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Frequency and thickness of snow cover at the foot of the Babia Góra Massif in the winter seasons 1960/61 to 2014/15*

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Abstract. The aim of the study was to gain knowledge about changes in the nival conditions prevailing in the lower part of the Babia Góra massif in the winter, during the period from 1960/61 to 2014/15.

The performed analyses concerned the daily snow cover thickness in the winter seasons of the years 1960/61–2014/15, and were based on data recorded by a meteorological station established by the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) in Zawoja (697 m altitude). The study was focused on the period from the first to the last day of the appearance of the snow cover in the season.

Based on long-term measurements carried out in in Zawoja, it was found that the average length of the occurrence of snow cover with the thickness of ≥ 1 cm was 104 days, which showed variability in individual seasons that ranged from 47 days in 2013/14 to 145 days in 1993/94. It was noted that the period of snow cover occurrence was shortened – from 118 days in the decade 1960/61–1969/70 to 96 days in the recent decade (2000/01–2009/10). The potential duration of snow cover was on average 157 days. The snowiest months were February and January, when snow cover occurred for 81% and 75% of all the observation days, respectively. The largest thickness of snow cover was recorded during these two months, with the maximum of 178 cm (January 30, 1976). In contrast, snow cover was not observed in July, August and September. The studied multi-year period was characterised by high variability of the winter snowiness index: from 1.61 in 2013/14 to 8.00 in 1962/63.

In the period 1960/61–2014/15, in Zawoja, there was observed the distinct periodicity (16–19 years) with regard to the number of days with snow cover, the average and total snow cover and the winter snowiness.

Keywords: snow cover, winter, climate change, precipitation, mountains, Carpathians

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1. Introduction

Snow cover results from atmospheric precipitation in the form of snow, however, its accumulation, and then duration, is mostly determined by thermal conditions, while at local and regional scales, also by wind speed (Czarnecka 2012) and land relief, exposition and way of use, including the vegetation cover type (Leśniak 1980, Nowosad 1994).

Snow cover is important for both the abiotic environment and living organisms. It causes changes in the water and heat balances due to the fact that snow hardly absorbs shortwave rays. The surface with snow cover is much brighter than the surface deprived of it, thus its albedo is much higher. Very strong reflection of sun rays and large heat radiation causes the air to cool down over the snow cover and incites an inversion (Kossowska-Cezak and Bajkiewicz-Grabowska 2008).

The low thermal conductivity of snow protects the soil against deep freezing (Nowosad 1994; Kossowska-Cezak and Bajkiewicz-Grabowska 2008). A long-term spring disappearance of snow cover delays both the air temperature rises beyond

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0°C (heat loss for snow sublimation and melting) and the commencement of vegetation season (Nowosad 1994; Keller et al. 2005; Bartoszek 2007). Snow cover is also important for water management, what can be observed in the mountain areas in the form of increased winter retention and runoff during spring melt and mid-winter flash floods (Bajkiewicz-Grabowska and Mikulski 2007; Vavrus 2007; Holko et al. 2011).

Numerous papers by the Polish authors account on temporal variability and spatial differentiation of the snow cover occurrence in different regions of the country. The snow conditions were studied on the country scale by, among others: Milata (1937, 1950), Chomicz (1953), Madany (1961), Hess (1965), Paczos (1982, 1987), Chrzanowski (1986, 1988), Bednorz (2004), Kasprowicz and Farat (2010), Czarnecka (2011, 2012), Falarz (2004, 2007, 2010) as well as by Falarz and Marsz (2005). Considerable attention was devoted to study the snow cover in the Polish Carpathians (Hess 1965; Leśniak 1984; Niedźwiedź and Obrębska-Starklowa 1991; Obrębska-Starklowa et al. 1995). The richest literature on the subject was produced for such regions, as: the Bieszczady Mts. (Nowosad 1987, 1991, 1994), the Upper Vistula catchments and, in particular, the Dunajec basin (Bury-Zalewska 1960, 1964; Lewińska 1963; Leśniak 1973, 1975, 1981, 1984), as well as for the Tatra Mts. (Milata 1950; Falarz 1999, 2001, 2002). In contrast, only single papers dealt so far with snow cover in the Babia Góra Massif (Obrębska-Starklowa 1982; Łajczak 2004), in the Gorce Mts. (Obrębska-Starklowa 1968) as well as in the Beskid Śląski Mts. (Kozak and Łepko 2015).

The aim of this paper was to examine the variability of snow cover at the lower part of the Babia Góra northern slope in Zawoja.

2. Study area

Babia Góra is the most highly elevated massif of the External Western Carpathians (Kondracki 2000), with Diablak, the peak, rising to the height of 1,725 m asl (Figure 1). The massif was raised to about 500 m above the surrounding mountain chains (Figure 2A), as a result of isostatic lifting of the hanging element of the wing, in the system of normal faults (Jankowski, Margielewski 2014). This led to the formation of the northern slope of the massif as a cuesta, with a slope of 20 to over 45°. The upper parts of the massif are characterised by higher inclination (Figure 2B), which results from their geological structure. The upper parts of Babia Góra (over 1000 m asl) are made of resistant thick-walled Magura sandstones, while the lower part is built of thin-walled sandstone hieroglyphic layers. Bottoms of the main valleys are filled with thick covers of the Quaternary sediments, which form the Pleistocene and Holocene terraces as well as cone-shaped alluvial fans (Książkiewicz 1974a, b).

A characteristic feature of the Babia Góra northern foothills is the fan-shaped, convergent system of the river network (Łajczak 1998, 2004). It is formed by the streams Jaworzyna and Czatożanka (Skawica), which merge at Zawoja Widły. The main tributaries of the above streams create the internal part of the network, including: Urwisko, Marków Stream, Rybny Stream, Dejaków Stream and Norczak. In addition, there are streams that drain parts of the Polica Range and Mędralowa Group as well as the Jałowieckie Range. Below the hydrographic node at Zawoja Widły, the Skawica Valley changes its relief and the main direction, from north to north-east (Figure 2A). The Babia Góra Massif, due to its significant elevation asl constitutes a distinct orographic barrier. However, the relatively largest area of the massif northern slopes is located in its lower parts. The largest area of the northern slope lies between the heights of 700–800 m asl. About a half of the northern slopes of Babia Góra spread out up to the height of approximately 900 m asl (Łajczak 2016).

The local climate conditions are affected by both the relief of Babia Góra and surrounding mountain ranges and its location in the External Western Carpathians (Obrębska-Starklowa 1963). In the years 1961–2015, the average annual air temperature in Zawoja amounted to 6.4°C. The area has typically a very short thermal summer (period with average daily temperatures above 15°C). The average length of summer at the northern foothills

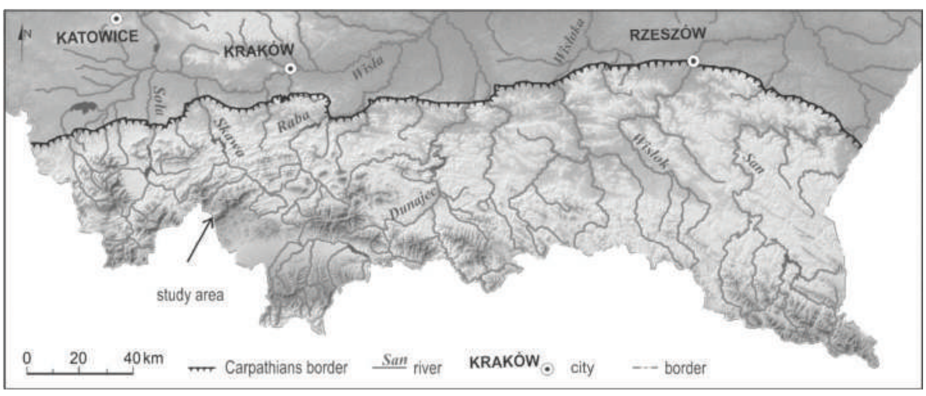

Figure 1. Localization of research area on the background of the Polish Carpathians

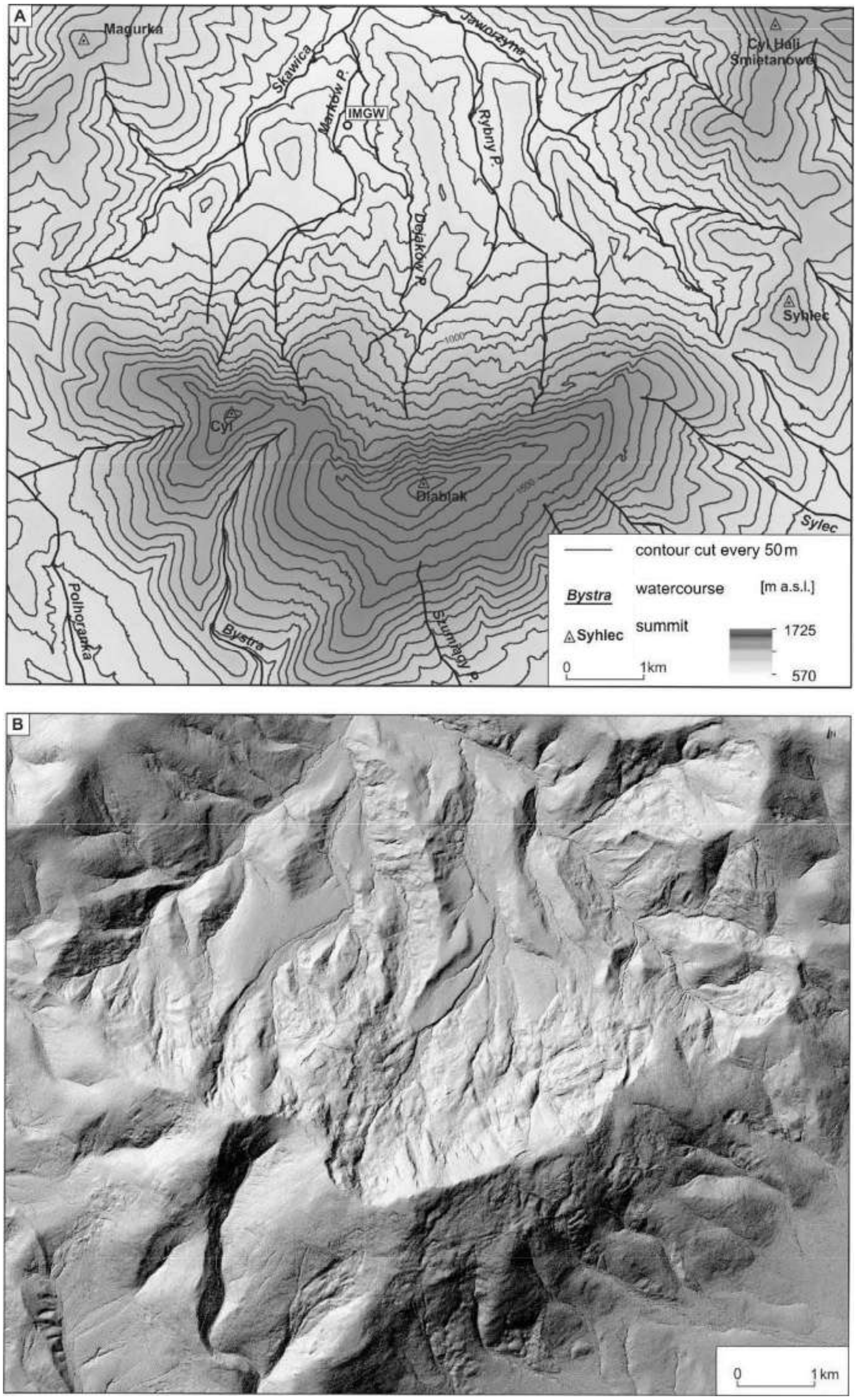

Figure 2. Hypsometric map of the Babia Góra massif and its northern foothills (A) and the Numeric Area Model of the studied area (B)

Source: Centralny Ośrodek Dokumentacji Geodezyjnej i Kartograficznej (CODGiK)

of Babia Góra in Zawoja was 41 days in the above-mentioned period. Whereas, the longest lasting season (97 days) was winter. It is noteworthy, however, that the average annual number of days with temperature not exceeding 5.0°C, in the pre-winter, winter and early spring season, was 163 (Sulikowska et al 2017). The average annual amount of atmospheric precipitation in Zawoja amounted to 1,225.6 mm, in the period 1961–2015. In the individual years, it ranged from 893.3 (1973) to 1,796.3

mm (2010). The average amount of atmospheric precipitation from November to April was 461.1 mm (47.6% of the annual sum). The highest average monthly rainfall totals were 156.9 mm in June, while the lowest in February – 63.5 mm. The average occurrence of atmospheric precipitation was 185 days on a year-to-year basis (Sulikowska et al 2017). Within the northern slopes of Babia Góra, a classical vertical zonation of vegetation floors has developed, including: foothill, lower montane-, upper montane-, mountain pine- and alpine zones (Wołoszyn et al. 2000; Pasierbek et al. 2009). The foothills reach up to of 550–600 m asl; in this zone some remnants of an oak-hornbeam woodland have been preserved up to now, while the rest of the area occupy settlements and farmland (Parusel 2017). The lower montane zone reaches up to 1,150 m asl, whereas the upper montane zone – up to 1390 m asl, and the mountain pine zone up to 1,650 m asl. Above that level there extends the alpine zone (Łajczak 2016). Forests are the main component of the natural environment of the Babia Góra massif. Woodland and shrub communities cover 95% within the area of the Babia Góra National Park (Holeksa et al. 2004). In the lower montane zone, at the northern foothills, there dominate the spruce-beech-silver fir forests with a large share of sycamore *Acer pseudoplatanus* L., grey alder *Alnus incana* (L.) Moench and European ash *Fraxinus excelsior* L. (Czaja and Kaczka 2014; Łajczak 2016). The forests in the lower montane zone are most diverse in terms of structure and species composition within the entire Babia Góra massif. There dominates Norway spruce *Picea abies* (L.) H. Karst taking 52% of the stand area, followed by European beech *Fagus sylvatica* L. – 34% and silver fir *Abies alba* Mill. – 7%. The stand density in the lower part of the lower montane zone is 785 trees/ha, and is much larger in the upper part – 986 trees/ha (Szwagrzyk et al. 1999). Trees in the lower montane zone are much thinner and their density is much higher than in the older stands of the upper montane zone (Holeksa et al. 2004). Large woodless areas taken by permanent settlements, arable fields and intensely overgrowing meadows are located in the lower slope parts of the Babia Góra massif. In the area under study, they occur mainly within the lower sections of valleys and on mountain ridges.

3. Materials and methods

The snow cover characteristics in the study area was developed based on daily measurements of snow cover thickness from the 55-year series of winter seasons 1960/61–2014/15 available at the Station of the Institute of Meteorology and Water Management – National Research Institute in Zawoja. Such a data series was considered reliable for the assessment of the snow

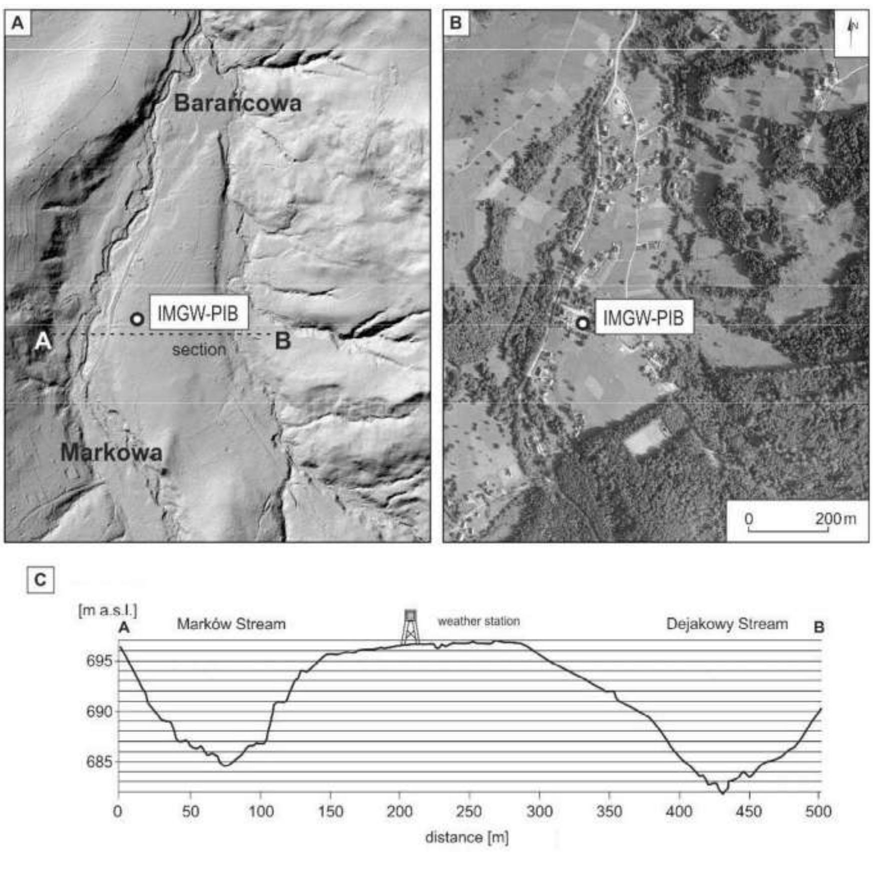

Figure 3. Location of the meteorological station in Zawoja (N 49°36'42 E 19°31'7) against the background of the Numerical Terrain Model (A) and orthophotomap (B); cross profile by Ficków Groń, on which the meteorological station is located (C)

cover variability. The station is located in the lower part of the Babia Góra northern slope within Ficków Ridge, in the fork of Marków Stream and Dejaków Stream, at an altitude of 697 m asl (Figure 3). The measurement results obtained from this station represent the snow conditions of the areas located at the upper limit of the moderately warm climate.

In order to determine the analysed indices, the daily data on the snow cover thickness was used for 6.00 h GMT. The input data was checked for completeness. The number of days with snow cover, medium and maximum thickness of snow cover during the snow season as well as the average thickness for all days of the analysed period 1960-2015 were considered, including days without cover (Paczos 1982, Falarz 2004; Kasprowicz and Farat 2010; Czarnecka) 2012). The sum of days during winter was assumed as the number of days with snow cover, and a day with snow cover was defined as a day when at least half of the surface under study was covered with snow layer exceeding 1 cm in depth (Kossowska-Cezak and Bajkiewicz-Grabowska 2008). The periods with snow persisting for at least five days without break were included to the days with the permanent snow cover (Lorenc 1964; Niedźwiedź 1998). To calculate the average monthly and seasonal thickness of snow cover, only days with snow cover were selected. The focus was on the period beginning from the first day of the snow cover appearance to the last day with snow cover in the season. The time of snow cover duration in individual months was calculated. The potential period of snow cover occurrence was also examined as well as the durability coefficient, understood as the quotient of the actual time of snow cover deposition and the length of the potential occurrence time (used, among others, in the works by Leśniak 1981; Falarz 2010 and Urban 2015). The winter snowiness was characterised based on the winter snowiness index values, proposed by Paczos (1982):

$$W_{sn} = 0{,}0409d_{ps} + 0{,}0246d_{ps20} + 0{,}00007S_{wś}$$

where:
W_{sn} – winter snowiness index (0–10),
d_{ps} – number of days with snow cover thickness ≥1 cm, in the period XII–III,
d_{ps20} – number of days with snow cover thickness ≥20 cm, in the period XII–III,
$S_{wś}$ – sum of snow cover height in cm, in the period XII–III.

Daily changes in the snow cover thickness (snow cover development and melt) were also examined by analysing differences in these characteristics from day to day. The variability of the characteristics was determined by means of arithmetic mean, standard deviation and variation coefficient. The magnitude of the trend was obtained from the linear regression equations. The statistical significance of the trend was checked using the Student's t-test. The calculations were made using Microsoft Excel (2010).

4. Results

4.1. Number of days with snow cover

The snow cover with a thickness ≥ 1 cm persisted in Zawoja Górna, at the northern foothills of the Babia Góra massif for an average of 104 days. The snow cover duration length varied between the individual winter seasons, from 47 days during the winter of 2013/14 to 145 days in the 1993/94 season. In the years 1960/61–2014/15, the frequency of days with snow cover showed a downward trend. The shortening rate was about 5 days for 10 years. The snowiest was the decade 1960/61–1969/70, as the snow cover lasted, on average, 118 days during the winter season. In the period 2010–2014/11–2014/15, the snow cover lasted shortly – on the average for 81 days. In the previous decade (2000/01–2009/10) snow cover persisted on average for 96 days. The periods with the longest snow cover persistence were winters in the following years: 1993/94 (145 days), 1981/82 (144 days), 1966/67 (143 days) and 1962/63 (138 days). In contrast, the shortest snow cover persistence was found for the following winters: 2013/14 (47 days), 1989/90 (58 days) and 2006/07 (58 days). The average number of days with at least 5 cm snow cover was smaller and amounted to 91 days for the examined multiannual. The longest lasting snow cover was found for the decade 1960/61–1969/70, on average 106 days in the winter season. Whereas, in recent decades, an increase was observed in the share of days with less than 5 cm snow in the winter season. The trend peaked during the season 1993/94, when snow cover with a depth not exceeding 5 cm occurred for 64% of days (Figure 4).

4.2. Potential duration time of snow cover and snow cover duration coefficient

The average length of potential snow cover deposition in the multiannual: 1960/61–2014/15 was less than 157 days, with a minimum period of 111 days (2013/14), and a maximum period of 214 days (1960/61). On the other hand, the potential period of snow cover deposition was shortened. The shortening rate was about 7 days for 10 years. The variation coefficient depicting the potential snow cover deposition is 8.8%, while the standard deviation is 13.7 days (Figure 5). The time of snow cover deposition is clearly shorter than the potential time of snow cover duration. The average long-term value of the snow cover durability coefficient was 67.1% in the period analysed. The lowest value of this coefficient (35.6%) was recorded in the winter season 1989/90, while the maximum possible value (100%) – in the winter season 1993/94. Low values of this coefficient (<50%) were also observed during winter seasons: 1971/72, 1973/74, 1990/91, 2006/07, 2009/10, 2010/11 and 2013/14. In turn, a very high (> 90%) coefficient of the snow

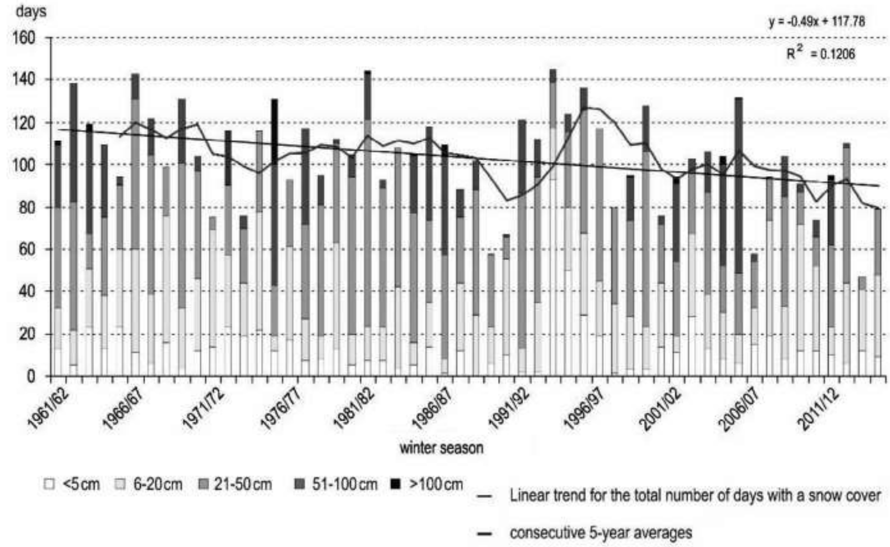

Figure 4. Annual number of days with a snow cover of varying thickness in Zawoja (1961/62–2014/15)

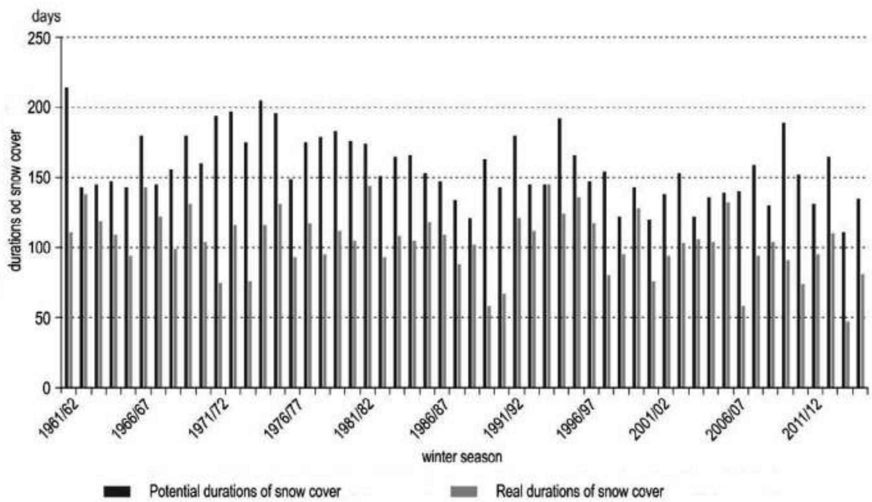

Figure 5. Potential and real durations of snow cover in Zawoja in the winter seasons of the 1961/62–2014/15 period

cover occurrence in relation to the potential time of its deposition was observed in the following seasons: 1962/63, 1999/00 and 2005/06. In the period analysed, the snow cover duration was found to be decreasing by 0.4% for 10 years.

4.3. Period of snow cover occurrence

In the multiannual 1960/61–2014/1, at the northern foothills of the Babia Góra massif, February was the snowiest month, with snow cover lasting for 81% of days, followed by January (75% of days). Likewise, snow cover remained on the ground for more than half of the month days in December (65% of days) and March (58% of days). The share of days with snow cover in the remaining months was shorter, and July, August and September were without snow cover. In May, the snow cover with a depth exceeding 5 cm was observed for one day (May 30, 1966), while in June it failed to reach a thickness of 5 cm.

In the 55-year long period examined (Figure 6B), the earliest occurrence of the first day with snow cover was on October 3 in the years 1972 and 1974, while the latest – on December 17 in 2000. The average first day with snow cover was November 7. The last day with snow cover (Figure 6A) occurred on June 7 (1962) at the latest, and on February 20 (1989) at the earliest. The snow cover vanished, on average, on April 14. It should be noted, however, that the relatively late occurrence of snow cover in the period from April to June was preceded by a shorter or longer snow-free periods. On the other hand, the snow cover in May or June usually occurred on single days or in a few day sequences.

The variability analysis (Table 1) of the first appearance dates of snow cover showed an upward trend, i.e. snow

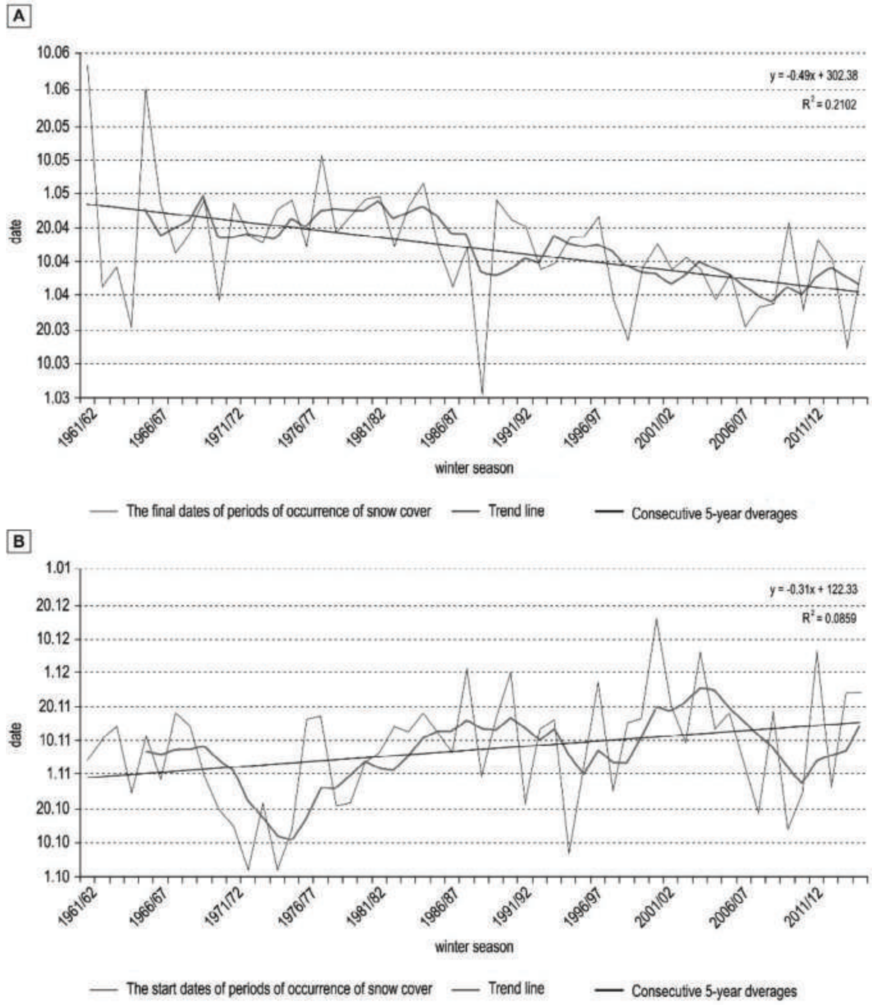

Figure 6. Variability to the start dates (A) and final dates (B) of periods of occurrence of snow cover in Zawoja in the winter seasons of the 1961/62–2014/15 period

Table 1. Selected characteristics of the start and final dates of periods of snow cover in Zawoja in the winter seasons of the 1960/61–2014/15 period

Date	Average [date]	The earliest one		The latest one		Standard devia- tion [days]	Variation coeffi cient [%]	Change [days/10 years]
		date	year	date	year			
Starting dates of snow cover	7.11	3.10	1972 1974	17.12	2000	6,8	5,2	3,1
Final dates of snow cover	14.04	20.02	1989	7.06	1962	5,9	2,0	–4,0

cover appeared there later by about 3.1 days for 10 years. In turn, snow cover vanished about 4 days earlier for 10 years. The variation coefficient describing the first day with snow cover is greater (5.2%) than the variation coefficient for the last day with snow cover (2.0%). Standard deviation in the case of the first day with snow cover attains almost 7 days, while in the case of the last day – up to 6 days.

4.4. Snow cover thickness

The average thickness of snow cover increased systematically on individual days, starting from the first days of October, and peaked in mid-February, reaching the highest average thickness. The highest average snow cover depth in the analysed period was on February 16 – 34.8 cm. The average thickness of snow cover exceeding 30 cm was registered at the turn of January and February and in the second half of February. From the turn of February and March, a rapid decrease in the average thickness of snow cover was observed (Figure 7). The average snow cover depth decreased in respective decades, as decreased the period of its occurrence. In the decade 1960/61–1969/70, snow cover accumulated since the beginning of November to reach a maximum thickness on February 28 (49.3 cm). In turn, in the period 2010/11–2014/15, snow cover started to increase dynamically by the end of November, after which, in the second half of December, it melted

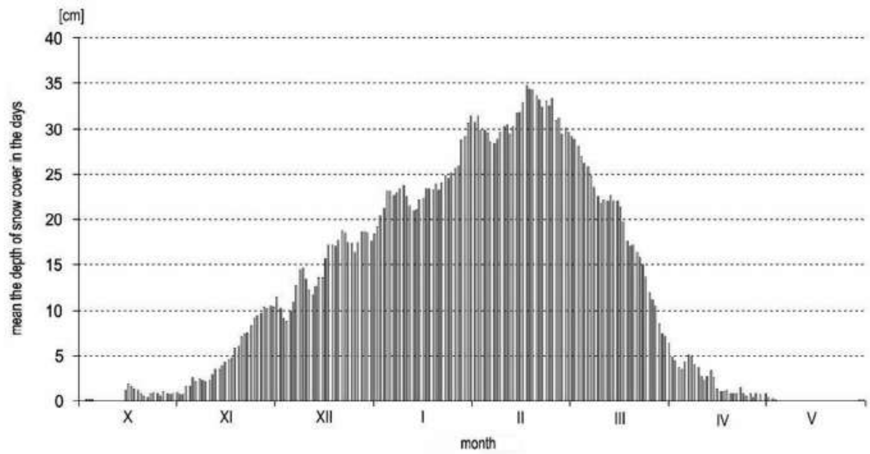

Figure 7. Mean thickness of snow cover in particular days in Zawoja (1961/62–2014/15)

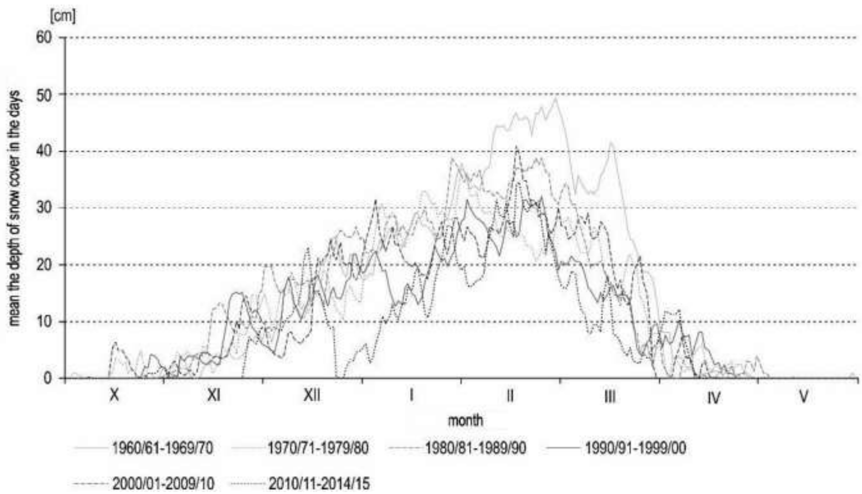

Figure 8. Mean the depth of snow cover in the days of its occurrence in Zawoja in the winter seasons of the 1961/62–2014/15 period

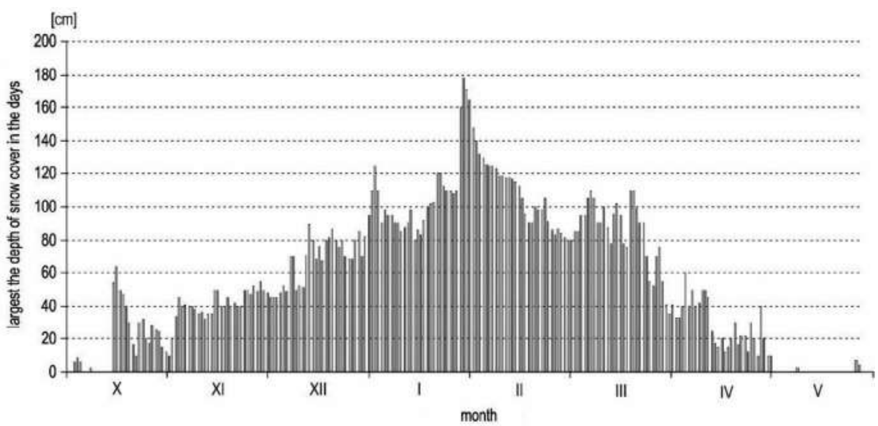

Figure 9. The largest daily thickness of snow cover in the days of its occurrence in Zawoja (1961/62–2014/15)

and started over to form. The highest average thickness was reached in mid-February (February 17) and attained 34.2 cm (Figure 8).

The snow cover ≥100 cm occurred from mid-January to mid-February (Figure 9). The largest thickness of snow cover was recorded on January 30, 1976, and attained 178 cm. The second largest thickness of snow cover (125 cm) occurred in January in the years 1987 and 2002. In the study period, there appeared 53 days with snow cover measuring ≥100 cm, of which as many as 31 were recorded during the winter of 1975/76.

The depth of snow cover changed gradually or very rapidly, depending on the prevailing weather conditions. The highest daily increase in the snow cover thickness was 54 cm, found on October 15, 2009 (there appeared fresh snow cover), and on February 16, 2012 (the snow cover increased from 46 to 100 cm). A little smaller daily increase in the snow cover depth (by 50 cm) occurred on January 29, 1976 (snow cover increased from 110 to 160 cm). On the other hand, the fastest melt of snow cover was observed on March 6, 1962, when it decreased by 47 cm, compared to the previous day and the snow cover melted completely. In addition, a daily reduction in the snow cover thickness by at least 30 cm was observed as many as 12 times in the study period.

The average multiannual sum of snow cover thickness was 2,968 cm in the study period (Figure 10). However, this value, informing about the winter snowiness, varied significantly from year to year, with the declining trend of changes. The minimum sum of the snow cover thickness of 477 cm was recorded in the winter season 2013/14. Winters with a low total snow cover thickness occurred in the years: 1971/72 (824 cm) and 1991/92 (874 cm). In turn, an exceptional thickness of snow cover of 8,800 cm was recorded in the winter of 1975/76. Other highest values during snowy winters were as follows: 6,508 cm (2005/06), 5,970 cm (1962/63) and 5,777 cm (1986/87).

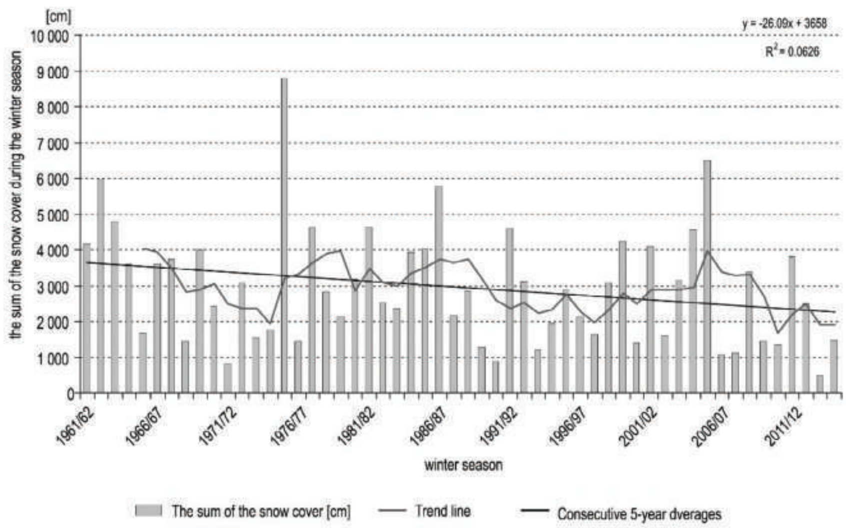

Figure 10. The sum of the snow cover thickness in Zawoja during particular winters (1961/62–2014/15)

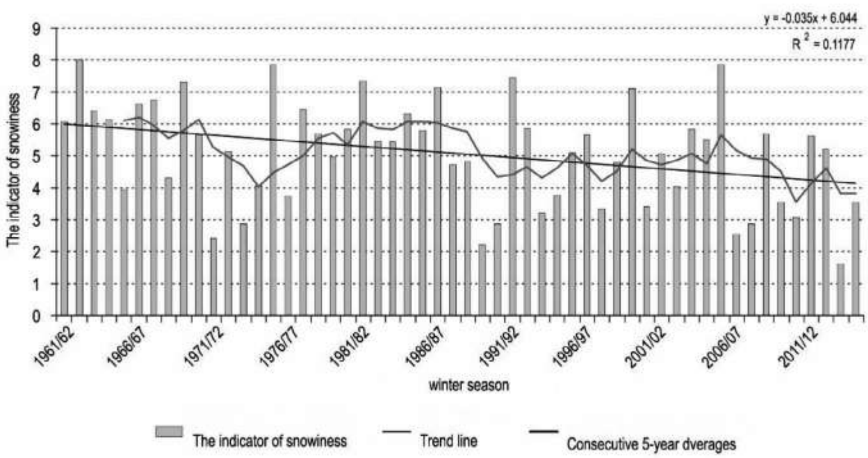

Figure 11. The indicator of snowiness in Zawoja (1961/62–2014/15)

4.5. Winter snowiness

The winter snowiness coefficient informs about winter snowiness, and is calculated for the period from December to March (Figure 11). This index reached the highest value of 8.00 (in the 10-grade classification) during the winter of 1962/63. Very high values of the index were also found for winters: 2005/06 (7.87) and 1975/76 (7.86). The lowest one (1.61) was for the winter of 2013/14. However, this winter was not an isolated case, because in the multiannual period under study there was a clear trend of declining winter snowiness, whereas several of the least snowy winters were recorded in the 21st century.

5. Discussion

The Babia Góra massif belongs to the areas with the longest snow cover persistence in Poland (Leśniak 1980; Leśniak and Obrębska-Starklowa 1983; Falarz 2007; Łajczak 2017). It rises in the Beskid Żywiecki Mts., in the basins of Upper Skawa and Upper Orawa rivers, which, as was shown by Leśniak (1980), are characterised by the longest time of snow cover deposition, at the same altitudes in the Polish Carpathians. The snow cover at the Babia Góra foothills in Zawoja, in the study 55-year period (1960/61–2014/15), lasted for an average of 118 days. The length of the snow cover duration in the same period in the Bieszczady, Beskid Niski or Śląski Beskid Mts. was a few days shorter (Leśniak and Obrębka-Starklowa 1983; Nowosad 1994; Laszczak et al. 2011).

The analysis of the long-term variability of snow cover occurrence in Zawoja did not show the statistically significant trends. A shortening of snow cover occurrence was observed in the multiannual 1960/61–2014/15, which was also confirmed by the results of studies of other authors, who examined similar periods in other mountain areas in Europe, including, among others: Nowosad 1994; Lapin and Fasko 1996; Beniston et al. 2003; Brown and Petkowa 2007; Micu 2009; Birsan and Dumitrescu 2014 and Urban 2015. At the foot of the Babia Góra massif, in the decade 2000/01–2009/10, the average number of days with snow cover, compared to the sixties of 20th century, was shortened by 22 days (by 18.6%). Other authors reported a similar trend from mountain areas in Poland, including Nowosad (1994) from the Bieszczady Mts. and Urban (2015) from the Sudety Mts., and from other regions in Europe including, among others: Beniston (1997); Hyvärinen (2003); Cazacioc and Cazacioc (2005); Bojariu and Dinu (2007); Brown and Petkowa (2007); Popova (2007); Durand et al. (2009), Micu (2009), Marity and Blanchet (2012). In turn, Falarz (2004) showed an increasing trend in the length of the snow cover deposition in Orawa, situated south of the Babia Góra massif. However, the above-presented results of study, cover mainly the period starting from the mid-twentieth century or a shorter one, during which the number of days with the snow cover occurrence was observed to decrease. As shown by Falarz (2002 a,b, 2007), on the example of a longer measurement series originating from Kraków (from 1921/22) and Zakopane (from 1914/15), in the period of 80-100 years, there were no significant changes in the snow cover duration since the twentieths of the 20th c. The average length of the potential snow cover deposition time varied greatly in the multiannual period examined. The difference between the beginning and the end of the snow cover deposition period in Zawoja was over 100 days between the extreme years. In the 55-year-long multiannual (1960/61–2014/15), the potential snow cover was 157 days on average. In this respect, the area under study has the same conditions as other regions located in the Carpathians at the same elevation, where according to Falarz (2007), the average potential period of snow cover duration exceeded 150 days, and during the extremely snowy winters – exceeded 200 days.

The potential period of snow cover duration in Zawoja in the examined multiannual was shortened by about 7 days for 10 years. In turn, Falarz (2007) showed that in most areas of the Carpathians (especially in its eastern part) this period was extended by 2–4 days for 10 years. However, these changes are insignificant in the Beskid Żywiecki Mts. On the other hand, a similar change as was found in Zawoja was observed by Urban (2015) in the Sudety Mts., in Lądek-Zdrój (461 m asl). At the stations located at lower slope elevation (likewise as in Zawoja), the rate of shortening of this period was about 4.5 days for 10 years, while at the Śnieżka Peak (1,603 m asl) these changes were much smaller, and amounted to 1.4 days/10 years. The major changes with negative trend were found for the lower stations, because the higher the area, the more stable the snow cover (Urban 2015. In the Carpathians, the potential snow cover duration may be extended by an average of 8-10 days for every 100 m of altitude asl (Leśniak 1980; Nowosad 1992), and the potential period of its occurrence shows smaller changes from year to year. In turn, large differences in its length have been observed from year to year in the lower parts of the slope of the Babia Góra Massif. The decrease in both numbers of days with snow cover and potential snow cover duration time, observed since the mid twentieth century in Poland, is related to the increase in Western advection (Niedźwiedź 2000; Falarz 2007). This results in the air temperature increase, especially during the winter months (Wibig and Głowacki 2002; Ustrul and Czekierda 2007; Michalska 2011). The negative trend of the above-mentioned features of snow cover may result both from the global temperature rise and local trends of the same features (Falarz 2002a). The snow cover is obviously affected by the local air temperature, which is playing the major role at lower elevations. At the higher altitudes, short-term increases in air temperature do not cause rapid melt of snow cover and its disappearance, as is the case in the valleys and lower parts of the slopes (Falarz 2002a). In the years 1961–2015, the highest increase in the average air temperature, attaining 1.8°C/50 years, was recorded in Zawoja in December and January. In the remaining months (from October to April) of the period examined, during which the snow cover was present, it ranged from 0.4°C/ 50 to 1.2°C/50 years, however, no statistically significant trends could be established for the individual months (Sulikowska et al. 2017). A strong positive correlation was reported by Bednorz (2002, 2004), between the time of snow cover occurrence and the number of days with the average temperature > 0°C within the territory of Poland. A distinct increase in the number of such days was observed in the winter season in Zawoja (Sulikowska et al. 2017).

In the period examined, both the average date of snow cover appearance and its disappearance date have changed. Snow cover used to appear on average on November 14, later about 3.1 days for 10 years. In turn, the snow cover disappearance was about 4 days earlier for 10 years, with the average appearance on April 14. The average date of snow cover disappearance in Zawoja is convergent with the end of the early spring, whose last day according to Sulikowska et al. (2017) was on April 9, in the years 1961–2015. On the other hand, the pre-winter began on October 29 and lasted for 35 days, therefore the first day with snow cover occurred on average in the middle of this period.

At the weather station located at the foot of the Babia Góra massif at 697 m asl, only July, August and September were free from snow cover, in the period examined. In contrast, at Markowe Szczawiny, located on the northern slope of Babia Góra at an altitude of 1,180 m asl, the snow cover was to be observed every month. The occurrence of snow cover in the period from April to June was most often associated with the occurrence of snowfall during the cold fronts moving actively over Poland, accompanying the low-pressure systems driven from northern Europe (Bartoszek 2007).

Changes in the snow cover development, its disappearance and persistence time, and above all, in its average thickness, are affected by the North Atlantic Oscillation Index (NAO Index). Its effect on the air temperature is particularly visible in winter and translates into winter snowiness (Ustrul and Czekierda 2007). Bednorz (2002, 2004) found a negative correlation between the snow cover duration in Poland and the NAO Index. A negative winter NAO phase increases the probability of snowy winters, whereas its positive phase – of less snowy winters (Bednorz 2002; Petkova et al. 2004; Cazacioc and Cazacioc 2005; Bojariu and Dinu 2007; Popova 2007).

The snow cover accumulates in Zawoja from the turn of October and November, reaching a maximum average thickness of many years at the turn of January and February, as well as in the second half of February, and then is quickly disappearing until its complete melt in April. A similar is true for other parts of the Polish Carpathians (Leśniak 1981, 1984; Nowosad 1991, 1994; Falarz 2000–2001, 2007; Kozak and Łepko 2015). In the analysed multiannual, in particular decades (from 1960/61–1969/70), a decrease in both the average and maximum daily thickness of snow cover was observed, as well as its earlier vanishing. At present, the mid-winter snow cover disappearance is more frequent, which incites changes in the outflow from the catchment. The snow retention decreases, and thaw freshets become more often and start earlier (Wilson et al. 2010; Pociask -Karteczka and Choiński 2012).

In addition to the decrease in the number of days with snow cover and the sum and average snow cover thickness, cyclical changes in these variables have been observed. The latter is apparently noticeable in the case of winter snowiness. The 5-year consecutive average indicates that the periodicity of winter snowiness in Zawoja attains, since the middle of the 20th century, 16–19 years. This index was around 2.00–3.00 during the least snowy winters, occurring in the early 70s and 90s of the 20th century, and at the turn of the 20th and the 21st century. On the other hand, this index was 6.00–8.00 during the most snowy winters, falling in the multiannual examined for the 1960s and 1980s, as well as at the turn of the 90s and the 21st century. Therefore, there were large differences, while the following winter periods will reveal, whether after a series of the least snowy winters since the middle of the twentieth century, the further seasons will still remain poorly snowy, or if, in accordance with the earlier periods, long and snowy winters will occur.

6. Conclusions

1) The average occurrence length of ≥1 cm thick snow cover in Zawoja, in winter seasons between 1961/61 and 2014/15, is 104 days, and varies greatly between the individual seasons. The period of snow cover persistence was observed to shorten by about 5 days for 10 years. In the individual decades, this period has been shortened from 118 days in the decade 1960/61-1969/70 to 96 days in the last decade (2000/01–2009/10).

2) The average length of potential snow cover deposition was 157 days, with a minimum period of 111 days (2013/14) and a maximum period of 214 days (1960/61), and showed a negative trend over time, what translates into shortening of the period by about 7 days for 10 years.

3) The snowiest months were February and January, when the snow cover occurred for 81% and 75% of days, respectively. The high share of the snow cover deposition was also found for December (65% of days) and March (58% of days), while no snow cover was observed in July, August and September.

4) The deepest snow cover developed since mid-February and its average thickness was 34.8 cm in the multiannual examined. Snow cover ≥100 cm occurred from mid-January

to mid-February, and its largest thickness (178 cm) was recorded on January 30, 1976.

5) The average multi-year sum of snow cover thickness in the season was less than 3,000 cm, and varied from 477 cm in the season 2013/14 to 8,800 cm in the 1975/76 season, showing a negative trend.

6) A significant variability of the winter snowiness coefficient was determined for the period examined, varying from 1.61 in the season 2013/14 to 8.00 in the season 1962/63.

7) In the multiannual period examined, a distinct periodicity of the number of days with the snow cover occurrence, the average and the sum of the snow cover and the winter snowiness, attaining 16–19 years, was observed in Zawoja.

Conflicts of interests

The author declares no potential conflicts of interests.

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