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ORIGINAL PAPER

Durability of snow cover and its long-term variability in the Western Sudetes Mountains

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Abstract

This paper presents the results of the analysis of the Western Sudetes' snow cover temporal and spatial changes, as well as it demonstrates the research on the long-term trends in the changes of snow cover durability. In order to conduct the study, the coefficient of snow cover durability (V) was used, which was defined as the quotient of the actual and the potential time of snow cover duration and expressed in percentage (1–100%). Moreover, the frequency of total disappearance of snow cover was established for the optimal winter season (December–March). Measurement data were obtained from 17 stations in the 1961–2015 period. The snow cover on the Western Sudetes' slopes with southern (S) macro-exposure lasts longer (has greater durability) than on the slopes in analogous altitude zones with northern (N) macro-exposure. At the altitudinal level of 600–700 m a.s.l., where the differences are the biggest, the average V values range from 60% at stations N to 75% in stations S. In the analysed area, excluding the upper ranges, slight negative trends in V changes have been noted. Snow cover persists for a shorter and shorter time. For the substantial majority of the stations, the trends in these changes are not statistically significant at the 0.05 level of statistical significance. They refer to the tendencies in other mountainous regions in Poland and Europe. Analogously, the stations with S macro-exposure, located at similar altitudes as stations with N macro-exposure, are characterised by two to three times lesser frequency of total disappearance of snow cover. Coefficient V is negatively correlated with the total disappearance of snow cover. At the stations with S macro-exposure in the Western Sudetes, these correlations are usually strong or very strong, whereas at the stations with N macro-exposure, at similar altitudes, they are usually moderate or very weak.

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1 Introduction

In mountain areas, where the winter touristic infrastructure is well developed and where tourism provides the livelihood for the local communities, the retention of continuous snow cover has a paramount importance. The lack of durability of snow cover not only adversely affects winter tourism but also poses a threat of exposing crops to unfavourably low temperatures, etc. All changes in the depth and durability of snow cover can have long-term environmental and economic impacts (Beniston 1997, 2000; Beniston et al. 2003; Schmucki et al. 2015). The conditions and changes of seasonal snow cover both in Poland (Leśniak 1981; Falarz 2000–2001, 2002, 2004, 2007, 2013; Bednorz 2002; Urban 2016; Urban et al. 2018) and all over the world (Gutzler and Rosen 1992; Groisman et al. 1994; Brown 2000; Bednorz 2004) are quite well recognised. Air temperature increase in the twentieth and at the beginning of the twenty-first centuries caused the global reduction of cryosphere, both on the lowlands (IPCC 2013) and in mountainous regions (Marty 2008; Durand et al. 2009; Valt and Cianfarra 2010; Pederson et al. 2013; Klein et al. 2016). Similarly, in the second half of the twentieth century in most of the area of Poland, a slight negative trend in the snow cover duration and depth of snow cover were noted. Only for some of the mountainous areas (in the case of snow cover duration) and north-eastern Poland (in the case of depth), trends of snow characteristics were positive (Falarz 2004). The foundational role in shaping these changes belongs to macro-scale atmospheric circulation (Bednorz 2002; Falarz 2007). According to Brown and Mote (2009), Poland lies in the zone where the decrease in the snow cover duration in 1966–2007 was the biggest due to the high sensitivity of this region to climate changes.

Taking into consideration the above-mentioned results of the research, the authors of the study decided to analyse the durability of snow cover in the Western Sudetes, mainly in their highest ranges, i.e. in the Karkonosze and the Izera Mountains—located in Central Europe, on the Polish–Czech border. The aim of this study is spatial and temporal analysis of the coefficient of the snow cover durability as well as to examine its change trends in the Karkonosze and the Izera Mountains, both on the Polish and Czech side of these two mountain ranges. The thesis was stated that at similar altitudes in the Western Sudetes, snow cover on slopes with northern macro-exposure is less durable and is subject to more frequent ablations that lead to its total disappearance than on the slopes with southern macro-exposure.

The premise for undertaking the study was the fact that to date literature on the subject, except for the work by Urban et al. (2018), lacked a comprehensive, methodologically uniform study that would cover such a long period and use a larger number of stations on both sides of the Polish–Czech border. The studies already published concerned the comparison of snow conditions on both sides of the border in the context of skiing opportunities (Urban and Richterová 2010) or were case studies (Ojrzyńska et al. 2010; Urban et al. 2011) but no evaluation of snow cover durability or change trends have hitherto been presented. Moreover, snow cover characteristics based on the coefficient of its durability have not been well recognised so far. The last article by the authors (Urban et al. 2018) concerned winter characteristics in the Western Sudetes and was based on the comprehensive winter severity and snowiness by Paczos (1982). In this work, significant differentiation of the mentioned indicators average values. It demonstrated that there is a clear differentiation between the average values of the above-mentioned indicators and the height above the sea level and macro-exposure of the slopes in relation to the dominant directions of advection of air masses. Furthermore, it was emphasised that the areas with macro-exposures SW and W (the Elbe river catchment) are characterised by better snow conditions and by being cooler in winter than the areas with macro-exposure NE and N (the Odra river catchment). The snow conditions, characteristic for the slope zone in the Elbe river catchment, occur approx. 250 m higher in the Odra river catchment. However, these indicators do not provide direct information on the time of logging and durability as well as the mid-season variability of the snow cover, which are so important from the point of view of many areas of the economy and human life. Therefore, on the basis on an analogous material (the same stations and the same research period), this work aims to deepen knowledge about the characteristics of the snow cover and its variability in the Western Sudetes using the coefficient of snow cover durability introduced to the source literature by Leśniak (1973, 1981). Using the coefficient makes sense for moderate geographical latitudes, where the snow cover shows a distinct seasonal rhythm (Leśniak 1981). This coefficient is commonly used in characterising snow conditions in the mountains as well as on the national scale (Leśniak 1973, 1981; Nowosad 1992; Falarz 1993, 2000–2001, 2010, 2013; Urban 2015; Franczak 2018).

In the present work, the main author continues the series of articles (Urban and Richterová 2010; Ojrzyńska et al. 2010; Urban et al. 2011; Urban et al. 2018), whose purpose is to characterise snow cover conditions and their long-term changes in the Western Sudetes. These characteristics are to be obtained in many contexts, including the orographic deformation of field of air masses flow at orographic barrier.

2 Source data and method

The time range of measurement data (1961/1962–2015/2016), the criteria for their selection and the area of research in this study were identical to the authors' previous article (Urban et al. 2018). As a reminder, homogeneous measurement data were derived from eight meteorological stations of the Institute of Meteorology and Water Management–National Research Institute (IMGW–PIB), eight stations of the Czech Hydrological and Meteorological Institute (CHMI) and 1 station—Meteorological Observatory of the University of Wroclaw (UWr) on Szrenica (Table 1).

The authors, similarly as in their earlier work (Urban et al. 2018), undertook efforts to document the distinct snow and temperature conditions on the opposite sides of the Sudetes Mountains which were expressed in terms of the coefficient of snow cover durability (V) as accurately as possible. For this reason, they used all the reliable available materials dating since 1961. Nevertheless, V was calculated for a uniform period consisting of the 30 consecutive seasons from 1981/1982 to 2010/2011 and measurements from fewer stations were used. In the case of each station described in Table 1, results were analogous to those obtained for the periods of different length (from 15 to 55 years). Calculations were carried out for

Table 1 Characteristics of weather stations

Station	H (m a.s.l.)	Latitude φN (°, ′, ″)	Longitude λE (°, ′, ″)	Affiliation	Morphological form	Climatic zone (according to Hess et al. 1980)	Macro-exposure	The scope of data
Śnieżka	1603	50° 44′ 10″	15° 44′ 23″	IMGW–PIB	Peak in the Karkonosze Mts	Very cold	N–S uncovered peak	1961–2015
Szrenica	1331	50° 47′ 27″	15° 30′ 44″	UWr	Slope below a peak on plateau in the Karkonosze Mts	Very cold	S	1961–2001
Benecko_1	880	50° 39′ 51″	15° 33′ 32″	CHMI	Slope in the Karkonosze Mts	Moderately cold	S	1961–1993
Jakuszyce	860	50° 49′ 23″	15° 26′ 31″	IMGW–PIB	Mountain pass between Karkonosze and Izera Mts	Moderately cold	S	1965–2015
Benecko_2	790	50° 40′ 18″	15° 33′ 00″	CHMI	Slope in the Karkonosze Mts	Moderately cold	S	1994–2015
Bedřichov	777	50° 48′ 54″	15° 08′ 14″	CHMI	Slope in the Izera Mts	Moderately cold	S	1961–2015
Desná-Souš	772	50° 47′ 22″	15° 19′ 11″	CHMI	Shallow valley in the Izera Mts	Moderately cold	S	1961–2015
Karpacz_1	720	50° 46′ 00″	15° 45′ 00″	IMGW–PIB	Slope in the Karkonosze Mts	Moderately cold	N	1951–1980
Harrachov	675	50° 46′ 54″	15° 25′ 12″	CHMI	Valley in the Izera Mts	Moderately cold	S	1961–2011
Vysoké nad Jizerou	670	50° 41′ 16″	15° 24′ 12″	CHMI	Slope in the Izera Mts	Moderately cold	S	1961–1978
Przesieka	650	50° 47′ 56″	15° 40′ 02″	IMGW–PIB	Slope in the Karkonosze Mts	Moderately cold	N	1961–2015
Szklarska Poręba	645	50° 50′ 04″	15° 31′ 45″	IMGW–PIB	Slope in the Karkonosze Mts	Moderately cold	N	2001–2015
Karpacz_2	580	50° 46′ 44″	15° 46′ 10″	IMGW–PIB	Slope in the Karkonosze Mts	Moderately warm	N	1983–2015
Horní Maršov	565	50° 39′ 35″	15° 49′ 15″	CHMI	Lower area of Karkonosze Mts	Moderately warm	S	1961–2015
Świeradów Zdrój	543	50° 53′ 54″	15° 21′ 31″	IMGW–PIB	Slope in the Izera Mts	Moderately warm	N	1961–2015
Hejnice	396	50° 53′ 04″	15° 10′ 59″	CHMI	Foothills of the Izera Mts	Moderately warm	N	1961–2015
Jelenia Góra	342	50° 54′ 01″	15° 47′ 20″	IMGW–PIB	Dale in the Karkonosze Mts	Moderately warm	N	1961–2015

11 out of 17 stations. Studies covering 30-year periods form the basis for determining the climate characteristics of individual areas, and the 1981–2010 multiannual period is currently recommended for analysis purposes by the World Meteorological Organisation and is the so-called standard or reference period (WMO 2011). A similar approach, using data series of different lengths, was applied to snow cover studies in Austria (Hantel et al. 2000), in the mountains of Bulgaria (Brown and Petkova 2007) or in the Karkonosze and the Izera Mountains (Urban et al. 2018).

This approach is consistent with the accepted view that even mean 10-year values of individual meteorological parameters can be used to capture the spatial diversity of climate and make it possible to detect general patterns that govern the phenomenon in question (Hess 1965; Hess et al. 1980). Huang et al. (1996) stated that if mean values are to be determined, the exact length of the period adopted for this purpose within the 10–30-year range is not significant. This view is confirmed by, among others, results obtained in this study for the average values of the snow cover durability coefficient (Chapter 3; Fig. 3) and its complete disappearance rate (Chapter 3.2; Table 4). Marty (2008), using the example of stations located on the northern and southern slopes of the Alps, demonstrated that when analysing long-term mean values, there is a considerable similarity between snow cover characteristics at stations located at comparable altitudes. This similarity is present despite the possible lack of homogeneity caused by the changes in station locations and the different characteristics of these locations. Long-term average data from several stations located at similar altitudes provide reliable information about the climate conditions in a given altitude zone.

In the present study, winter is assumed to form a period from 1 August year X to 31 July year $X+1$. This was due to the fact that in the upper parts of the Karkonosze Mountains (Mount Śnieżka—1603 m a.s.l., Mount Szrenica—1331 m a.s.l.), snow cover on the ground can occur in summer months. This approach has already been applied before (Falarz 2000–2001; Urban 2015, 2016; Urban et al. 2018). Moreover, most research of snow cover changes in the context of global warming emphasises only climatological winter season (Dec-Jan-Feb) and often ignores significant changes that occur in spring and autumn (Klein et al. 2016). Thus, it seems more justified to analyse snow cover changes that take place throughout the whole year. In turn, the day with a snow cover was assumed to be a day when the measured height of the snow cover at 6.00 UTC was not less than 1 cm and occupied a minimum of 50% of the area.

Snow cover characteristics were established based on the coefficient of snow cover durability (V), which is defined as the quotient of the actual and the potential time of snow cover retention and expressed in percentage (1–100%). The actual time of snow cover retention is to be understood as the number of days on which snow depth ≥1 cm in winter season, whereas the potential time of snow cover presence is the number of days between the first to the last occurrence of snow on the ground in winter season. If the coefficient of snow cover durability equals 100%, this means that in the given season, snow cover remained throughout its whole duration. The smaller is the value of V, the longer is the period without snow cover on the ground. The previous analysis of snow conditions based on V was carried out by Leśniak (1973, 1981), who coined the term in Polish literature, Nowosad (1992), Falarz (1993, 2000–2001, 2010, 2013), Urban (2015) and Franczak (2018). Also, variability of V was defined as coefficient of variability (Vz), which is the quotient of standard deviation and arithmetic mean. In addition, the authors determined the frequency of the total disappearance of snow cover during optimal winter season, which in the study was assumed as the period from December to March. The foundation for assuming such timeframe was the fact that in the upper parts of the Sudetes Mountains already in December thick continuous snow cover lies on the ground and in March its depth is maximal (Reunier 1935; Kosiba 1949; Głowicki 1977; Kwiatkowski 1985; Limanówka et al. 2012; Sobik et al. 2014; Urban 2016). For the purpose of this study, total disappearance of snow cover was assumed as lack of continuous snow cover during observation at 07 UTC on 1 day, provided that the previous day the snow depth was not smaller than 1 cm.

For stations with the longest 55-year of measurement data, the tendencies of changes in the snow cover durability coefficient were also determined. Student's t test was used to verify the statistical significance of those trends at the $p = 0.05$ significance level. In the period 1981/1982–2010/2011, the relationship between the coefficient of snow cover durability and its total disappearance was also examined. Correlation coefficients and the strength of this relationship were determined. The statistical significance of the relationship was also checked with Student's t test at the $p = 0.05$ significance level.

3 Results and discussion

The average values of the coefficient of snow cover durability (V) in the Karkonosze Mountains and the Izera Mountains range from ca. 46–47% in the lowest localisations (Jelenia Góra, Hejnice) to ca. 81–82% in the upper ridges of the mountains (Śnieżka, Szrenica) (Fig. 1). Equally high average values of V are characteristic for stations with southern macro-exposure located in the altitude zone of 750–900 m a.s.l., e.g. Jakuszyce, Bedřichov, Desná–Souš (Fig. 2). The calculated average values of V relate to its average values in Poland, where they range from 40% in the west to 60% in the south-east and to over 70% in the highest reaches (Falarz 2013). In the Polish Sudetes and their foreland, the average V decreases within the range of 40–50 to 80% (Urban 2015).

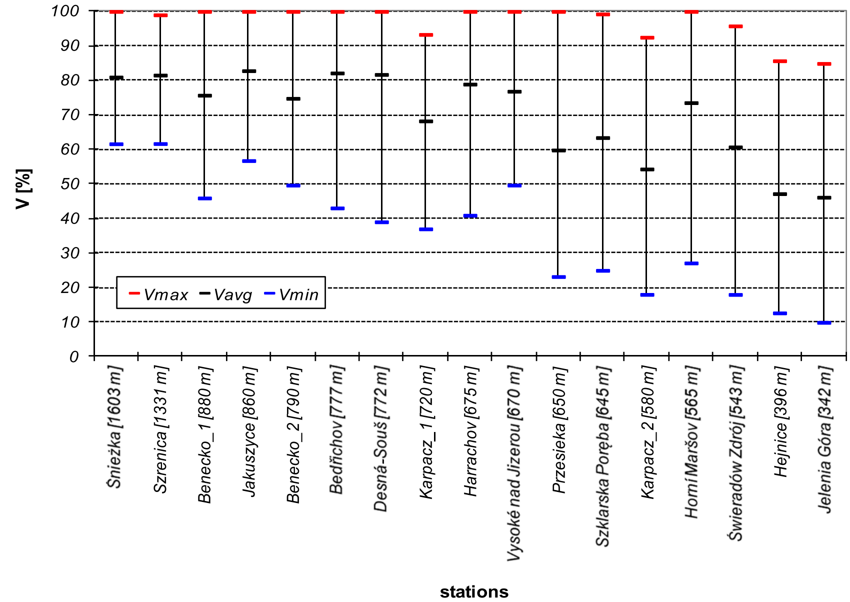

Fig. 1 Average (Vavg), maximum (Vmax) and minimum (Vmin) values of coefficient of snow cover durability (V) at the analysed stations

The big denivelation of over 1250 m (from the station Jelenia Góra, located in a valley, to the highest peak Śnieżka) and the great variety of the topography of the area, as well as the exposure of the station cause the noticeable spatial variety of V value. This variety results from many factors, as in the case of snowiness and severity index of winters (Urban et al. 2018), including altitude and orographic deformation of the flow field of air masses that shape precipitation and air temperature. In consequence of this deformation, there emerges the distinct contrast between the snowiness in the river catchment of the Elbe (S, SW and W macro-exposures) compared with the Odra river catchment (NE and N macro-exposures). The areas with SW and W exposures are characterised by the longer period of retention and bigger depth of snow cover. This result corresponds with the previous study on the thermal and precipitation variety of the Karkonosze Mountains (Sobik et al. 2014) or of the Karkonosze and the Izera Mountains (Urban et al. 2018). This contrast stands out especially in the altitude range of 500–900 m a.s.l. (Fig. 2). In the upper ridges, the differences are becoming less distinguishable due to the snow blowing alternately from one to the other side of the range.

These were Sobik et al. (2014), as well as Urban et al. (2018), who pointed out to the fact that in the Karkonosze Mountains the essential differences in precipitation at similar altitudes exist not in the east–west direction, but between the southern of northern sides of the mountains. Also, they emphasised the increase in winter precipitation in the upper river catchment of the Kamienna and in the western part of the Polish Karkonosze. This should be accounted for by the

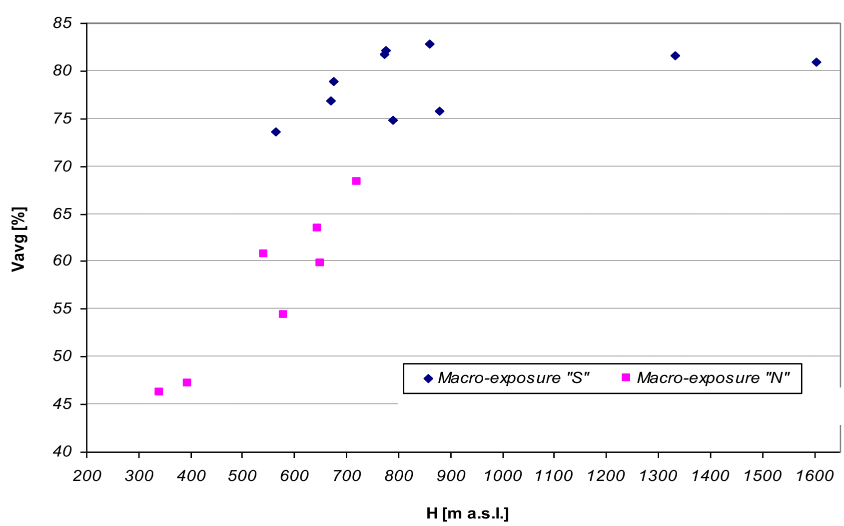

Fig. 2 The relationship between a station altitude (H) and the average values of the coefficient of snow cover durability (V) for southern (S) and northern (N) macro-exposures

weaker descending air currents with the southern circulation. The latter in turn results from the fact that a relatively low Main Ridge of the Karkonosze, located in the west of Szrenica, and not much lower, parallel to the Karkonosze High Ridge of the Izera Mountains hinder descending foehn currents (Kwiatkowski 1985). Similarly, as Falarz (2002) proved, foehn effect plays a significant role in shaping the Polish Tatra Mountains' nival conditions and their diversification, as well as the component of the meridional atmospheric circulation contributes to these conditions to a greater extent than its zonal counterpart.

The above-described and graphically presented (Figs. 1 and 2) patterns for various periods at the analysed stations confirm the results obtained for the multiannual period of 1981–2010 at the selected stations (chapter 2 features the methodical justification). The average values of V (that illustrate climactic patterns) for the stations from the period 1981–2010 are almost identical to the ones from the periods in Table 1. The results are similar for extreme values (Fig. 3).

3.1 The temporal and spatial variability of the coefficient of snow cover durability and its trends of changes

Based on the multiannual mean values of the coefficient of snow cover durability (V) and its standard deviation, winter seasons with moderate V (Vavg-δ < V < Vavg+δ; where: δ – standard deviation) dominated at all analysed stations. In addition, the character of winter seasons defined by V has changed since the turn of the 1980s and 1990s. Namely, everywhere, apart from Śnieżka Mountain, the increase in frequency of seasons with small V (V ≤ Vavg-δ) and the decrease in frequency of seasons with high V (V ≥ Vavg+δ) were noted. Seasons with low V values in the Karkonosze and the Izera Mountains consist of the following periods: 1988/1989–1990/1991, 1997/1998, 2006/2007, 2013/2014 and 2015/2016 (Table 2). The seasons 1989/1990 (for stations located above 650 m a.s.l.), 2006/2007 and 2013/2014 (for stations located below 650 m a.s.l.) were marked by extremely low V, whereas winter seasons with high V values (with stable/continuous snow cover) occurred at most of the stations in the 1960s and 1986/1987, 1995/1996 and 2005/2006. Among those seasons with the highest V (100% at as many as seven stations), the period 2005/2006 stood out. High values of V were noted for season 1995/1996, but primarily at stations located below 700 m a.s.l (Table 2). Incidentally, seasons with high V only in the upper (1974/1975, 1981/1982, 1991/1992) or lower part of the altitude profile (1986/1987, 2003/2004) occurred. These results were similar to the ones presented in the earlier article by Urban et al. (2018). Since the end of the 1980s, the thermal structure in the Western Sudetes changed. Namely, gentle winters occurred more frequently than the severe ones. This pattern coincides with the ones that were obtained for Europe (Twardosz and Kossowska-Cezak 2016). The increase of warm winters occurrence was also observed in, among other regions, the Swiss Alps (Scherrer et al. 2004; Marty 2008) or in the USA (Mayes Boustead et al. 2015).

The variability of the coefficient of snow cover durability in the analysed winter seasons expressed by the coefficient of variability (Vz) allows for the comparison of V variability in temporal series as well as between the stations. The smallest values of Vz (around 10–15%) occur in the upper parts of the Karkonosze and the Izera Mountains. This means that the snow cover there is more stable and is subject to smaller fluctuations, whereas the biggest values of Vz (around 35%) occur at the stations that are located at the lowest altitudes (Table 2). Generally, the variability of the coefficient of snow cover durability is inversely proportional to altitude. This result is consistent with the previously gained conclusions for the coefficient of the variability of parameters of snow cover in the Polish Tatra Mountains (Leśniak 1973; Falarz 2000–2001) or in the Polish Sudetes (Urban 2015, 2016).

Nonetheless, in the wide slope zone 600–700 m, the variability of coefficient V varies significantly. This is especially noticeable in the zone 600–700 m (Harrachov, Vysoké nad Jizerou), where the stations with macro-exposure S are

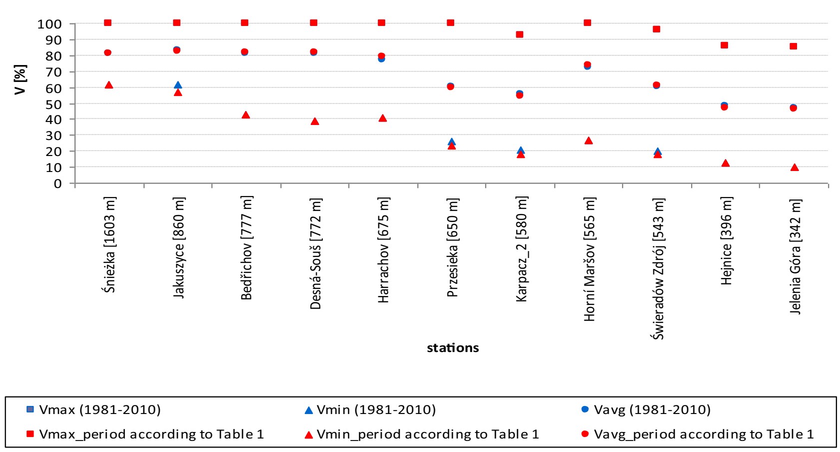

Fig. 3 Average (Vavg), maximum (Vmax) and minimum (Vmin) values of coefficient of snow cover durability (V) at selected stations in the period 1981–2010. Note: in Karpacz_2 station start of data from 1983

Table 2 The coefficient of snow cover durability and its standard deviation (δ), coefficient of variability (Vz) and frequency (N) of seasons with stable and unstable snow cover

Winter season	Śnieżka [1603 m]	Szrenica [1331 m]	Benecko_1 [880 m]	Jakuszyce [860 m]	Benecko_2 [790 m]	Bedřichov [777 m]	Desná-Souš [772 m]	Harrachov [675 m]	Vysoké nad Jizerou [670 m]	Przesieka [650 m]	Szklarska Poręba [645 m]	Karpacz_2 [580 m]	Horní Maršov [565 m]	Świeradów Zdrój [543 m]	Hejnice [396 m]	Jelenia Góra [342 m]
1961/62	74.0	70.1	74.3			90.5	76.0	72.6	69.6	68.7			100.0	62.9	58.3	51.8
1962/63	77.1	74.8	91.9			92.5	80.5	95.7	100.0	68.6			94.5	71.4	72.1	58.9
1963/64	68.5	69.2	72.3			85.0	84.4	81.6	77.3	66.2			67.1	74.3	53.2	48.0
1964/65	85.2	85.1	74.1	80.0		86.9	72.5	82.1	82.4	82.9			93.4	68.3	68.5	71.8
1965/66	87.5	83.3	90.8	92.9		96.1	95.7	95.5	86.2	71.9			93.5	72.9	53.1	64.0
1966/67	84.3	83.0	84.2	92.5		84.5	93.6	94.7	87.6	59.2			82.1	64.3	38.7	37.3
1967/68	72.1	77.6	84.3	77.4		90.0	90.6	97.1	92.6	66.2			90.4	81.0	57.4	56.6
1968/69	65.2	80.0	74.1	92.1		79.1	80.2	81.3	76.0	73.2			75.8	74.7	39.3	50.6
1969/70	84.6	88.7	74.9	79.1		97.6	92.3	97.6	85.9	89.0			86.9	88.3	75.6	79.6
1970/71	72.8	91.9	77.6	87.8		74.7	80.5	74.5	66.4	48.3			72.2	49.7	50.4	51.5
1971/72	72.6	79.0	46.5	58.6		51.5	51.5	61.3	49.7	40.5			47.9	38.6	26.8	29.4
1972/73	88.2	82.2	59.4	83.4		90.7	85.9	56.8	57.6	47.0			48.4	59.7	28.5	24.0
1973/74	84.1	86.7	67.0	80.4		71.4	67.3	73.9	63.9	33.3			96.9	39.2	25.0	25.2
1974/75	100.0	92.0	74.0	98.5		87.0	91.7	85.6	75.3	34.6			48.8	40.4	15.7	12.5
1975/76	84.6	85.5	89.2	79.9		94.6	94.0	92.9	88.6	61.9			83.8	68.3	43.4	37.3
1976/77	83.0	75.3	80.0	85.8		93.1	90.3	84.2	81.1	60.5			72.3	65.1	52.7	53.1
1977/78	82.4	77.9	78.3	87.2		88.9	85.0	78.3	77.2	64.0			78.8	64.2	47.3	30.1
1978/79	78.0	79.6	68.9	79.9		78.6	87.6	96.3	66.3	73.7			91.8	81.5	64.9	63.4
1979/80	84.3	90.2	81.1	90.6		87.9	89.9	74.7		69.7			69.6	68.7	47.2	41.0
1980/81	67.7	85.5	68.4	76.4		75.0	76.6	72.9		53.7			60.6	57.3	46.2	49.4
1981/82	97.3	96.3	82.2	91.0		92.2	91.7	85.9		50.0			75.4	54.3	49.4	45.3
1982/83	80.9	85.9	80.9	94.1		88.9	90.1	82.1		55.7			62.4	48.3	39.9	45.0
1983/84	81.7	83.4	78.3	88.0		89.7	82.3	84.8		66.5		29.7	74.7	68.1	40.6	25.6
1984/85	73.2	75.1	79.5	81.3		83.8	75.3	76.3		63.9		55.8	71.9	64.9	50.9	47.6
1985/86	83.2	80.7	85.9	87.6		90.6	89.4	81.8		64.1		62.3	74.5	65.4	54.3	54.7
1986/87	75.6	71.4	71.7	100.0		74.5	79.9	100.0		100.0		92.5	100.0	83.9	84.4	81.5
1987/88	87.8	79.9	74.4	77.7		80.9	77.6	75.0		60.7		60.5	64.5	63.5	50.0	40.8
1988/89	76.9	93.2	75.4	86.3		82.1	77.5	74.2		30.4		20.9	66.7	37.8	30.5	18.0
1989/90	61.7	61.7	46.0	66.0		43.1	39.1	41.0		29.0		26.3	46.3	37.0	20.9	20.8
1990/91	78.2	79.6	58.0	68.0		59.4	62.1	73.2		46.2		43.6	41.7	55.2	45.1	36.1
1991/92	100.0	99.0	80.9	91.2		85.2	94.7	90.3		70.4		62.0	85.3	73.2	46.7	46.5
1992/93	100.0	98.9	74.7	83.2		80.0	80.0	73.4		50.3		47.9	76.1	65.8	52.9	62.2
1993/94	73.8	67.3	100.0	86.4		92.3	94.8	89.5		62.4		52.0	100.0	54.2	46.9	44.7
1994/95	84.9	73.9		61.9	64.6	56.3	68.4	63.1		54.9		54.5	85.3	62.4	47.2	41.3
1995/96	82.4	77.0		85.2	83.3	100.0	83.9	83.7		95.3		91.0	98.2	95.8	71.3	84.8
1996/97	75.8	68.8		80.2	80.5	94.2	93.4	87.3		76.0		68.7	74.8	75.9	53.8	54.5
1997/98	81.6	73.1		69.4	51.4	63.9	56.3	48.1		27.6		34.9	43.1	37.3	32.7	26.6
1998/99	80.9	85.2		92.8	84.4	84.7	89.7	86.2		64.6		57.1	95.3	54.9	58.3	63.5
1999/00	74.0	86.5		98.1	94.9	97.3	98.0	94.1		75.4		69.6	88.1	80.2	57.1	40.9
2000/01	83.1	70.6		91.6	68.3	90.0	92.9	86.5		49.6		51.2	72.1	64.0	34.2	38.3
2001/02	78.1	98.4		94.3	80.3	91.1	92.6	85.9		56.2	64.0	53.7	72.1	61.0	40.9	44.1
2002/03	89.0			78.4	68.9	75.6	75.1	69.8		53.4	50.0	50.3	62.0	50.0	39.0	43.1
2003/04	86.8			61.7	55.9	77.6	65.9	56.9		87.9	68.6	83.5	93.7	87.8	71.7	64.9
2004/05	76.6			89.2	78.3	85.9	88.1	84.3		54.4	67.0	66.4	78.6	49.2	42.5	58.5
2005/06	82.9			100.0	100.0	100.0	100.0	100.0		100.0	95.9	91.2	100.0	91.8	85.7	84.9
2006/07	82.5			70.7	50.3	61.1	60.1	50.7		26.4	40.6	33.7	27.1	20.3	12.7	9.9
2007/08	79.7			87.8	87.1	79.8	90.2	65.3		43.6	59.5	38.9	43.8	36.3	34.7	34.3
2008/09	72.5			85.5	98.6	100.0	100.0	99.3		84.1	99.3	66.1	69.0	64.8	58.1	53.6
2009/10	81.2			72.5	68.3	69.1	75.0	69.4		56.9	66.5	53.2	64.1	58.9	50.3	51.8
2010/11	78.7			72.1	62.6	76.8	76.3	64.6		50.6	56.9	47.5	63.6	48.8	41.2	47.8
2011/12	75.8			100.0	94.4	97.6	100.0	53.8		66.9	80.2	56.5	76.2	60.8	49.6	44.6
2012/13	76.3			85.1	84.8	84.1	83.4			70.6	73.4	68.9	76.9	67.9	60.1	63.8
2013/14	94.0			56.8	57.0	47.5	50.3			23.2	25.0	18.0	62.2	18.0	13.5	16.7
2014/15	94.0			81.2	82.4	83.7	85.6			49.2	55.5	43.7	69.5	60.8	40.6	29.0
2015/16	74.8			69.5	49.7	64.8	70.2			42.2	49.7	41.8	36.8	32.3	24.7	38.2
average	80.9	81.6	75.7	82.8	74.8	82.2	81.7	78.9	76.9	59.9	63.5	54.4	73.6	60.8	47.2	46.2
δ	8.3	9.1	11.5	10.9	16.0	13.5	13.4	14.4	12.8	18.1	19.4	19.0	18.0	17.0	16.3	17.5
Vz [%]	10.3	11.2	15.2	13.1	21.3	16.4	16.4	18.3	16.7	30.3	30.5	34.9	24.5	28.0	34.5	38.0
stable N_ [%]	10.9	17.1	12.1	13.5	18.2	12.7	9.1	19.6	11.1	12.7	13.3	12.1	20.0	14.5	14.5	14.5
unstable N_ [%]	12.7	17.1	12.1	17.3	22.7	14.5	14.5	15.7	16.7	14.5	13.3	18.2	16.4	18.2	16.4	16.4

Explanations:
- (blue) indicates season with stable snow cover (V≥Vavg+δ),
- (red) indicates season with unstable snow cover (V≤Vavg-δ),
- (white) indicates season with moderately stable snow cover (Vavg-δ<V<Vavg+δ).

characterised by the variability of V (16–18%), which is distinctly smaller than that of the stations with macro-exposure N (Szklarska Poręba, Przesieka) (ca. 30%). Therefore, at similar altitudes, snow cover at the stations with southern macro-exposure is subject to smaller fluctuations than at the stations with northern macro-exposure (Table 2).

The spatial and temporal variabilities of V are well illustrated by its line at stations Harrachov and Przesieka, which are located on the opposite sides of the main ridge of the Karkonosze and at similar altitudes. The significantly smaller amplitude of V changes characterises slopes with southern macro-exposure (Harrachov) than those with southern macro-exposure (Przesieka). Moreover, in Harrachov, the lowest values of V incidentally drop below 50%, while in Przesieka, profound drops occur relatively frequently, often reaching even the values below 30%. The occurrence of low V values has been observed since the beginning of 1990s, whereas on slope S, the coefficient of snow cover reaches the value 90% or above much more frequently than on slopes N. As a result, the multiannual difference in V value between Harrachov and Przesieka equals ca. 20% points (Fig. 4). The correlation the value of V between Harrachov and Przesieka is positive and strong. The correlation coefficient *R* calculated between Harrachov and Przesieka for 1961/1962–2011/2012 winter seasons was 0.6.

Contrary to common expectations, the maximum values of the coefficient of snow cover are noted not only at the stations that are located at the highest altitudes but also on the slopes, Pogórze or intermontane valleys. Possibly in a given season, the stations located at lower altitudes can have higher coefficient V than those located at considerably higher altitudes. Such situation took place between Jelenia Góra (342 m a.s.l.) and Szrenica (1331 m a.s.l.) stations in winter seasons 1986/1987, 1995/1996 or Harrachov (675 m a.s.l.) as well as Szrenica/Śnieżka in several seasons in the 1960s: 1978/1979, 1986/1987 and 1999/2000 (Table 2). This result is consistent with the earlier results of Leśniak (1981), who demonstrated analogous patterns in the river basin of the upper Wisła. The author explains this fact by the renewal of snow cover at higher altitudes during spring recurrent cold spells. This sometimes significantly prolongs the potential time of snow cover retention, while the actual time of this retention is only slightly longer. At the stations located at lower altitudes, the thermal conditions during recurrent cold spells in spring are far less likely to facilitate propitious conditions for forming snow cover again. Similarly, in autumn, in the upper parts of the mountains, snow cover appears quite early (September–October), prolonging the potential time of snow cover retention. Also, Urban (2015) obtained analogous results for the Polish Sudetes and their foreland.

The calculated trends of V changes are negative for most of the analysed stations in the Western Sudetes (Table 3). This means that the values of V successively decreased, indicating at the same time, that the time of retention shortened in successive winters. This result is confirmed by the previous study on snow cover in Śnieżka in the period 1901–2000 (Głowicki 2005) or in the Polish Sudetes and their foreland in 1951–2007 (Urban 2015, 2016). The pace of decrease fell within the range from ca. − 0.6% points (pp)/decade in station Desná–Souš to ca. − 2.7 pp/decade in Świeradów Zdrój station or even − 3.1 pp/decade in station Horní Maršov. The average pace of the drop of coefficient V for all stations for which its trends of changes were determined was − 1.43 pp/decade (Table 3). The trend of V change is statistically significant at the $p = 0.05$ significance level merely for one out of eight stations which were selected for the analysis of snow conditions (Table 3). A slight decreasing trend in the characteristics of snow cover was observed in most of Polish area in the second half of the twentieth century. The changes in snow cover relate to the changes in the atmospheric circulation and especially with the increased frequency of the advection of air masses from the western sector (Falarz 2004). The more frequent occurrence of winters with a relatively low V coefficient might be related to the changes in atmospheric circulation

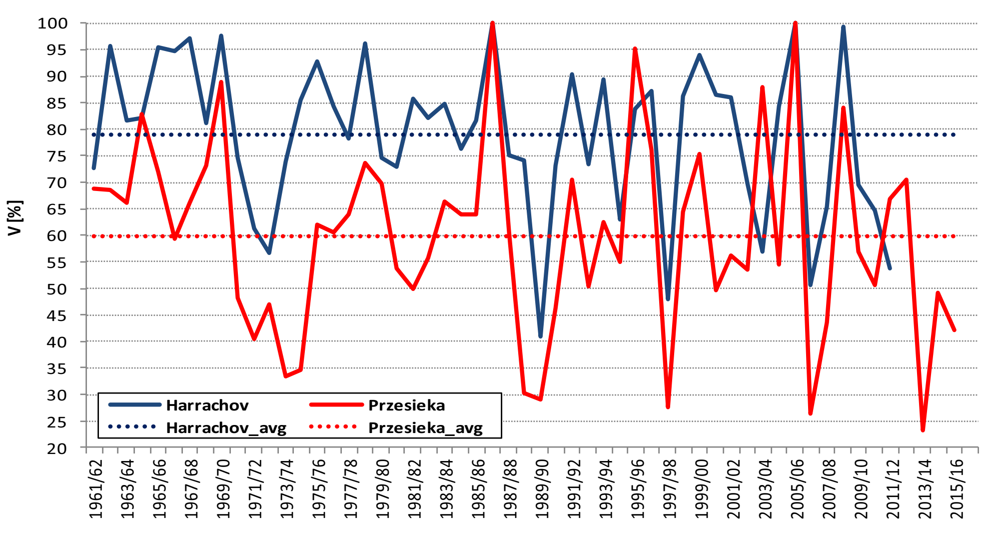

Fig. 4 The course of values of the coefficient of snow cover durability V (%) with the average value (dotted line)

Table 3 Change trend magnitude, correlation coefficient (*R*) and the statistical significance of the coefficient of snow cover durability

Station	Trend (pp/decade)	*R*	Number of seasons
Śnieżka	+ 0.504	0.097	55
Bedřichov	− 1.591	0.189	55
Desná–Souš	− 0.563	0.067	55
Przesieka	− 1.568	0.139	55
Horní Maršov	− 3.097*	0.275	55
Świeradów Zdrój	− 2.745	0.259	55
Hejnice	− 1.514	0.149	55
Jelenia Góra	− 0.905	0.082	55

*Significant statistically at the 0.05 significance level

types over the Northern Atlantic. The growth of zonal cyclonic circulation from the south-western direction in last decades of the twentieth century was proved by Migała (2005) and Migała et al. (2016). This circulation generates in Western and Mid-Europe a vast atmospheric front with increased cloudiness and brings warming and precipitation in the cold season (Urban et al. 2018).

This does not relate to the upper zone of the mountains (Śnieżka, Szrenica), where winters are more snowy and severe, and, as a result of snow blowing alternately from one to the other side of the mountain, no significant changes of snow cover durability are observed. On the contrary, a slight positive trend of the coefficient of snow cover durability is noticed there (Table 3). In certain areas, as well as in the upper zone of the Western Sudetes, an increasing trend in snow cover retention is noted (Räisänen 2008). Such phenomenon has been observed in the recent decadesin the Alps (Zemp et al. 2008) or in Norway (Andreassen et al. 2005).

A direct cause of the decrease in days with snow cover should be sought in the long-term change of air temperature and precipitation (Falarz 2004). Primary proofs of this can be the significantly increasing trends of air temperature in both Poland (Kożuchowski and Żmudzka 2001; Wibig and Głowicki 2002) and Europe (Schönwiese and Rapp 1997). This fact remains in close relation to the increase of the frequency of western circulation over Poland (Ustrnul 1998). Winter temperature increase can reduce winter precipitation share in general precipitation, the trends of which in the majority of Polish area in the years 1930–1980 were upward (Kożuchowski 1985). In consequence of all this, the durability of snow cover might reduce.

3.2 Spatial and temporal variabilities of disappearance of snow cover

Similar patterns described for the coefficient of snow cover durability also mark the distribution of snow cover disappearance with relation to the macro-exposures and altitudes of analysed stations. On average in December–March period, snow cover on the ground disappears completely from ca. 0.4 times at the stations in the upper ridges to ca. 6–7 times at the stations located at the lowest altitudes (Fig. 5; Table 4). For many years, the maximum number of cases of snow cover disappearance in these months decreases within the range from 4 to 17. The minimum can be zero (Fig. 5). Beside Śnieżka and Szrenica, the stations on the slopes with southern macro-exposure (e.g. Bedřichov, Desná-Souš, Harrachov, Vysoké nad Jizerou, Horní Maršov) are distinctly characterised by a small number of snow cover disappearance. On average, this number ranges from 1.5 to 3.0. The stations with northern macro-exposure (Przesieka, Szklarska Poręba, Karpacz_1, Karpacz_2) and localised at similar altitudes as the ones with southern macro-exposure are characterised by 2 ÷ 3 times bigger frequency of total disappearance of snow cover. The situation in the eastern part of the Karkonosze Mts looks particularly unfavourable—in the area of the stations representing middle and lower parts of the slopes, i.e. Karpacz_1, Przesieka and Karpacz_2, the average number of total disappearance in the middle of winter season equals 4 ÷ 6 (Fig. 5; Table 4). This is due to the warming impact of the foehn effect on leeward slopes (with the wind dominating in the winter from SW and S directions—perpendicular to the course of the Karkonosze), which contributes to the faster disappearance of the snow cover (Kwiatkowski 1972, 1975, 1979). The greater the height difference between the ridge and the station, the stronger the effect is. In the Eastern Karkonosze, the denivelation is approx. 200 m larger than in their western part. This phenomenon is unpropitious, because the region features many winter sports centres, including skiing ones.

In the multiannual course, for the selected pairs of the stations that are located on similar altitudes, but with opposite exposures, the significantly greater frequency of total disappearance of snow cover characterises slopes with northern macro-exposure (red continuous line in Fig. 6). However, there are seasons when total ablations occur more frequently at the stations located on the slopes with southern macro-exposure. The examples of extreme differences in this respect can be the seasons 1993/1994 and 1997/1998 (Fig. 6). In the first of them, ablations at the stations with northern macro-exposure (Przesieka, Karpacz_2) evidently outnumber the ones at the stations with southern macro-exposure (Harrachov, Horní Maršov). In the other period, the situation is the opposite. Probably, this extreme results from the domination of the opposite directions of atmospheric circulation. Namely, in the period December–March 1993/1994, the north-eastern direction of circulation occurred, according to classification by Lityński (1969), three times less frequently than in the same months in the season 1997/1998 (Pawłowska et al. 2000). NE direction is perpendicular to the course of the Sudetes massif. Thus, in the season 1993/1994 at the stations

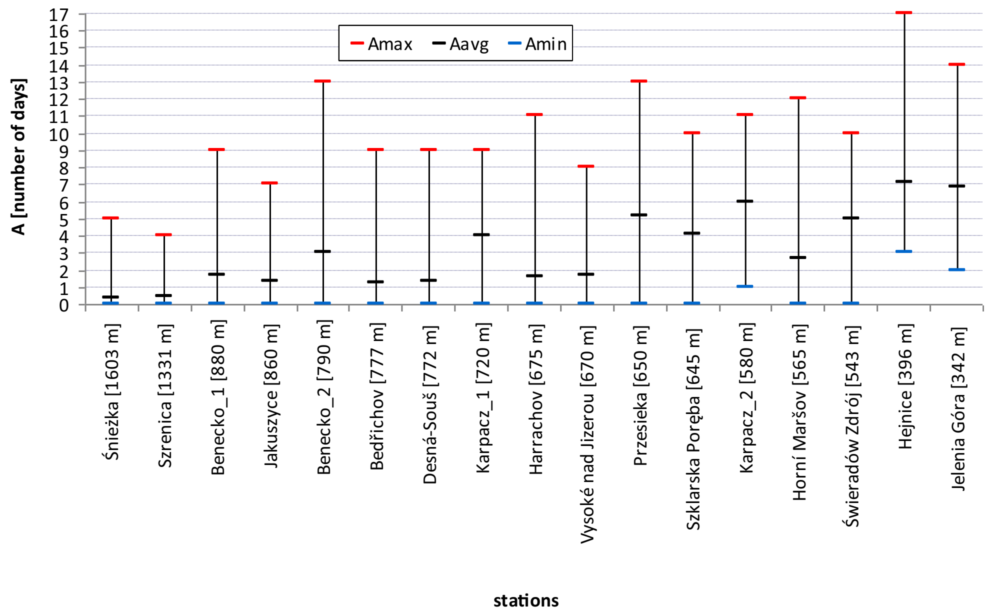

Fig. 5 Average (Aavg), maximum (Amax) and minimum (Amin) values of total disappearance of snow cover at the analysed stations in the period December–March

with southern macro-exposure, there appeared more frequent foehn phenomena and the adiabatic warming of descending air on the leeward side of the orographic barrier. The advancing frequency of the advection of polar and sea air masses from SW and W directions in the cold season in the Sudetes as well as their thermal and precipitation implications have already drawn attention of the researches in this field (Kwiatkowski 1972, 1975, 1979; Sobik et al. 2014; Urban et al. 2018). Although the correlation of the number of days with total disappearance of snow cover between Harrachov-Przesieka and Horní Maršov-Karpacz_2 stations is positive, it is clearly weaker than in the case of the V coefficients. The calculated correlation coefficient R for the common period 1983/1984–2010/2011 in the pairs of mentioned stations were 0.3.

The results presented in Fig. 5 and Table 4 are further specified in the graphic representation of the number of days with total disappearance of snow cover, depending on the altitude of the station with southern or northern macro-expositions. Here total disappearance of snow cover in the period December–March at the stations with northern macro-exposure significantly outnumbers (over twice) the ones at the stations with southern macro-exposure. This is especially visible at the altitude zone 500–900 m a.s.l. (Fig. 7).

3.3 Relationship between snow cover durability coefficient and total disappearance of snow cover

Analysis of the relationship between the snow cover durability coefficient V and total snow disappearance in the winter seasons 1981/1982–2010/2011 indicates that there is a negative correlation between these features. The linear correlation coefficients R in the analysed stations range from 0.0 to 0.7. In the stations with southern macro-exposure and at Śnieżka Mt., they are significant statistically at the 0.05 significance level. The correlation coefficient is clearly differentiated depending on the macro-exposure and altitude (Table 5). Namely, the stations with southern macro-exposure (eg Bedřichov, Harrachov, Horni Maršov) are characterised by the explicitly higher R values (0.7 ÷ 0.5) than stations with northern macro-exposure (eg. Przesieka, Karpacz_2, Świeradów Zdrój), where R is in the range of 0.3 ÷ 0.2. Thus, in the stations on the slopes of the Western Sudetes with southern macro-exposure, these features are usually strongly or very strongly correlated with each other, whereas in the stations with northern macro-exposure, the strength of the relationship is usually moderate or very weak. This is well illustrated by the correlations of the selected stations located at similar altitudes, but with opposite macro-exposures, i.e. Horní Maršov—Karpacz_2 and Harrachov—Przesieka (Fig. 8). In addition, the strongest correlation occurs in the middle parts of the slopes with macro-exposure S and SW. The weakest correlation (0.0 ÷ 0.1) or even lack of it is shown by the stations with the lowest locations and northern macro-exposure, i.e. Hejnice and Jelenia Góra (Table 5). This is due to differences (already mentioned in the study) in temperatures and winter precipitation in slope stations with opposite macro-exposures conditioned by the foehn effect and the altitude above sea level.

4 Summary and conclusions

The analysis of snow cover durability in the Western Sudetes, which was conducted based on the available measurement

Table 4 Average number of total disappearance of snow cover in the period December–March

Station/period	Śnieżka	Szrenica	Benecko_1	Jakuszyce	Benecko_2	Bedřichov	Desná-Souš	Karpacz_1	Harrachov	Vysoké nad Jizerou	Przesieka	Szklarska Poręba	Karpacz_2	Horní Maršov	Świeradów Zdrój	Hejnice	Jelenia Góra
H (m a.s.l.)	1603	1331	880	860	790	777	772	720	675	670	650	645	580	565	543	396	342
According to Table 1	0.4	0.4	1.7	1.3	3.0	1.3	1.3	4.0	1.6	1.7	5.2	4.1	6.0	2.7	5.0	7.2	6.9
1981/1982–2010/2011	0.5	0.7	n.d	1.5	n.d	1.5	1.5	n.d	2.1	n.d	4.9	n.d	n.d	3.0	5.2	7.3	6.8
1994/1995–2011/2012	0.3	0.9	n.d	1.2	2.4	1.3	1.2	n.d	2.2	n.d	4.6	n.d	5.8	3.3	5.5	7.3	6.0

n.d. no data

data from the winter seasons 1961/1962–2015/2016, enables us to put forward the following claims:

- The spatial distribution of the average coefficient of snow durability is the resultant of many factors, including altitude, the location of the mountain barrier (on WNW–ESE axis) in relation to the south-western direction of circulation that dominates in cold season and the orographic deformation of the flow field of air masses. As a result of this deformation, the snowiness of the river Elbe catchment (S–SW–W macro-exposure) distinctly contrasts with the one in the river Odra catchment (N–NE macro-exposure). The average value of V increases with altitude. The areas with macro-exposure SW and W (windwards) are characterised by better snow conditions than the ones situated at similar altitudes, but with macro-exposure N–NE (the Odra river catchment). This contrast is particularly noticeable in the altitude range 500–900 m a.s.l. In the upper ridges, the differences are disappearing, as the snow often alternately blows from one to the other side of the mountain massif. These results are similar to the ones obtained for the same area by the authors and presented in the earlier work concerning the thermal severity and snowiness of winters (Urban et al. 2018).
- The stations located on the northern side of the mountains, below their upper ridges, are subject to a warming influence of foehn more frequently than the ones located on the southern side. The impact of foehn wind is greater when the denivelation between the ridge and the station is bigger. That is why in winter, stations with northern macro-exposure are warmer than the ones located at similar altitudes, but with southern macro-exposure. Thus, the first are characterised by a weaker durability of snow cover and, as it was stated before, by less snowy and severe winters (Urban et al. 2018).
- Seasons with the moderate values of V ($Vavg-\delta < V < Vavg+\delta$) prevailed.
- Since the turn of the 1980s and 1990s, everywhere except for Śnieżka, the increase in the frequency of seasons with small V ($V \leq Vavg-\delta$) and the decrease in frequency of seasons with high V ($V \geq Vavg+\delta$) were noted. Seasons 1989/1990 (for the stations located above 650 m a.s.l.), 2006/2007 and 2013/2014 (for the stations located below 650 m a.s.l.) were marked by extremely low V, whereas winter seasons with high V values (with continuous snow cover) occurred at the majority of the stations in the 1960s and 1986/1987, 1995/1996 and 2005/2006. Among those seasons with the highest V (100% at as many as seven stations), the period 2005/2006 stood out. The high values of V were noted for the season 1995/1996, but primarily at the stations located below 700 m a.s.l. Incidentally, seasons with high V feature only in the upper (1974/1975) or lower part of the altitude profile (2003/04).

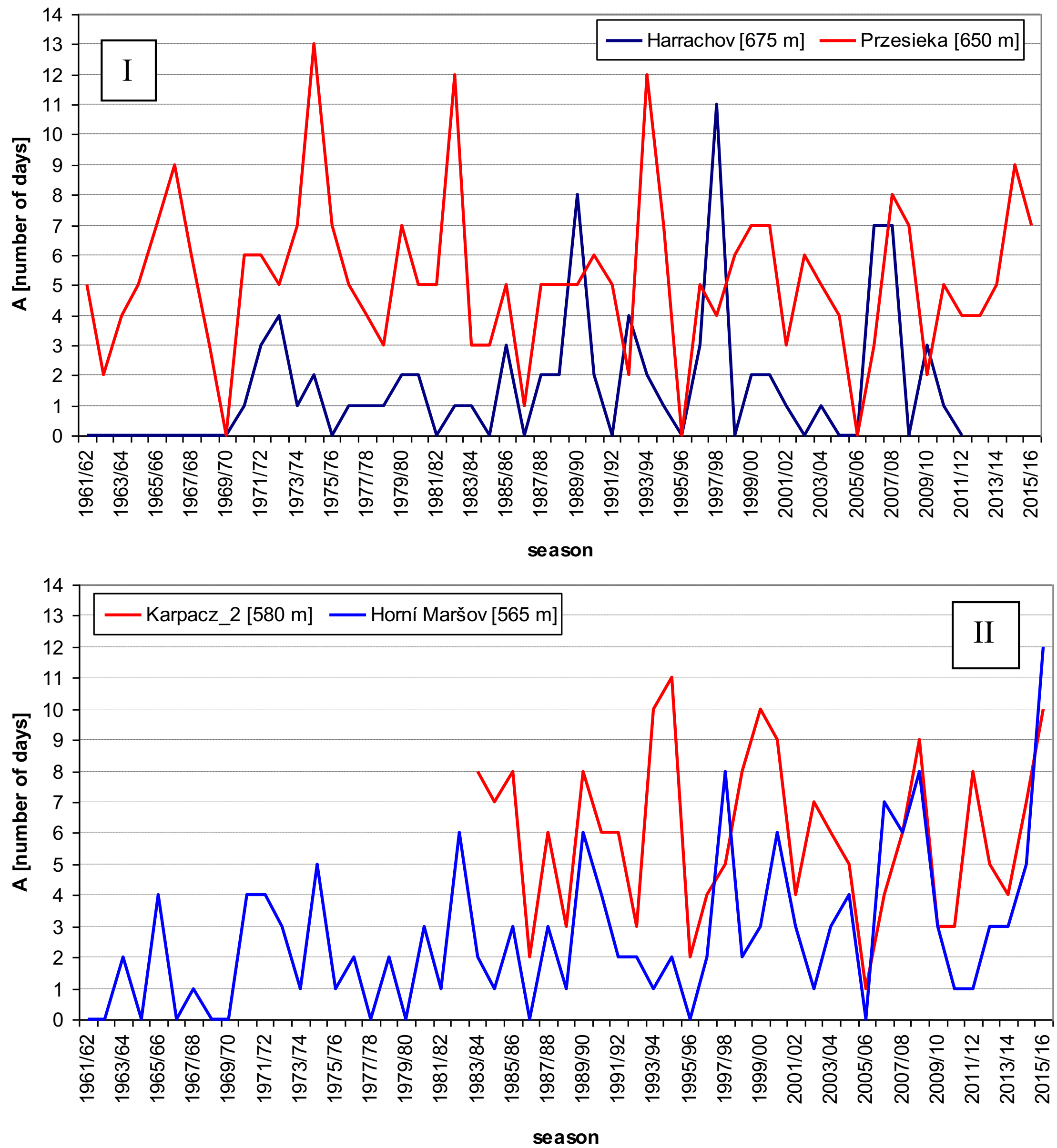

Fig. 6 The course of number of days with total disappearance of snow cover (A) at the stations: Harrachov–Przesieka (I) and Horní Maršov–Karpacz_2 (II) in the period December–March

Fig. 7 The relationship between station altitude (H) and total disappearance of snow cover (A) in the period December–March for southern (S) and northern (N) macro-exposures

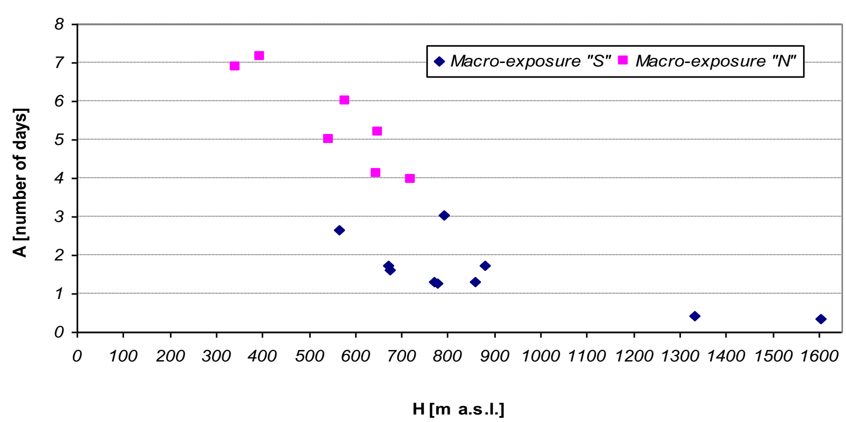

Table 5 Pearson's linear correlation values (*R*) and strength of the relationship between the snow cover durability coefficient and total snow disappearance in 1981/1982–2010/2011 winter season in the selected stations

Station (m a.s.l.)	*R*	Strength of relationship
Śnieżka (1603)	0.6*	Strong
Jakuszyce (860)	0.5*	Strong
Bedřichov (777)	0.7*	Very strong
Desná-Souš (772)	0.6*	Strong
Harrachov (675)	0.5*	Strong
Przesieka (650)	0.3	Moderate
Karpacz_2 (580)	0.2	Very weak
Horní Maršov (565)	0.7*	Very strong
Świeradów Zdrój (543)	0.3	Moderate
Hejnie (396)	0.0	No relationship
Jelenia Góra (342)	0.0	No relationship

In Karpacz_2 station in 1983/1984–2010/2011 winter seasons

*Significant statistically at the 0.05 significance level

– The variability of the coefficient of snow cover durability is inversely proportional to altitude. The lowest values of Vz (around 10–15%) occur in the upper ridges of the Western Sudetes. This means that the snow cover is more stable and is subject to smaller fluctuations, whereas the biggest values of Vz (around 35%) occur in the stations that are localised at the lowest altitudes.

– In the wide slope zone, the variability of the coefficient V varies significantly. This is especially noticeable in the zone 600–700 m, where the stations with macro-exposure S are characterised by a distinctly smaller variability of V (16–18%) than the stations with macro-exposure N (ca. 30%). Snow cover at similar altitudes at the stations with southern macro-exposure is subject to smaller fluctuations than at the stations with northern macro-exposure.

– On both sides of the mountains, the trends of the coefficient of snow cover are mostly negative, which indicates that the time of the retention of snow cover shortened in successive winters. However, in the overwhelming majority of cases, these trends are not statistically significant at the $p = 0.05$ significance level.

– The stations with northern macro-exposure that are located at similar altitudes as the ones with southern macro-exposure are characterised by 2 ÷ 3 times bigger frequency of total disappearance of snow cover. This is particularly visible at the altitude zone 500–900 m a.s.l.

– Trends of snow conditions changes for winters in the Western Sudetes expressed by V relate to the trends in the other mountain areas of Poland and Europe.

– The snow cover durability coefficient is negatively correlated with total snow disappearance. In stations on the slopes of the Western Sudetes with southern macro-exposure, these correlations are usually strong or very strong. However, in the stations with northern macro-exposure, at similar altitudes, the strength of the relationship is usually moderate or very weak. The strongest correlation occurs in

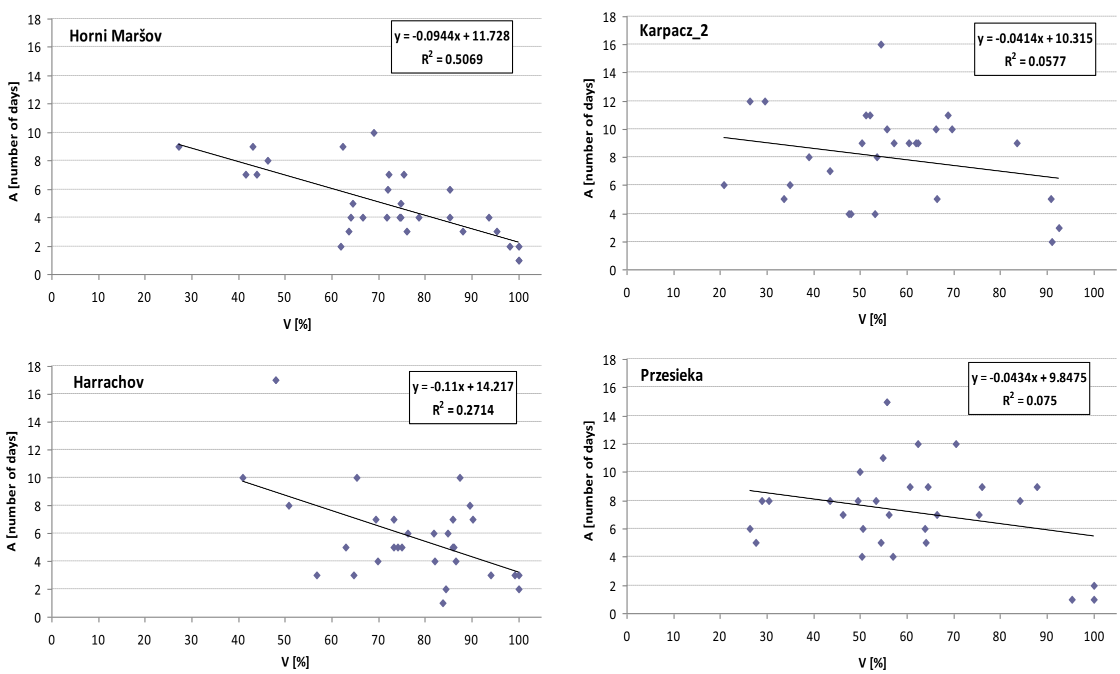

Fig. 8 The relationship between snow cover durability coefficient (V) and total snow disappearance (A) in 1981/1982–2010/2011 winter seasons alongside their trend lines (black bold lines) and simple regression equations in selected macro-exposure stations S (left column) and macro-exposure N (right column). Note: in Karpacz_2 station in 1983/1984–2010/2011 winter seasons.

the middle parts of the slopes with southern and south-western macro-exposure. In stations with southern macro-exposure and at Śnieżka Mt, these correlations are statistically significant at the 0.05 significance level.

The negative trends of the coefficient of snow cover durability were noted in the Western Sudetes for the vast majority of stations (except for the ones located in the upper zone of the ridges). The further phase of the research (in the next paper) will aim at investigating the reasons for such status quo, and the authors will attempt to answer the question whether this ensues from the changes of the dates of appearance and disappearance of snow cover, the number of days with snow cover, its depth, etc. The results of this research may provide the basis for further study on snow cover in mountain areas.

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