

Quantifying snow-cover dynamics from time-lapse photography in the High Tatras (Slovakia)

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Abstract: Snow cover is a critical component of the hydrological cycle in mountain regions. Monitoring mountain snow cover has become increasingly urgent due to climate warming. To analyse its seasonal dynamics, manual snow-depth measurements with a snow stake at the Skalnaté Pleso Observatory (1778 m a.s.l.) were complemented by time-lapse trail-camera observations of the surrounding area. Analyses of time-lapse images over four winter seasons (2021/22–2024/25) revealed pronounced interannual variability in snow cover dynamics and showed that the camera reliably captured snow conditions during both continuous-snow and snow-poor winters. In the 2024/25 season, average snow depth was exceptionally low (9.5 cm), while average snow cover remained around 50%, suggesting far-reaching consequences for environmental systems. A clear non-linear relationship was found between snow depth and camera-derived snow cover, with rapid increases in areal cover at low snow depths and saturation at approximately 30–40 cm ($R^2 = 0.76$). Time-lapse imagery, after image alignment, mask application, and automatic image classification, proved to be a robust and cost-effective complement to point-based measurements.

Key words: snow coverage, camera, image analysis, snow depth

1. Introduction

Snow cover is a key component of the hydrological cycle in mountainous areas, serving as an important water reservoir. Monitoring regional and global snow cover has become increasingly important in recent years, as rising temperatures have led to declines in snow cover across many regions. Warming at high elevations (*Barry, 2008; Marty and Meister, 2012; Wang*

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et al., 2016) is comparable to the global average (Ohmura, 2012), and in some regions, higher elevations are warming faster than lower ones (Pepin *et al.*, 2015). Increased evaporation and atmospheric moisture may lead to more frequent and intense snowfall; however, they also shorten the snow season and accelerate snowmelt (Steger *et al.*, 2013; Jiménez Cisneros *et al.*, 2014). Whether snow cover will be reduced or increased depends on several factors, such as topographic features (elevation, aspect, and terrain shading), orography, and synoptic situations (Ceppi *et al.*, 2012; Räisänen and Eklund, 2012). In the Northern Hemisphere, snow cover is likely to migrate northward, with higher loss rates between latitudes 45°–49° N, and to higher altitudes in the future (DeMaria *et al.*, 2016). There is still less consensus on the time horizon for snow disappearance, but model projections, combined with a low-to-no snow definition, suggest ~ 35 –60 years before low-to-no snow becomes persistent at these latitudes if greenhouse gas emissions continue unabated (Siirila-Woodburn *et al.*, 2021).

Snow stakes have the longest history of measurements. In recent years, this manual method has increasingly been complemented by camera systems, which enable continuous observation of snow depth without the need for an on-site observer (Dong and Menzel, 2017; Bartík *et al.*, 2019; Škvarenina *et al.*, 2023). However, this traditional method is point-specific, whereas snow depth can vary significantly across short distances due to wind, topography, or shading. This makes the single-stake method, whether combined with an observer or a camera system (Bongio *et al.*, 2021), less representative of overall conditions. Snow stakes are often replaced by automatic sensors that reduce long-term operational costs by minimising human intervention and increasing efficiency. Data from these modern sensors, such as microwave radars, gamma-ray sensors or snow pillows, can be directly integrated into hydrological, weather, or climate models.

In addition to traditional point-based measurements, a wide range of observational approaches is used to monitor snow cover dynamics across different spatial scales. In this context, data from remote sensing observations are widely used (Asamani and Sun, 2023). Satellite measurements provide high spatial resolution, enabling large-scale analysis of spatial patterns and temporal changes in snow cover extent (Hall *et al.*, 2001; Tong *et al.*, 2020; Çakir *et al.*, 2025; Poussin *et al.*, 2025). In remote or mountainous areas, drones and airborne LiDAR (Light Detection and Ranging) systems are also

used for snow cover mapping (*Deems et al., 2013; Ruttner et al., 2025*). An effective and relatively low-cost alternative is the use of time-lapse camera systems, which can capture gradual changes in snow cover, including snow accumulation and melt dynamics. The advantage of camera-based observations is the deployment in remote and harsh environments without the need for frequent site visits (*Breen et al., 2023; Portenier et al., 2020; Parajka et al., 2012; Salvatori et al., 2011; Kučera et al., 2024*).

The integration of traditional methods with automated sensors, satellite data, and predictive models improves the accuracy of environmental monitoring and snow cover projections. In this study, we analysed data from optical monitoring using a time-lapse camera permanently installed on the roof of the Skalnáté Pleso Observatory (SPO), as well as meteorological and snow depth measurements at SPO. The data were used to investigate snow cover dynamics in a high-mountain environment over the period 2021–2025. The main objective was to validate camera-derived snow cover against ground-based observations, particularly snow depth measurements. Furthermore, we analysed air temperature thresholds associated with snow accumulation and melt in relation to precipitation, and evaluated the responsiveness of camera-derived snow cover to these changes.

2. Data and methods

2.1. Study area

The study area is located in the alpine treeline ecotone of the High Tatra Mountains, near the Skalnáté Pleso Observatory (SPO: lat. 49.18928° N, long. 20.23410° E; 1778 m a.s.l.), within the Tatra National Park (Fig. 1). The monitored area is characterised by a cold climate; however, changes in key climatic parameters have been observed between the two reference periods 1961–1990 and 1991–2020. Annual precipitation increased by 195.6 to 1477.2 mm, and the number of days with precipitation exceeding 1 mm rose by 6 to a total of 154 days. Annual maximum air temperatures increased by 1.2°C to 6.5°C, minimum temperatures by 0.8°C to −0.5°C, and mean temperatures by 1.1°C to 2.8°C. In addition, the total annual sunshine duration increased by 52 hours, reaching 1475.5 hours in the period 1991–2020 (*Lukasová et al., 2023a*).

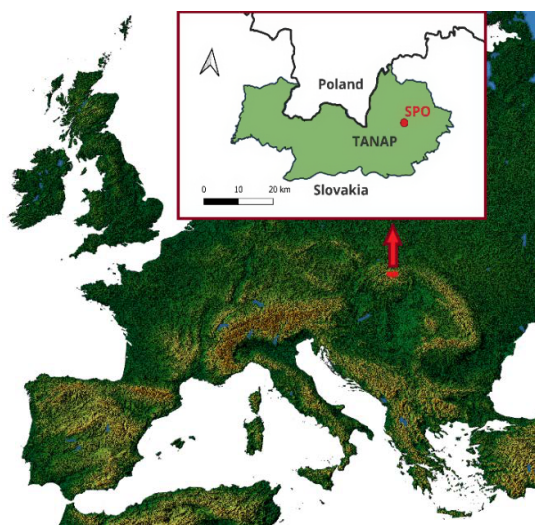


Fig. 1. Location of the study area and the Skalnate Pleso Observatory (SPO, red point) in Tatra National Park (TANAP) in Slovakia, shown in a European context.

2.2. Meteorological measurements

Meteorological observations at the SPO are conducted in a dual regime, combining standard manual measurements and automatic monitoring systems (Lukasová *et al.*, 2023b, 2024). Manual observations are carried out by professionals using established methods and instruments, and are performed three times per day, at 07:00, 14:00, and 21:00 local mean time (LMT). Snow depth is measured using a traditional snow stake, with observations recorded to a precision of 1 cm. Snow depth measurements have been conducted since 1943, when the observatory was relocated to its current building. In 1979, the position of the snow stake was shifted by approximately 15 metres within the observatory area. This adjustment was necessary because the original location was frequently affected by snowdrift due to terrain irregularities and strong winds. In this study, only snow depth data from the period 1979–2025 were analysed. The snow season was defined from November 1 to April 30, and the average snow depth was calculated for this period. In addition, the 30-year climatological normal was derived for the reference period 1991–2020.

2.3. Processing of time-lapse images

Snow cover in the study area was monitored using a Tetrao Spromise S328 camera trap equipped with a time-lapse function. The camera has been permanently installed on the roof of the Skalnaté Pleso Observatory (SPO) since October 2021, capturing the south-eastern slope of the High Tatra Mountains below Huncovský Peak. The acquisition scheme was set to capture two images per day at 08:00 and 13:00 CET, with the second image captured 10 minutes after the first. The camera is capable of transmitting images in near real time. The dataset used in this study included images from November to the end of May for the winter seasons 2021/22 to 2024/25. The processing of time-lapse images included a three-step image analysis:

1. Horizon detection based on edge responses and automatic image-to-image alignment (Fig. 2a). The input image was first converted to gray-scale and processed with the Canny edge detector to extract high-contrast structural boundaries. For each vertical column in the resulting edge map, the algorithm identified the uppermost nonzero pixel, which was interpreted as the candidate horizon point. To minimise the influence of noise and spurious discontinuities, a threshold-based filtering step was applied, to discard abrupt vertical jumps exceeding a predefined threshold. This procedure ensured that the estimated horizon line (Fig. 2b) captured the dominant horizontal edge structure while remaining robust to local artefacts and terrain irregularities. To maintain spatial consistency across the dataset, an automatic image alignment procedure was developed based on the detected horizon lines. After extracting horizon profiles from both the base and target images, the algorithm identified the subset of columns with valid (non-NaN) horizon values. By leveraging the horizon as a dominant structural feature, the method enabled reliable global alignment (Fig. 2c) without reliance on explicit point correspondences, while maintaining low computational complexity.
2. Mask Creation. To exclude irrelevant areas such as the sky and regions outside the area of interest, a binary mask was generated by manually selecting a polygonal region within a reference image. The polygon was filled using OpenCV's `fillPoly` function, after which the bounding rectangle of the selected area was extracted to crop the image accord-

ingly (Fig. 2d). This ensured that only the relevant ground region was retained for further analysis, while non-informative areas were consistently excluded from the subsequent snow classification procedure.

3. Automatic Snow Classification. Snow classification was conducted using the method proposed by *Salvatori et al. (2011)* and applied by *Portenier et al. (2020)*, which analyses the blue-band digital number frequency histogram to determine a snow threshold. The histogram was smoothed with a moving-average window of 5, after which the snow threshold was automatically set to the first local minimum with an intensity of 127 or higher. If no local minimum was found, the threshold defaulted to 127. Pixels with values equal to or greater than this threshold were classified as snow, while lower values were considered snow-free. The snow-covered area (Fig. 2d) was then quantified as the ratio of snow-classified pixels to the total masked area, expressed as a percentage (0%–100%).

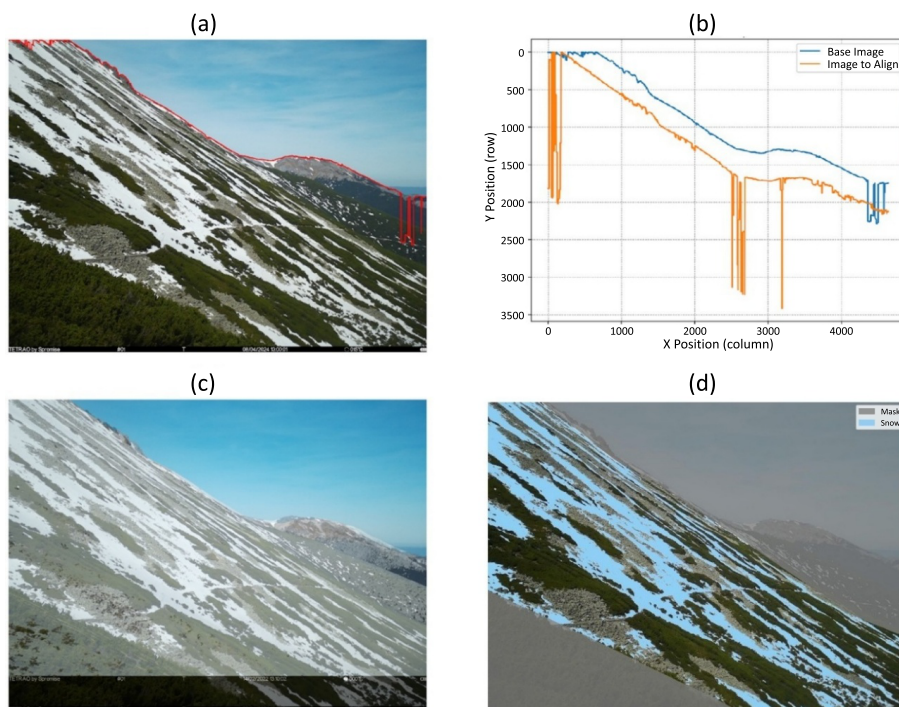


Fig. 2. Processing of time-lapse image including (a) horizon detection, (b) image-to-image alignment, (c) overlapped view, and (d) mask application.

2.4. Data analysis

Long-term changes in snow conditions were assessed by analysing the trend in average snow depth. Long-term trends in seasonal snow depth were evaluated using the non-parametric Mann–Kendall test and Sen’s slope, a widely used method for hydroclimatic time series due to its robustness to non-normal distributions and outliers.

The relationship between snow depth and camera-derived snow cover was modelled to quantify how increasing snow depth translates into areal snow cover and to identify the saturation behaviour of snow cover at higher snow depths.

For all statistical tests, results were considered statistically significant when $p < 0.05$.

3. Results

3.1. Snow and climate conditions in the study area

Figure 3 presents snow cover observations over four winter seasons from 2021 to 2025. The 2021/22 and 2022/23 seasons were similar, with persistent snow cover beginning in late November and lasting until the end of May. In contrast, during the 2023/24 season, continuous snow cover developed earlier, at the beginning of November, but ended already in early April, more than one month earlier than in the previous two seasons. Although time-lapse imagery suggested rapid snowmelt at the end of 2023/24 winter, snow depth measurements indicated that the average snow depth remained above the 1991–2020 climatological normal (Fig. 4) until the April (Fig. 3). In the 2021/22, 2022/23, and 2023/24 seasons, the study area reached 100% snow cover for at least two months, indicating complete coverage of the surface, including low vegetation. In contrast, the 2024/25 season showed weak, intermittent snow cover, with frequent fluctuations, no period of complete (100%) coverage, and snow depth remaining below monthly normals (Fig. 3).

The average snow depth from November 1 to April 30 for the 1991–2020 winter seasons was 27.5 cm. During the four analysed winter seasons, two seasons (2021/22 and 2023/24) exhibited average snow depth above the 1991–2020 normal, while the other two (2022/23 and 2024/25) were below

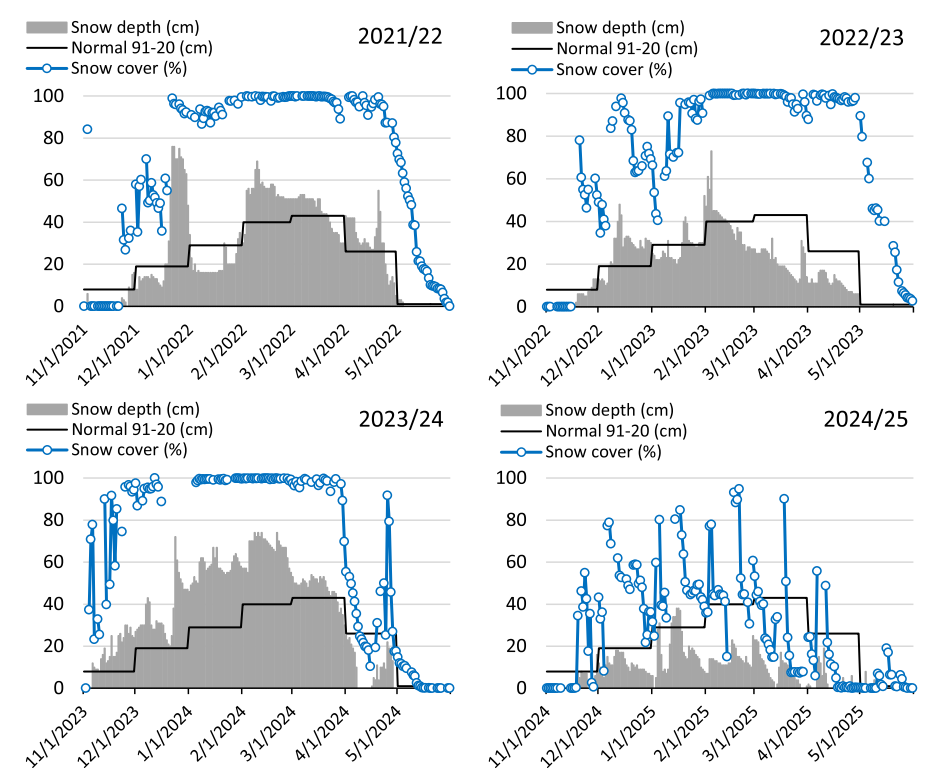


Fig. 3. Snow depth and snow cover in the study area over four winter seasons, 2021/22–2024/25, including the monthly normal snow depth of 1991–2020.

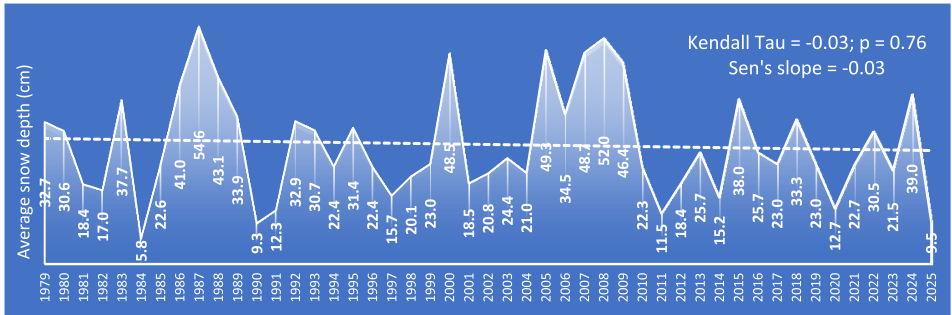


Fig. 4. Average seasonal snow depth over the years 1979–2025, and its trend.

normal. This pattern is consistent with the long-term evolution of snow conditions at the site, where average seasonal snow depth showed a very weak, statistically non-significant negative trend (Sen’s slope = $-0.03\text{ cm}\cdot\text{year}^{-1}$, $p > 0.05$, Fig. 4).

The average snow depth in 2024/25 was only 9.5 cm, while values in the other analysed seasons were several times higher (Fig. 4). In the context of the long-term record (1979–2025), this value is exceptional, as it falls below the 5th percentile of all analysed values. The lowest average snow depth was recorded in the 1983/84 season, at 5.8 cm. The insufficient snow cover during the 2024/25 winter season was primarily caused by low precipitation totals. During the five main cold-season months (November to March), total precipitation reached only 310.4 mm, compared to the 1991–2020 normal of 403.2 mm (Fig. 5). Over the same period, precipitation totals were considerably higher in previous seasons, reaching 526.4 mm in 2021/22, 477.6 mm in 2022/23, and 679.3 mm in 2023/24. Furthermore, during the 2024/25 season, average air temperatures were above normal in all cold months except February while remaining close to 0 °C (Fig. 5).

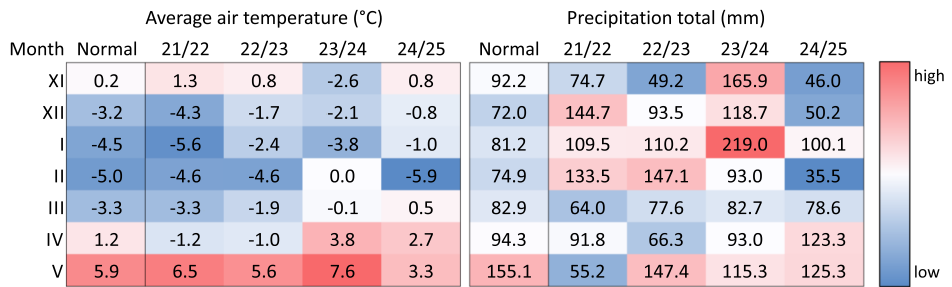


Fig. 5. Heatmaps of climate conditions, monthly air temperatures, and precipitation during the analysed seasons 2021/22–2024/25.

3.2. Snow depth to cover relationship

Figure 6 demonstrates a clear non-linear relationship between snow depth and camera-derived snow cover, with rapid increases in coverage at low snow depths, indicating that initial snow accumulation has the greatest impact on surface coverage. Snow cover approached saturation at approximately 30–40 cm, beyond which further increases in depth did not significantly affect the percentage of covered area, as the snow-cover fraction became in-

sensitive to additional increases in snow depth once near-complete coverage was reached. A substantial scatter was observed at low snow depths (below ~ 20 cm), where similar depths corresponded to a wide range of snow cover values, reflecting strong spatial heterogeneity driven by local factors such as wind redistribution, microtopography, vegetation, and terrain exposure. All tested models (exponential, logistic, Weibull, and Richards) exhibited nearly identical performance ($R^2 = 0.76$), suggesting that simpler models may be sufficient. Nevertheless, the model explained about 76% of the variability, with the remaining unexplained portion likely associated with processes not captured by snow depth alone, including surface heterogeneity and observational uncertainties. Overall, the results confirmed that snow depth is a key predictor of snow cover, but also indicate that additional meteorological variables are required to fully represent snow accumulation and melt dynamics.

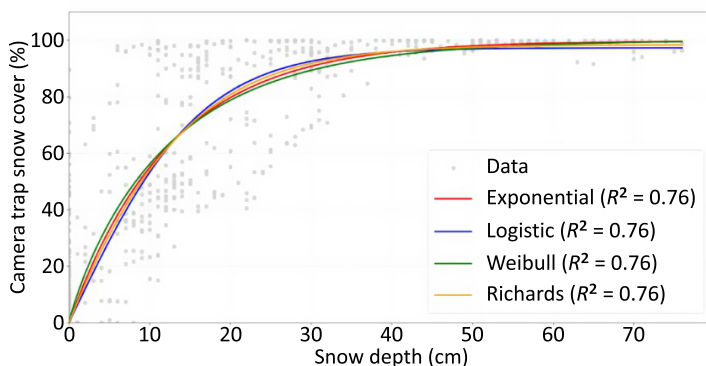


Fig. 6. Relationship between snow depth and camera-trap-derived snow cover. Grey points represent observed data, while coloured curves show fitted non-linear growth models, including exponential, logistic, Weibull, and Richards functions with their coefficients of determination shown in the legend.

4. Discussion

4.1. Advantages of landscape-scale time-lapse photography for snow cover monitoring

Landscape-scale time-lapse photography is not intended to replace traditional snow depth measurements but rather to complement them. Point-based snow depth observations remain essential for quantifying snowpack

thickness and long-term climatological variability as presented in this study. However, in mountain environments, their representativeness may be limited by strong local effects, particularly wind-driven redistribution of snow and its placement affected by microtopography and vegetation (*Lamare et al., 2023; Shirley et al., 2025*). In this context, time-lapse photography provides an important advantage, as it captures the spatial expression of snow cover over a broader area and is therefore less sensitive to the limitations of a single measurement point.

A further advantage is the feasibility of deployment in remote mountain environments at relatively low cost. Once installed, camera systems can operate continuously with minimal maintenance, making them suitable for long-term monitoring in harsh, difficult-to-access terrain. Their usefulness is further enhanced when equipped with a data transmission system, such as a camera used in this study, which enabled us to access near-real-time images and monitor both environmental conditions and camera operation remotely. This makes time-lapse photography a practical alternative or complement to more expensive observation systems.

Time-lapse photography is also highly valuable as a ground reference for validation (*Parajka et al., 2012; Ide and Oguma, 2013*). Unlike many ground-based datasets, which are reduced to binary snow presence/absence, camera-derived observations can provide information on continuous snow cover dynamics. Owing to their much higher temporal resolution than satellite data, they can capture seasonal snow trajectories (*Melón-Nava and Santos-González, 2025*). This makes them particularly useful not only for validating remote sensing products but also for modelling seasonal snow cover dynamics.

At the same time, we acknowledge several limitations of the method, including the unidirectional camera view and sensitivity to changing light conditions. In future work, we plan to continue the time-lapse monitoring and extend it by incorporating multiple viewing angles. Snow accumulation on the camera lens may introduce additional uncertainty into time-lapse monitoring. In this study, the camera trap was installed in a protective housing, which reduced direct snow deposition, and snow accumulation on the lens was observed only rarely. In most cases, accumulated snow melted naturally within 24 h. If image quality remained affected for longer periods, the lens was manually cleaned by observatory staff. Such interventions were

minimised because each camera manipulation slightly altered the viewing geometry and affected image alignment.

4.2. Effect of albedo

The amount and condition of snow cover strongly influence surface albedo, which, in turn, affects the local microclimate, particularly air temperature. A landscape continuously covered by snow reflects more solar radiation than any other surface type, thereby substantially reducing the amount of energy absorbed by the ground (*Randal et al., 1994; AMAP, 2012*). The intermittent snow cover observed during the 2024/25 winter reduced the albedo of the high-mountain environment, thereby contributing to higher surface and ambient temperatures. Temperature conditions during the 2024/25 season indicate that the mean air temperature already reached 0.5 °C in March, which is exceptionally high for this month and exceeds the 1991–2020 climatological normal by 3.8 °C (Fig. 5). February was therefore the last winter month in which the monitored area recorded a negative mean monthly temperature. In contrast, the mean March temperatures in the 2021/22, 2022/23, and 2023/24 seasons remained below zero, slowing the melting of existing snow and supporting the persistence of newly fallen snow. The unusually high temperatures in March 2025 may also have been influenced by temperature inversions, which will be analysed in future work.

4.3. Environmental aspects of snow depth trends

Climate change poses a major challenge to mountain tourism, which is particularly vulnerable because of the high sensitivity of mountain environments (*Steiger et al., 2024*). In winter, ski tourism is among the most affected sectors (*Mitterwallner et al., 2024*). Recent studies have reported shorter ski seasons due to reduced snow reliability and declining natural snow cover (*Steiger et al., 2019*). In the 21st century, the highest number of Alpine Ski World Cup race cancellations due to warm weather and a lack of snow was recorded in Slovenia, Croatia, and Bulgaria, followed by France (*Klobučnik et al., 2026*).

However, reduced snow cover affects not only human activities and the ski industry, but also alpine ecosystems and high-mountain species. Under low-snow conditions, alpine vegetation is exposed to sub-zero temperatures

and large temperature fluctuations, which may lead to winter desiccation damage (Neuner *et al.*, 1999). Symptoms of low-temperature damage to the photosynthetic apparatus, such as degradation of leaf pigments, occur primarily when exposure to very low temperatures is accompanied by high solar radiation intensity (Goh *et al.*, 2011). In the case of discontinuous snow cover, vegetation damage may also result from repeated freeze–thaw cycles and from abrasion of needles and shoots by wind-blown ice crystals. After the winter of 2024/25, characterised by intermittent snow cover, extensive areas of damaged bilberry (*Vaccinium myrtillus*) were recorded in the study area (Mucha, 2026). Lukasová *et al.* (2021) reported that mountain pine (*Pinus mugo* Turra) in the High Tatras is also sensitive to insufficient snow cover. However, not only the amount of snow but also the duration of snow cover and the timing of snowmelt can be critical for alpine vegetation. Due to the early disappearance of snow combined with exceptionally warm late-winter conditions in the 2023/24 season, the phenological cycles of alpine vegetation started prematurely. A subsequent freezing episode in the second half of April caused frost damage to *Vaccinium myrtillus* and *Pinus cembra*, manifested by the formation of degenerated reproductive organs and fruits (Lukasová *et al.*, 2025).

Snow cover plays an important role not only in the seasonal development and survival of vegetation but also in the overall functioning of high-mountain ecosystems. Changes in snow-cover conditions may affect high-mountain fauna by altering shelter availability, foraging conditions, and seasonal resource availability. These effects are particularly relevant to hibernating species. In the Tatra Mountains, the winter ecology of the Tatra marmot (*Marmota marmota latirostris*) is closely associated with hibernation burrows in habitats characterised by substantial winter snow cover (Ballová and Šibík, 2015), with a thinner snowpack being associated with reduced juvenile survival (Rézouki *et al.*, 2016) and litter size (Tafari *et al.*, 2013).

Although the long-term trend in average snow depth in the High Tatras shows only a slight and statistically non-significant decrease, the warming trend in this environment is unprecedented (Varšová *et al.*, 2025). The coming years will determine whether increasing winter precipitation can compensate for snow losses caused by rising temperatures (Lukasová *et al.*, 2023b).

5. Conclusion

From a methodological perspective, the time-lapse camera proved to be a robust and cost-effective complement to point-based measurements. Image analysis of time-lapse photography enabled quantification of snow cover with sufficient sensitivity to capture seasonal contrasts. Monitoring over four winter seasons (2021–2025) confirmed marked interannual variability and showed that time-lapse photography successfully captured snow conditions in both winters with continuous snow cover and anomalously snow-poor seasons.

Camera-derived data showed that, while complete (100%) snow cover persisted for at least two months during the 2021/22 to 2023/24 seasons, snow cover in winter 2024/25 remained around 50% and full coverage of the monitored area did not occur. Low precipitation totals, higher temperatures, and an early shift toward positive mean March temperatures were also reflected in the exceptionally low average snow depth recorded at the Skalnaté Pleso Observatory, with the 2024/25 season ranking among the most snow-deficient winters of the recent 47 years. When combined with snow depth measurements, the snow cover data can provide valuable input for modelling snow amount within the catchment, validating and gap-filling satellite snow products, and supporting hydrological applications.

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