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Variability and trends of selected snow cover characteristics in the Tatra Mountains region in Slovakia 1981–2020

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Over the last decades, snow seasons in Europe were reported to become shorter with lower abundance of snow. However, at some stations situated above certain elevation, the amount of snow cover was found to be increasing. This is also the case of high mountains in Slovakia, where number of snow-related studies showed some differences related to the elevation. In this study we report on the trends of selected snow cover characteristics such as the number of days with snow cover (DSC) for 1, 10 and 20 cm depths, summed snow depths (SSD) and mean snow depths (MSD). The data used in this study were collected by the Slovak Hydrometeorological Institute (SHMI) at eight stations in the Tatra Mountains region during the 39 seasons 1981–2020 (01/07 to 30/06 the following year). Some increasing trends were observed for stations above 1100 m while stations below this elevation had generally decreasing estimates. The DSC for 1 cm ranged from 297 days at station elevated at 2635 m a.s.l. to 25 days for station at 640 m a.s.l. The MSD ranged from 100 to 7 cm on average for the whole period. Apart from global warming, other factors play role, and these can be complex in the mountainous regions making any trends more ambiguous to interpret.

KEY WORDS: snow cover, Western Carpathians, Tatra Mountains, climate change

Introduction

Snow cover is important climate characteristic and its amount and duration depend on various direct or indirect physical, geographic, vegetation, atmospheric or anthropogenic variables (Fiema, 2008). Based on satellite and station data, snow cover extent in the Northern Hemisphere has declined significantly over the past 90 years, with most reductions occurring since 1980 (EEA, 2021). The duration of snow seasons became shorter in Europe because of earlier snowmelt in spring and it is projected to decrease significantly by the end of this century, by over 100 days in some regions (EEA, 2023).

Studies of snow cover, its spatial and temporal variability and trends, are important in terms of climatological, hydrological or ecological processes (Holko et al., 2001, 2022; Brziak et al., 2021). Understanding of the long-term snow cover trends is key in relation to increasing air temperatures due to climate change (Falarz, 2004). Snow impacts the air by cooling, it reflects most of the radiation back into the atmosphere and thawing processes slow down rising temperatures during springtime in the northern hemisphere (Foster et al. 1983). In terms of water balance, it stores water that is later released during meltdown and supplies important moisture for new vegetation growth (Hríbik and Škvarenina, 2006). It also serves as an important insulant and protects plants from wind and deep-freezing temperatures (Elenberg, 1988; Hríbik and Škvarenina, 2006).

Long-term trends in snow cover were studied in Europe, for example in Poland (Falarz, 2002; Falarz, 2004), in Slovakia (Konček and Briedoň, 1964; Briedoň et al. 1974; Šamaj and Valovič 1988; Lapin and Faško 1996; Holko et al. 2009; Siman and Polčák, 2017), Switzerland (Beniston et al., 1994) or Estonia (Jaagus, 1997). Whole region of Eurasia was summarized by Clark et al. (1999), Bulygina et al. (2009) and of the whole of Northern Hemisphere by Brown (2000).

Considering climate change scenarios, increase in winter precipitation by 20% above 1100 m a.s.l. is expected in mountainous regions in Slovakia during this century (Lapin et al., 2007). A study by Holko et al. (2016) in Western Tatras showed that temperature increase was more pronounced in the colder season (December to March) and the number of snow-weak winters since 2010 was higher and snow cover duration shorter than in the decade before. Faško et al. (2020) in a 100-year study showed that from 1990s till recent there was a significant increase in mean values of air temperature and the decline in the amount of snow in Slovakia was most pronounced in the most recent decade 2011–2020.

First snow records in Tatras originated in the 16th century but these were only made on an occasional basis. First consistent scientific study on regular snow records was published by Konček and Briedoň (1964) in which readings from 208 stations in Slovakia were presented during the 1921/22–1950/51 period. Changes in snow cover were later summarized by Chomicz and Kňazovický (1974). Briedoň et al. (1974) published a complex information on snow and other climate characteristics of Tatra Mountains. Snow conditions from 149 stations for the period 1920/21–1979/80 with some new statistical characteristics were reported by Šamaj and Valovič (1988). Snow cover in Low Tatras during the period 1921–1995 was examined by Faško et al. (1997) who observed that although daily sums of snow cover increased, the total number of days with snow was reduced at most stations.

Monthly snow characteristics and their correlation with mean monthly air temperature and precipitation values in the High and Low Tatras in Slovakia during the 1921–2006 period was analyzed by Lapin et al. (2007). Their study pointed out unequal snow conditions in the region influenced by air temperature, precipitation variability but also by altitude and local topographic conditions. During the 85-year period they showed an increase in air temperature by 1.2°C and a significant increase in winter precipitation. Siman and Slavková (2019) observed an increased number of days with snow cover of ≥ 20 cm in Tatras, and consequently increase in the sum and the average height of the snow cover. Increasing trend in snow cover was observed in altitudes around 2600 m a.s.l. and decline at stations located at about 1000 m a.s.l. on south and south-east slopes (Pribullová et al., 2009). Dynamics of snow cover in middle and high areas in Tatras were also studied by Vojtek (2010) and substantial work on snow variability in high mountains in Slovakia was undertaken by Holko (2000), Holko et al. (2001; 2005; 2011; 2021). Holko et al. (2005) observed snow depths in catchments in Tatras and Low Tatras during a 40-year period and found drop in duration of snow cover and snow water equivalent since 1980s at lower situated stations. Changes of snow cover in selected synoptical situations during 1966 to 1996 were studied in Polish Tatras by Fiema (2008) who showed that West and Northwest circulations have positive effect on snow cover duration and the amount of snow is related to the frequency of cyclonal situations.

The aim of this study is to examine temporal and spatial snow cover characteristics at eight selected stations in Tatra Mountains region in Slovakia during period 1981–2020. We analyse interannual variability and trends in characteristics of snow cover duration for stations above and below 1100 m, the summed and the mean depths of snow. We also establish and compare elevation gradients and temporal trends for selected snow characteristics and compare this data with another regional and international studies. The knowledge about duration and thickness of snow cover plays also curtail role in correction of cosmogenic exposure ages which attempt to date Quaternary landforms in mountain environments, like rock-slope failures and glacial moraines (e.g. Engel et al., 2015; Pánek et al., 2017; Makos et al., 2018; Zasadni et al., 2020).

Station network and methods

Eight stations operated by the Slovak Hydrometeorological Institute (SHMI) were chosen to evaluate snow cover parameters in Tatra Mountains, Low Tatras and surrounding areas such as Popradská and Liptovská basins, in Slovakia. Their main characteristics are summarized in Table 1.

Lowest mean annual temperature (-3.1°C) and the highest precipitation (1722 mm) occurs at Lomnický štít (Table 1). Mean annual temperature at Chopok (2005 m a.s.l.) is -0.4°C, in contrast with Liptovský Hrádok (640 m a.s.l.) 7.1°C. The highest mean summer precipitation was recorded at Skalnaté Pleso (1778 m a.s.l), closely followed by Tatranská Javorina (1013 m a.s.l), but the winter precipitation was most significant at Lomnický štít. The station with lowest precipitation is Poprad (613 mm per year). The differences are given mainly by elevation, slope orientation and prevailing winds.

For the eight stations, following snow cover characteristics for the period of 39 years – 1981/82 to 2019/20 seasons were analysed: (1) the number of days with snow cover (DSC) ≥1 cm, ≥10 cm, ≥20cm; (2) the summed snow depth (SSD) and (3) the mean snow depth (MSD).

Table 1. List of stations selected for the study, their elevation [m a.s.l.], orographic position and their mean air temperature and precipitation characteristic (1981–2020)

Code	Station		Elevation	Orography	MAT	MST	MWT	MAP	MSP	MWP
11874	Liptovský Hrádok	LHR	640	basin	7.1	16.7	-2.6	711	255	119
11916	Chopok	CHOP	2005	peak	-0.4	7.5	-7.7	1145	388	244
11930	Lomnický štít	LOM	2635	peak	-3.1	4.3	-10.1	1722	463	462
11931	Skalnaté Pleso	SKP	1778	hillside	2.5	10.1	-4.6	1424	562	218
11933	Štrbské Pleso	STR	1322	hillside	3.9	12.6	-4.4	1057	357	214
11934	Poprad	POP	693	basin	6.6	16.0	-3.0	613	247	79
11936	Tatranská Javorina	TAJ	1013	valley	4.4	12.9	-3.9	1364	551	191
11938	Telgárt	TEL	901	hillside	5.5	14.7	-3.6	872	321	125

Note: MAT – mean annual air temperature in °C, MST – mean summer air temperature (June–August), MWT – mean winter air temperature (December to February), MAP – mean annual precipitation totals in mm, MSP – mean summer rainfall (June–August), MWP – mean winter rainfall (December to February). Based on 1981–2020 data.

The mean depth of snow cover was calculated as the summed daily heights of snow cover divided by the number of days with snow cover (not the number of days of duration of snow cover). Summed snow depth was calculated as the sums of daily heights of snow cover. To include all the annual data, seasons were divided from 01/07 to 30/06 the following year.

The data were analysed for each snow attribute of the 1981/82–2019/20 period, as absolute values and by a coefficient of variation. Some correlations and trends were established, and some observations on the impact of snow depth or duration on elevation gradient were made and tested against some published work (e.g. Petrovič, 1972, Briedoň et al., 1974) in the studied region.

Results and discussion

Number of days with snow cover during winter months more or equal to 1, 10 and 20 cm are the basic characteristics of snow cover. The eight stations were divided according to their elevation into two groups: stations with elevations below 1100 m a.s.l. and stations situated above this elevation. Data of snow cover duration in days for each snow height interval and for each season (July to June) from 1981 to 2020 were plotted alongside their trendlines (Fig. 1). Also trends and coefficients of variability were compared, and overall changes established (Table 2).

Although some snow weak winters such as 1989/90, 1997/98, 2006/7 or 2010/11 alternate with snow rich winters such as 1995/96, 1999/2000 or 2007/08, some weaker trends can be observed in the number of days with characteristic snow cover. This trend appears to be decreasing for stations below 1100 m a.s.l. and steady or increasing for stations above this elevation. This was purposed as the effect of global warming, which is causing less solid precipitation at lower elevations, but more (solid) precipitation occurs at higher elevations (Holko et al. 2005).

With regards to the number of days with 1 cm snow cover, the steepest decrease was recorded at Tatranská Javorina (-0.836 days year^{-1}) which means this period could be shorter by about 8 days per decade. Poprad and Liptovský Hrádok would drop by about 6 days per decade. Maximum mean number of days with 1 cm snow cover occured at Lomnický štít (260 days) with the absolute maximum of 297 days in 1996/97 season and the minimum in Poprad (77 days) in 2006 with the absolute minimum in Liptovský Hrádok, recorded in the 2013/14 season.

Considering the mean number of days with 10 cm snow cover, the maximum was at Lomnický štít (236 days) and the minimum at Poprad (only 28 days). However, the highest estimated difference per decade is expected in

Table 2. Statistical summary and mean estimated decadal differences for number of days with characteristic snow cover at selected stations, based on data for the 1981/82–2019/20 period. Stations are ordered from highest to lowest elevation. SD stands for standard deviation

	LOM (2635)	CHOP (2005)	SKP (1778)	STR (1322)	TAJ (1013)	TEL (901)	POP (693)	LHR (640)
DAYS WITH 1 CM SNOW COVER								
Mean	259.51	198.59	171.56	158.74	145.10	103.62	76.74	80.97
SD	17.57	15.63	16.19	14.90	21.60	25.49	23.56	24.74
Minimum	223	169	134	123	86	54	38	25
Maximum	297	248	202	182	180	144	130	127
Trend	-0.451	-0.264	0.137	-0.332	-0.836	-0.453	-0.602	-0.632
Diff. per decade	-4.5	-2.6	1.4	-3.3	-8.4	-4.5	-6.0	-6.3
Pearsons coeff.	0.292	0.179	0.096	0.254	0.440	0.202	0.292	0.291
DAYS WITH 10 CM COVER								
Mean	235.56	173.77	138.95	139.28	116.41	64.49	28.36	36.87
SD	21.58	21.32	27.90	23.16	30.86	37.16	23.99	26.34
Minimum	188	97	49	74	37	4	0	0
Maximum	278	230	178	180	171	138	102	99
Trend	0.095	0.064	0.260	-0.001	-0.855	-0.145	-0.208	-0.802
Diff. per decade	0.9	0.6	2.6	-0.01	-8.5	-1.5	-2.1	-8.0
Pearsons coeff.	0.050	0.035	0.115	0.000	0.315	0.045	0.098	0.347
DAYS WITH 20 CM COVER								
Mean	218.97	158.87	104.36	121.69	95.03	40.54	10.85	16.10
SD	23.35	23.25	37.80	31.38	37.81	34.93	19.36	21.04
Minimum	168	56	10	47	6	0	0	0
Maximum	263	227	172	170	170	118	94	79
Trend	0.083	-0.034	0.313	0.122	-0.995	0.00	0.103	-0.305
Diff. per decade	0.8	-0.3	3.1	1.2	-10.0	0.0	1.0	-3.1
Pearsons coeff.	0.041	0.017	0.094	0.045	0.300	0.008	0.061	0.166

Tatranská Javorina and Liptovský Hrádok, both by about 8 days. During 1994/95 season, there was not a single day with snow cover of 10 cm and more recorded at Poprad station and in 1997/98 it was only one such day. In Liptovský Hrádok there were no days with 10 or more cm of snow during the 2013/14 season and during 2019/20 this was the case for both stations.

Similar trends have been observed for the number of days with snow cover of 20 cm and more. Mean maximum was understandably at Lomnický štít (219 days) and minimum at Poprad (11 days), with 11 seasons without this snow cover height at both Poprad and Liptovský Hrádok stations. Interestingly, the trend was most obvious at Tatranská Javorina suggesting possible 10 days drop of this snow cover per decade.

Despite the fact the trends were weak, it was interesting to see that they were decreasing for DSC/1 cm at 7 stations, with mean decrease -4.3 days per decade (± 2.9). For DSC/10 cm, the trend was increasing or steady at stations above 1100 m and decreasing for the rest. The mean was -2 days (±4.1). And the DSC/20 cm trend revealed interestingly insignificant difference, except Tatranská Javorina station, where it was -10 days per decade, causing mean difference to be -0.9 days.

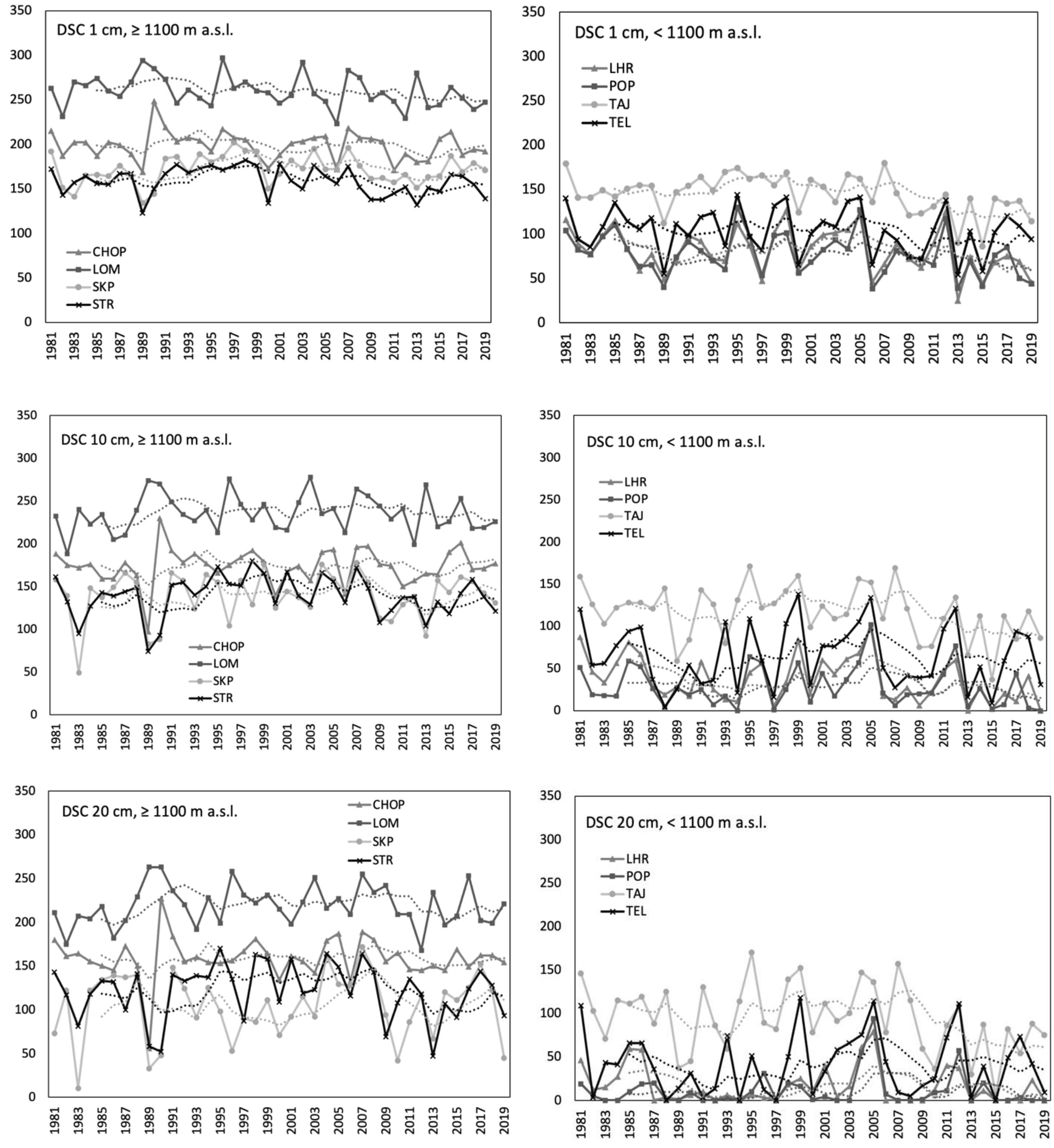

Fig. 1. Interannual course of number of days with snow cover (DSC) with 1 cm, 10 cm and 20 cm for seasons 1981/82 to 2019/20. The dotted lines represent the 5-year moving average.

Following weak trends were observed with regards to the snow depth variations. Two characteristics were analysed: the summed snow depth (SSD) and the mean snow depth (MSD), (Table 3). Mean SSD during the 39 seasons was highest at Lomnický štít (299 m), with the maximum of 509 m in 2007/08 season. The lowest mean SSD was observed at Poprad (7.56 m) but the lowest SSD overall occurred in Liptovský Hrádok during the 2013/14 season and it was only 0.88 m. Trend pointed out to a considerable decadal increase at Lomnický štít (24 m) followed by Chopok (12 m). Other stations showed only a slight decrease. SSD at Liptovský Hrádok has decreased by 1.8 m per decade. Coefficient of variation was obtained as the standard deviation divided by the mean*100 to illustrate the rate of interseasonal changes. The lowest coefficient of variation was at Lomnický štít (30.6%) and the highest occurred at Poprad (82%).

As the MSD depends on the SSD and number of days with 1 cm snow cover, therefore the trends are similar. The maximum values were obtained again for Lomnický štít (1 m) with decadal increase of 8 cm day^{-1} (same as Chopok). These results fit the estimated critical level, above which the snow trends become positive, which lies in 1800 m a.s.l. on northern and in 2300 m a.s.l. on southern slopes (Vojtek et al. 2003). Coefficient of variation reflecting on the interseasonal variability ranged from 30% at Lomnický štít to 73% at Telgárt. Also Poprad and Liptovský Hrádok showed high data variability.

Table 3. Statistical summary and mean estimated decadal differences for summed snow depths (SSD) for the full 12 months and mean snow depths (MSD) based on data for the 1981/82–2019/20 period (in cm). Stations are ordered from highest to lowest elevation. CV is the coefficient of variation

	LOM (2635)	CHOP (2005)	SKP (1778)	STR (1322)	TAJ (1013)	TEL (901)	POP (693)	LHR (640)
SUMMED SNOW DEPTH (SSD)								
Mean [cm]	29927	17210	5224	7769	5106	2237	757	957
SD	9168	6047	2341	3377	2547	1801	623	715
Minimum	14018	3233	1156	2218	751	296	124	88
Maximum	50942	32471	10146	16363	10364	7606	3028	2901
Trend	243	117	-5	-54	-37	-3	-1.53	-17
Difference [cm]	2432	1171	-47	-544	-369	-29	-15	-175
Pearson	0.302	0.221	0.022	0.184	0.165	0.020	0.028	0.279
CV [%]	30.64	35.14	44.82	43.50	49.89	80.54	82.24	74.73
MEAN SNOW DEPTH (MSD)								
Mean [cm]	99.81	71.25	25.77	42.99	32.27	15.70	7.02	9.92
SD	29.77	26.20	11.39	17.31	14.39	11.46	4.46	6.03
Minimum	45.66	12.06	5.78	14	8.16	2.9	1.75	1.87
Maximum	159.65	134.73	48.78	84.78	63.49	48.14	22.10	31.53
Trend	0.809	0.808	0.042	-0.173	-0.041	0.016	-0.002	-0.162
Difference [cm]	8	8	0.4	-1.7	-0.4	0.2	0	-2
Pearson	0.310	0.352	0.042	0.114	0.033	0.014	0.006	0.306
CV [%]	29.83	36.77	44.21	40.25	44.60	73.00	63.59	60.73

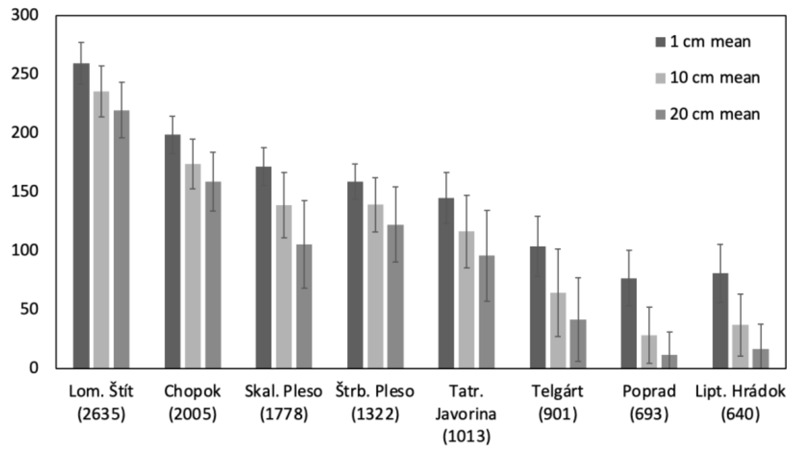

Fig. 2. Mean number of days with characteristic snow cover for studied stations ordered from highest elevation. (The error bars indicate the standard deviation).

To establish the differences amongst the stations, mean number of days with characteristic snow cover (1 cm, 10 cm and 20 cm) was graphically compared (Fig. 2). There were significant differences in all three categories between stations (P≤0.05). Lomnický štít had the highest number of days in all three characteristics but there was no significant difference between these, and Poprad revealed the lowest values that were very similar to Liptovský Hrádok. Skalnaté Pleso, despite being situated 456 m higher, had slightly lower number of days with 20 cm snow depth than Štrbské Pleso, which could be caused by orography. Also, station in Poprad is situated slightly higher than Liptovský Hrádok, by 53 m, yet had 9 days less with snow cover ≥10 cm. This could be caused by the orographic barrier effects as the Popradská basin is generally drier than Liptovská basin situated to the west. According to Chomitz and Šamaj (1974), based on data from 1901–1960, there was 107 mm year^{-1} less annual rainfall in Poprad than in Liptovský Hrádok. Based on data from Table 1 looking at the study period, this difference was similar, 98 mm year^{-1}.

Additionally, the correlation of elevation with the number of given snow cover characteristic in number of days was evaluated (Fig. 3.). The fitted logarithmic trendlines illustrate an increasing duration of snow cover for each snow depth category ($R^2 \approx 0.9$). All curves have similar shape and direction with the 20 cm data being the lowest. Additionally, some computed data were plotted using equations developed by Briedoň et al. (1974). According to their work, elevation gradient can be established using three equations: (1) $D=43+0.094*E$ for lower situated stations below 1500 m a.s.l.; (2) $D=68+0.077*E$ for stations above 1500 m a.s.l.; (3) $D=177+0.0225*E$, and for peak stations above 2000 m a.s.l., where D is the number of days and E is the elevation. The computed data showed a slight overestimation (e.g. 16 days on average for 1 cm data) based on the data collected at the SHMI stations, but both linear and logarithmic trends had strong fit (R = 0.99 and 0.95). However, it must be noted, that these equations were established from field data collected in the 1930 to 1960 period. The mean number DSC/1 cm calculated by Briedoň et al. (1974) came to 163.5 days (± 48.8), while the mean number of days with 1 cm based on the 1981–2020 data was 149.4 (± 58.3), which is a roughly 14 days drop. This result can assume that the equations are valid also today if the effect of shorter snow seasons is taken into the consideration.

The main issue of the temporary trends presented earlier is the small statistical significance presented by the values of Pearson's correlation coefficient up to 0.44 (Tables 2 and 3). Some interesting trends came for the SSD and MSD, for the highest Chopok and Lomnický štít stations, where there was an increase in the amount of snow cover. Other stations showed a drop or occasionally no difference. The visualization of trends (Fig. 4) suggests that there are more negative values at stations below 1100 and positive (increase) especially for SSD and MSD at the stations above 2000 m. Numerous studies e.g. from Swiss Alps pointed out decrease in snow cover since 1980s, especially in stations below 1300 m a.s.l. (Laternser and Schneebeli, 2003) which was attributed to an increase in local temperature. Same conclusions were mentioned also in the study from Slovak Tatra Mountains by Lapin et al. (2007) who reported on the snow cover trends that was attributed to

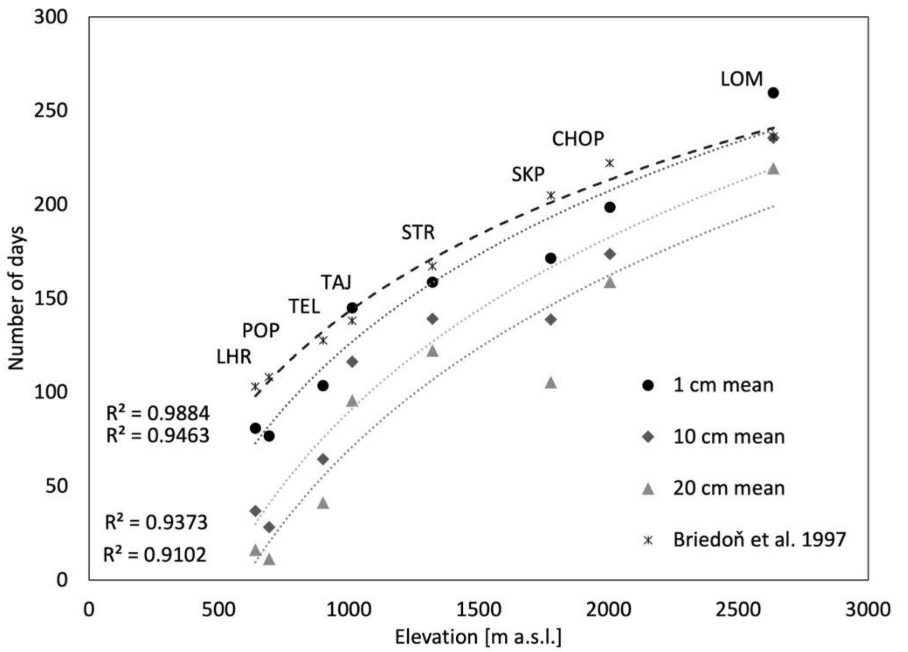

Fig. 3. Mean number of days (y axis) with characteristic snow cover related to elevation in m a.s.l. (x axis). The trendlines are logarithmic trends. The star markers are computed data based on elevation gradient equations by Briedoň et al. (1974) used to estimate the number of days with 1 cm snow cover or more.

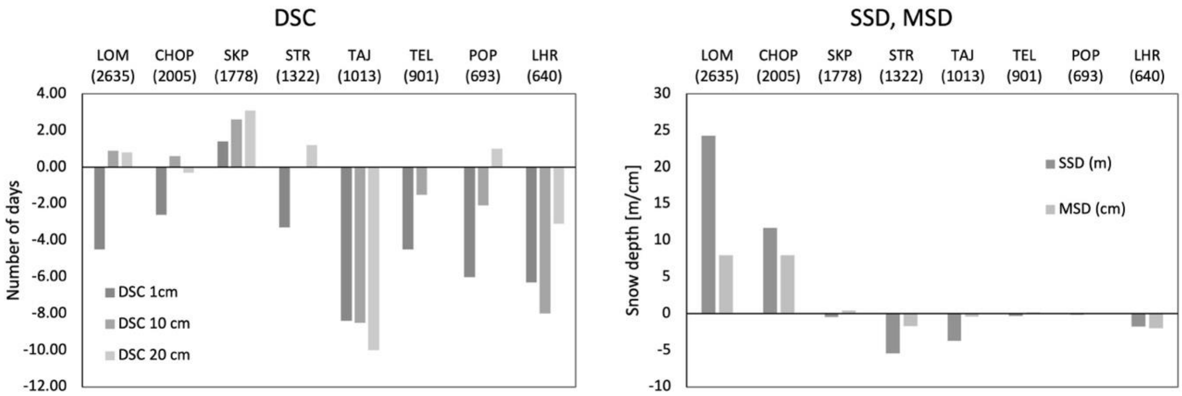

Fig. 4. Graphical interpretation of linear trends for days with snow cover (DSC) for 1 cm, 10 cm and 20 cm characteristic height as number of days expected to rise (positive values) or drop (negative values) per decade (on the left) and expected decadal differences for summed snow depths (SSD) in m and mean snow depths (MSD) in cm.

the air temperature and precipitation variability, but also to the change in atmospheric circulation patterns. For the period 1920–2006 they reported on a significant decrease of snow cover in Slovakia, but pointed out that northern and mountainous regions are exceptions and are more likely to have rising snow trends. Similar conclusions were made by a study Faško et al. (2023), who analysed trends since 1921 and the most significant decrease appeared in the 21st century. Furthermore, a study by Onderka and Pecho (2022) showed that due to ongoing climate change, there was higher occurrence of snow during Christmas for the 1951–1980 period compared to the 1981–2020.

In addition to the elevation, other factors such as slope orientation or relief were mentioned as an important phenomena that has an impact on snow trends (Lapin at al. 2007), however, more stations would be needed to compare the topographic attributes. Our stations were situated on the south-facing slopes, on peaks or in basins, only one station was at north-facing slope. In our study, we have observed the lee effect by lower snow cover at Poprad station. However, it must be stressed, that the complex conditions in the Tatra Mountains make it more difficult to understand the changes that occurred during the studied period. There was higher incidence in increase of snow cover in the stations above 1100 m a.s.l. and the trends in lower lying stations were generally decreasing. Also, there was less interannual data variability in higher situated stations which suggests that climate change related events are more likely to influence the foothill and basin areas rather than the peaks. Another approach with larger number of stations and longer study period could be useful in finding more statistically sound correlations.

Conclusion

Snow cover is one of the most important indicators of climate change, but it also has important functions in creating runoff, water supply, for vegetation dynamics, albedo etc. Numerous studies pointed out the decline in the snowpack and in the duration of the periods with characteristic heights of snow cover worldwide caused by global warming. However, the trends behave differently with increasing elevations and there could be point, where the snow cover could be increasing. It is therefore critical to observe the spatial and temporal trends of the snow cover both at lower and higher elevations.

In Slovakia, SHMI and their predecessors collected data on daily snow heights from Tatra Mountains since 1921. Westerns Carpathians, and their highest ridges, the Tatra Mountains, were chosen for this study to compare five selected snow cover parameters for period of 39 years (1981–2020). Not just winter seasons were considered, but because at some stations snow cover occurs also during warmest months, we divided the seasons from 1 July to 30 June the following year. Eight stations were selected, four with elevation above and four below the 1100 m a.s.l. There was clear relationship between the snow cover and elevation that was in accordance with the gradient equations proposed by Briedoň et al. (1974), but the temporary trends for the study period had weak correlations (maximum Pearson's coefficient was 0.44) so it is questionable whether and how these can be interpreted. However, the graphical visualization of the proposed change per decade suggested that the amount of snow and the number of days with snow cover was generally increasing for the stations above 1100 m a.s.l. and there was a decline expected for the stations situated at lower elevations.

These results are in accordance with the number of international but also national studies analyzing the effect of global warming on snow cover. But the complexity of mountainous terrain, the changes in circulation patterns, wind conditions, slope orientation etc. can have an important effect on the trends. Therefore, more stations or longer periods of data could be useful in establishing reliable trends and patterns in relation to other important factors. Based on our findings, we can conclude that our study was in the agreement with similar ones in the field, but we cannot confidentially suggest the trends in the snow cover parameters that are likely to be happening in the future solely due to global warming.

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References

Beniston, M., Rebetez, M., Giorgi, F., Marinucci, M. R. (1994): An analysis of regional climate change in Switzerland. Theoretical and Applied Climatology, vol. 49, 135–159.

Briedoň V., Chomicz K., Konček, M. (1974): Snehové pomery. In Konček et al. 1974: Klíma Tatier, Veda, Bratislava, 865 s.

Brown, R. D. (2000): Northern Hemisphere snow cover variability and change, 1915–97. Journal of climate, vol. 13, no. 13, 2339–2355.

Brziak, A., Kubáň, M., Kohnová, S., Szolgay, J. (2021): Comparison of the variability of snow cover parameters of the HBV model using lumped and distributed precipitation inputs and multi-basin calibration. Acta Hydrologica Slovaca, vol. 22, no. 1, 2021, 40–49.

Bulygina, O.N., Razuvaev, V.N.–Korshunova, N.N. (2009): Changes in snow cover over Northern Eurasia in the last few decades. Environmental Research Letters, vol. 4, no. 4, 6 p., ISSN 1748-9326.

Chomicz K., Kňazovický L. (1974): Avalanches. In: Konček M. et al.: Klíma Tatier, VEDA, Bratislava, 581–600.

Chomitz, K., Šamaj, F. (1974): Zrážkové pomery (Precipitation characteristics). Klíma Tatier. Veda, Bratislava, 443–536.

Clark, M. P., Serreze, M. C., Robinson, D. A. (1999): Atmospheric controls on Eurasian snow extent. International Journal of Climatology: A Journal of the Royal Meteorological Society, vol. 19, no. 1, 27–40.

EEA (2023): Snow cover. Indicator Assessment. https://www.eea.europa.eu/publications/europes-changing-climate-hazards-1/snow-and-ice/snow-and-ice-snow

EEA (2021): Snow and ice — snow, glaciers and ice sheets. https://www.eea.europa.eu/data-and-maps/indicators/snow-cover-3/assessment

Ellenberg, H. (1988): Vegetation ecology of central Europe. Cambridge University Press, 731 p. ISBN 9780521236423.

Engel, Z., Mentlík, P., Braucher, R., Minár, J., Léanni, L., (2015): Geomorphological evidence and 10Be exposure ages for the Last Glacial Maximum and deglaciation of the Veľká and Malá Studená dolina valleys in the High Tatra Mountains, central Europe. Quaternary Science Reviews, vol. 124, 106–123. https://doi.org/10.1016/j.quascirev.2015.07.015

Faško P., Handžák Š., Lapin M. (1997): Selected snow cover characteristics change in the Low Tatras Region in 1921–1995. Slovak National Climate Program, 7/97, 46–67, MŽP SR, SHMÚ Bratislava.

Faško, P., Markovič, L., Pecho, J., Bochníček, O. (2020): Decadal changes in snow cover characteristics in Slovakia over the period 1921–2020, EGU General Assembly 2020, 4–8 May 2020, EGU2020-3405.

Faško, P., Markovič, L., Bochníček, O. (2023): Changes in snow accumulation and snow depth in Slovakia in the 1921 – 2021 period, EGU General Assembly 2023, Vienna, Austria, 24–28 April 2023, EGU23-5554.

Falarz, M. (2002): Long-term variability in reconstructed and observed snow cover over the last 100 winter seasons in Cracow and Zakopane (southern Poland). Climate Research, vol. 19, no. 3, 247-256.

Falarz, M. (2004): Variability and trends in the duration and depth of snow cover in Poland in the 20th century. International Journal of Climatology: A Journal of the Royal Meteorological Society, vol. 24, no. 13, 1713–1727.

Fiema, A., (2008): Changes of snow coverage in selected synoptical situations in the period 1966/67–1995/96. Meteorologický časopis, vol. 11, no. 1–2, 31–37, ISSN 1335-339X.

Foster, J., Owe, M., Rango, A. (1983): Snow cover and temperature relationships in North America and Eurasia. Journal of Applied Meteorology and Climatology, vol. 22, no. 3, 460–469.

Holko L. (2000): Vyhodnotenie dlhodobých meraní parametrov snehovej pokrývky v horskom povodí (Evaluation of variability of the long-term snow characteristics of a mountain catchment), Acta Hydrologica Slovaca vol. 1, no. 1, 15–22. (in Slovak)

Holko, L., Kostka, Z., Parajka, J. (2001): Snehová pokrývka, Životné prostredie, vol. 35, 138–141. (in Slovak)

Holko, L., Kostka, Z., Pecušová, Z. (2005): Snow. In: Pekárová, P. and Szolgay, J. (eds.); Scenarios of changes of selected components of hydrosphere and biosphere in catchment basin of Hron River and Vah River as consequence of climatic change, 496 p; ISBN 80-224-0884-0; Worldcat; 105–167.

Holko, L., Škvarenina, J., Kostka, Z., Frič, M., Staroň, J. (2009): Impact of spruce forest on rainfall interception and seasonal snow cover evolution in the Western Tatra Mountains, Slovakia. Biologia, vol. 64, no. 3, 594–599.

Holko, L., Gorbachová, L., Kostka, Z. (2011): Snow hydrology in central Europe. Geography Compass, vol. 5, no. 4, 200–218.

Holko, L., Danko, M., Hlavčo, J., Kostka, Z. (2016): Dlhodobé údaje o priebehu vybraných klimatických a hydrologických prvkov v povodí Jaloveckého potoka (Západné Tatry, Liptovská kotlina). Životné prostredie, vol. 50, no. 2, 81 – 86. (in Slovak)

Holko, L., Danko, M., Sleziak, P. (2021): Snowmelt characteristics in a pristine mountain catchment of the Jalovecký Creek, Slovakia, over the last three decades. Hydrological Processes, vol. 35, no. 4, e14128.

Holko, L., Danko, M., Jančo, M., Sleziak, P. (2022): Empirical models to calculate the snow water equivalent in the high mountain catchments of the Western Carpathians. Acta Hydrologica Slovaca, vol. 23, no. 2, 241–248. DOI: https://doi.org/10.31577/ahs-2022-0023.02.0027

Hríbik M., Škvarenina J. (2006): Influence of altitude, exposition, forest stand and type of forest stand on hydrophysical characteristics of snow cover in Biosphere reserve Poľana, in winter times 2003/2004 a 2004/2005), 11th annual snow hydrology meeting, Czech Hydrometeorological Institute, 30–40.

Jaagus, J. (1997): The impact of climate change on the snow cover pattern in Estonia. Climatic Change, vol. 36, no. 1–2, 65–77.

Konček, M., Briedoň, V. (1964): Sneh a snehová pokrývka na Slovensku. Bratislava: Vydavateľstvo SAV. 76 p. (in Slovak)

Lapin, M., Faško, P. (1996): Snow cover and precipitation changes in Slovakia in the 1921–1995 period. In: Proceedings on the 24th International Conference on

Alpine Meteorology, Bled (Slovenia), 9–13 September 1996, 259–266.
Lapin, M., Faško, P., Pecho, J. (2007): Snow cover variability and trends in the Tatra Mountains in 1921–2006. 29th International Conference on Alpine Meteorology. Extended Abstracts. Oral Sessions, vol. 1.
Laternser, M., Schneebeli, M. (2003): Long-term snow climate trends of the Swiss Alps (1931–99). International Journal of Climatology: A Journal of the Royal Meteorological Society, vol. 23, no. 7, 733–750.
Makos, M., Rinterknecht, V., Braucher, R., Tołoczko-Pasek, A., Arnold, M., Aumaître, G., Bourlès, D., Keddadouche, K. (2018): Last Glacial Maximum and Lateglacial in the Polish High Tatra Mountains - Revised deglaciation chronology based on the 10Be exposure age dating. Quaternary Science Reviews, vol. 187, 130–156. https://doi.org/10.1016/j.quascirev.2018.03.006
Onderka, M., Pecho, J. (2022): Fingerprinting the North-Atlantic and Arctic oscillation signals in rainfall and fresh snowpack in the Western Carpathian Mountains. Research Square, https://doi.org/10.21203/rs.3.rs-1587740/v1
Pánek, T., Mentlík, P., Engel, Z., Braucher, R., Zondervan, A., Aster Team. (2017): Late Quaternary sackungen in the highest mountains of the Carpathians. Quaternary Science Reviews, vol. 159, 47–62.
Petrovič, P. (1972): Výpočet výparu zo snehovej pokrývky v povodí Nitry. In: Vodohospodársky časopis, vol. 20, no. 1, 1972, 1–15.
Pribullová, A., Pecho, J., Bičárová, S. (2009): Analysis of snow cover at selected meteorological stations in the High Tatra Mountains. In: Sustainable Development and Bioclimate. Reviewed Conference Proceedings. Stará Lesná, 56–57.
Siman, C., Polčák, N. (2017): Vplyv kontinentality podnebia na vybrané charakteristiky snehovej pokrývky na Slovensku v období rokov 1981/1982–2010/11. Meteorologický časopis. vol. 20, no. 1, 11–18. ISSN 1335-339X. (in Slovak)
Siman, C., Slavková, J. (2019): Vývoj snehovej pokrývky na Slovensku v období rokov 1981/1982–2017/2018 (Development of snow cover in Slovakia in the period 1981/1982 – 2017/ 2018). Bratislava: SHMÚ. (in Slovak)
Šamaj, F., Valovič, Š. (1988): Snehové pomery na Slovensku. In: Zborník prác SHMÚ, zv. 14/III, Bratislava, Alfa, 128 p. (in Slovak)
Vojtek, M., Faško, P., Šťastný, P. (2003): Some selected snow climate trends in Slovakia with respect to altitude. Acta Meteorologica Universitatis Comenianae, vol. 32, no. 1, 17–27.
Vojtek, M. (2010): Climate trends of snow cover in mountainous regions of Slovakia. Meteorologický časopis, vol. 13, no. 2 – 3, 57 – 61. ISSN 1335-339X.
Zasadni J., Kłapyta P., Broś E., Ivy-Ochs S., Świąder A., Christl M., Balážovičová L. (2020): Latest Pleistocene glacier advances and post-Younger Dryas rock glacier stabilization in the Mt. Kriváň group, High Tatra Mountains, Slovakia. Geomorphology, vol. 358, 107093. doi: 10.1016/j.geomorph.2020.107093

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