped by glaciers; C3 (11) sinuous, west- to south-west-facing gullies outside the deflation plateaus that narrow strongly downslope, mainly in Dlouhý důl and on the slopes of Sněžka; C4 (5) narrow, straight and deeply incised south- to south-east-facing gullies with the lowest solar radiation; and C5 (16) steep, often rocky and short east- to north-east-facing gullies, mostly below the western deflation plateau. For brevity, we refer to them as cirque paths (C1), valley-head paths (C2), sinuous gullies (C3), incised gullies (C4) and rocky gullies (C5). The types therefore reflect not only relief form but also position within the anemo-orographic system: C1 and C5 lie on the leeward margins of the deflation plateaus, C3 outside them and C2 at valley heads. These labels are interpretive: they combine the morphometric profiles of the types (Fig. 4c) with the geomorphological character and location of their paths and do not denote individually quantified properties.

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Figure 4. Morphometric typology of the 55 avalanche paths. (a) Dendrogram of Ward-type hierarchical clustering (Ward.D2, Manhattan distances) of the rotated component scores F1–F5 (see Supplement); leaves are labelled with path codes, and the dashed line marks the five-cluster cut. (b) Fusion distances; the open circle marks K = 5. (c) Mean component scores of path types C1–C5. (d) Spatial distribution of the path types, labelled with the path codes used in (a); the right panel shows the Dlouhý důl area (rectangle in the middle panel) at a larger scale. Map windows have different scales; background: shaded relief derived from the digital terrain model of the Krkonoše Mts. National Park Administration.

3.3 Morphology-dependent temporal response

Climatic changes (B1). The estimated shift towards warmer and sunnier avalanche-day climatic conditions was positive for all five path types, with no statistically significant Period × Cluster interaction ($p = 0.938$; Fig. 5a; Table 2).

Path activity (B2). Recorded path activity declined differently among path types (Period × Cluster, $p < 0.001$; Fig. 5b; Table 2). The decline was strongest in C1, where the observed proportion of active path-winters fell from 55 % in P1 to 21 % in P4 (mixed-model odds ratio P4/P1, conditional on path and winter, 0.11, 95 % confidence interval 0.04–0.32), whereas C4 remained comparatively active (27 % and 20 %; Fig. 5b). The decline was not monotonic: C1 and C5 reached their highest activity in P3 before dropping in P4.

The persistence of C4 partly reflects the Murová dráha path (6C), a small path first recorded in 2001/02; the path-activity result persisted after excluding the eight paths without recorded avalanches in P1 (Table S5).

Avalanche magnitude and geometry (B3). Avalanche area also changed differently among path types (Period × Cluster, $p = 0.004$; Fig. 5c; Table 2). Between P1 and P4, avalanche area decreased by about 62 % in C1, 50 % in C4 and 38 % in C5, whereas no clear change occurred in C2 and C3. The raw distributions of all events show the same overall decline in area and width but little change in length (Fig. S4).

The decline was expressed mainly as narrowing: avalanche width decreased much more than length (Fig. 5d). Width decreased by 74 % in C4 and 43 % in C5 while length hardly changed, whereas C1 contracted in all dimensions (width −58 %, length −24 %). Estimated deposit-height ratios were below one in all clusters, although the confidence interval included one for C2; crown height showed no consistent change among path types (Table 2).

The area and width results were robust to the change in recording precision and to a locality random effect. Within a single valley (Obří důl), avalanche width still declined much more than length, whereas differences in area and length among path types were not significant (Table S4).

Table 2. Change between P1 and P4 by path type (mixed-effects models).

Response	Period × Cluster	C1	C2	C3	C4	C5
Climatic PC1 score (Δ P4−P1)	$\chi^2(12) = 5.53$; $p = 0.938$	+1.76 [1.00, 2.53]	+2.02 [−0.27, 4.30]	+2.33 [0.50, 4.16]	+0.59 [−1.03, 2.21]	+1.97 [0.90, 3.05]
Active path-winter (OR P4/P1)	$\chi^2(12) = 33.92$; $p < 0.001$	0.11 [0.04, 0.32]	0.28 [0.05, 1.54]	0.30 [0.07, 1.25]	0.57 [0.15, 2.21]	0.41 [0.14, 1.25]
Avalanche area (ratio P4/P1)	$\chi^2(12) = 29.20$; $p = 0.004$	0.38 [0.26, 0.57]	0.78 [0.26, 2.33]	1.18 [0.53, 2.63]	0.50 [0.26, 0.96]	0.62 [0.39, 0.98]

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Avalanche width (ratio P4/P1) — secondary	$\chi^2(12) = 58.37$; $p < 0.001$	0.42 [0.33, 0.54]	0.86 [0.37, 1.97]	0.89 [0.49, 1.62]	0.26 [0.17, 0.42]	0.57 [0.42, 0.78]
Avalanche length (ratio P4/P1) — secondary	$\chi^2(12) = 19.13$; $p = 0.085$	0.76 [0.63, 0.91]	1.06 [0.60, 1.86]	1.15 [0.76, 1.75]	1.09 [0.78, 1.52]	0.95 [0.76, 1.20]
Crown height (ratio P4/P1) — secondary	$\chi^2(12) = 20.56$; $p = 0.057$	0.76 [0.53, 1.09]	0.63 [0.28, 1.39]	1.23 [0.66, 2.30]	1.08 [0.62, 1.87]	0.96 [0.64, 1.45]
Deposit height (ratio P4/P1) — secondary	$\chi^2(12) = 8.71$; $p = 0.728$	0.41 [0.30, 0.56]	0.55 [0.27, 1.10]	0.57 [0.33, 0.98]	0.37 [0.23, 0.60]	0.45 [0.32, 0.64]

Note: PC1 row: P4−P1 difference; activity: odds ratio; geometry: back-transformed P4/P1 ratios (< 1 = decline); estimates with 95 % confidence intervals. Interaction tests: B1 and B2 Wald, B3 likelihood-ratio (Supplementary Methods).

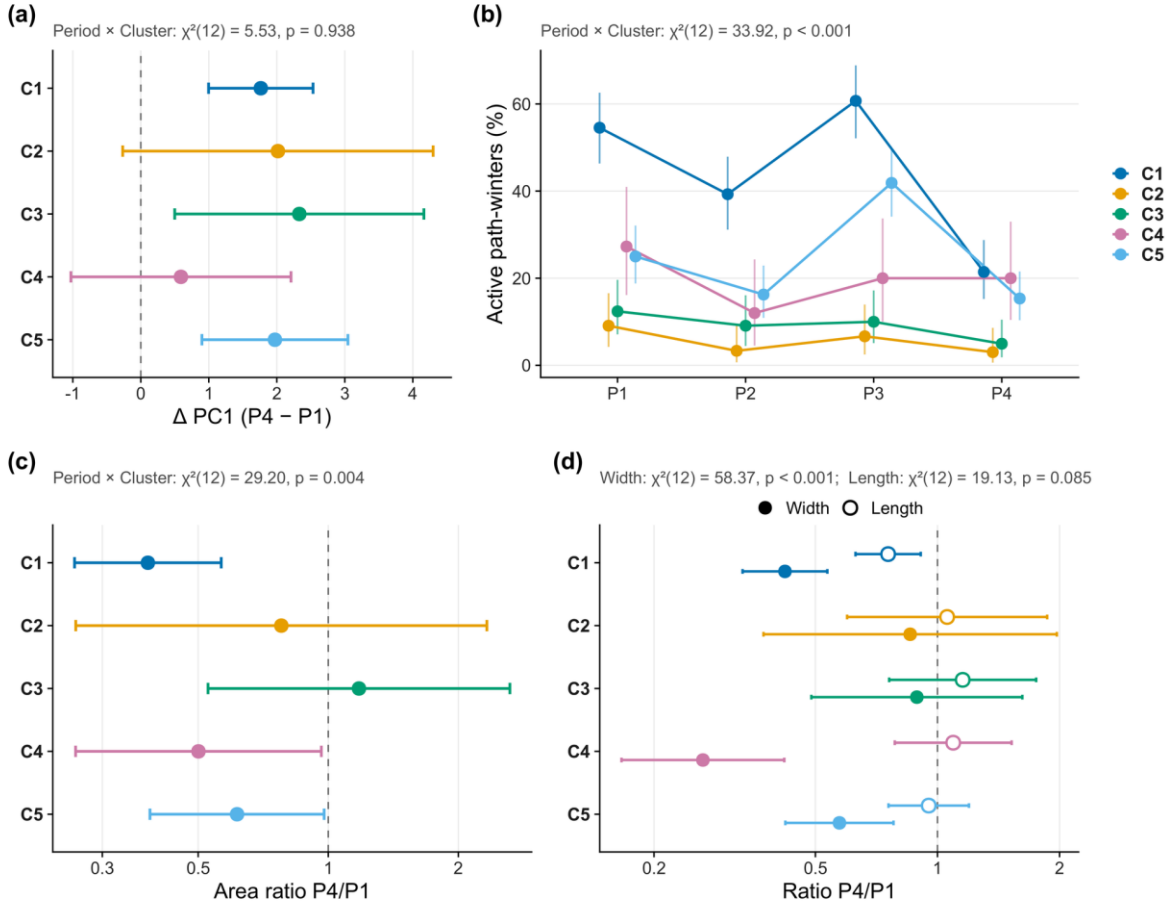


Figure 5. Change between P1 and P4 by path type: (a) climatic PC1 (B1); (b) proportion of active path-winters with 95 % Clopper–Pearson intervals (B2); (c) avalanche area and (d) width (filled) and length (open) (B3; log scale). Bars are 95 % confidence intervals; panel headers give the Period × Cluster tests.

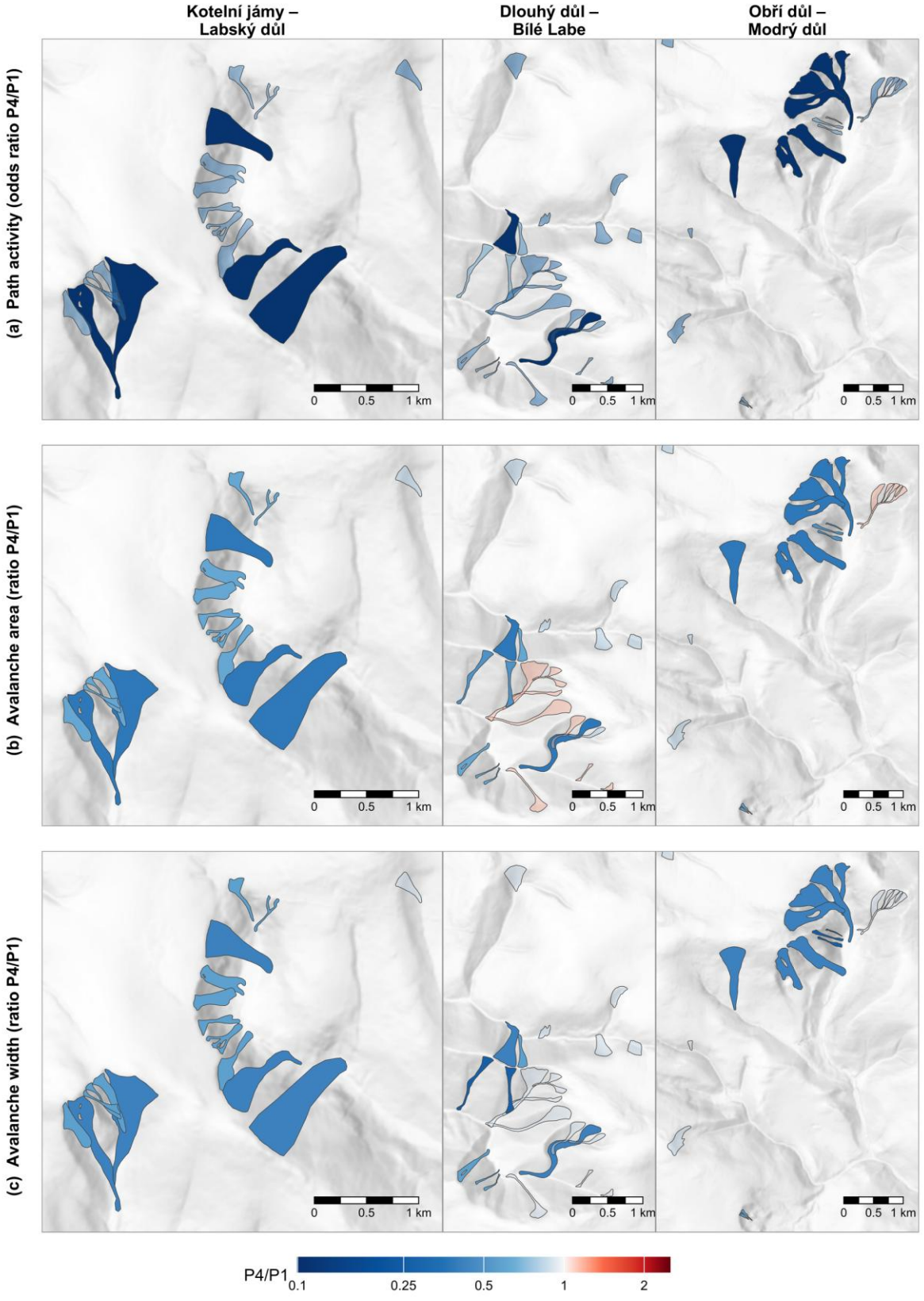
3.4 Spatial patterns, large avalanches and tree-cover change

Spatial synthesis. Model estimates by path type place the strongest declines in activity, avalanche area and width in the large cirque paths of the Obří důl valley, the Kotelní jámy cirque and the Labský důl valley, where C1 paths prevail (Fig. 6).

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Observed changes on individual paths broadly support this pattern: activity declined on almost all recorded paths of the Obří důl valley and on most paths of the Kotelní jámy cirque and the Labský důl valley, whereas changes around the Dlouhý důl valley and the Bílé Labe valley were mixed, with several increases and many sparsely recorded paths (Fig. S5).

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Figure 6. Model-estimated change between P1 and P4 by path type: (a) odds ratio of path activity, (b) ratio of avalanche area, (c) ratio of avalanche width (log scale; lighter tones = 95 % confidence interval includes 1). Path polygons and background shaded relief (derived from the digital terrain model): Krkonoše Mts. National Park Administration.

Large avalanches. Changes differed across event-size thresholds (Fig. S6; Table S6). For avalanches larger than 5.0 ha (75th percentile), annual frequency declined from 7.1 in P1 to 1.5 in P4 (rate ratio P4/P1 = 0.21, 95 % confidence interval 0.07–0.59; overall Period effect, $p = 0.019$), while their share among recorded natural avalanches fell from 36 % to 15 %. No statistically significant period effect was detected for the very largest events (> 8.1 ha) or path-overrunning events, although their rarity resulted in substantial uncertainty. Large events were particularly concentrated in P3, notably in 1999/00, 2001/02 and 2004/05.

Tree cover. Between 1953 and 2024, area-weighted tree cover increased from 12.4 % to 17.0 % on the avalanche paths (+4.6 pp), compared with increases of 11.9 pp within 0–25 m and 11.2 pp within 25–50 m of the paths (Fig. 7; Fig. S7; Table S7). The similar increases in both zones indicate no marked concentration of tree-cover gain immediately adjacent to the paths. Encroachment around the paths was strongest for C3 and C2 and weaker for C1, C4 and C5; on the paths themselves, tree cover increased most in C3 and C5 and declined slightly in C4. No statistically significant association was detected between tree-cover change and changes in recorded path activity or avalanche area (Fig. S7). Marked tree loss was restricted to a few small paths after avalanches that filled or exceeded the mapped path, notably Murová dráha (6C; first recorded avalanche in 2001/02) and Stoh 1 and 2 (16A, 16B; both first recorded in 2011/12) (Fig. 7a).

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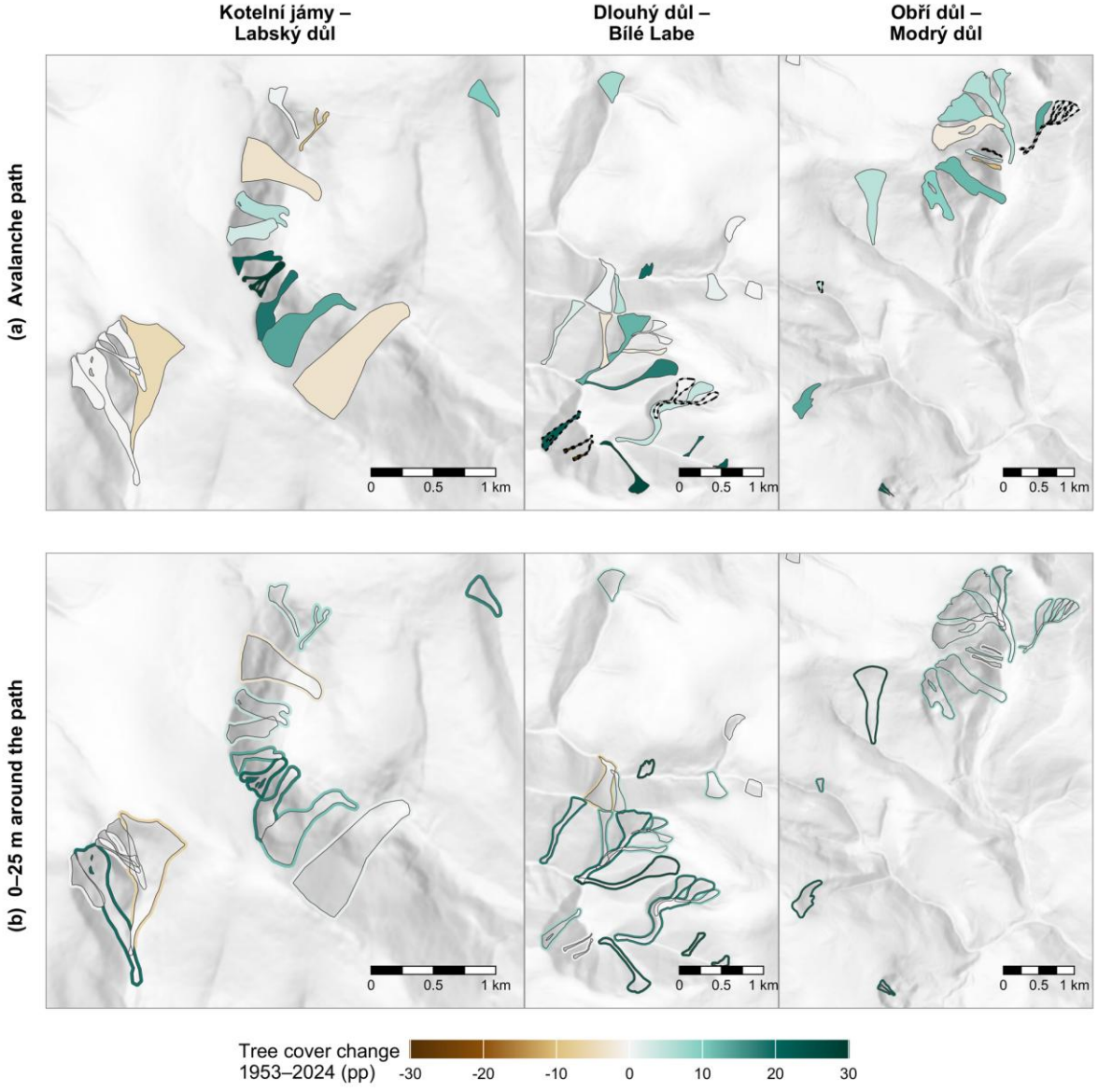


Figure 7. Change in tree cover 1953–2024 (percentage points) (a) on the avalanche paths and (b) within 0–25 m around them; dashed outlines mark paths without avalanches in P1. Tree cover vectorized by the authors from ČÚZK orthophotos (1953, 2024); path polygons and background shaded relief (derived from the digital terrain model): Krkonoše Mts. National Park Administration.

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4 Discussion

4.1 Shift and concentration of avalanche-day climate in a mid-elevation mountain range

The regional analysis revealed a gradual shift towards warmer and sunnier climatic conditions on days when avalanches occurred, while the dominant multivariate climatic gradient remained largely stable. Therefore, the observed change primarily reflects displacement along a persistent statistical gradient, rather than a fundamental reorientation of the main relationships among meteorological variables.

This pattern is consistent with declining snow cover and snow water equivalent in the Sudetes (Urban et al., 2023; Urban, 2024). Evidence that warming in Central European mountains has occurred mainly within prevailing circulation types, rather than through major changes in their frequency (Tichopád et al., 2026), suggests that the shift in avalanche-day conditions may partly reflect a warmer climatic background. This interpretation is also consistent with changes in precipitation phase and snowmelt: winter rainfall has increased in the Krkonoše (Součková et al., 2022), the solid fraction of cold-season precipitation has declined across Czechia (Hynčica and Huth, 2019), and earlier snowmelt and spring runoff have been documented in Central European mountain catchments (Urban et al., 2023; Vlach et al., 2026). Seasonally differentiated precipitation trends in the Sudetes, including wetter winters and drier springs (Ojrzyńska et al., 2026), further suggest that changes in snow conditions cannot be attributed to temperature alone. However, the effects of atmospheric circulation types and precipitation phases were not analysed directly here.

The broader European literature documents a decline in dry-snow avalanche activity, as well as shifts in wet-snow avalanche occurrence and considerable differences among elevations and regions (Eckert et al., 2024; Mayer et al., 2024; Reuter et al., 2025). Recent evidence from Haute-Maurienne also suggests that large avalanche cycles may decline more slowly than mean annual activity (Doussot et al., 2026). Our results complement these studies by describing changes in multivariate meteorological conditions specifically associated with recorded natural avalanche days. Unlike the avalanche-occurrence models of Součková et al. (2022), which compared avalanche and non-avalanche days to identify meteorological drivers, our analysis examines how climatic conditions within the recorded avalanche-day sample have changed over time. The two approaches therefore provide complementary, rather than interchangeable, evidence of avalanche–climate relationships.

The decline in effective dimensionality suggests that avalanche-day climatic variability is moderately concentrated along fewer dominant multivariate dimensions. Unlike the progressive shift in climatic centroids, this change occurred unevenly, mainly between P2 and P3, followed by a slight increase in P4. Consequently, the mean climatic state and the relative structure of multivariate variability did not change at the same pace. However, lower effective dimensionality does not demonstrate a contraction of the absolute range of avalanche-conducive conditions, nor a change in avalanche probability relative to the background winter climate. These distinctions may be particularly significant in mid-elevation ranges, where snow processes are sensitive to temperature and the rain–snow transition. This is also evident in studies of rain-on-snow events in Central European catchments (Hotový et al., 2025).

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4.2 From a shared regional shift to divergent local responses: the role of topographic filtering

Building on the earlier analysis of avalanche-type trends and meteorological drivers in the Krkonoše (Součková et al., 2022), our study extends the investigation to differences among morphometrically defined avalanche-path types. Although avalanche-day climatic conditions shifted in a broadly similar way across these types, changes in recorded path activity, avalanche area and width differed markedly. This pattern is consistent with topographic setting, including path morphology and position within the anemo-orographic system, acting as a spatial filter of regional climatic change.

Wind-driven snow redistribution provides a plausible mechanism for such differentiation. Exposed source areas supply snow to preferential accumulation zones on leeward slopes and within gullies and cirques. This produces local differences in snow loading and stability under similar regional weather conditions (Mott et al., 2018). Elevation, aspect, solar exposure and topographic confinement may also influence snow retention, release conditions and avalanche propagation. A comparable role for topographic setting in organising spatial differences in disturbance has been observed in the Central Low Tatras, where terrain position and wind exposure influenced forest damage during a major windstorm (Šagát et al., 2023). However, the disturbance processes differ from those governing avalanches.

The contrasting responses of cirque paths and incised gullies demonstrate the importance of distinguishing between recorded activity and avalanche-event geometry. Large cirque paths (C1) exhibited significant reductions in recorded activity, as well as in avalanche area, width, and length. In contrast, incised gullies (C4) exhibited comparatively persistent activity and longitudinal avalanche extent despite significant narrowing, while rocky gullies (C5) displayed a similar but weaker pattern. The absence of a clear decline in avalanche area on sinuous gullies (C3), coupled with the sparse records for valley-head paths (C2), further emphasises that the responses were not uniform. Therefore, a path may remain active even if the dimensions of its recorded avalanche events change substantially. This distinction is relevant to the interpretation of historical avalanche records, because changes in occurrence, lateral extent and longitudinal extent provide different, complementary information about the evolution of avalanche behaviour.

The stronger reduction in width than in length is particularly important because longitudinal extent alone may underestimate changes in avalanche-event geometry. Narrow, incised and relatively shaded gullies may retain locally favourable snow conditions and constrain lateral avalanche propagation even as regional snow conditions change. By contrast, the reduction of both lateral and longitudinal extent on large cirque paths may reflect greater sensitivity to changes in snow supply and release conditions. These explanations remain hypotheses: although the path types differ in measured terrain characteristics, local snow accumulation, snowpack stability and released snow volume were not observed directly.

Terrain-dependent responses to climatic forcing have also been documented for other snow-related processes (Hotový et al., 2025). Changes in rain, melt–freeze cycles and avalanche type may further modify local responses: liquid-water input can destabilise snow in the short term, while subsequent refreezing may increase stability (Conway and Raymond, 1993), and the relative importance of wet-snow avalanches has changed in other European mountain ranges (Giacona et al., 2021; Eckert et al., 2024; Mayer et al., 2024). In the Krkonoše, reduced availability of transportable snow could also weaken wind-driven

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coupling between summit deflation plateaus and accumulation zones (Jeník, 1961; Mott et al., 2018). Whether these mechanisms explain the observed differences among path types remains to be tested using snowpack and snow-redistribution data.

4.3 Implications for mountain ecosystems, avalanche hazard and protected-area management

Avalanches help maintain open corridors and promote habitat heterogeneity within subalpine forests and treeline ecotones (Bebi et al., 2009). This disturbance function is particularly relevant in the High Sudetes, where naturally treeless subalpine habitats are scarce and vulnerable to forest encroachment (Zeidler et al., 2023). The observed narrowing of avalanche events suggests that changes in the extent of disturbances could affect the lateral dimensions of open corridors before affecting their longitudinal continuity. However, the dimensions of avalanche events cannot be equated directly with vegetation boundaries, as these also depend on recurrent disturbances, vegetation recovery, and local environmental conditions.

Between 1953 and 2024, tree cover increased considerably less within avalanche paths than in their immediate surroundings. This pattern is consistent with the continuing role of avalanche disturbance in maintaining open habitats. Nevertheless, gains in tree cover were not concentrated at path margins, and no statistically significant association was detected between changes in tree cover and changes in recorded path activity or avalanche size. Vegetation dynamics are influenced by interacting factors, including historical land-use abandonment, conservation management, warming, and topographic constraints (Treml et al., 2016; Klinkovská et al., 2023; Hejda et al., 2025). Spruce growth near the treeline is sensitive to temperature and nutrient availability (Kuželová et al., 2025), while recent warming has accelerated tree establishment in some alpine forest–grassland ecotones (Nicoud et al., 2025). Furthermore, the longer period covered by the orthophotos and the availability of only two snapshots of tree cover prevent the attribution of vegetation change to more recent avalanche trends.

Potential ecological responses may differ among habitats and only emerge after substantial delays. Warming has already been linked to changes in the cover and functional composition of high-mountain vegetation (Steinbauer et al., 2022), yet the establishment of woody plants at treelines is still limited by factors such as moisture, topography, species interactions, and disturbance (Lu et al., 2025). The relationship is further complicated by differences in the responses of spruce and dwarf pine (Šenfeldr et al., 2021), changing spring moisture conditions (Ojrzyńska et al., 2026), and local snow accumulation and geomorphic disturbance (Treml and Migoń, 2015). Therefore, declining avalanche disturbance could relax one constraint on woody establishment without necessarily producing immediate or spatially uniform vegetation change.

Similar caution is required regarding the implications for avalanche hazard. Recorded path activity does not equate to a quantitative estimate of avalanche hazard, which requires information on event probability and intensity; avalanche risk additionally depends on exposure and vulnerability (Techel et al., 2015; Eckert et al., 2024). Although declines in recorded activity and event dimensions were particularly pronounced in the major glacial cirques, some gullies retained substantial activity or longitudinal extent, while trends in the largest, path-overrunning events remained statistically uncertain. Evidence from the Alps likewise suggests that changes in large avalanche cycles need not mirror mean activity (Doussot et al., 2026). Our findings therefore highlight the importance of considering path-specific changes in both activity and event geometry

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when interpreting long-term avalanche records and planning continued monitoring. Declining recorded activity alone should not be taken as evidence of a uniform reduction in avalanche hazard, particularly in heavily visited mountain environments (Erlebach and Romportl, 2021). Individual large events may also continue to affect forested slopes, as illustrated by tree-cover losses on several paths first recorded in later winters, although the first recorded avalanche does not necessarily indicate the formation of a new path.

For protected-area management and avalanche-hazard communication, our results extend previous region-wide assessments (Součková et al., 2022) by identifying distinct patterns of change among topographically defined path types. This differentiation supports path-specific monitoring rather than assuming uniform changes in avalanche disturbance across the mountain range. Monitoring is particularly valuable where declining activity coincides with vulnerable Arctic–Alpine tundra habitats and their characteristic or threatened plant species. Paths with substantial activity or longitudinal avalanche extent remain relevant for communicating hazards. Repeated vegetation surveys and high-resolution remote sensing, including UAVs and multi-temporal satellite imagery, can help detect changes in avalanche-influenced habitats and inform adaptive conservation management (Klinkovská et al., 2023; Kupková et al., 2023). This spatial evidence could also supplement the communication of avalanche hazards by mountain rescue services along specific paths (Blahut et al., 2017).

4.4 Limitations, transferability and outlook

Several limitations affect the interpretation of these results. Historical avalanche inventories may be influenced by changes in observation coverage and recording practices. In the Krkonoše record, the numerical precision of avalanche dimensions changed around 2009/10, as indicated by less frequent rounding in later records; meteorological sensors were also modified, and the Labská bouda record was interrupted during 1999/00–2001/02. The trapezoidal approximation of avalanche area introduces additional geometric uncertainty, particularly for curved paths, although uncertainty also affects expert delineations of avalanche extent (Hafner et al., 2023). Sensitivity analyses supported the robustness of the main results to documented changes in measurement records (Tables S3 and S4), although the geometric uncertainty of the area approximation could not be assessed directly. The path-activity findings also persisted after excluding paths without recorded events in P1 (Table S5). Nevertheless, unrecorded changes in observation effort and historical completeness cannot be ruled out.

Layer A characterises the climatic conditions of recorded natural avalanche days rather than changes in avalanche occurrence probability relative to all winter days. Unlike the occurrence-based analysis of Součková et al. (2022), our approach does not include non-avalanche days; neither the observed climatic shift nor the decline in effective dimensionality can therefore establish whether the overall range or frequency of avalanche-conducive conditions has changed relative to the background winter climate.

The morphometric typology represents an interpretable stratification of continuous terrain variation, not sharply separated natural classes. Although the main Layer B results were robust to merging C2 and C3 (Table S2), the sparse records for C2 limit interpretation. Moreover, the spatial clustering of path types within particular cirques and valleys means that

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morphology and geographical position cannot be fully separated. The observed differences may therefore incorporate unmeasured local snow-climate and exposure effects. The interpretation of topographic setting as a spatial filter is consistent with the spatial differentiation of avalanche responses, but the physical mechanisms remain unresolved because snow redistribution, snowpack stratigraphy and avalanche dynamics were not directly modelled.

The tree-cover analysis captures net change between two orthophoto horizons (1953 and 2024) that differ in resolution and image quality and span a longer period than the avalanche record. The mapping excludes dwarf pine and young trees and treats disturbed stands as forest; it therefore cannot establish the timing or causes of woody establishment. Intermediate orthophotos, including those from 1977 and 2005, and detailed remote-sensing approaches previously used to document tundra vegetation change in the Krkonoše (Kupková et al., 2017; Potůčková et al., 2021) could help resolve these temporal relationships. Future work should also incorporate lidar-derived vegetation structure, explicit measures of path position relative to deflation plateaus and wind fetch, and snow-redistribution modelling. Applying the same regional-to-local framework in other mid-elevation, wind-dominated mountain ranges would provide a direct test of its transferability.

5 Conclusions

Four decades of avalanche records from the Krkonoše Mountains show a marked shift towards warmer and sunnier climatic conditions on days when avalanches occurred, accompanied by a moderate concentration of climatic variability along fewer dominant dimensions. While the climatic shift was broadly similar across morphometrically defined avalanche path types, changes in recorded path activity and avalanche event geometry varied between them.

Large cirque paths showed the strongest reductions in recorded activity and avalanche area, whereas incised gullies retained comparatively persistent activity and longitudinal avalanche extent despite substantial narrowing. These contrasting responses are consistent with topographic setting, including path morphology and position within the anemo-orographic system, acting as a spatial filter through which a shared regional climatic shift is expressed locally.

Tree cover increased substantially less within avalanche paths than in their surroundings, suggesting a possible continuing role of avalanche disturbance in maintaining open habitats. At the same time, trends in the frequency of the very largest avalanche events remained uncertain owing to their small number, which cautions against assuming uniformly declining avalanche hazard.

By extending previous regional avalanche research to independently defined morphometric path types, this study demonstrates how a broadly shared shift in avalanche-day climatic conditions can be accompanied by divergent local changes in recorded avalanche activity and geometry. The regional-to-local framework provides a transferable approach for evaluating spatially differentiated changes in avalanche records and demonstrates why path morphology, recorded activity and event geometry should be considered jointly when interpreting long-term changes relevant to avalanche monitoring.

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Code and data availability

The original avalanche records, avalanche-path and release-zone polygons, treeline layers and the 0.5 m digital terrain model were provided by the Krkonoše Mts. National Park Administration, and the meteorological data by the Czech Hydrometeorological Institute. These data are subject to the data policies of the respective institutions and are available from them upon request. The pre-processed data used in the analyses (avalanche event attributes, avalanche-day climatic variables, morphometric variables of the avalanche paths and tree-cover data) and the R scripts used for the statistical analyses and figures are available at Zenodo (https://doi.org/10.5281/zenodo.23976848; Erlebach et al., 2026).

Author contributions

ME: conceptualization, methodology, investigation, formal analysis, visualization, project administration, writing (original draft). MV: data curation, formal analysis, methodology, validation, writing (original draft). PK: conceptualization, supervision, writing (original draft).

Competing interests

The authors declare that they have no conflict of interest.

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