UDC 551.578.4:551.524(477.87)

# TRENDS AND VARIABILITY OF SNOW COVER IN SLAVSKO DURING 1948–2020 UNDER CLIMATE CHANGE

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Snow plays a significant role in the climate system by altering soil properties, land–atmosphere heat and moisture exchange, the surface radiation balance, and key components of the hydrological cycle. As a major element of the cryosphere, snow cover shapes local meteorological conditions while simultaneously influencing atmospheric processes across broader spatial and temporal scales, including general circulation anomalies, Rossby wave modifications, the dynamics of sudden stratospheric warmings, and features of the East Asian summer monsoon. Given the high sensitivity of snow cover to changes in temperature, analysing its long-term dynamics is critically important, particularly in the context of the strong positive air-temperature trends observed during the winter and winter–spring transition periods.

The paper presents a comprehensive analysis of long-term snow-cover dynamics at the Slavsko meteorological station (Ukrainian Carpathians) for the period 1948/49–2019/20, one of the longest continuous observational records in the high-mountain regions of Ukraine. Using daily meteorological data, a physico-statistical and climatic assessment was performed of the duration of the snow season, the period of stable snow cover, the timing of snow formation and melt, maximum and mean snow depth, and integral indicators of snow accumulation. For the first time for the Slavsko station, a classification of winter seasons was conducted using snowiness and winter-severity index, which allowed the identification and systematisation of 22 winter types and helped trace their evolution in response to climatic perturbations.

These results provide a detailed understanding of snow-cover dynamics in the Ukrainian Carpathians, capturing long-term trends and the rising variability of recent decades. Such evidence is vital for strengthening climate-adaptation strategies in winter tourism, hydrology, transportation infrastructure, and the broader mountain economy.

**Keywords:** snow cover, snowiness coefficient, winter types, climate variability, Ukrainian Carpathians, Slavsko.

## 1. INTRODUCTION

Snow cover is widely recognized as a critical element of the climate system, acting as both a climatic regulator and an ecological and hydrological driver. Because of its high albedo, thermal insulation properties, and capacity to modulate surface energy fluxes, snow cover plays a major role in shaping regional climate feedbacks and influencing atmospheric circulation patterns [3,6,13]. Numerous global assessments highlight snow cover as one of the most sensitive climate indicators, responding rapidly to variations in air temperature and precipitation. Observational and reanalysis datasets show a persistent decline in Northern Hemisphere the spring snow extent since the late twentieth century [6, 7, 12, 22], accompanied by a shift toward earlier melt and reduced seasonal snow accumulation. These trends are consistent with climate-model projections, which suggest substantial future reductions in snow reliability, particularly in mid-elevation mountain zones [14, 20].

Studies across major mountain regions provide detailed evidence of these transformations. In the European Alps, long-term observations demonstrate a notable decrease in snow-cover duration and snow depth at elevations below 1500 m [4, 20], where temperatures frequently oscillate around the freezing point. Warming winters reduce the likelihood of snowfall, increase the frequency of mid-winter melt events, and compress the effective snow season [21]. Similar findings have been reported in the Pyrenees [24] and the Tatra Mountains [17], where the regional warming signal has intensified since the 1980s. High-resolution modelling further shows that even modest temperature increases can lead to disproportionately large declines in snow-cover duration at lower elevations [18], reinforcing the vulnerability of mountain ecosystems and winter-based economies.

Long-term climatological analyses also emphasize the strong linkage between snow-cover variability and large-scale atmospheric circulation. The North Atlantic Oscillation (NAO), Arctic Oscillation (AO), and changes in North Atlantic storm tracks modulate the frequency and intensity of cold-air outbreaks, snowstorms, and warm advection events across Europe [13]. Positive NAO phases typically correspond to warmer winters and reduced snow cover in Central and Eastern Europe, while negative phases favour increased snowfall and longer snow persistence [10]. These circulation-driven impacts are particularly pronounced in transitional mountain zones such as the Carpathians, which lie at the interface of Atlantic, continental, and Mediterranean air-mass influences. As a result, snow regimes in this region exhibit strong interannual variability, with abrupt transitions between mild, low-snow winters and cold, snowy seasons.

Research specific to Eastern Europe and the Carpathian region, though less extensive than Alpine and Scandinavian studies [8, 11, 12], consistently identifies declining snow-cover duration, earlier melt dates, and reduced snow depth over recent decades. Analyses from Slovakia, Poland, and Romania report shortened snow seasons, reduced maximum snow depth, and stronger mid-winter instability linked to warming [1, 5, 10]. In the Western and Eastern Carpathians, meteorological station data show delayed onset of stable snow cover and more frequent interruptions due to warm spells [5]. Mountain catchments in the region have shown shifts in the timing of spring snowmelt and associated streamflow peaks, indicating broader hydrological consequences [1, 5, 10].

However, despite growing interest in climate-change impacts on Carpathian snow regimes, comprehensive multi-decadal station-based analyses remain limited, and gaps persist in understanding local-scale variability, elevation-dependent responses, and the role of orographic factors. The Ukrainian Carpathians, in particular, have received comparatively little systematic attention. Existing studies document tendencies toward decreasing seasonal snow depth, more frequent winter thaws, and increased interannual variability, yet few utilize long-term daily observations to analyse detailed snow-cover dynamics. The Slavsko meteorological station, with its continuous multi-decade record, provides a valuable empirical basis for addressing this gap, including a recent analysis of snow-cover variability at this site for 1990–2010 [15].

This study aims to quantify long-term changes and variability in snow-cover characteristics at the Slavsko meteorological station over the 1948/49–2019/20 period

## 2. MATERIALS AND METHODS

This paper is based on daily data for the winter seasons from 1948/49 to 2019/20, i.e. months in which occurrence of snow cover was actually observed – in this case the period from September to May. The analysis was based on occurrence of snow cover and snow cover thickness on subsequent days in particular winter seasons. Measurements were performed in the meteorological station Slavsko (48°54'00″ N, 23°30'00″ E).

For each season, we calculated the total number of days with snow cover, the mean and maximum snow depth, and characteristics of daily snow accumulation. The mean snow depth was calculated as the total snow depth over the winter period divided by the number of days in the period. The winter period was defined as December through March inclusive, as proposed in [27].

The duration of particular seasons was calculated as the number of days between the first and last day on which snow cover was observed. The frequency of occurrence of days with a decrease and increase in snow cover depth was calculated for pentads in winter seasons.

Linear trend analysis, moving averages, and comparative analysis of different periods were applied to identify long-term changes and interannual variability. Long-term trends in snow-cover characteristics were evaluated using both the least-squares method, which provides an estimate of the linear trend, and the Sen’s slope estimator [25]. Trend magnitude was estimated using least-squares regression and Sen’s slope, while statistical significance was assessed using the Mann–Kendall test at the 0.05 significance level, with trends considered statistically significant when $|Z| \geq 1.96$.

A shifted moving average was calculated by averaging values within a fixed temporal window and assigning the resulting mean to a time point shifted by 10 years relative to the original series.

The snowiness of winter was defined by the thickness and duration of the snow cover.

The snowiness of winter in this study was determined using the winter snowiness index proposed in [23] and further used in [27].

$$W_{sn} = 0.0409D_{sc} + 0.0246D_{sc20} + 0.00007S_{sctd}$$

where $W_{sn}$ is the winter snowiness coefficient; $D_{sc}$ is the number of days with snow cover of 1 cm or more during the period December–March; $D_{sc20}$ is the number of days with snow cover of 20 cm or more during the same period; $S_{sctd}$ is the total (cumulative) snow depth in centimetres during December–March.

The formation of snow cover depends on the air temperature. For this purpose, the winter severity index [16, 26] was calculated based on daily air temperature data for the research period:

$$W_{sev} = (1 - 0.25t)0.8325 + 0.0144d_w + 0.0087d_f + 0.0045d_{vf} - 0.0026S_t$$

where $W_{sev}$ is the winter severity index; $t$ is the mean air temperature for the winter period; $d_w$ is the number of days with mean daily temperatures below 0°C during December – March; $d_f$ is the number of frost days (days with daily maximum temperature below 0°C) during December–March; $d_{vf}$ is the number of very frost days (days with maximum temperature below –10°C) during December – March; $S_t$ is the sum of mean daily temperatures below 0°C during December – March.

Based on the long-term mean values of the snowiness and winter severity coefficients, as well as their standard deviations, the study [27] classified winters into several categories. According to thermal severity, winters were defined as **severe** ($W_{sev} \geq \bar{W}_{sev} + \sigma$), moderately severe ($\bar{W}_{sev} - \sigma < W_{sev} < \bar{W}_{sev} + \sigma$), and mild winters ($W_{sev} \leq \bar{W}_{sev} - \sigma$) . According to snowiness, winters were classified as snowy according to snowiness: snowy ($W_{sn} \geq \bar{W}_{sn} + \sigma$), moderately snowy ($\bar{W}_{sn} - \sigma < W_{sn} < \bar{W}_{sn} + \sigma$), and low snowy winters ($W_{sn} \leq \bar{W}_{sn} - \sigma$).

These combined categories are referred to as thermal–snow types of winter.

## 3. RESULTS

The study was conducted for the Slavsko region, located in the southern sector of Lviv Oblast, Ukraine, within the northern part of the Ukrainian Carpathians (fig. 1). Geographically, the settlement lies in the upper basin of the Opir River (a left tributary of the Dniester) and is situated at elevations of approximately 600–650 m a.s.l. The surrounding terrain is characterized by mid-mountain ridges of the Skole Beskids, with local summits – such as Trostian, Pohar, and Menchil – ranging from 1000 to 1230 m a.s.l. The area exhibits a complex orographic structure, with steep slopes, narrow valleys, and substantial elevation gradients that exert a strong influence on local climatic and snow regimes [2].

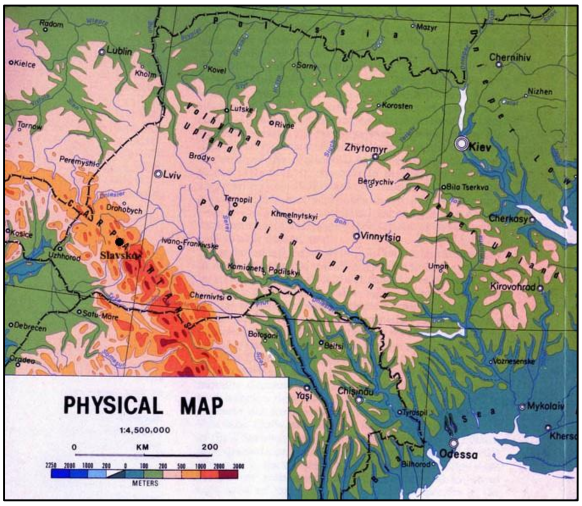


**Figure 1** – Relief and elevation of the Ukrainian Carpathians

Slavsko is located in a temperate mountain climate zone, influenced by both Atlantic and continental air masses [19]. Orography enhances precipitation totals and governs the spatial distribution of snow accumulation and retention. Winters are typically cold with frequent snowfall, but long-term warming trends have modified the duration, stability, and depth of seasonal snow cover. Owing to its complex relief and long, continuous observational record, the Slavsko meteorological station provides a valuable case study for analysing local-scale snow-cover variability and long-term changes under specific orographic conditions, with important implications for winter tourism, natural hazards, and ecosystem processes in the region [26].

### 3.1. Number of days with snow cover

The number of days with snow cover at Slavsko (fig. 2) demonstrates pronounced interannual variability but also a long-term decreasing tendency.

Earlier in the record, most winters were characterised by long and stable snow seasons, whereas in recent decades winters with shorter snow cover periods became more frequent. This is clearly seen from the time series of seasonal numbers of snow-cover days and moving averages.

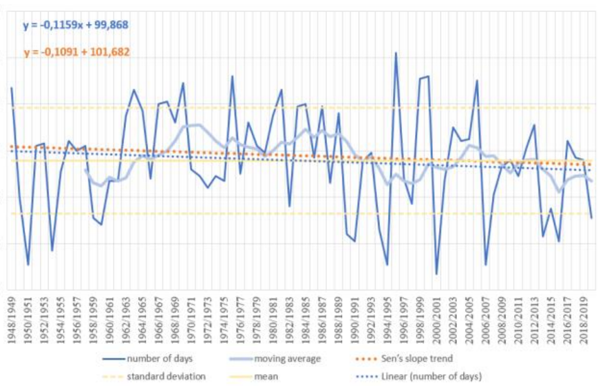


**Figure 2** – Number of days with snow cover at Slavsko for winter seasons from 1948/49 to 2019/20.

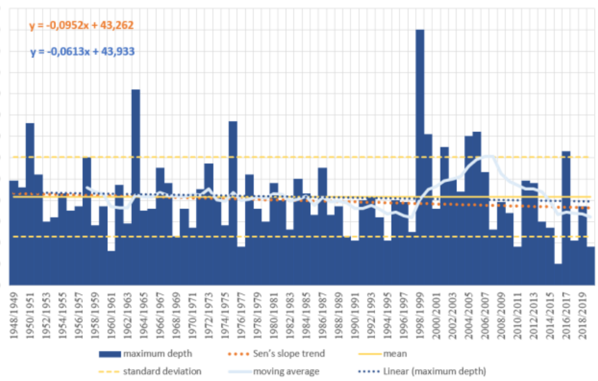


**Figure 3** – Maximum seasonal snow depth at Slavsko.

The number of days with snow cover at Slavsko ranges from approximately 55–60 days in the least snowy winters to about 145–150 days in the snowiest winters. The long-term mean is close to 100 days, with most winters falling within a range of roughly 80 to 120 days, as indicated by the standard deviation.

Both the least-squares trend and Sen's slope show a small but consistent decrease of about 1.0–1.2 days per decade, amounting to an overall decline of roughly 8 days across the full observation period. While this suggests a gradual shortening of the seasonal snow-cover duration, the Mann–Kendall test ($Z = -0.82$) shows that the trend is not statistically significant. The observed changes should therefore be interpreted as weak tendencies embedded within substantial interannual variability rather than as a robust long-term trend.

### 3.2. Maximum and mean snow depth

Figures 3, 4 present the seasonal maximum (fig. 3) and the seasonal mean (figs. 4) snow depth for the winter periods 1948/1949–2019/2020.

The maximum seasonal snow depth (fig. 3) shows substantial interannual variation, with values ranging from approximately 15–20 cm in the least snowy seasons to nearly 120–130 cm in the snowiest ones. The long-term mean is close to 45 cm, and most seasons fall within a range of roughly 25–65 cm, as indicated by the standard deviation bounds. Both the least-squares regression and Sen's slope demonstrate a gradual decrease of about 0.06–0.10 cm per year, equivalent to roughly 0.6–1.0 cm per decade, suggesting a slow but consistent reduction in peak seasonal snow accumulation.

The moving-average trajectory highlights a shift from predominantly higher maxima earlier in the record toward generally lower values in recent decades. However, the Mann–Kendall test ($Z = -0.97$) indicates that this decrease is **not** statistically significant and should be interpreted as a weak tendency within pronounced interannual variability.

Mean seasonal snow depth (fig. 4) also exhibits strong year-to-year fluctuations. Seasonal mean depth ranges from approximately 5–8 cm in the thinnest snow seasons to nearly 35–38 cm in the snowiest ones.

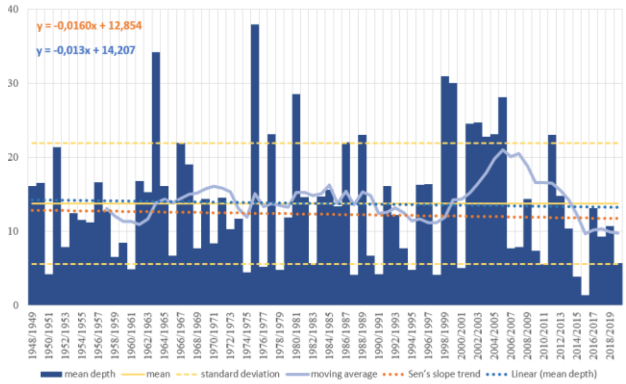


**Figure 4** – Mean seasonal snow depth at Slavsko

The long-term mean is around 14-15 cm, with most winters falling between 10 and 20 cm. Trend estimates indicate a small but persistent decline: the least-squares trend yields about −0.016 cm per year, and Sen's slope yields approximately −0.013 cm per year, corresponding to a reduction of roughly 0.1–0.2 cm per decade. The moving average shows that higher mean depths were more common in the central portion of the record, while recent decades are characterised by generally lower average snow depths.

However, the Mann–Kendall test ($Z = -0.33$) indicates that this decrease is not statistically significant and represents a weak tendency within pronounced interannual variability.

Extremely snowy winters with very high snow depth were more frequent in the middle of the twentieth century, while in recent decades winters with relatively low snow depth occur more often. Nevertheless, individual winters with high snow depth still appear against the general background of warming.

### 3.3. Snow cover depth and its variability

To characterise snow accumulation processes, we analysed several indicators, including the share of days with variable snow cover depth (fig. 5), the number of days with positive and negative daily snow-depth changes (fig 6), the maximum daily snow-depth increase within each season (fig. 7), and the mean intraseasonal evolution of snow depth and snow cover duration (fig. 8).

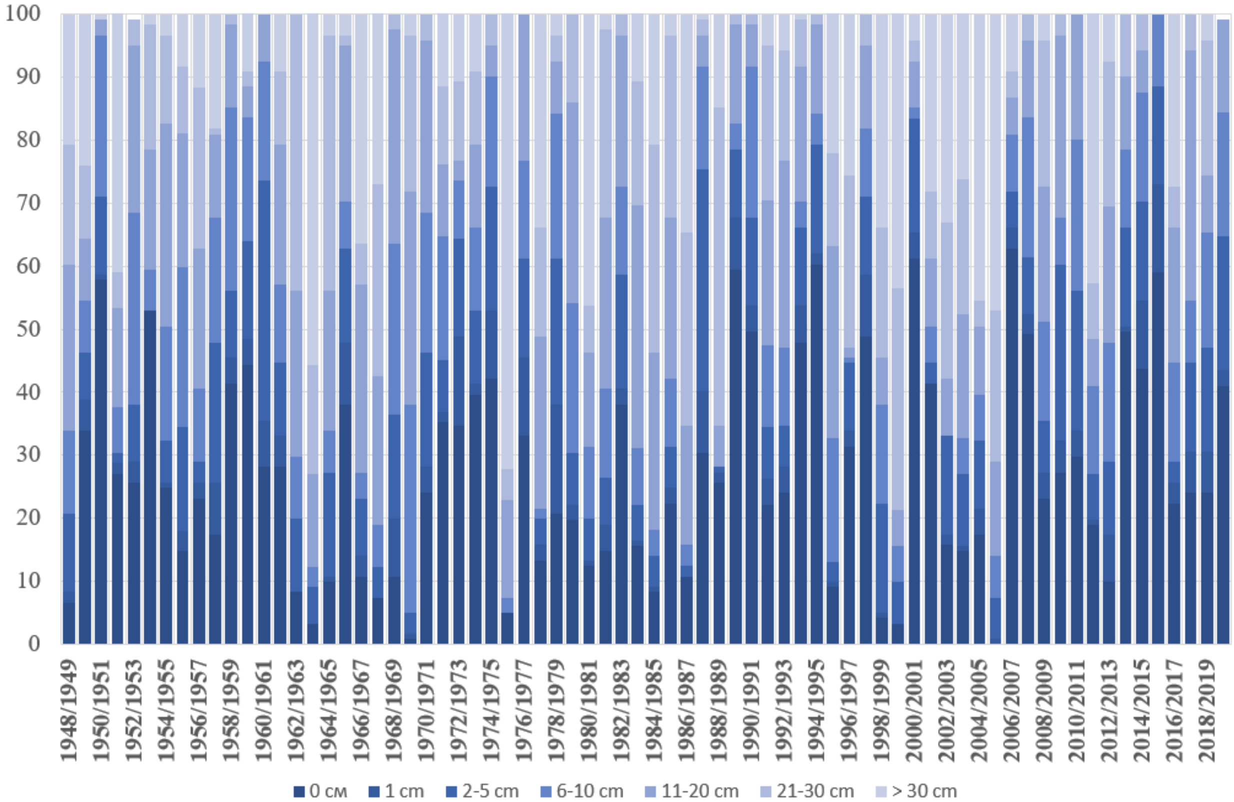


**Figure 5** – The share (%) of days with variable snow cover depth in Slavsko in winter seasons 1948/1949–2019/2020

In the majority of years, the highest percent share concerns days without snow cover (fig. 5). The stacked distribution shows the proportion of days falling into different snow-depth classes, constructed according to the snow-depth classification proposed in [9]. Winters with deep snow (>30 cm) occur, but their share is relatively small and exhibits a decreasing tendency over time. Conversely, the proportion of days with shallow snow (0–5 cm) or snow absence has increased. Intermediate categories (6–20 cm) remain the most frequent, but their dominance fluctuates. Overall, the distribution indicates a shift toward shallower snowpacks, consistent with the declining trends in maximum and mean snow depth.

The seasonal distribution of daily snow-depth changes (fig. 6) shows that days with positive snow-depth change (snowfall accumulation) peak at about 17–19 days per period, while days with negative snow-depth change (melting/settling) reach 28–30 days at their maximum.

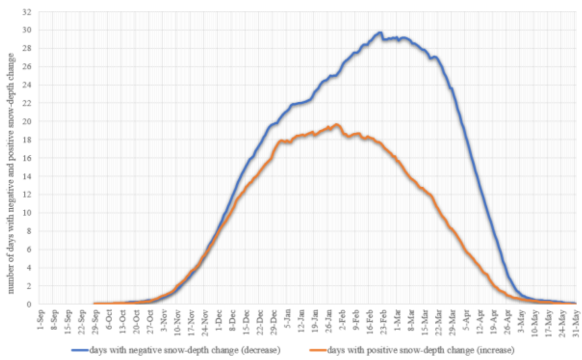

**Figure 6** – Number of days with positive and negative daily snow depth changes in Slavsko – 7-pentad running averages for the years 1948/1949–2019/2020

Snowmelt days exceed snowfall days throughout most of the winter season, especially from mid-winter onward.

This pattern illustrates the dominance of snow metamorphism, compaction, and melt processes compared with new snow accumulation during a typical winter.

The seasonal cycle (fig. 7) shows a rapid increase in snow depth from late autumn, with multi-year mean daily snow depth rising from 0 cm to 1520 cm during the peak winter period.

Maximum mean depths occur in mid-winter, after which the snowpack gradually diminishes through spring. The number of days with snow cover follows a similar seasonal progression, reaching 60–75 days during the core winter period. This figure illustrates the typical timing of snow accumulation and melting and highlights the strong seasonality of snow processes in the Carpathian region.

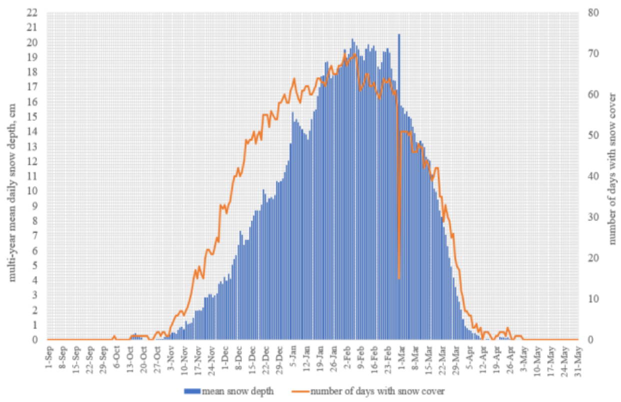


**Figure 7** – The change in the average snow cover depth (cm) and frequency of days with snow cover (%) in Slavsko in seasons 1948/1949–2019/2020

The maximum seasonal daily increase in snow depth (fig. 8) at Slavsko exhibits pronounced interannual variability, with values generally ranging from about 10–15 cm in winters with weak accumulation events to approximately 70–80 cm in seasons characterised by intense snowfall. The long-term mean is close to 20 cm, and most observations fall within a range of roughly 10–30 cm.

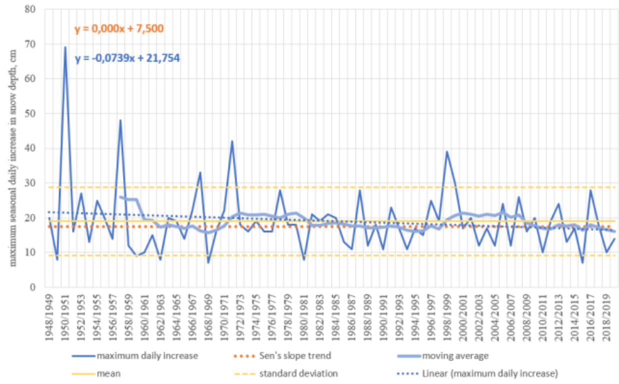


**Figure 8** – Maximum daily snow depth increases per season

Both the least-squares regression and Sen's slope indicate a very weak positive trend, amounting to only a few tenths of a centimetre per decade. The moving average highlights multi-decadal fluctuations, but no persistent long-term change dominates the record. However, the Mann–Kendall test $(Z = -0.41)$ indicates that this tendency is not statistically significant.

### 3.4. Indices of snowiness and winter severity

The winter snowiness coefficient (Fig. 9) and the winter severity index (Fig. 10) both exhibit an overall decreasing tendency over the study period, indicating a long-term reduction in snow accumulation, snow-cover duration, and the intensity of cold conditions. Both indices range from 0 to 10 and were used to classify winters at Slavsko into types spanning from very mild and low-snow to very severe and highly snowy conditions. Analysis of these classifications shows that severe winters were more common in the earlier decades of the record, whereas mild and low-snow winters have become increasingly prevalent in recent decades.

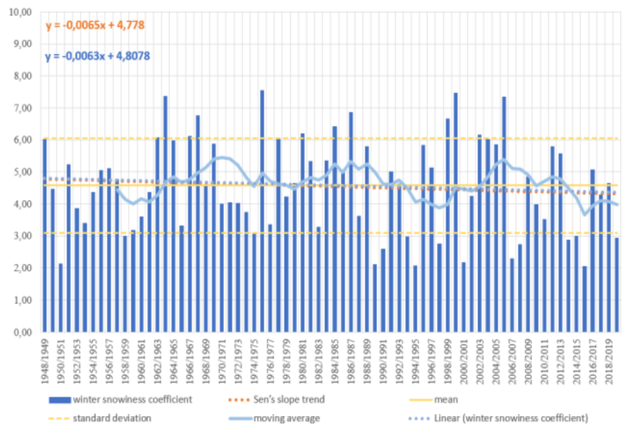


**Figure 9** – Winter snowiness coefficient at Slavsko.

Trend analysis of the winter snowiness coefficient supports these observations. Both the least-squares method and the Sen's slope estimator indicate a slight but persistent decline of approximately 0.06 units per decade. Although modest in magnitude, this decrease is consistent with reduced snow accumulation and may contribute to enhanced surface warming. Decadal-scale fluctuations are evident in the moving-average series; however, the Mann–Kendall test $(Z = -1.08)$ indicates that the observed tendency is not statistically significant.

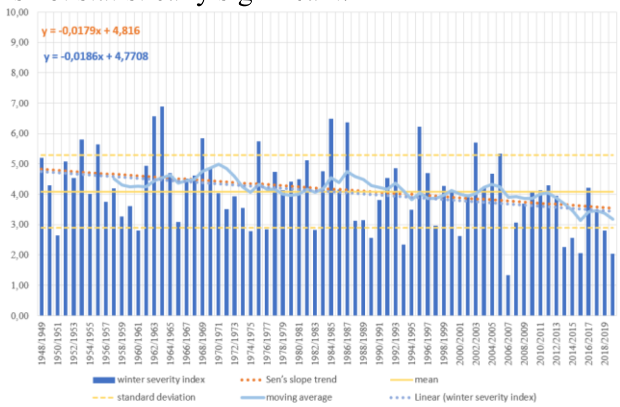


**Figure 10** – Winter severity index at Slavsko

In contrast, analysis of the winter severity index reveals a more pronounced downward trend. Both the least-squares method and the Sen's slope estimator show a decline of about 0.2 units per decade. The Mann–Kendall test yields a standardized statistic of $(Z = -2.84)$, indicating that this decreasing trend is statistically significant at conventional significance levels.

The correspondence between winter types and specific coefficient values is presented in Table 1.

More than half of all winters (58.3%) fall into the low-snow categories: "very little snow" (19.4%), "moderately little snow" (16.7%), and "little snow" (22.2%). The snowiness index ranges from 2.1 to 7.6, with a mean value of 4.6, corresponding to a "little snow" winter. No winters were classified as exceptionally or unusually low-snow, nor as unusually or exceptionally snowy. The snowiest winter was 1975/1976, followed by 1963/1964, 1999/2000, and 2005/2006.

Altogether, 11 winters were classified as snowy, most of them between 1961 and 1990. After 1990, only the seasons 1998/1999, 2002/2003, and 2003/2004 fell into this category. Prior to 1961, only one snowy or very snowy winter was recorded (1948/1949). Conversely, winters with very little snow have become far more frequent in recent decades: of 14 such winters, 12 were observed after 1991. The lowest snowiness coefficient occurred in 2015/2016.

Winter severity exhibits a comparable pattern. Most winters are classified as cool (36.1%) or moderately cool (23.6%). The winter severity index varies from 1.3 (2006/2007) to 6.9 (1963/1964), with a mean of 4.1, corresponding to a cool winter. Only five severe winters occurred during the entire record, the last in 1995/1996, while the warmest winter (2006/2007) was the only one classified as mild.

Snowiness and severity are strongly linked: mild, moderately mild, and moderately cold winters consistently show low snow cover and low snowiness coefficients. A significant positive correlation between the two indices (r = 0.75) supports this relationship. The most frequent winter type is cool (30.5%), with snowiness ranging from "little snow" to "snowy," while low-snow mild winters account for 20.8% of all cases.

**Table 1** – Classification of winter seasons (1948/1949–2019/2020) at Slavsko by snowiness and severity

| Type | Mild | Moderately mild | Moderately cold | Cold | Moderately severe | Severe |
|---|---|---|---|---|---|---|
| **Very little snow** | *2006/2007* | *1950/51, 1989/90, 1993/94, 1997/98, 2000/01, 2013/14, 2014/15, 2015/16, 2019/20* | *1958/59, 1990/91, 1994/95, 2007/2008* | | | |
| **Moderately little snow** | | *1960/61, 1974/75, 1976/77, 1982/83* | *1959/60, 1965/66, 1973/74, 1987/88* | *1952/53, 2009/10, 2010/11* | *1953/54* | |
| **Little snow** | | *2008/09, 2018/19* | *1954/55, 1971/72, 1972/73, 2001/02, 2017/18* | *1949/50, 1957/58, 1961/62, 1970/71, 1978/79,* | *1968/69* | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | *1979/80, 1985/86, 1992/93* | | |
| **Moderately snowy** | | *1988/1989* | *1956/57, 2012/13* | *1964/65, 1969/70, 1983/84, 1991/92, 1996/97, 2004/05, 2011/12, 2016/17* | *1951/52, 1955/56, 1981/82* | *1995/96* |
| **Snowy** | | | *1966/67, 1967/68, 1977/78, 1980/81, 1998/99, 2003/04* | *1948/49, 2002/03* | *1962/63, 1984/85, 1986/87* | |
| **Very snowy** | | | 1999/00 | 1975/76, 2005/06 | 1963/64 | |

The fig. 11 presents the temporal evolution of seasonal snow-cover duration (days) over the study period. Year-to-year values (blue line) exhibit pronounced interannual variability, with snow-cover duration ranging from roughly 80–90 days in the shortest seasons to 160–170 days in the longest ones.

Both the Sen's slope estimator and the least-squares trend indicate a slight positive tendency, on the order of +0.08 to +0.10 days per year (roughly +0.8 to +1.0 days per decade). Given the small magnitude of this trend, there is no basis for asserting substantial long-term changes in the duration of the snow season over the study period.

The results of the Mann–Kendall test ($Z = 0.55$) confirm that the detected tendency is not statistically significant. Accordingly, interannual variations in snow-cover duration remain within the bounds of natural climatic variability.

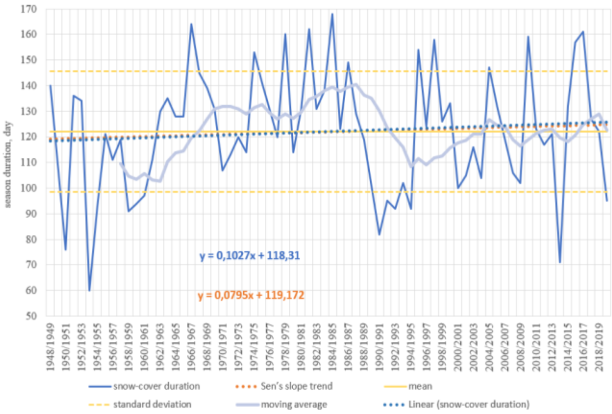


**Figure 11** - Duration of the winter period at Slavsko, defined as the interval between first appearance and final disappearance of snow cover.

The moving-average curve illustrates multi-decadal fluctuations, with periods of longer snow-cover seasons alternating with intervals of shorter seasons. Earlier decades show high variability with several very long seasons, while recent decades are dominated by winters of moderate length, yet still within the historical range.

## 4. DISCUSSION

The long-term evolution of snow-cover characteristics at the Slavsko station reveals a complex interplay of gradual climatic warming, internal variability, and local orographic influences. Although nearly all indicators demonstrate declining tendencies, the magnitude, timing, and statistical coherence of these trends vary substantially among different snow-cover metrics. This indicates that the response of snow processes to regional climate change is non-uniform and cannot be inferred from a single indicator.

The total number of snow-cover days at Slavsko exhibits a detectable but weak negative tendency of approximately 1.0–1.2 days per decade. However, this decrease is not statistically significant and should therefore be interpreted as a modest tendency embedded within pronounced interannual variability rather than as a robust long-term decline. This indicates that, despite regional winter warming, the regular occurrence of seasonal snow cover in the mid-mountain zone of the Ukrainian Carpathians (600–650 m a.s.l.) remains largely preserved, reflecting the stabilising influence of local orographic conditions.

At the same time, this weak aggregate tendency conceals more nuanced structural changes in snow-cover characteristics. Analysis of the relative shares of days belonging to different snow-depth classes reveals that the observed reduction is not uniform across the snow-cover spectrum. The proportion of days with shallow snow cover and snow-free conditions has increased, while the share of days with moderate snow depths has declined. In contrast, days associated with deep snow cover represent a relatively small fraction of the seasonal distribution and exhibit no consistent long-term decrease. This redistribution indicates that recent changes primarily affect the persistence and continuity of intermediate snow-cover conditions rather than the occurrence of episodic deep-snow events. As a result, winters with substantial snow accumulation remain possible, but the duration of snow conditions most relevant for winter tourism and seasonal hydrological recharge is becoming increasingly fragmented.

The temporal structure of winters characterised by a higher share of deep snow-cover days further complicates linear interpretations. Although the largest proportions of deep-snow conditions occurred during 1961–1990, winters with elevated shares of deep snow were also recorded between 1998 and 2007, despite an overall warming background. This behaviour underscores the importance of internal climate variability and episodic circulation patterns, which can temporarily enhance snowfall and snow retention even under progressively warmer mean conditions. Consequently, reliance on monotonic trend analysis alone would oversimplify snow-cover dynamics at Slavsko and underestimate the combined influence of orography, precipitation variability, and atmospheric circulation in shaping mountain snow regimes.

The behaviour of maximum snow depth illustrates this issue clearly. Despite long-term downward trends of roughly 0.7–1.1 cm per decade, the moving-average series shows a pronounced period of increasing maximum values between 1998 and 2015, producing the absolute peak in 1999/2000. This paradoxical rise during a warming period highlights that snow depth is strongly controlled by precipitation variability and the occurrence of episodically intense snowstorms, which may temporarily counteract thermal limitations. Such findings call into question interpretations that rely solely on thermal trends to explain snow decline.

Mean snow depth also displays significant long-term reductions but at very small rates (0.1–0.2 cm per decade). Compared with the behaviour of maximum snow depth, mean depth appears more stable and less sensitive to extreme snowfall events. This stability suggests that the overall snow regime is becoming less persistent rather than less intense: snow accumulates in short, isolated episodes but does not remain long enough to affect the mean depth strongly.

Importantly, these interpretations are consistent with the trend analysis, which shows that linear trends for most snow-cover characteristics are not statistically significant, indicating weak long-term tendencies superimposed on pronounced interannual and multi-decadal variability rather than robust monotonic change. Comparable findings have been reported across different European climatic and physiographic settings, including lowland temperate regions such as Estonia and more topographically complex areas such as Slovakia [27], suggesting that non-significant linear trends in snow characteristics are not uncommon.

The two synthetic indicators – the winter snowiness index and the winter severity index – provide a broader climatological interpretation. While both exhibit downward tendencies, the severity index declines at a far more pronounced rate (0.2 units per decade compared with 0.06 units for snowiness). This imbalance indicates that thermal changes outpace changes in snowfall or accumulation processes. In other words, winters are warming faster than they are losing their snow-accumulation capacity. The strong correlation ($r = 0.75$) between severity and snowiness further demonstrates that thermal and snow-related processes remain tightly coupled, but the weakening of severity may foreshadow a future decoupling where snow is increasingly constrained by temperature thresholds.

The classification of 36 winter types confirms this shift: the most frequent are cool low-snow or moderately snowy winters and moderately mild winters with very little snow—together representing roughly one-third of all winters. The relative scarcity of very snowy or very severe winters in recent decades points to a transition toward thermally milder but still variable snow conditions.

Snow accumulation dynamics show a clear asymmetry between gain and loss processes: throughout nearly the entire season, days with negative snow-depth change outnumber those with positive increments. Even during the main accumulation period (January–February), melt and compaction processes frequently dominate. This highlights the increasing fragility of snow cover under warming conditions, where occasional snowfall events are insufficient to maintain stable accumulation.

Another striking indicator of climatic change is the behaviour of unstable snow cover (discontinuous snow cover). While stable snow-cover duration is shrinking, the duration of unstable snow cover has increased at approximately one day per decade. This divergence implies a transitional climatic state in which winter no longer guarantees sustained snow cover but does retain frequent, short-lived snow episodes. In practical terms, ecosystems and socioeconomic sectors dependent on stable winter conditions (e.g., ski tourism, forestry, hydrology) face increasing unpredictability.

Finally, cumulative seasonal snow depth varies enormously – from as little as 181 cm to over 5236 cm – demonstrating that interannual snowfall variability remains very high. Nevertheless, long-term declines of 22–25 cm per decade indicate a gradual depletion of total winter snowfall, consistent with both reduced snow-cover persistence and warmer winter temperatures. The exceptionally strong 1998–2015 cycle again cautions against interpreting downward trends without considering multidecadal oscillatory behaviour.

## 5. CONCLUSIONS

The Slavsko station, located on the slopes of the Ukrainian Carpathians at an elevation of 592 m above sea level, is characterized by a relatively substantial mean snow depth of 12 cm, with an absolute maximum of 120 cm. On average, the snow-cover season may last 122 days, of which 96 days are days with actual observed snow cover. The mean duration of a continuous snow-cover period is 81 days, although in some winters a continuous snow cover is completely absent.

Snow cover typically forms in October–November, gradually increasing over the following winter months and reaching its maximum in February, when the mean snow depth attains 19 cm, after which it declines to minimal values in April–May. The largest snow-depth increases occur in January–February, although throughout most of the season the snow cover tends to decrease at a higher rate than it increases.

Based on the snowiness and winter-severity index classes, 22 winter types were identified at Slavsko, ranging from mild winters with very little snow to severe winters with abundant snow. The most frequent types are cool low-snow or moderately snowy winters, along with moderately mild winters with very little snow, together accounting for 34% of all winters. A strong linear relationship is observed between the severity index and the snowiness index.

Future research should expand the spatial and methodological scope of snow-cover analysis in the Ukrainian Carpathians by incorporating data from additional meteorological stations across different elevation levels, which would allow a more detailed assessment of elevation-dependent responses and help distinguish local orographic effects from regional climate signals. Integrating station observations with satellite products and reanalysis datasets would further improve the validation of spatial patterns of snow-cover change and help address data gaps, particularly in high-mountain areas. In addition, future studies should focus on extreme snow-cover characteristics and their links to large-scale atmospheric circulation, providing a stronger basis for modelling future snow-cover changes and supporting applied research in water resources, winter tourism, and climate-change adaptation in mountain regions.

The results obtained in this study form the scientific basis for the establishment of a Living Lab in Slavsko, aimed at translating long-term observations of snow-cover variability into applied knowledge and decision-support for winter tourism, water resources, and local climate adaptation in mountain environments.

This work was implemented within the framework of the SUNRISE project (2024-1-IT02-KA220-HED-000256685).

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## ТРЕНДИ ТА МІНЛИВІСТЬ СНІГОВОГО ПОКРИВУ В СЛАВСЬКОМУ В ПЕРІОД 1948–2020 РР. В УМОВАХ ЗМІНИ КЛІМАТУ

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Сніг відіграє важливу роль у кліматичній системі, змінюючи властивості ґрунту, тепло- та вологообмін у системі «суходіл–атмосфера», радіаційний баланс поверхні та ключові компоненти гідрологічного циклу. Як провідний елемент кріосфери, сніговий покрив формує локальні метеорологічні умови та водночас впливає на атмосферні процеси у ширших просторових і часових масштабах, зокрема на аномалії загальної циркуляції, модифікації хвиль Россбі, динаміку раптових стратосферних потеплінь і особливості літнього мусону Східної Азії. З огляду на високу чутливість снігового покриву до змін температури, аналіз його довгострокової динаміки є вкрай важливим, особливо в контексті виражених позитивних трендів температури повітря, спостережуваних узимку та в перехідний зимово-весняний період.

У статті представлено ґрунтовний аналіз довгострокової динаміки режимних характеристик снігового покриву на метеорологічній станції Славсько (Українські Карпати) за період 1948/49–2019/20, що є одним із найдовших безперервних рядів спостережень у високогірних районах України. На основі щоденних метеорологічних даних проведено фізико-статистичну та кліматичну оцінку тривалості снігового сезону, періоду сталого снігового покриву, дат утворення та сходження снігу, максимальної та середньої товщини снігу, а також інтегральних показників снігонакопичення. Вперше для станції Славсько виконано класифікацію зимових сезонів за коефіцієнтами сніжності та зимової суворості, що дало змогу ідентифікувати та систематизувати 22 типи зим і простежити їхню еволюцію у відповідь на кліматичні збурення.

Отримані результати забезпечують детальне розуміння динаміки снігового покриву в Українських Карпатах, відображаючи довгострокові тенденції та зростаючу варіабельність останніх десятиліть. Такі дані є важливими для посилення стратегій адаптації до зміни клімату в зимовому туризмі, гідрології, транспортній інфраструктурі та ширшій гірській економіці.

**Ключові слова:** сніговий покрив, коефіцієнт сніжності, зимова суворість, кліматична мінливість, Українські Карпати, Славсько.

*Подання до редакції* **: 25. 11. 2025**
*Надходження остаточної версії* **: 22. 12. 2025**
*Публікація статті* : **23. 12. 2025**