Snow cover and its variability in the Polish Sudetes Mts. and the Sudetic Foreland

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ABSTRACT The paper presents the snow cover characteristics in the vertical profile of the Polish Sudetes Mountains and their foreland during the period of 1965/66–2007/08. The analysis was based on the number of days with snow cover ≥ 1 cm and its depth in a month, winter season (December–February) and entire year (season). Data was collected at 20 weather stations operated by the Institute of Meteorology and Water Management. The maximum depth of snow cover in the foreland and lower parts of the Sudetes Mountains was recorded in January, in higher parts of the mountains in mid-February or in March. On the average, the maximum depth of the snow cover varied from ca. 15÷25 cm in the foreland zone and lower slopes up to 120÷150 cm in the upper slopes and mountain tops. During the multi-annual period of 1951/52–2007/08, the maximum depth of snow cover showed a small decreasing trend, statistically insignificant at the 0.05 level, in 4 representative stations in the vertical profile of the Sudetes Mountains.

KEY WORDS snow cover – Sudetes Mts. – regression equation – change trends

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1. Introduction

Snow cover significantly affects natural environment and different areas of human activities. Due to its role in modifying energy stream and humidity between surface and atmosphere, snow cover is considered to be a crucial component of the global climate system (Brown, Goodison 2005; Vavrus 2007). Furthermore, it is a very good indicator of winter season climate change because of its direct and indirect response to climate elements and factors and both its presence and absence impact several climate elements (Foster, Owe, Rango 1983). The knowledge of long term trends of snow cover in Poland appears to be important due to the increasing, statistically significant, trend of air temperature which is particularly evident during winter (Kożuchowski, Żmudzka 2001; Wibig, Głowicki 2002).

The condition and temporal variability of snow cover in Poland, especially on plains, are rather well described (Bednorz 2002; Falarz 2004, 2007, 2010; Kasprowicz 2010). In the second half of the 20th century, in the major part of area of Poland, small negative trends of snow cover duration and depth were determined. Positive trend of snow cover duration was found only in several mountain regions, and in case of its depth – in north-eastern Poland (Falarz 2004).

The subject of spatial conditions of snow cover distribution in Sudetes was examined in many papers. They emphasize the increase of snow cover duration and depth relative to the altitude (Reunier 1935; Kosiba 1949; Kwiatkowski 1978, 1985; Hladný, Sýkora 1983). Authors of these works also indicate the effect of local relief and vegetation on variability of snow density and duration. Differentiation of snow cover parameters is high even in small areas due to land cover and exposure (Bac 1961; Szarejko 1984a, b; Mrugasiewicz, Sobik 2000; Sobik et al. 2009; Ojrzyńska et al. 2010; Urban, Richterová 2009; 2010; Urban, Richterová, Vajskebr 2011).

However, the number of works discussing snow cover variability based on long term data series seems to be insufficient, especially for mountainous areas.

Research of long term trends of snow cover which included the entire country area were carried out in several European countries and include, besides Poland, Slovakia (Lapin, Faško 1996); Switzerland (Beniston 1997, Beniston et al. 1994) and Estonia (Jaagus 1997).

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This work aims to characterize snow cover in the Polish Sudetes and their foreland as well as to provide the analysis of its variability in different hypsometric zones based on the number of days and depth of snow cover.

2. Source materials and methodology

Snow condition characteristics were based on number of days with snow cover ≥ 1 cm and its depth in consecutive months, 3-month winter periods (D-F) and entire years (seasons). Winter season is defined as a period beginning on August 1st of a given year and ending on July 31st of the following year. Analogical approach was used earlier by Falarz (2000–2001). The analyzed parameters were determined using daily data of snow cover depth at 06 GMT taken in selected the Institute of Meteorology and Water Management (IMWM) weather stations located in the Polish part of the Sudetes and their foreland spanning 43 consecutive winter seasons (1965/66–2007/08). The selection of weather stations was based on the availability of long data series and completeness of measurement series. The methodology of snow cover measurements was homogenous and complying to the guidelines of the National Hydrological-Meteorological Service of IMWM (Janiszewski 1988). Additional criteria of the selection were continuity of location and representation of different Sudetes altitude zones (Tab. 1, Fig. 1).

Using linear regression equations, vertical profile was determined for respective parameters for the entire population of the analyzed weather stations for the

Tab. 1 – The list of the stations from the Polish Sudetes Mts. and their foreland, used for characteristics of snow cover

No.	Station	H (m a.s.l.)	Morphological form	Physico-geographical macroregion according to Kondracki's classification (1988)	Climatological zone according to Hess et al. (1980)
1	Legnica	122	valley	Nizina Śląsko-Łużycka	moderately warm
2	Zgorzelec	203	valley	Pogórze Zach.-sudeckie	moderately warm
3	Otmuchów	212	valley	Przedgórze Sudeckie	moderately warm
4	Pszenno	225	valley	Przedgórze Sudeckie	moderately warm
5	Jelenia Góra	342	basin	Sudety Zachodnie	moderately warm
6	Głuchołazy	350	slope	Sudety Wschodnie	moderately warm
7	Kłodzko	360	basin	Sudety Środkowe	moderately warm
8	Długopole Zdrój	393	valley	Sudety Środkowe	moderately warm
9	Szczawno Zdrój	430	slope	Sudety Środkowe	moderately warm
10	Lądek Zdrój	461	slope	Sudety Wschodnie	moderately warm
11	Walim	490	slope	Sudety Środkowe	moderately warm
12	Bukówka	510	slope	Sudety Środkowe	moderately warm
13	Paprotki	540	slope	Sudety Środkowe	moderately warm
14	Świeradów Zdrój	550	slope	Sudety Zachodnie	moderately warm
15	Słoszów	555	slope	Sudety Środkowe	moderately warm
16	Rościszów	575	slope	Sudety Środkowe	moderately cold
17	Przesieka	650	slope	Sudety Zachodnie	moderately cold
18	Międzygórze	675	slope	Sudety Wschodnie	moderately cold
19	Jakuszyce	860	mountain pass	Sudety Zachodnie	moderately cold
20	Śnieżka	1,603	peak	Sudety Zachodnie	very cold

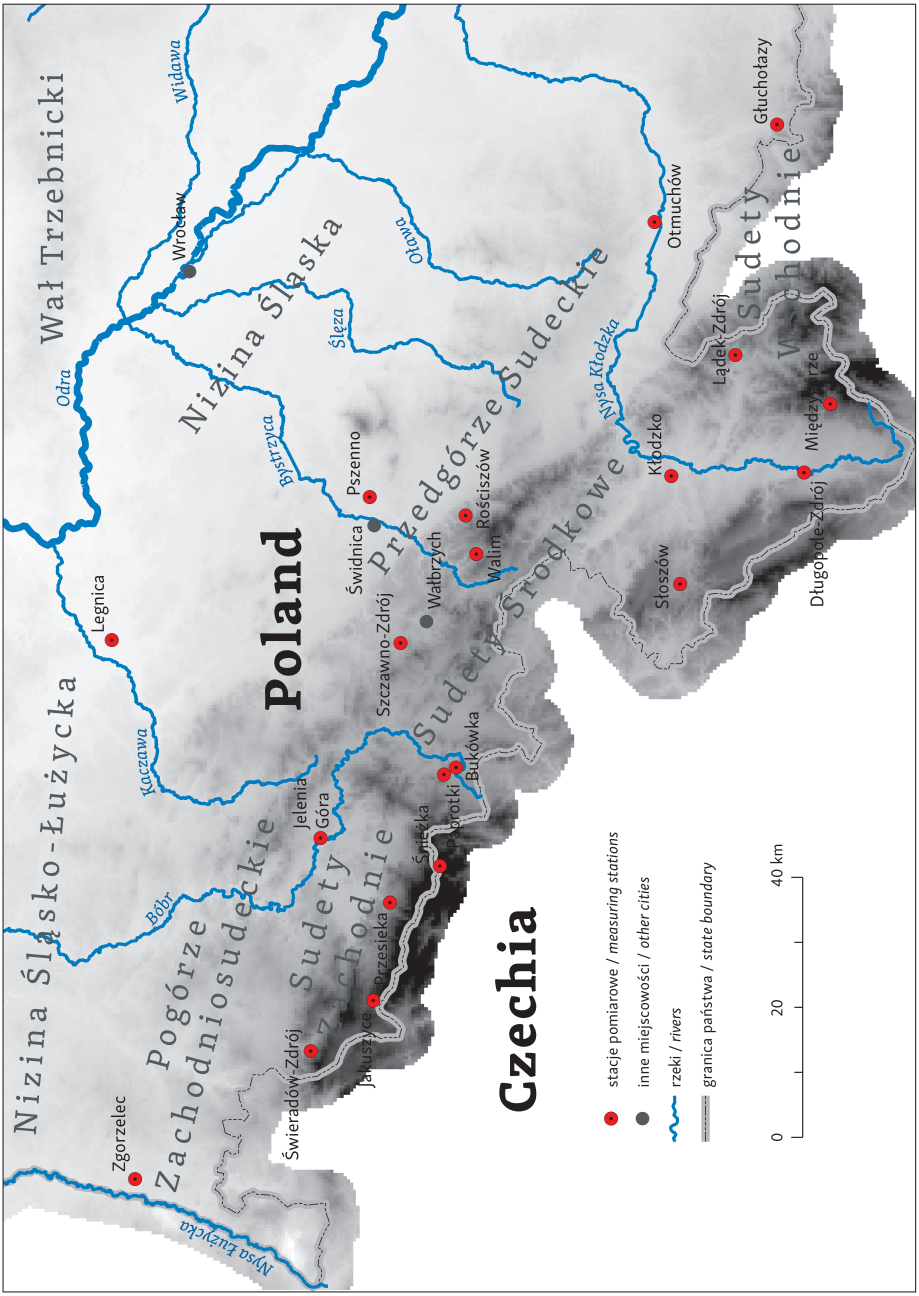

Fig. 1 – Location of the stations considered in the paper in the background of the region

period of 1965/66–2007/08. Further, equation of dependence for each snow cover parameter was created to show changes of snow conditions in vertical profile for the entire area of the Polish Sudetes and their foreland. Regression equations provide generalizations that do not reflect specific local conditions shaped by i.a. relief, exposure, vegetation, all of which create considerable topoclimatic variability. Moreover, a relatively small number of weather stations and their distribution disproportion (or even absence) in particular hypsometric levels (Tab. 1) preclude in-depth analyses. Analogical approach to the study of the Sudetes was used earlier by Dusza (1977). Regression method in examining climate conditions of the Sudetes was used by, among others, Kosiba (1949); Hess, Niedźwiedź, Obrębska-Starklowa (1980); Ustrnul (1991); Migała (2005, 2008). Furthermore, in case of selected weather stations with homogenous data series representing different climate conditions and morphological forms (Śnieżka Mt. – peak zone, Lądek Zdrój – lower part of slopes, Jelenia Góra – bottom of a large intermontane Sudetes valley, and Zgorzelec – the Sudetes foreland), an analysis of variability of selected snow parameters in 1951/52–2007/08 seasons was carried out. Measurement data from the aforementioned stations are homogenous and reliable for the purpose of detection of climate change in the Sudetes Mts. (Głowicki 2008). Using Student's t-test, trend statistical significance at the level of 0.05 was examined.

Other characteristics of snow cover and their changeability such as dates of appearance and disappearance of snow cover, its permanence at the same stations during the same long-term period presented here were examined by author in a different article (Urban 2015).

3. Results and discussion

3.1. Mean annual number of days with snow cover

Mean annual (seasonal) number of days with snow cover ≥ 1 cm (NDSC) determined for 1965/66–2007/08 seasons in 20 weather stations increases with altitude from ca. 40–45 days in the Polish Sudetic Foreland to 193 days on Śnieżka Mt. The increase of mean number of days with snow cover with altitude, described by linear regression equation, shows close correlation dependence (R = 0.966) and is 11.4 days / 100 m (Fig. 2). This result is almost identical with the result for Lower Silesia Region in multi-annual period of 1971–2000 (Głowicki et al. 2005) and also a much earlier created formula characterizing changes of snow cover in south-western Poland in 1919–1940 (Kosiba 1949).

The changes of number of days with snow cover with altitude indicate a visible positive anomaly in duration in the 800–900 a.s.l (moderately cold) zone represented by Jakuszyce weather station. In this area, positive anomalies of

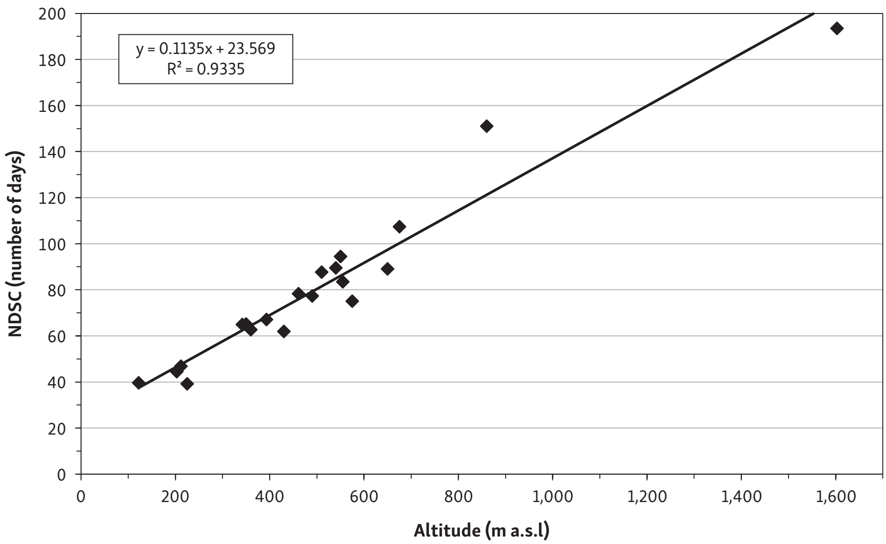

Fig. 2 – Correlation between average annual number of days with snow cover depth ≥ 1 cm and altitude in the Polish Sudetes Mts. and their foreland in the 1965/66–2007/08 period

snow cover duration increase proportionally to snow cover depth. The actual snow cover duration is longer here than the theoretical one (determined from regression equation) by 25% days per year for number of days with snow cover ≥ 1 cm and up to 85% for number of days with snow cover 50 cm (Figs. 2, 6, 9). Jakuszyce vicinity is characterized by positive anomaly of snow cover depth (Dubicki, Głowicki, Woźniak 1997) and exceptionally high and even annual distribution of atmospheric precipitation, with total exceeding 100 mm, and secondary maximum occurring in January (Sobik 1998; Błaś, Sobik 2005). This area represents typical snow conditions in the central part of the Jizera Mountains characterized by Mrugasiewicz and Sobik (2000), among others. The absence of protection by morphological forms in the area of Jakuszyce against the dominant snow producing air masses during winter is conductive to high atmospheric precipitation. In winter, air masses from south reaching the Sudetes Mts. are "snow producing" because of their high moisture content from the area of origin (the Mediterranean Sea). In the then windward area of the southern (Czech) Sudetes, orographic air damming occurs resulting in precipitation of moisture. The northern (Polish) Sudetes are then leeward area where descending air causes its adiabatic warming and decrease of the observed precipitation totals. For example, winter season precipitation totals at weather stations located in the Karkonosze Mts. at similar altitudes above sea level are 25% higher in the Czech area than on the Polish side (Sobik et al. 2009, 2014). Moreover, Jakuszyce location in the shallow valley of the upper Kamienna River, part of the upland mountain passing, creates favorable conditions for stagnation of cold air masses which preserve snow cover by slowing down ablation processes. Additionally, in this area, snow is not strongly blown off as it is the case in the conditions of the upper-summit parts (Śnieżka), above the tree line. Due to all the above factors, this region is characterized by the best snow conditions at this altitude level in the Polish Sudetes (Urban, Richterová 2010).

3.2. Temporal and spatial variability of days with snow cover, long-term trends

The extreme values of seasonal number of days with snow cover in the vertical profile of the Sudetes did not occur simultaneously in the analyzed period. The lowest number of days with snow cover value in the lower part of the profile was noted in 2006/07 season, while the highest during 1995/96 season, among others. At the peak level (Śnieżka), the lowest number of days with snow cover was recorded during 1958/59 season and the highest in 1974/75. The differences between the lowest and the highest parts of the vertical profile are also apparent in the variability rate of snow conditions parameters. Changes of seasonal number of days with snow cover in the period of 1951/52–2007/08 in the peak zone of the Karkonosze Mts. (Śnieżka) show increasing trend of 2.59 days / 10 years. In the lower parts of the altitudinal profile of the Polish Sudetes, a visible decrease of this snow parameter can be noticed, and in case of Lądek Zdrój it is 4.26 days / 10 years (Fig. 3, Tab. 2). Both at Śnieżka Mt. and in Lądek Zdrój, the determined trends are statistically significant at the 0.05 level. However, in case of 100-year observation series of annual number of days with snow cover at Śnieżka Mt., only slightly decreasing trend of number of days with snow cover was found. Student's t-test indicated that this trend is not statistically significant at the 0.05 level (Głowicki 2005). Calculated linear trends of number of days with snow cover in 1951/52–2007/08 season for other representative stations, i.e. Jelenia Góra and Zgorzelec, are not statically significant at the level of 0.05.

Tab. 2 – Selected characteristics of average number of days with snow cover in the 1951/52–2007/08 period

Number of days with snow cover depth ≥1 cm								
Station	Average (days)	The highest one		The lowest one		Standard deviation (days)	Variation coefficient (%)	Change (days) / 10 years
		(days)	season	(days)	season			
Śnieżka	190	229	1974/75	136	1958/59	19.3	10.2	2.59
Lądek Zdrój	81	138	1995/96	26	2006/07	24.4	30.2	−4.26
Jelenia Góra	66	139	1995/96	14	2006/07	24.2	36.9	−1.32
Zgorzelec	46	109	1969/70	8	2006/07	20.7	44.9	−3.03

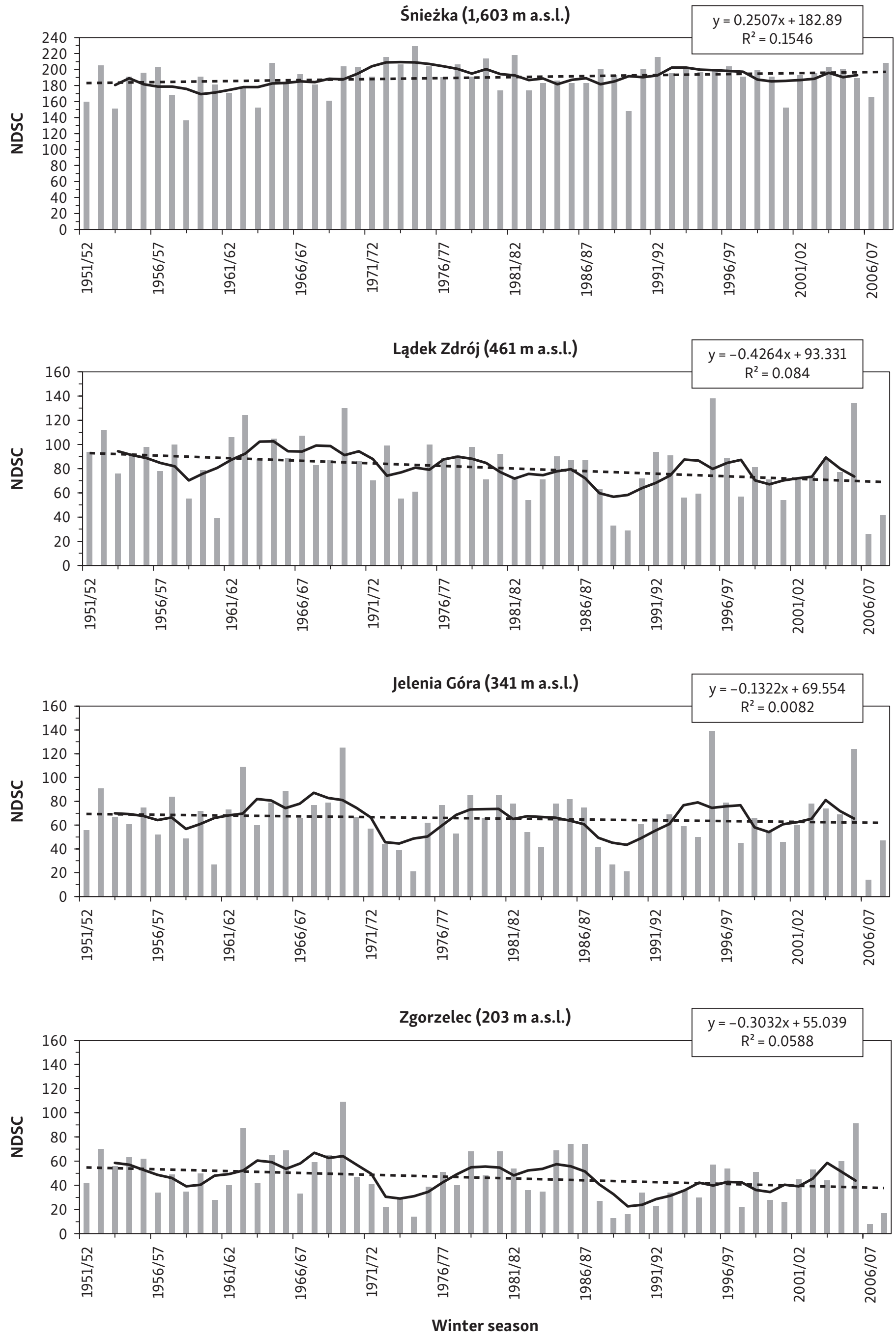

Fig. 3 – Course of average annual number of days with snow cover, and its tendency line (the dashed line), equation of regression and a 5-year consecutive average (the solid line) in the 1951/52–2007/08 period

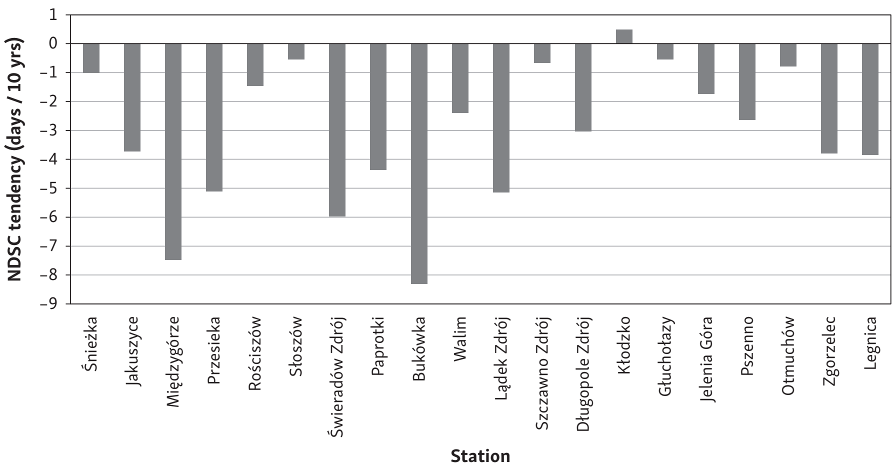

Fig. 4 – Number of days with snow cover tendency (days / 10 yrs) in the Polish Sudetes Mts. and their foreland in the 1965/66–2007/08 period

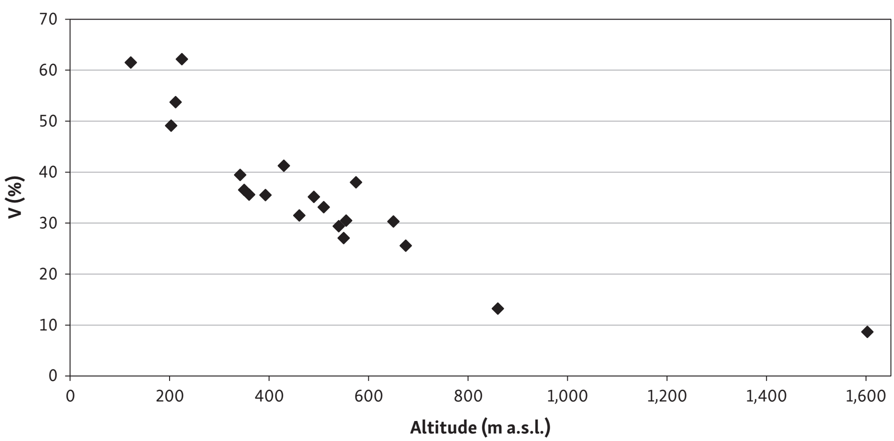

Fig. 5 – Variation coefficient (V) of number of days with snow cover in the Polish Sudetes Mts. and their foreland in the 1965/66–2007/08 period

Similarly, in the long term period of 1965/66–2007/08 at all analyzed stations (except Kłodzko), negative trends of number of days with snow cover were determined (Fig. 4). These trends are statistically significant at the significance level of 0.05 in case of Międzygórze and Bukówka stations and not statistically significant at the 0.05 level at all other stations.

Snowiness variability of particular winters, expressed by number of days with snow cover is very high. Winter seasons are characterized by a considerable irregularity of snow cover occurrences which is most evident in lower part of altitudinal profile of the Sudetes. Number of days with snow cover variability is inversely proportional to its duration and, accordingly, to the altitude above sea level. This is supported by the values of variation coefficient – the highest 30÷45% in stations located in the lower parts of the profile and the lowest – ca. 10% in the peak zone (Tab. 2). During shorter time period (1965/66–2007/08), at stations located in the lowest parts of the profile, they reach as high as nearly 50÷60% (Fig. 5). However, due to the strong influence of the local relief, the decrease of variation coefficient and the increase of number of days with snow cover with the altitude in vertical profile are not linear (Fig. 5). Periods with no snow in the middle of a winter are not exceptions in the lower parts of the profile. For example, the range of the annual number of days with snow cover expressed in (%) of multi-year mean value of number of days with snow cover varies from 42% on Śnieżka to 250% in Pszenno and up to 270% in Legnica. These results are evidence of high variability and instability of snow cover in the lower parts of the altitudinal profile of the Sudetes and their foreland. The decrease of snow cover duration, particularly in the low altitude parts, was also found in other mountain regions in Europe (Scherrer, Appenzeller Laternser 2004) and western parts of North America (Mote 2006). The results of air temperature measurements at Śnieżka which have been carried out since 1881 and provide valid evidence of warming process observed on a global scale, confirm the increase of number of days with mean daily temperature above 0.0 °C and two-fold faster increase rate of minimum temperature than maximum temperature. The effects of the progressing warming are shorter winters, earlier spring snow melting, etc. (Migała, Urban, Tomczyński 2015). In high altitude regions, where winters are colder, the decrease of snow cover occurrences is smaller and some areas snow cover occurrences even show increasing trends (Räisänen 2008). The latter phenomenon has been observed in the last decades in the Alps, among others and Norway (Andreassen et al. 2005).

3.3. Snow cover depth and its variability

The relatively poor observation material does not allow for an in-depth analysis of snow cover depth changes in the hypsometric profile of the Polish part of the Sudetes Mts. and the Sudetic Foreland. In the examined area, average depth of snow cover during winter 3-month period (D–F) does not exceed 5 cm in the Sudetic Foreland and bottoms of large mid-Sudetes basins, while in the lower and middle parts of the slopes, it is no higher than 15 cm. In the upper zone of the Karkonosze Mts., on the other hand, snow cover reaching over 70 cm in depth is registered (Fig. 6, Tab. 3).

The comparison of snow cover depth per month given by Chrzanowski (1988) and results in Table 3 shows that in respective months, the area of the Sudetic

Tab. 3 – Average depth of snow cover (cm) in the 1965/66–2007/08 period. The highest average values are in italics

Station	H (m a.s.l.)	XII	I	II	III	winter (XII–II)
Śnieżka	1,603	48.6	77.8	96.8	*109.8*	74.4
Jakuszyce	860	38.5	66.6	*82.3*	74.3	62.5
Międzygórze	675	14.3	23.1	*24.5*	19.1	20.6
Przesieka	650	8.4	12.7	*15.1*	12.5	12.1
Rościszów	575	5.9	*10.4*	9.8	8.9	8.7
Słoszów	555	7.7	13.3	*14.1*	9.2	11.7
Świeradów Zdrój	550	9.5	15.4	*15.7*	12.6	13.6
Paprotki	540	8.3	14.8	*16.6*	12.9	13.2
Bukówka	510	8.5	14.2	*14.9*	10.8	12.5
Walim	490	6.5	*11.7*	11.2	9.4	9.8
Lądek Zdrój	461	5.8	*8.8*	8.3	6.3	7.6
Szczawno Zdrój	430	3.4	*6.9*	6.5	4.9	5.6
Długopole Zdrój	393	5.6	*11.8*	11.2	6.5	9.5
Kłodzko	360	2.7	*4.9*	4.7	2.5	4.1
Głuchołazy	350	3.5	*5.5*	5.2	3.5	4.7
Jelenia Góra	342	4.1	*7.3*	5.7	3.6	5.7
Pszenno	225	1.4	*3.9*	2.9	1.5	2.8
Otmuchów	212	2.1	*3.9*	3.4	1.6	3.1
Zgorzelec	203	2.0	*5.2*	3.1	1.3	3.5
Legnica	122	1.2	*3.1*	2.4	1.1	2.3

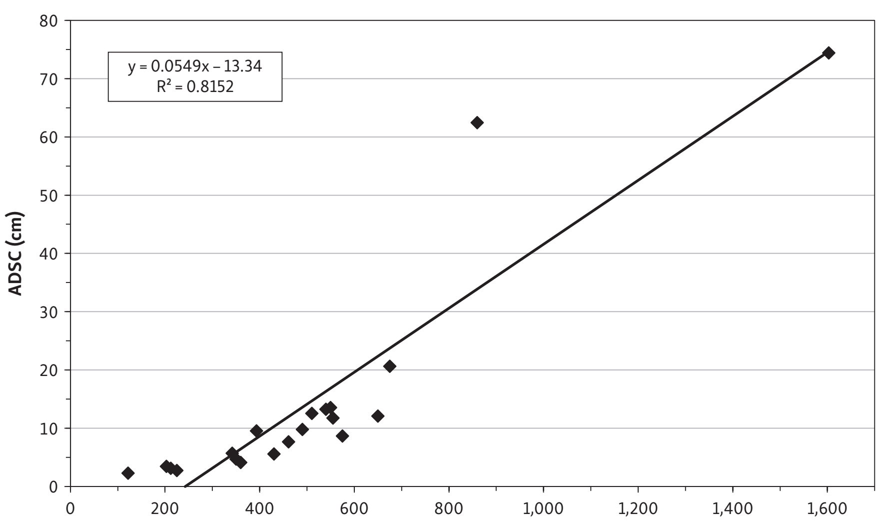

Fig. 6 – Correlation between average depth of snow cover in the term of winter (XII–II) and altitude in the Polish Sudetes Mts. and their foreland in the 1965/66–2007/08 period

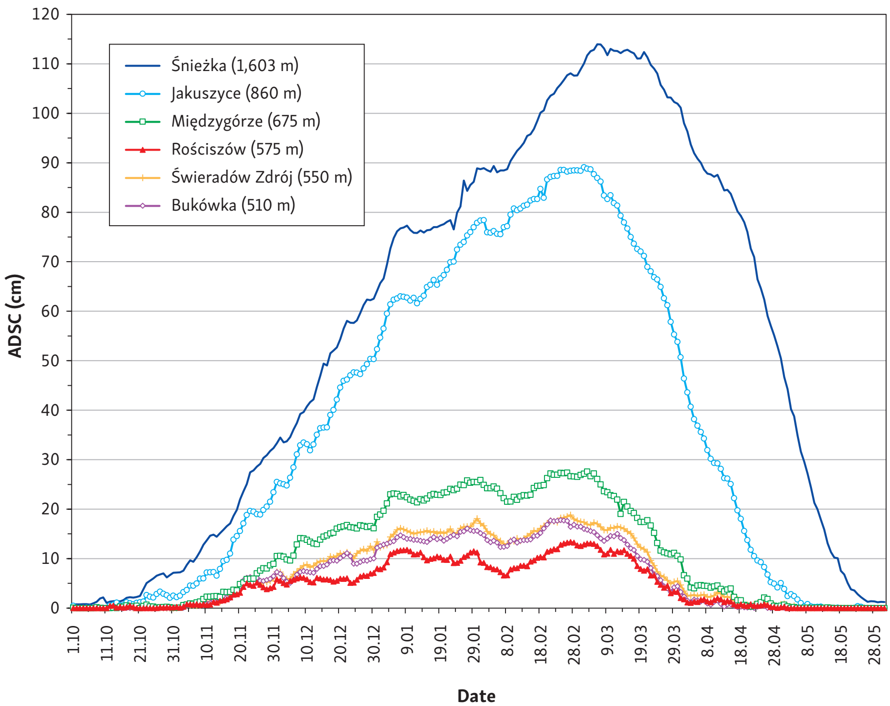

Fig. 7 – Daily course of average depth of snow cover in X–V in the 1965/66–2007/08 period at the selected stations located above 500 m a.s.l.

Foreland and lower parts of slopes (up the altitude of ca. 500 m a.s.l) is characterized by a thin and moderate snow cover (average depth of snow cover 1÷5 cm and 6÷10 cm, respectively). In the altitude zone of 500–600 m a.s.l., a deep snow cover (average depth of snow cover 11÷20 cm) prevails, while the upper areas and the Jakuszyce region are characterized by an exceptionally deep snow cover (average depth of snow cover over 30 cm).

Average depth of snow cover increase rate relative to the altitude oscillates between 3.6 cm / 100 m in December and 7.9 cm / 100 m in March while the 3-month average winter value is 5.5 cm / 100 m as described by the equations in Table 4. The highest average monthly value of snow cover in the upper parts of the altitudinal profile occurs in March and a little lower in February while, in case of the Sudetic Foreland and basins, in January (Tab. 3). A more detailed evidence is provided by, for example, daily change of mean snow cover depth from stations located above 500 m a.s.l. It shows that the maximum average depth of snow cover in the upper parts of the vertical profile of the Polish Sudetes occurs in the first decade of March and, in the lower parts, in the mid-February (Fig. 7). The differences that can be noticed in the variability of average depth of snow cover values at

Tab. 4 – Correlation between average depth of snow cover (ADSC) depth ≥ 1 cm and the altitude (H) in the Polish Sudetes Mts. and their foreland in the 1965/66–2007/08 period

Month	Regression equation	Correlation coefficient „R”
December	ADSC = 0.0357×H−8.6193	0.92
January	ADSC = 0.0569×H−12.652	0.90
February	ADSC = 0.0722×H−18.749	0.90
March	ADSC = 0.0792×H−24.388	0.92
Winter (December–January)	ADSC = 0.0549×H−13.340	0.90

Tab. 5 – Maximum annual values of the depth of snow cover (cm) and the date of occurrence of the maximum in the Polish Sudetes Mts. and their foreland in the 1965/66–2007/08 period

Station	Elevation (m a.s.l.)	Max	Date
Śnieżka	1,603	247	14.–15.03.2005
Jakuszyce	860	214	13.03.2005
Międzygórze	675	118	14.–15.03.2006
Przesieka	650	98	13.–15.03.1988
Rościszów	575	106	18.–19.03.2006
Słoszów	555	130	07.03.1970
Świeradów Zdrój	550	116	14.03.1988
Paprotki	540	94	12.03.2005
Bukówka	510	105	12.03.2005
Walim	490	80	12.03.2006
Lądek Zdrój	461	70	12.–13.02.2006
Szczawno Zdrój	430	58	06.03.1970
Długopole Zdrój	393	101	06.03.1970
Kłodzko	360	37	04.01.1971
Głuchołazy	350	50	07.–08.03.1993
Jelenia Góra	342	60	06.031970
Pszenno	225	38	04.–07.01.1971
Otmuchów	212	30	30.01.1987
Zgorzelec	203	52	17.01.1979
Legnica	122	37	29.01.1979

stations located at similar altitude can be explained by the effects of morphological protection or exposure of a given station to the dominant directions of air masses advection during the cold part of a year. This conclusion is supported by previous studies of snow cover in the Karkonosze Mts. (Sobik et al. 2009, 2014). However, it must be noticed that the increase of snow cover depth with the altitude above sea level is highly irregular and strongly affected by the local morphology and land cover.

The maximum depths of snow cover indicate high variability and fluctuate from 30 cm in Otmuchów (30.01.1987) to 247 cm on Śnieżka (14.–15.03.2005) and even reaching over 100 cm in the lower parts of slopes (Tab. 5). The average maximum

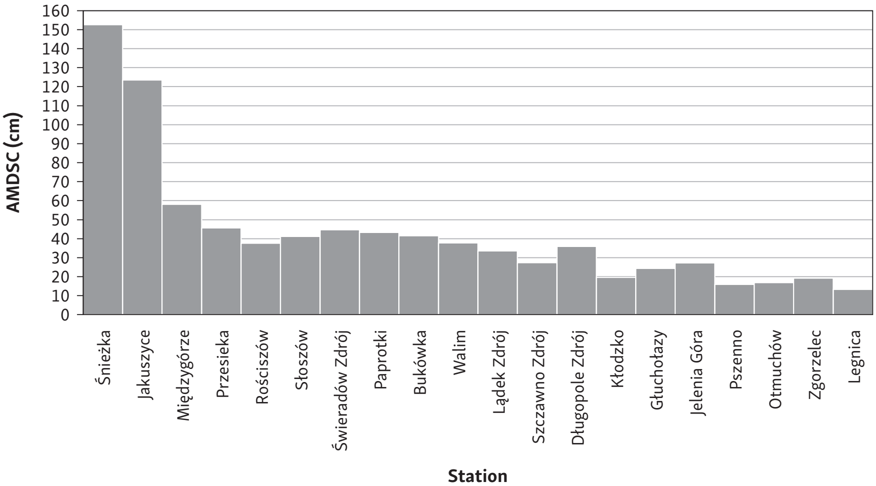

Fig. 8 – Average maximum depth of snow cover (cm) in the Polish Sudetes Mts. and their foreland in the 1965/66–2007/08 period

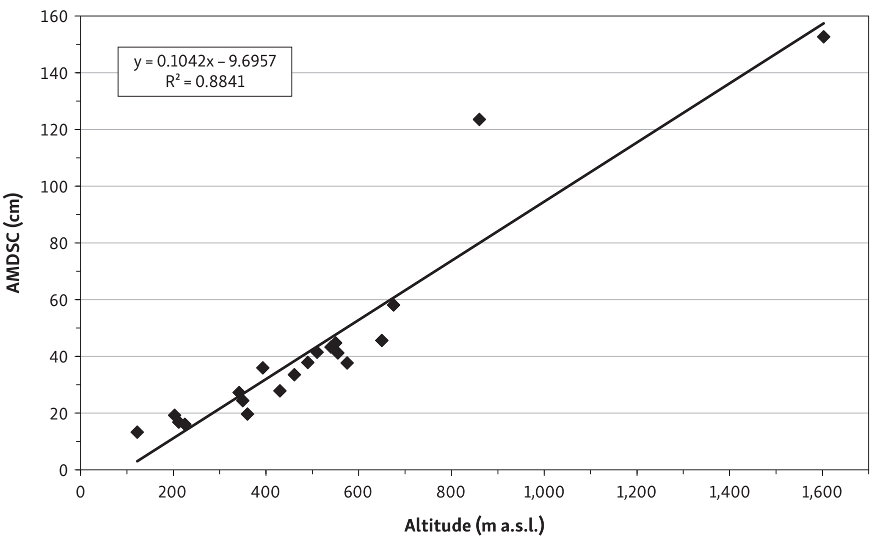

Fig. 9 – Correlation between average maximum depth of snow cover and altitude in the Polish Sudetes Mts. and their foreland in the 1965/66–2007/08 period

values, however, are a better indicator of a potential snow depth in a given location (as they are not affected by the randomness of an episodic snow occurrence or one specific winter). They vary from 13 cm in Legnica to 153 cm on Śnieżka Mt. (Fig. 8). This conclusion is well illustrated by the linear regression equation fitted into a relative dense point cloud and high determination coefficient R^2 (Fig. 9). The

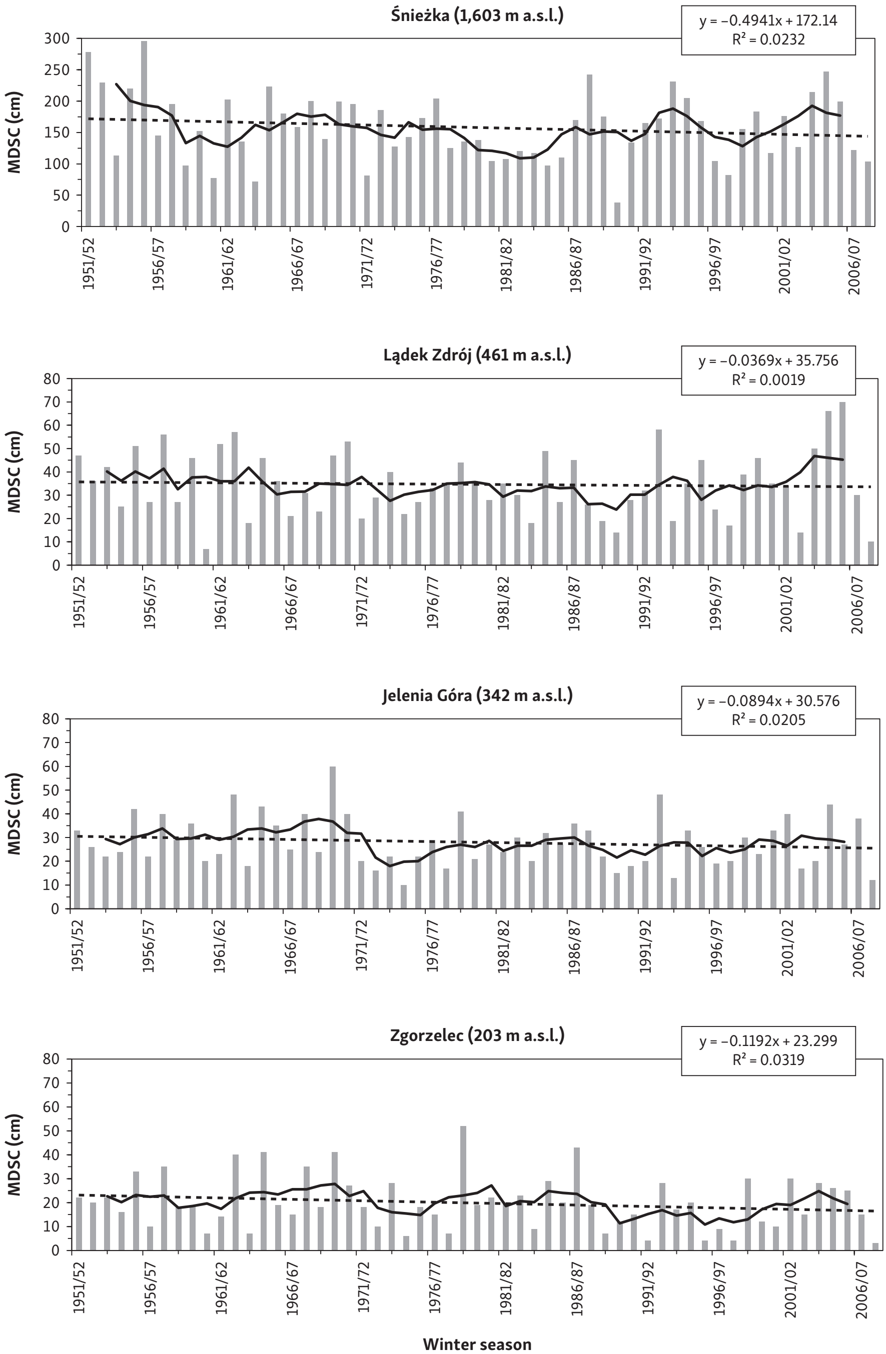

Fig. 10 – Course of maximum annual depth of snow cover, its tendency line (the dashed line), equation of regression and a 5-year consecutive average (the solid line) in the 1951/52–2007/08 period

Tab. 6 – Selected characteristics of annual maximum depth of snow cover in the 1951/52–2007/08 period

Maximal depth of snow cover of the depth ≥ 1 cm								
Station	Average (cm)	The highest value		The lowest value		Standard deviation (cm)	Variation coefficient (%)	Change (cm) / 10 years
		(cm)	Season	(cm)	Season			
Śnieżka	158	295	1955/56	38	1989/90	53.9	34.1	–4.94
Lądek Zdrój	35	70	2005/06	7	1960/61	14.1	40.7	–0.37
Jelenia Góra	28	60	1968/70	10	1974/75	10.4	37.1	–0.89
Zgorzelec	20	52	1978/79	3	2007/08	11.1	55.8	–1.19

values of maximum depths of snow cover and average maximum values rise with increasing altitude above sea level at the rate of 16.5 cm / 100 m and 10.4 cm / 100 m respectively.

The changes of annual maximum depth of snow cover in selected locations indicate weak decreasing tendency from ca. 0.5÷1 cm / 10 years in the Sudetes foreland and lower parts of the slopes to ca. 5 cm / 10 years in the summit zone (Fig. 10). The presented trend values are not statistically significant at the significance level of 0.05. A similar regularity can be noted in the 50-year data series (1949/50–1998/99) of snow cover in the Polish Tatra Mts. (Falarz 2000–2001) and the central and northern Tyrol in the period of 1895–1991 (Fliri, Baumkirchen 1991). Moreover, maximum depths of snow cover values show high interannual variance. However, unlike the annual number of days with snow cover, the maximum depths of snow cover values are characterized by a more even temporal distribution in the vertical profile. This is supported by coefficients of variations which oscillate between 34% in the upper locations to 56% in the Sudetic Foreland (Tab. 6). In case of the majority of the analyzed stations located above 500 m a.s.l., the maximum depth of snow cover was registered in the 2004/05 season during the 1965/66–2007/08 period.

4. Summary and conclusions

Snow cover in the Polish part of the Sudetes Mts. and their foreland shows very high temporal and spatial variability. The increase of the annual mean value of number of days with snow cover with altitude above sea level is 11.4 days / 100 m. The period of the actual snow cover occurrences is from 40–50 days in the Sudetic Foreland to 150–200 days in the upper parts as the annual average. Snow cover is, for the most occurrences, unstable, it appears and disappears during winter season. High instability of occurrences of snow cover periods mostly characterizes the lower part of the vertical profile of the Sudetes Mts. and their foreland.

Number of days with snow cover changeability is inversely proportional to snow cover duration.

In the studied area, average depth of snow cover in winter quarter (Dec.–Feb.) does not exceed 5 cm in the region of the Sudetes foreland and in the bottoms of large intramontane basins. In lower and higher parts of the mountain slopes, average depth of snow cover usually is not higher than 15 cm, while in the upper and peak zones of the Karkonosze Mts. is reaches over 70 cm.

The increase rate of average depth of snow cover in proportion to altitude above sea level varies from 3.6 cm / 100 m in December to 3.6 cm / 100 m in March, while in winter quarter (Dec.–Feb.) it is 5.5 cm / 100 m. The highest monthly mean depth of snow cover in the upper parts of the vertical profile is noted in March, at slightly lower altitudes – in February, and in the Sudetes Mts. foreland as well in basins – in January. Snow cover depth increase proportional to altitude above sea level is highly irregular and is strongly influenced by local morphology and land cover.

Maximum depths of snow cover is noted in January in the lower parts of the Sudetes Mts. and their foreland while in the upper parts of the mountains, it occurs in the second half of February or March. The average values of maximum depths of snow cover vary from ca. 15÷25 cm in the foreland and lower areas of the slopes up to 120÷150 cm in the upper and peak zones.

In the long term period of 1951/52–2007/08, maximum depths of snow cover, measured at four representative stations in the vertical profile of the Sudetes Mts. and their foreland, showed slightly decreasing trend, not statistically significant at the significance level of 0.05. Number of days with snow cover (except Śnieżka Mt.) was also characterized by downward trend. In case of Śnieżka and Lądek Zdrój, the number of days with snow cover change was statistically significant at the level of 0.05.

The results of the study of snow cover conditions in the vertical profile of the Polish Sudetes Mts. and their foreland are a significant contribution to regional estimate of the present climate in Poland. They can be a basis for further detailed research of snow cover in the Sudetes Mts. These results can also be used to compare snow cover conditions of the Polish Sudetes and their foreland and other mountain ranges. Moreover, combined with analysis of meteorological and morphological causative factors, they can support papers in fields such as tourism, spatial management, forestry and others.

References

ANDREASSEN, L.M., ELVEHØY, H., KJØLLMOEN, B., ENGESET, R.V., HAAKENSEN, N. (2005): Glacier mass balance and length variations in Norway. Annals of Glaciology, 42, 1, 317–325. DOI: 10.3189/172756405781812826

BAC, S. jr. (1961): Szata śnieżna w zlewni źródliskowej Bobru. Zeszyty Naukowe WSR we Wrocławiu, 19, 61–72.
BEDNORZ, E. (2002): Snow cover in western Poland and macro-scale circulation conditions. International Journal of Climatology, 22, 5, 533–541. DOI: 10.1002/joc.752
BENISTON, M. (1997): Variations of snow depth and duration in the Swiss Alps over the last 50 years: links to changes in large-scale climatic forcings. Climate Change, 36, 3–4, 281–300. DOI: 10.1023/a:1005310214361
BENISTON, M., REBETZ, M., GIORGI, F., MARINUCCI, M.R. (1994): An analysis of regional climate change in Switzerland. Theoretical and Applied Climatology, 49, 3, 135–159. DOI: 10.1007/bf00865530
BŁAŚ, M., SOBIK, M. (2005): Osobliwości klimatu Karkonoszy i Gór Izerskich. In: Krzemień, K, Trepińska, J., Bokwa, A. (eds.): Rola stacji terenowych w badaniach geograficznych. Kraków, IGiGP UJ, 109–121.
BROWN, R.D., GOODISON, B.E. (2005): Snow cover. In: Encyclopedia of Hydrological Science, Andersen, M. G., McDonell, J.J. (eds.): Wiley & Sons Ltd., 4, 2463–2474.
CHRZANOWSKI, J. (1988): Pokrywa śnieżna w Polsce. Klasyfikacja jej grubości i regionalizacja. Materiały Badawcze IMGW, seria: Meteorologia, 15, 43.
DUBICKI, A., GŁOWICKI, B., WOŹNIAK, Z. (1997): Wieloletnie badania hydrometeorologiczne w małych zlewniach sudeckich. Materiały Badawcze IMGW, seria: Hydrologia i oceanologia, 22, 95–106.
DUSZA, S. (1977): Prawdopodobieństwo występowania dobowych sum opadów o określonych wartościach w profilu pionowym Sudetów. Praca magisterska. Zakład Klimatologii, UJ, Kraków.
FALARZ, M. (2000–2001): Zmienność wieloletnia występowania pokrywy śnieżnej w polskich Tatrach. Folia Geographica, seria: Geographica Physica, 31–32, 101–123.
FALARZ, M. (2004): Variability and trends in the duration and depth of snow cover in Poland in the 20th century. International Journal of Climatology, 24, 13, 1713–1727. DOI: 10.1002/joc.1093
FALARZ, M. (2007): Potencjalny okres występowania pokrywy śnieżnej w Polsce i jego zmiany w XX wieku. In: Piotrowicz, K., Twardosz, R. (eds.): Wahania klimatu w różnych skalach przestrzennych i czasowych. IGiGP UJ, Kraków, 205–213.
FALARZ, M. (2010): Współczynnik trwałości pokrywy śnieżnej w Polsce – rozkład przestrzenny, ekstrema, zmiany wieloletnie. In: Bednorz E. (ed.): Klimat Polski na tle klimatu Europy. Warunki termiczne i opadowe, seria: Studia i Prace z Geografii i Geologii, 15. Bogucki Wydawnictwo Naukowe, Poznań, 167–179.
FLIRI, F, BAUMKIRCHEN, H. (1991): Die Schneeverhältnisse in Nord- und Osttirol in der Periode 1895–1991. Mitteilungen der Österreichischen Geographischen Gesellschaft, 133, 7–25.
FOSTER, J., OWE, M., RANGO, A. (1983): Snow cover and temperature relationships in North America and Eurasia. Journal of Climate and Applied Meteorology, 22, 3, 460–469. DOI: 10.1175/1520-0450(1983)022<0460:scatri>2.0.co;2
GŁOWICKI, B. (2005): Klimat Karkonoszy. In: Mierzejewski, M. (ed.): Karkonosze – przyroda nieożywiona i człowiek, Wydawnictwo UWr, 381–397.
GŁOWICKI, B. (2008): Ekstremalne zjawiska termiczne w Sudetach w okresie współczesnych zmian klimatu. Infrastruktura i ekologia terenów wiejskich, 8, 29–40.
GŁOWICKI, B., OTOP, I., URBAN, G., TOMCZYŃSKI, K. (2005): Klimat. In: Blachowski, J., Markowicz-Judycka, E., Zięba, D. (eds.): Opracowanie ekofizjograficzne dla województwa dolnośląskiego. Zarząd Województwa Dolnośląskiego. WBU we Wrocławiu, 53–61.

HESS, M., NIEDŹWIEDŹ, T., OBRĘBSKA-STARKLOWA, B. (1980): O prawidłowościach piętrowego zróżnicowania stosunków klimatycznych w Sudetach. Rocznik Naukowo-Dydaktyczny WSP w Krakowie, 71, Prace Geograficzne, VIII, 167–201.

HLADNÝ, J., SÝKORA, B. (1983): Klimatologie, hydrologie, sněhová pokrývka. In: Sýkora, B. (eds.): Krkonošský Národní Park. Státní zemědělské nakladatelství, Praha, 33–44.

JAAGUS, J. (1997): The impact of climate change on the snow cover pattern in Estonia. Climate Change, 36, 1–2, 65–77. DOI: 10.1023/a:1005304720412

JANISZEWSKI, F. (1988): Instrukcja dla stacji meteorologicznych. Wydawnictwa Geologiczne. Warszawa.

KASPROWICZ, T. (2010): Prawidłowości przestrzenne występowania pokrywy śnieżnej Polsce i próba ich regionalizacji. In: Bednorz, E. (ed.): Klimat Polski na tle klimatu Europy. Warunki termiczne i opadowe, seria: Studia i Prace z Geografii i Geologii, 15. Bogucki Wydawnictwo Naukowe. Poznań, 181–198.

KONDRACKI, J. (1988): Geografia fizyczna Polski. PWN, Warszawa.

KOSIBA, A. (1949): Częstość szaty śnieżnej na Ziemiach Śląskich. Prace Wrocławskiego Towarzystwa Naukowego, B, 21, Wrocław, 91.

KOŻUCHOWSKI, K, ŻMUDZKA, E. (2001): Ocieplenie w Polsce: skala i rozkład sezonowy zmian temperatury powietrza w drugiej połowie XX wieku. Przegląd Geofizyczny, 46, 1–2, 81–122.

KWIATKOWSKI, J. (1978): Pokrywa śnieżna Sudetów, jej gęstość i zawarty w niej zapas wody. Czasopismo Geograficzne, 49, 4, 419–435.

KWIATKOWSKI, J. (1985): Szata śnieżna, szadź i lawiny. In: Jahn A. (ed.): Karkonosze Polskie, Ossolineum, 117–144.

LAPIN, M., FAŠKO, P. (1996): Snow cover and precipitation changes in Slovakia in the 1921–1996 period. In: Rakovec, J., Zagar, M. (eds.): Proceedings of the 24th International Conference on Alpine Meteorology, HMI of Slovenia, Bled; 259–266.

MIGAŁA, K. (2005): Piętra klimatyczne w górach Europy a problem zmian globalnych. Acta Universitatis Wratislaviensis, 2718, Studia Geograficzne, 78, 140.

MIGAŁA, K. (2008): Prognoza zmian pluwio-termicznych w piętrach roślinno-klimatycznych na obszarze średniogórza europejskiego. In: Monitoring ekosystemów leśnych w Karkonoskim Parku Narodowym. KPN, Jelenia Góra, Wyd. ARGI Wrocław, 72–81.

MIGAŁA, K., URBAN, G., TOMCZYŃSKI, K. (2015): Long-term air temperature variation in the Karkonosze mountains according to atmospheric circulation. Theoretical and Applied Climatology. DOI: 10.1007/s00704-015-1468-0

MOTE, P.W. (2006): Climate-driven variability in mountain snowpack in western North America. Journal of Climate, 19, 23, 6209–6220. DOI: 10.1175/jcli3971.1

MRUGASIEWICZ, P., SOBIK, M. (2000): Morfologiczne i środowiskowe uwarunkowania pokrywy śnieżnej w polskiej części zlewni Izery. Acta Universitatis Wratislaviensis, 2269, Studia Geograficzne, LXXIV, 159–172.

OJRZYŃSKA, H., BŁAŚ, M., KRYZA, M., SOBIK, M., URBAN, G. (2010): Znaczenie lasu oraz morfologii terenu w rozwoju pokrywy śnieżnej w Sudetach Zachodnich na przykładzie sezonu zimowego 2003/2004. Sylwan, 154, 6, 412–428.

RÄISÄNEN, J. (2008): Warmer climate: less or more snow? Climate Dynamics, 30, 307–319. DOI: 10.1007/s00382-007-0289-y

REUNIER, H. (1935): Höhe und Andauer der Schneedecke im Riesengebirge. Meteorologische Zeitschrift, 52/3.

SCHERRER, S.C., APPENZELLER, C., LATERNSER, M. (2004): Trends in Swiss alpine snow days – the role of local and large-scale climate variability. Geophysical Research Letters, 31. DOI: 10.1029/2004GL020255

SOBIK, M. (1998): Specyficzne cechy klimatu Gór Izerskich. In: Migała, K., Sobik, M. (eds.) Problemy klimatyczno-botaniczne Gór Izerskich, 21.–23.9.1998, Świeradów Zdrój, 29.
SOBIK, M., URBAN, G., BŁAŚ, M., KRYZA, M., TOMCZYŃSKI, K. (2009): Uwarunkowania zalegania pokrywy śnieżnej w Sudetach Zachodnich w sezonach zimowych 2001/2002–2005/2006. Wiadomości Meteorologii Hydrologii Gospodarki Wodnej, IMGW, Warszawa, t. III, 2–3, 31–47.
SOBIK, M., BŁAŚ, M., MIGAŁA, K., GODEK, M., NASIÓŁKOWSKI, T. (2014): Klimat. In: Knapik, R., Raj, A. (eds.) Przyroda Karkonoskiego Parku Narodowego. Karkonoski Park Narodowy, Jelenia Góra, 147–186.
SZAREJKO, Z. (1984a): Obserwacje nad zanikaniem pokrywy śnieżnej na terenie zlewni górnej Kamiennej. In: Ogólnopolskie Sympozjum Naukowe: Problematyka hydrologiczna i meteorologiczna małych zlewni rzecznych, Wrocław, 27–29 września 1984, Polskie Towarzystwo Geofizyczne, Wrocław, 230–231.
SZAREJKO, Z. (1984b): Struktura przestrzenna pokrywy śnieżnej na terenie zlewni górnej Kamiennej. In: Ogólnopolskie Sympozjum Naukowe: Problematyka hydrologiczna i meteorologiczna małych zlewni rzecznych, Wrocław, 27–29 września 1984, Polskie Towarzystwo Geofizyczne, Wrocław, 232–233.
URBAN, G. (2015): Zaleganie pokrywy śnieżnej i jego zmienność w polskiej części Sudetów i na ich przedpolu. Przegląd Geograficzny, 87, 3, 497–516, DOI: 10.7163/PrzG.2015.3.5
URBAN, G., RICHTEROVÁ, D. (2009): Assessment of snow conditions for skiing on selected examples from the Polish-Czech order area in the Western Sudetes Mountains. In: Pribullová, A., Bičárová, S. (eds.): Sustainable Development and Bioclimate, Reviewed Conference Proceedings, Geophysical Institute of the SAS, 5.–8.10.2009, Stará Lesná, 60–61.
URBAN, G., RICHTEROVÁ, D. (2010): Warunki śniegowe a uprawianie narciarstwa w Sudetach Zachodnich na polsko-czeskim pograniczu. Wiadomości Meteorologii Hydrologii Gospodarki Wodnej, IMGW, Warszawa, t. III, 1–4, 3–28.
URBAN, G., RICHTEROVÁ, D., VAJSKEBR, V. (2011): Pokrywa śnieżna w październiku 2009 w Sudetach Zachodnich jako przykład zjawiska ekstremalnego. Wiadomości Meteorologii Hydrologii Gospodarki Wodnej, IMGW, Warszawa, t. V (LV), 4, 75–96.
USTRNUL, Z. (1991): Porównawcza analiza stosunków termicznych Tatr i Karkonoszy. Acta Universitatis Wratislaviensis, 1213, t. V, 173–178.
VAVRUS, S. (2007): The role of terrestrial snow cover in the climate system. Climate Dynamics 29, 1, 73–88. DOI: 10.1007/s00382-007-0226-0
WIBIG, J., GŁOWICKI, B. (2002): Trends of minimum and maximum temperature in Poland. Climate Research, 20, 123–133. DOI: 10.3354/cr020123

SHRNUTÍ

Sněhová pokrývka a její proměnlivost v polských Sudetech a jejich podhůří

Tato studie je jedním z výsledků výzkumného a vývojového projektu, který provedl Ústav pro meteorologii a vodní hospodářství (POIG 01.03.01-14-011/08-00 „KLIMAT“). Na jeho financování se podílela Evropská unie. Jmenuje se „Důsledky klimatických změn pro životní prostředí, hospodářství a společnost (změny, důsledky a jejich zmírňování, vliv na vědu, technické projekty a ekonomické plánování)“.

Příspěvek předkládá charakteristiky sněhové pokrývky u vertikálního profilu polských Sudet a jejich podhůří v období 1965–1966 až 2007–2008. Analýza vycházela z počtu dnů se sněhovou pokrývkou nad 1 cm a její výškou během určitého měsíce, zimního období (prosinec až únor) a celého roku. Údaje byly shromažďovány na dvaceti meteorologických stanicích, jež řídí Ústav pro meteorologii a vodní hospodářství. Výběr meteorologických stanic vycházel z dostupnosti dlouhodobých datových řad a úplnosti měření. Dalšími měřítky výběru byly kontinuita umístění a zastoupení různých výškových pásem Sudet. Veškeré parametry byly zkoumány ve vertikálním profilu. Předkládané regresní rovnice jsou obecné povahy a neodrážejí konkrétní místní poměry.

V případě vybraných meteorologických stanic s homogenní datovou řadou zastupujících různé klimatické poměry a morfologické typy (Sněžka – vrcholové pásmo, Lądek Zdrój – nižší svahy, Jelenia Góra – dno velkého údolí mezi horami Sudet – a Zgorzelec – sudetské podhůří) byla navíc vypracována analýza proměnlivosti vybraných sněhových parametrů v letech 1951–1952 až 2007–2008.

Sněhová pokrývka v polské části Sudet a jejich podhůří vykazuje velmi vysokou proměnlivost v čase i prostoru. Růst roční průměrné hodnoty počtu dnů se sněhovou pokrývkou podle nadmořské výšky nad mořskou hladinou činí 11,4 dní na 100 m. Období skutečného výskytu sněhové pokrývky trvá v ročním průměru od 40–45 dnů v sudetském podhůří až po 150–200 dnů v horních polohách. Sněhová pokrývka je většinou nestabilní a během zimního ročního období se objevuje a zase mizí. Vysoká nepravidelnost období se sněhovou pokrývkou charakterizuje zejména nižší polohy výškového profilu Sudet a jejich podhůří. Počet dnů s proměnlivostí sněhové pokrývky je nepřímo úměrný jejímu trvání.

Průměrná výška sněhové pokrývky ve sledované oblasti nepřesahuje v zimním období (prosinec až únor) 5 cm v oblasti sudetského podhůří a na dně velkých horských údolí. V nižších a vyšších polohách horských svahů není průměrná výška sněhové pokrývky zpravidla silnější než 15 cm, kdežto ve vyšších a vrcholových pásmech Krkonoš přesahuje 70 cm.

Míra přírůstku průměrné výšky sněhové pokrývky v poměru k nadmořské výšce nad hladinou moře kolísá od 3,6 cm na 100 m v prosinci až po 3,6 cm na 100 m v březnu, kdežto v zimním období (prosinec až únor) činí 5,5 cm na 100 m. Nejvyšší průměrná měsíční výška sněhové pokrývky v horních polohách vertikálního profilu byla zaznamenána v březnu, kdežto v mírně nižších nadmořských výškách v únoru a v sudetském podhůří a v horských údolích v lednu. Růst výšky sněhové pokrývky úměrně s nadmořskou výškou je vysoce nepravidelný a silně ho ovlivňuje místní morfologie a půdní pokryv.

Maximální výška sněhové pokrývky bývá v nižších polohách Sudet a jejich podhůří zaznamenána v lednu, kdežto v horách se vyskytuje v druhé polovině února až březnu. Průměrné hodnoty maximální výšky sněhové pokrývky se pohybují mezi 15 až 25 cm v podhůří a nižších úsecích svahů až po 120 až 150 cm v horních a vrcholových pásmech.

Maximální výška sněhové pokrývky měřená na čtyřech reprezentativních stanicích ve vertikálním profilu Sudet a jejich podhůří, vykazovala v dlouholetém období 1951–1952 až 2007–2008 mírně klesající trend, který nebyl na úrovni 0,05 statisticky významný. Počet dnů se sněhovou pokrývkou (až na Sněžku) byl rovněž charakterizován klesajícím trendem. V případě Sněžky a kraje Lądek Zdrój byla změna počtu dnů se sněhovou pokrývkou statisticky významná na úrovni 0,05.

Výsledky studie sněhových poměrů ve vertikálním profilu polských Sudet a jejich podhůří představují významný příspěvek k regionálnímu rozboru současného klimatu v Polsku. Mohou fungovat jako podklad k dalšímu, podrobnějšímu výzkumu sněhové pokrývky v Sudetech. Tyto výsledky lze též využít ke srovnání sněhových poměrů v polských Sudetech a jejich podhůří a dalších pohořích. Ve spojení s rozborem meteorologických a morfologických kauzálních faktorů také mohou být užitečné při výzkumu v takových oblastech, jako je turistika, územní plánování, lesnictví apod.

Obr. 1 Umístění stanic uvedených v příspěvku ke zkoumání regionu. V legendě: měřicí stanice, ostatní města, řeky, hranice států.

Obr. 2 Korelace mezi průměrným ročním počtem dnů s výškou sněhové pokrývky nad 1 cm a nadmořskou výškou v polských Sudetech a jejich podhůří v období 1965–1966 až 2007–2008.

Obr. 3 Průběh průměrného denního počtu dnů se sněhovou pokrývkou a čára jeho výskytu (čárkovaná čára), regresní rovnice a výsledný pětiletý průměr (plná čára) v období 1951–1952 až 2007–2008.

Obr. 4 Počet dnů s výskytem sněhové pokrývky (počet dnů za deset let) v polských Sudetech a jejich podhůří v období 1965–1966 až 2007–2008.

Obr. 5 Variační koeficient (V) počtu dnů se sněhovou pokrývkou v polských Sudetech a jejich podhůří v období 1965–1966 až 2007–2008.

Obr. 6 Korelace mezi průměrnou výškou sněhové pokrývky v zimním období (prosinec až únor) a nadmořskou výškou v polských Sudetech a jejich podhůří v období 1965–1966 až 2007–2008.

Obr. 7 Denní průběh průměrné výšky sněhové pokrývky v říjnu až květnu v období 1965–1966 až 2007–2008 na vybraných stanicích ležících více než 500 m nad mořem.

Obr. 8 Průměrná maximální výška sněhové pokrývky (cm) v polských Sudetech a jejich podhůří v období 1965–1966 až 2007–2008.

Obr. 9 Korelace mezi průměrnou maximální výškou sněhové pokrývky a nadmořskou výškou v polských Sudetech a jejich podhůří v období 1965–1966 až 2007–2008.

Obr. 10 Průběh maximální roční výšky sněhové pokrývky, čára jejího výskytu (čárkovaná čára), regresní rovnice a výsledný pětiletý průměr (pevná čára) v období 1951–1952 až 2007–2008.