MELTING OF THE SNOW COVER IN THE POLISH TATRA MOUNTAINS – LONG-TERM CHANGES AND THE IMPACT OF ATMOSPHERIC CIRCULATION

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Abstract: The aim of the research is to present the annual distribution and long-term changes in the melting of the snow cover in the Tatras. An additional aim is to explain the causes of rapid snow cover melt related to atmospheric circulation. The paper uses data from three meteorological stations located at different altitudes in the Polish Tatra Mountains for two periods, 1966–2023 and 1991–2023. The conditional probability was calculated for the occurrence of rapid snow cover melting under different atmospheric circulation conditions. The most important results of the study are as follows: (1) the highest number of days with snow cover melting in the winter season (i.e. snow season) occurred in March in Zakopane, in April in Hala Gąsienicowa and in May on Kasprowy Wierch; (2) statistically significant long-term trends were found mainly for melting rate characteristics (in cm) and in the majority of cases in the period 1966/1967–2022/2023; furthermore, a positive, statistically significant trend in the number of days with snow cover melting was found for Kasprowy Wierch. In the period 1991/1992–2022/2023, one statistically significant trend was detected: a negative tendency in the average seasonal melting of snow cover in Hala Gąsienicowa and (3) rapid melting of snow is favoured by the inflow of tropical air masses over southern Poland, the advection of air from the southern sector with cyclonic conditions and the passage of a warm weather front.

Keywords: snow cover, melting, Tatra Mountains, climate trends, atmospheric circulation, climate change

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Introduction

Mountain ecosystems are sensitive to climate fluctuations and changes (Trepińska 2002, Migała 2005). The meteorological stations located there are influenced by anthropogenic global change and by local and regional factors, especially at the foot of the mountains. The ongoing climate change (IPCC 2021, 2023) has a direct impact on snow cover, which is the result of the changes in air temperature, precipitation, solar radiation and wind, and indirect impact of atmospheric circulation.

Snow cover is strongly linked to hydrographic conditions as well as vegetation, which protects above all from frost while providing the necessary moisture to the soil and influencing the length of the growing season (Daubenmire 1973). Snow cover is considered one of the main components of the Earth's climate system because of

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its role in altering the flow of energy and moisture between the soil surface and the atmosphere (Brown, Goodison 2005).

Snow cover itself as well as snow avalanches have been areas of interest to many past and present researchers. In Poland, systematic research on snow and avalanches in the Tatra Mountains was commenced by M. Kłapowa in the 1960s. It was carried out at the Nival Research Station at Hala Gąsienicowa (Kłapowa 1980, Paryski, Radwańska-Paryska 1995). A great deal of research has also been conducted to date on precipitation occurring in the Tatras (Cebulak 1983, Niedźwiedź 2003, Żmudzka 2010, Ustrnul et al. 2015) and on long-term changes in air temperature (Hess 1965, Głowicki 1998, Niedźwiedź 2004, Żmudzka 2009, Żmudzka et al. 2015, Migała et al. 2016). Snow cover is a widely described component of the Tatra climate. Numerous researchers have made contributions to describe the snow cover duration as well as its depth and density also for other mountain areas in Poland, including the Sudetes (Sadowski 1977, Kwiatkowski 1978, Urban 2015). However, the vast majority of the studies concern the Carpathians, especially the Tatras (Kłapowa 1980, Falarz 2000–2001, 2002, Fiema et al. 2007, Kędzia et al. 2023), the Bieszczady (Nowosad 1992a, b, 2000) and the Beskids (Łajczak 1996, Dyszy, Szyga 2020). There are few studies comparing snow conditions between the individual mountain ranges in Poland, e.g. the Tatras and the Karkonosze (Błażejczyk 2019) or between ranges located in Poland and abroad (Błażejczyk, Skrynyk 2019).

Melt trends have been studied in various alpine areas around the world. Long-term trends of snow melt dates in the Alps were described by Vorkauf et al. (2021) who found a close correlation between these dates and spring air temperature at all altitudes above sea level. Senese et al. (2015) also studied the air temperature thresholds at which snow or ice melts on the Forni glacier in the Italian Alps in the April–June period. Various aspects of snow cover melt have also been studied in the mountains of Asia (Sarangi et al. 2020, Tang et al. 2020) and North America (Welch et al. 2016). Changes in the Baltic Sea basin were also described, including seasonal snow cover, frozen soil and small glaciers in Sweden and Norway (Rasmus et al. 2015). Studies of rapid snow cover melting conditions in the Tatras have been undertaken quite rarely. These conditions have not been explored in detail to date. Studies of melting in the Tatras have been undertaken in the hydrological (Krajčí et al. 2016), chemical (Siwek et al. 2023) and biological (Bartík et al. 2014) aspects. The issue of melting and, in particular, rapid melting of snow cover is important from the point of view of forecasting river water levels and flood events.

The aim of the research is to present the distribution of seasonal and long-term changes in snow cover melting in the Tatras with a particular focus on rapid melting. An additional aim is to explain the causes of rapid snow cover melt related to regional atmospheric circulation. In the face of global warming (IPCC 2023), negative trends in snow cover in large areas of the Northern Hemisphere (Choi et al. 2010) and the statistically significant negative trends of: the potential duration of snow cover season, the last day with snow in the season and snow cover duration (statistically significant only in Zakopane) in the Tatra Mountains (Wibig, Jędruszkiewicz 2023), the question arises about the time structure of changes in melting and reduction of snow cover depth in mountainous areas, where it remains for a particularly long time. Water from melting is important in shaping hydrological conditions, affects the time distribution of water levels and flows in rivers and the level of groundwater in foothill areas and in the foreground of mountains. This is particularly important in spring when good soil moisture is needed for developing crops and wild plants. The rapid melting and disappearance of snow cover cause rapid changes in the albedo of the Earth's surface, increasing the absorption of shortwave radiation by the Earth's surface and thus affecting the radiation balance. The conditions for the persistence and melting of snow cover are also important for winter sports and its economic effects.

Data and methods

The study used data from three meteorological stations located at different altitudes in the Polish Tatra Mountains. The coordinates of the stations and their locations are shown in Table 1.

Two study periods were considered in this paper. For the first period, 1966–2023 (58 years),

Table 1. Meteorological stations included in the analysis and their characteristics.

Station	Latitude	Longitude	Altitude [m a.s.l.]	Landform	Study period(s)
Zakopane	49°17'37"N	19°57'32"E	852	Concave	1966–2023 1991–2023
Hala Gąsienicowa	49°14'38"N	20°00'20"E	1508	Convex	1991–2023
Kasprowy Wierch	49°13'57"N	19°58'54"E	1987	Peak	1966–2023 1991–2023

data from two meteorological stations, Kasprowy Wierch and Zakopane, were included due to the lack of available daily data on snow cover at Hala Gąsienicowa in 1966–1990. For the second, shorter period, 1991–1923 (33 years), the analysis includes all three stations. Daily measurement and observation data from the archives of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB 2024) were used to investigate long-term trends in snow cover melting in the Tatras. Daily depth of the snow and maximum air temperature were considered. The data series were complete, and the meteorological stations did not change their location during the study period. Days with negative differences in snow depth from one day to the next, when the maximum daily temperature was ≥0.1°C, were considered melt days. Other cases of snow cover loss are associated with causes other than melting (metamorphism of snow structure leading to compaction, wind deflation and sublimation). In addition, we take into account that in midwinter, the reduction of snow cover depth is most often caused by the metamorphism of snow structure, leading to compaction and a decrease in the depth of the snow layer. So, for the winter period, it is more appropriate to use the terms ‘reduction’ or ‘decrease’ of snow depth. Furthermore, days with a large loss of snow cover (≥20 cm) when the snow cover was 0 cm on the following day were not considered. Such situations were very likely to occur when on the previous day an observer classified the snow cover condition as intermittent snow cover (>50% of the area covered by snow cover) when reporting the snow depth, and on the following day classified the snow cover as patches of snow cover (<50% of the area covered by snow) reporting a snow layer depth of 0 cm in accordance with the World Meteorological Organisation (WMO) guide.

The following were calculated:

– the average monthly and seasonal snow cover duration and maximum snow cover depth;
– the average monthly and seasonal number of melt days;
– average monthly and seasonal melting rate of snow cover (in cm);
– the absolute maximum of snow cover melt (in cm) per month and per season.

The annual distribution and long-term trends of all the above-mentioned characteristics were examined using the simple regression analysis, and their statistical significance was determined by using a *t*-test (for a significance level of 0.05). The 5-year moving average was calculated for the smoothing of the series. The winter season (snow season) was assumed the period from August to July of the following year. The 1966/1967 season was called the 1966 season in the charts. The threshold values for rapid snow melt were defined as the 90th percentile of all melt days. The conditional probability was calculated for the occurrence of rapid snow cover melting under different atmospheric circulation types, with different air masses arriving over southern Poland and with different atmospheric fronts in two periods:

1. longer: from October to May, i.e. months of at least 25 days with rapid snow melt throughout the whole period (1991–2023) and
2. shorter: from February to May, i.e. months of at least 65 days with rapid snowmelt throughout the whole period.

Data on circulation conditions (types of circulation, air masses, atmospheric fronts) were taken from the Calendar of Atmospheric Circulation Types for southern Poland compiled by Niedźwiedź. Conditional probability was calculated according to the method applied by Twardosz, Niedźwiedź (2001) as a quotient, expressed as a percentage, of the number of days with rapid melting, with a particular air mass/front/type of circulation and the total number of days with the occurrence of a particular air mass, front or type of circulation in the entire study period.

Results

Number of days and maximum seasonal depth of snow cover

At the foot of the Tatra Mountains (Zakopane), snow cover occurred for an average of 122 days in the winter season, in Hala Gąsienicowa for 180 days and on the top of Kasprowy Wierch for 217 days. The maximum number of days with snow cover was observed in the winter season 1995/1996 in Zakopane, when snow cover occurred for 164 days, the 1996/1997 season in Hala Gąsienicowa (215 days) and the 1972/73 season on Kasprowy Wierch (258 days). At all the stations studied, the duration of snow cover was characterized by negative trends in the multi-year period (Fig. 1A). These trends were statistically significant in Hala Gąsienicowa (−7.3 days per 10 years) and in Zakopane (−4.6 days per 10 years). The average maximum snow cover depth in the winter season was 59 cm in Zakopane, 159 cm in Hala Gąsienicowa and 196 cm on Kasprowy Wierch. The highest depth was recorded in the 1975/1976 season in Zakopane (101 cm), 1997/1998 in Hala Gąsienicowa (267 cm) and 1994/1995 on Kasprowy Wierch (355 cm). Long-term trends in the maximum depth of snow cover were slightly negative in Zakopane and Hala Gąsienicowa and slightly positive on Kasprowy Wierch (Fig. 1B). None of these trends were statistically significant.

During the year, the average maximum depth of snow cover is the highest in February in Zakopane (on average 46 cm in the period 1991–2023), in March in Hala Gąsienicowa (126 cm) and in April on Kasprowy Wierch (191 cm). The longest snow cover occurs in January in Zakopane (on average 27 days in the period 1991–2023), from December to March in Hala Gąsienicowa (28–30 days in each month) and from December to April on Kasprowy Wierch (28–31 days in each month).

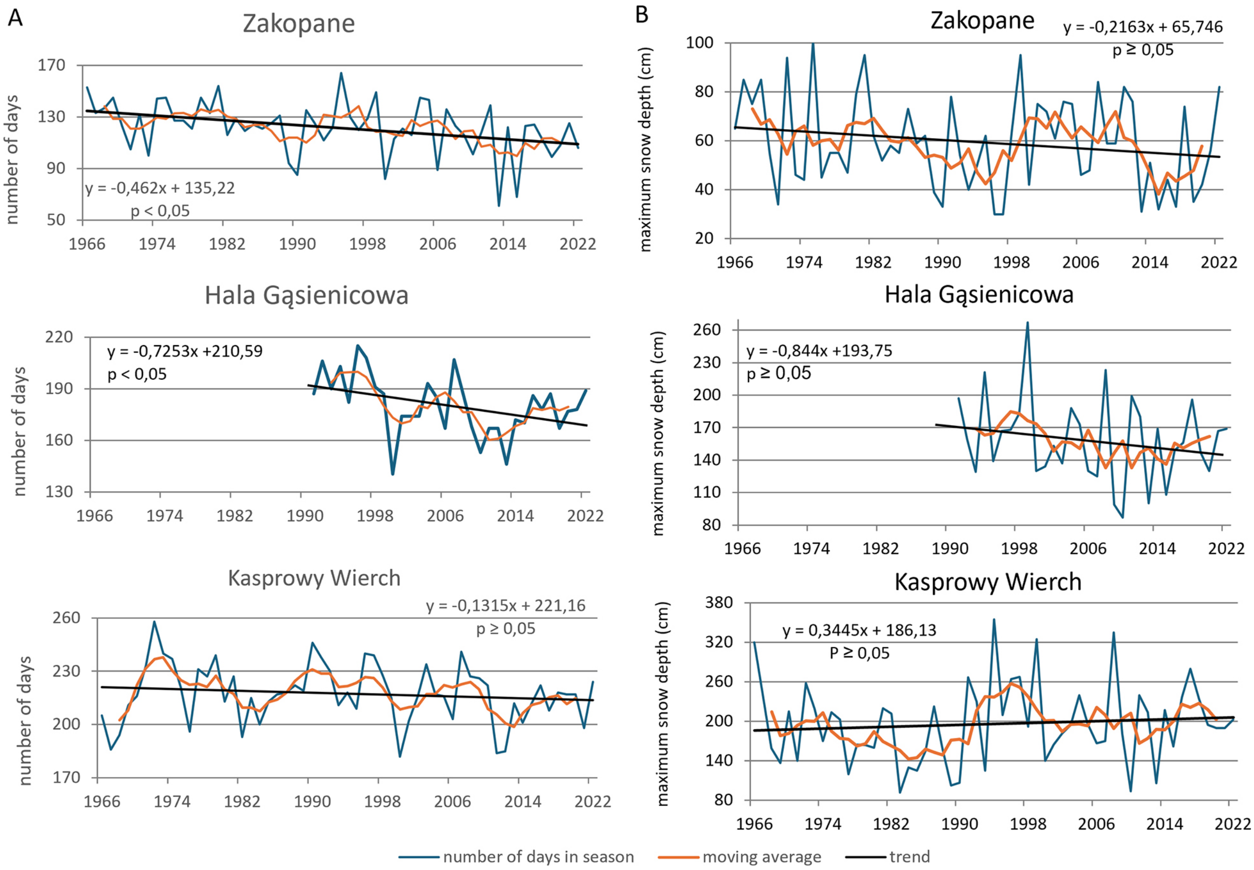

Fig. 1. Number of days with snow cover (A – left column) and maximum seasonal snow cover depth (cm; B – right column) in Zakopane (1966–2023), Hala Gąsienicowa (1991–2023) and on Kasprowy Wierch (1966–2023). Data: IMGW-PIB

Melting of the snow cover in the period 1966–2023

The highest number of days with snow melt in Zakopane, averaged for the long-term period, occurred in March (11.8 days) and February (10.1 days; Fig. 2A). The cover melted from October (1.8 days) to May (0.5 days), with an apparent tendency to increase the number of days from October to reach a maximum in March. From April (4.8 days), melting decreased until the snow disappeared. On Kasprowy Wierch, melting occurred in every month of the year (Fig. 2B). The highest number of melt days per month occurred during the spring thaw in May (13.7 days a month on average) and in April (13.3 days a month). The least snow melted in the summer months, i.e. July (0.4 days) and August (0.2 days). During winter, there was a noticeable decrease in days with snow cover reduction (3.0 days in January and 2.6 days in February) due to the rare occurrence of days with positive temperatures during this period.

In the long-term course, the number of melt days in Zakopane showed a decreasing trend (about 8 days over the whole long-term period), but this change is not statistically significant (Fig. 3A). On Kasprowy Wierch, the situation was reversed, and a significant increase in the number of melt days was observed, by about 20 days over the long-term period (3.5 days per 10 years). The trend is statistically significant (Fig. 3B). In addition, the curve of 5-year moving averages shows an approximately 8-year periodicity in the number of days with melting at the summit of Kasprowy Wierch since the mid-1980s.

The largest daily decreases in snow depth were observed in the Tatra foothills during spring, (April 4.9 cm and March 3.8 cm on average; Fig. 4A). The values increased gradually from October (2 cm), with a small decrease during winter, i.e. in January (3.2 cm) and February (3.3 cm), until reaching the highest daily melt in April. In summer, melting did not occur due to the lack of snow. In the summit area of the Tatras, the highest average rates of snow melt also occurred in spring (May 6.5 cm and April 6.4 cm on average; Fig. 4B). The second maximum rate of melting on Kasprowy Wierch was recorded in autumn (October 3.8 cm). In winter, the snow decrease was small (1.8 cm in January) as is the case of summer (1.0 cm in July and 0.7 cm in August).

A decrease in the average snow cover reduction rate (cm) in the winter season was observed

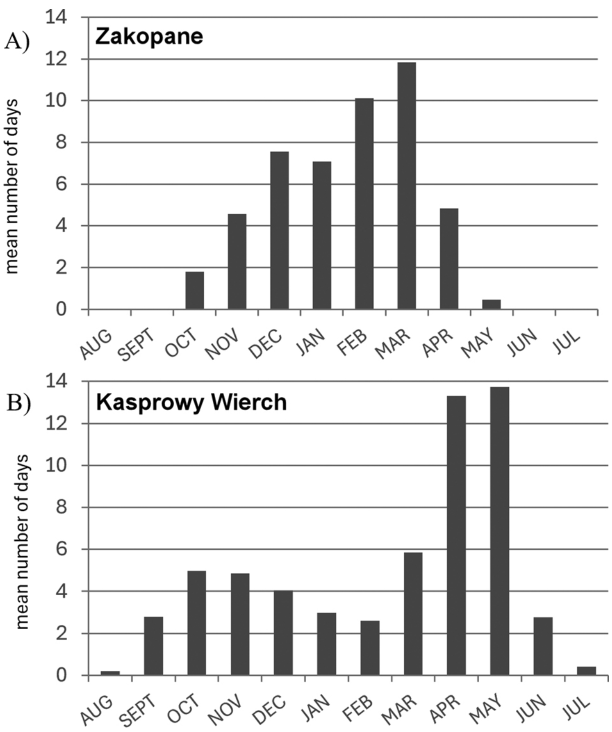

Fig. 2. Average monthly number of days with snow cover melt for the stations: A – Zakopane and B – Kasprowy Wierch (1966–2023). Data: IMGW-PIB.

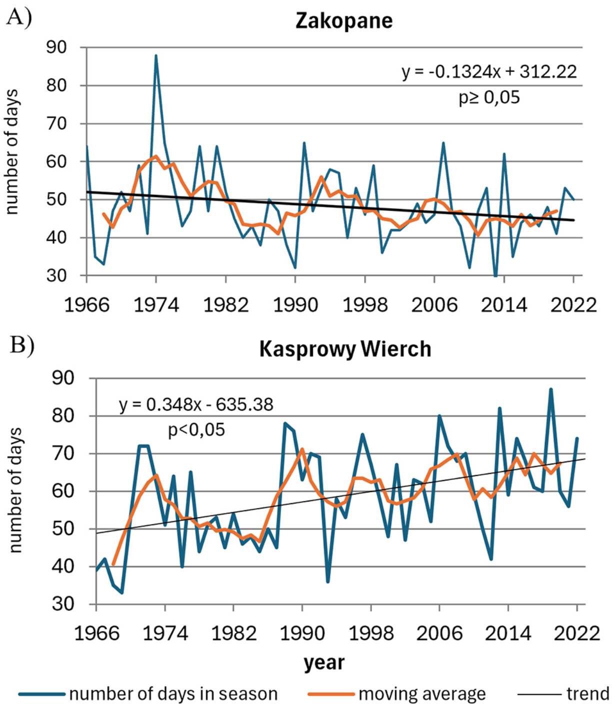

Fig. 3. Long-term variability and trend in the number of melt days: A – in Zakopane and B – on Kasprowy Wierch (1966–2023). Data: IMGW-PIB.

at both stations in the long-term distribution (Fig. 5). The difference in both cases is approximately 1 cm over the entire long-term period (approximately −0.2 cm per 10 years), and this is a trend showing statistical significance for each station.

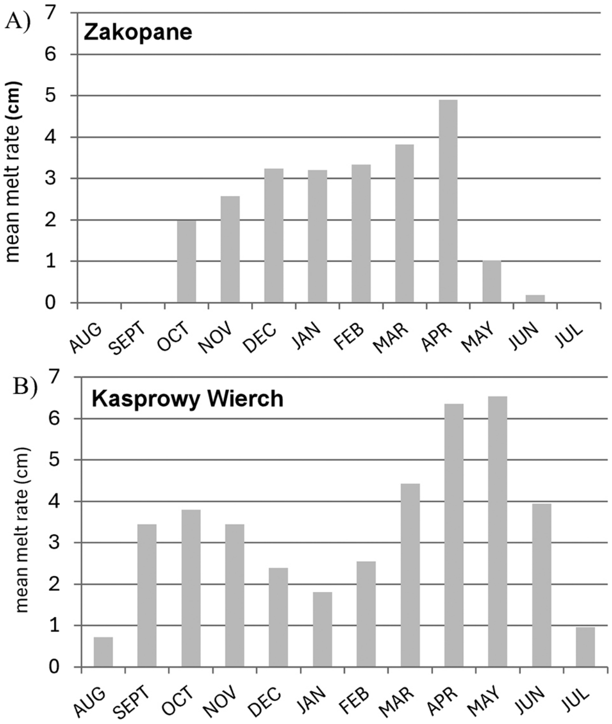

Fig. 4. Average monthly rate of snow melt rate (cm) for the stations: A – Zakopane and B – Kasprowy Wierch (1966–2023). Data: IMGW-PIB.

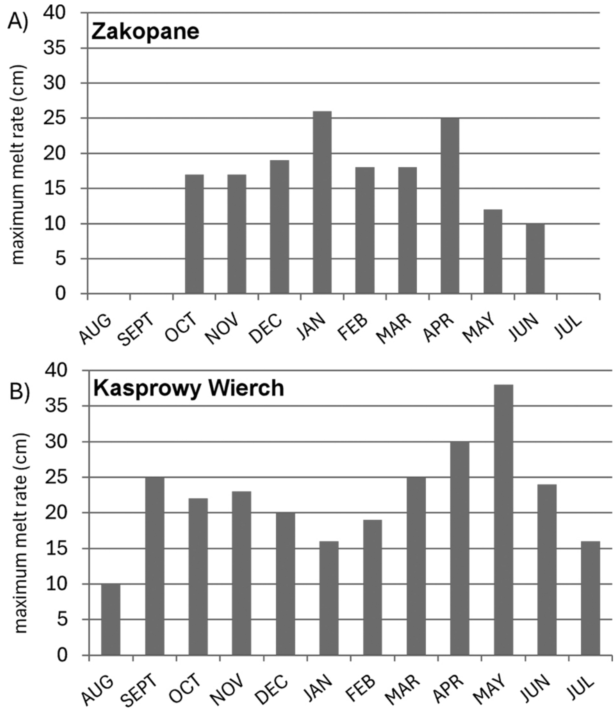

Fig. 6. Absolute monthly melt maxima (cm) for the stations: A – Zakopane and B – Kasprowy Wierch (1966–2023). Data: IMGW-PIB.

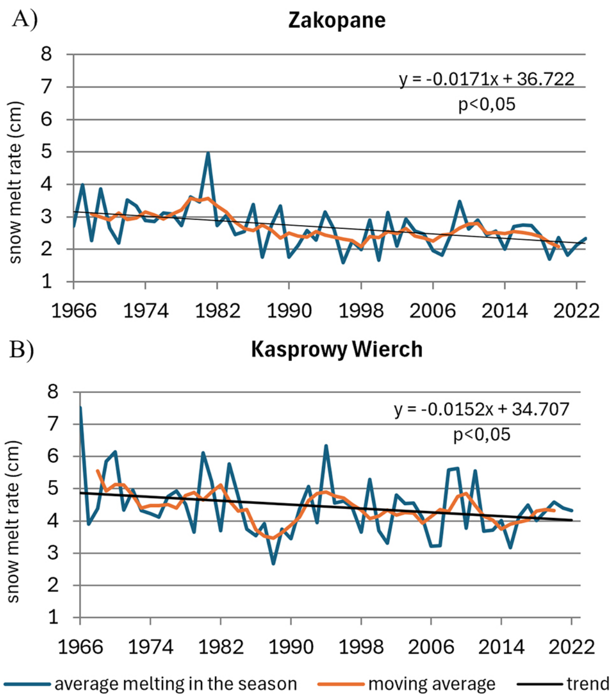

Fig. 5. Long-term course of average daily snow cover melt rate per season (cm) for the stations: A – in Zakopane and B – on Kasprowy Wierch (1966–2023). Data: IMGW-PIB.

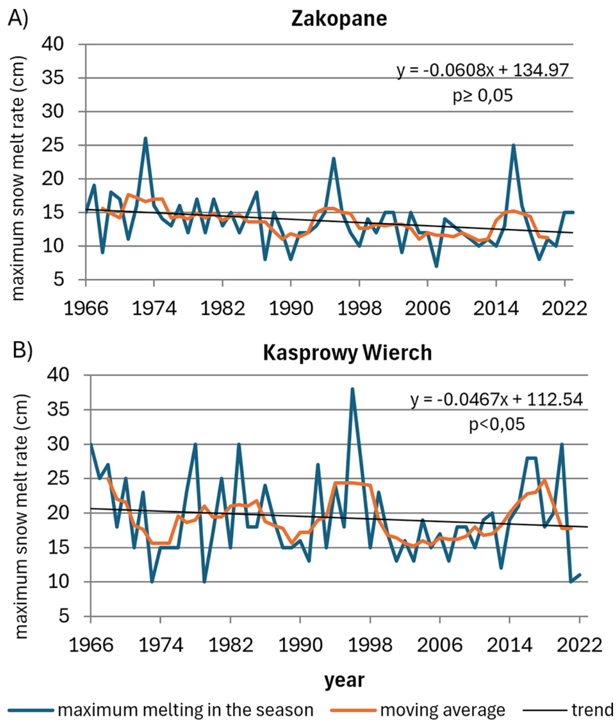

Fig. 7. Long-term course of absolute seasonal maxima of daily snow cover melt (cm) for the stations: A – Zakopane and B – Kasprowy Wierch (1966–2023). Data: IMGW-PIB.

The highest absolute maximum of snow reduction rate in the winter season in Zakopane occurred in January (26 cm (19 January 1974); Fig. 6A) and in April (25 cm; 21 April 2017). In the summer and early autumn months (between June and October), there is no snow cover in Zakopane, and in the other months, the values ranged from 10 cm in June to 19 cm in December. At the station on Kasprowy Wierch, the maximum absolute melting rate was the greatest in May (38 cm (4 May 1997); Fig. 6B). Melting occurred in every month of the year; two maxima were observed in the season: in September and May. The lowest of the melt maxima occurred in August (10 cm).

A statistically significant decreasing trend was seen for the absolute seasonal maxima of the melt rate values (cm) at the Zakopane station (Fig. 7A). The decrease in the maximum melt rate values over the whole long-term period was almost 3 cm (−0.6 cm per 10 years). On Kasprowy Wierch, the trend was slightly negative and not statistically significant (Fig. 7B). However, significant fluctuations year-to-year can be observed here.

Melting of snow cover in the period 1991–2023

In the period 1991/1992–2022/2023, each of the stations recorded the highest average number of melt days in a different month, which is related to the differences in accumulation and the seasonal course of snow cover depth at different altitudes. In Zakopane (852 m a.s.l.), the highest number of melt days was in March (11.8 days; Fig. 8A), at Hala Gąsienicowa (1508 m a.s.l.) in April (17.5 days; Fig. 8B) and on Kasprowy Wierch (1987 m a.s.l.) in May (15.2 days; Fig. 8c). Record monthly average number of melt days, among all stations, was at Hala Gąsienicowa (17.5 days). In Zakopane, the number of melt days increased from October to March and then decreased, reaching 0.2 days in May. Melt days at Hala Gąsienicowa also increased from September to April, with a slight decrease in January and February. On Kasprowy Wierch, only in August, there was no or very little melting, and the distribution of the number of days with melting in the season was quite irregular. A significant number of melt days was observed in April and May (about 15 days).

Also during this shorter and more recent period, the number of melt days per season showed a decreasing trend in Zakopane (Fig. 9A) and a slightly negative trend in Hala Gąsienicowa (Fig. 9B). On Kasprowy Wierch, an increase in the number of days with snow cover melting was noticeable (Fig. 9C). For all the stations, the long-term changes were not statistically significant. In Zakopane and Hala Gąsienicowa, the highest seasonal number of days with snow melting occurred in the same winter season in 2007/2008 (65 days in Zakopane and 102 days in Hala Gąsienicowa). The highest number of melt days on Kasprowy Wierch occurred in the 2019/2020 season (87 days). However, there is no temporal consistency in the occurrence of the lowest

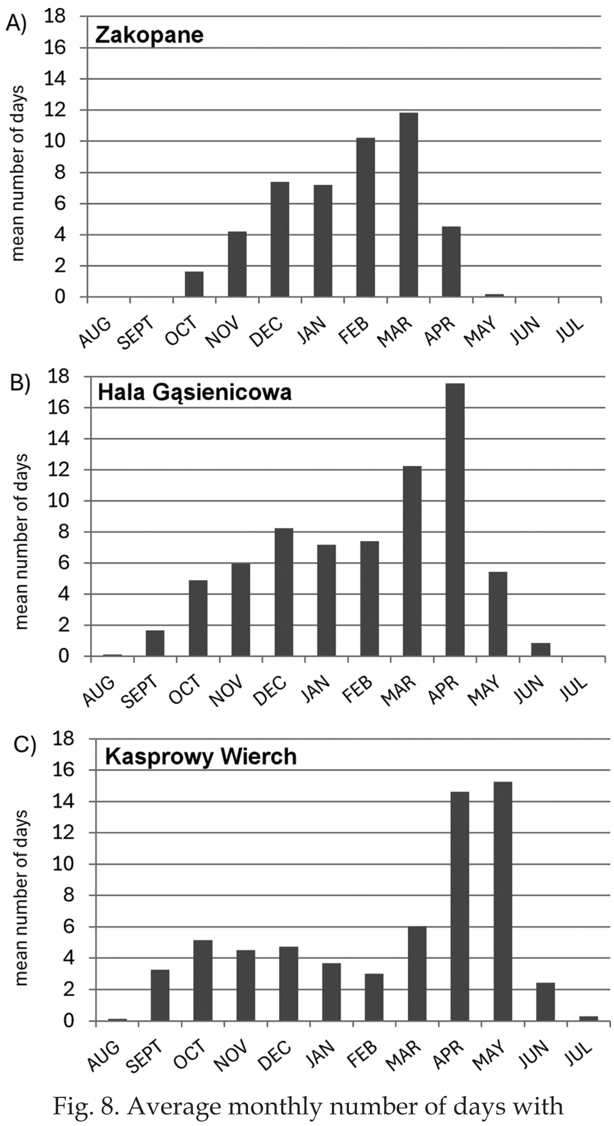

Fig. 8. Average monthly number of days with snow melt for the stations: A – Zakopane, B – Hala Gąsienicowa and C – Kasprowy Wierch (1991–2023). Data: IMGW-PIB.

number of days with melting in the elevation profile of the Tatras. The lowest number of melt days occurred in Zakopane in the 2013/2014 season (28 days), in Hala Gąsienicowa in the 2009/2010 season (45 days) and on Kasprowy Wierch in the 1993/1994 season (36 days).

The values of the average monthly decrease in day-to-day snow depth in Zakopane regularly increased from October to April (Fig. 10A). In April, the highest monthly decrease in snow depth was recorded in the Tatra foothills (4.7 cm on average). The least amount of snow melted towards the end of spring, in May (0.5 cm per day), and there was no melting in the summer months. Hala Gąsienicowa was characterised by two melting maxima: in October (4.9 cm on average; Fig. 10B) and April (5.9 cm on average). The rate of snow reduction in Hala Gąsienicowa was lower in winter (in December, 3 cm on average). After this period, the values increase again until April. Occasional melting also occurred in the summer months (0.1 cm in July and 0.3 cm in August). On Kasprowy Wierch, as in the case of Hala Gąsienicowa, melting occurred throughout the whole year, with two distinct maxima, in May (6.5 cm on average) and in October (4 cm; Fig. 10C). A decrease in the snow reduction rate during the winter period in January (only 2 cm on average) was noticeable here as well as a gradual, renewed increase in the rate of melting during the spring period. The lowest melt rate occurred in August and July (0.5 cm).

In Zakopane, in the period 1991–2023, the long-term trend of the average melt rate is close

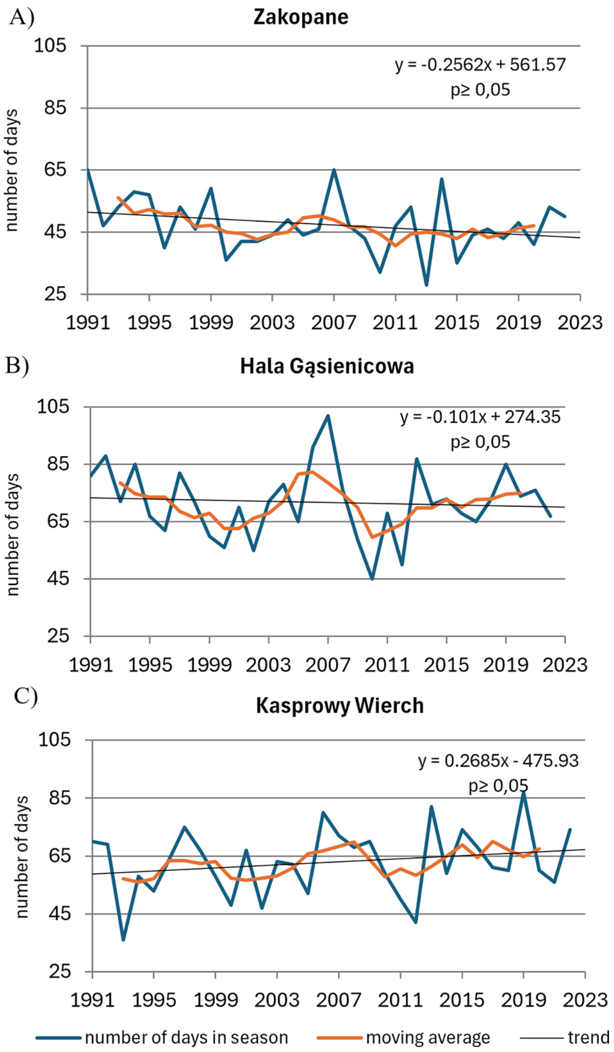

Fig. 9. Long-term course of the number of days with snow melt: A – in Zakopane, B – in Hala Gąsienicowa and C – on Kasprowy Wierch (1991–2023). Data: IMGW-PIB.

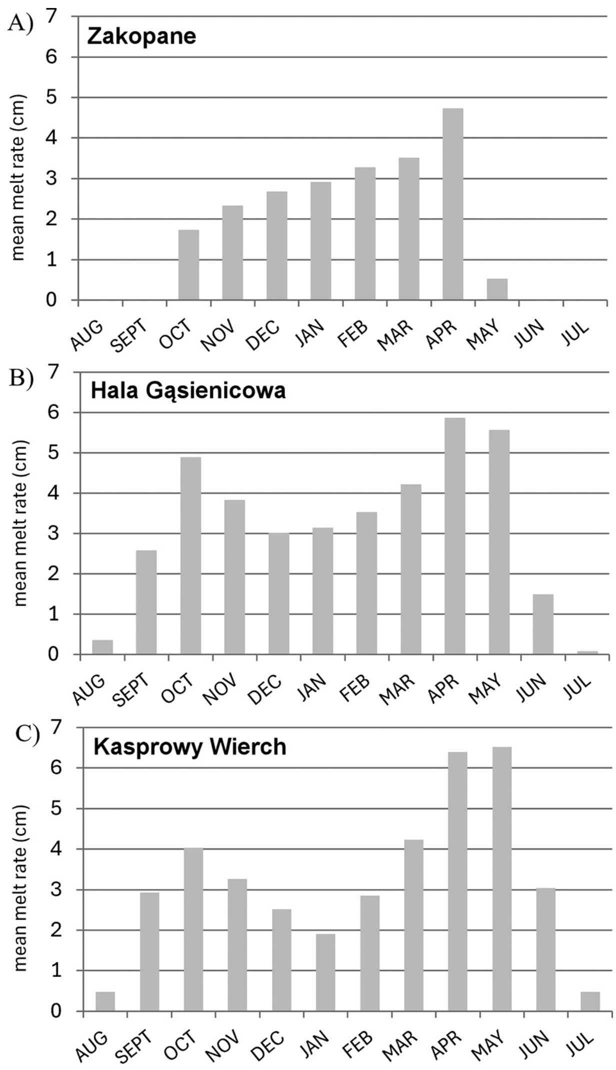

Fig. 10. Average monthly snow melt rate (cm) at the stations: A – Zakopane, B – Hala Gąsienicowa and C – Kasprowy Wierch (1991–2023). Data: IMGW-PIB.

to zero (Fig. 11A) and slightly decreased in Hala Gąsienicowa and on Kasprowy Wierch. The greatest change occurred at the Hala Gąsienicowa station (−0.2 cm/10 years; Fig. 11B). Currently, on average, almost 0.7 cm less snow melts occurred per day than at the beginning of the study period; this change is statistically significant. The situation is similar at the Kasprowy Wierch station (Fig. 11C); the reduction in the melt rate over the entire study period was about 0.5 cm, and the trend is not statistically insignificant. The exceptionally low value of daily melting in the 2001/2002 season in Hala Gąsienicowa (1.8 cm) was noted. At the stations in Zakopane and Hala Gąsienicowa, the maximum melt rate occurred in the same winter season of 2009/2010. In this season, maximum snow cover depth was particularly low in Hala Gąsienicowa (99 cm; see Fig. 1).

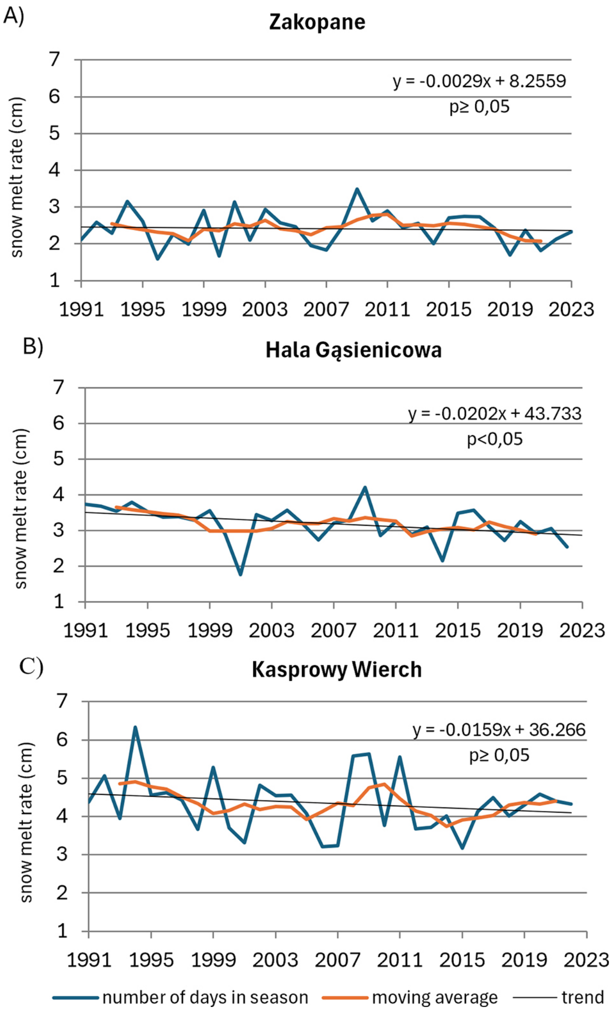

Fig. 11. Long-term course of the average snow cover melt per season (cm) at the stations: A – in Zakopane, B – in Hala Gąsienicowa and C – on Kasprowy Wierch (1991–2023). Data: IMGW-PIB.

The high melt rate was the result of temperature conditions. It was a season with a particularly large number of days with rapid melting of snow cover at this station (16 days compared to the long-term average of 10 days).

In the snow season pattern, the highest maximum absolute snow melt in Zakopane in the period 1991–2023 occurred in April (25 cm; 21 April 2017; Fig. 12). Values for the other months remained at a similar level – approximately 15 cm of the highest snow melt from October to March. On Kasprowy Wierch, the maximum melt rate was quite irregular, with the highest value in May (38 cm; 4 May 1997). A similar situation was also observed in Hala Gąsienicowa, where the maxima have different values, with the highest

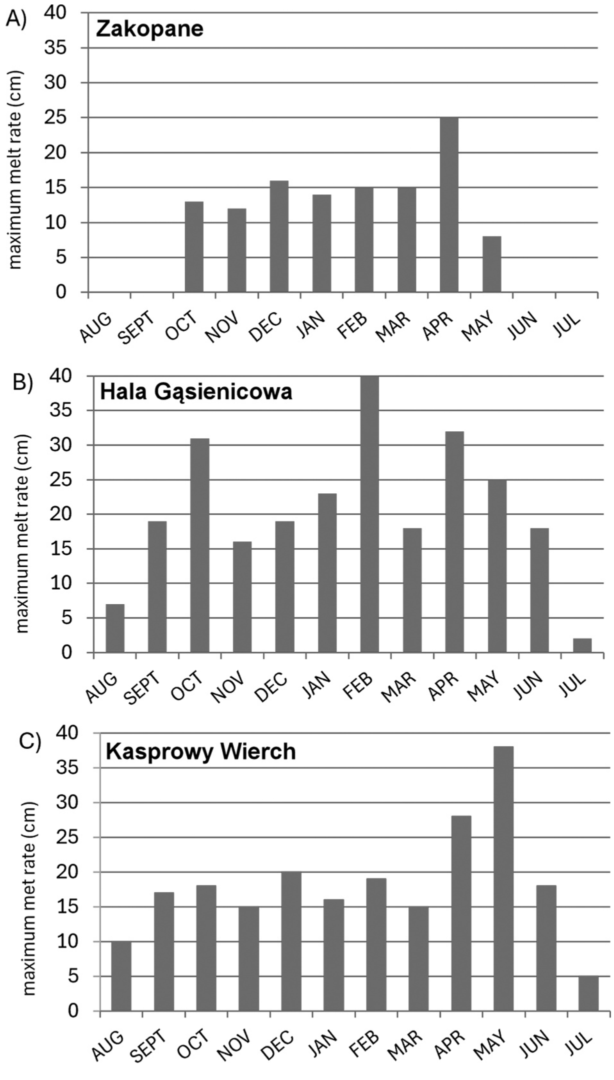

Fig. 12. Absolute monthly maxima of melt rates (cm) for the stations: A – Zakopane, B – Hala Gąsienicowa, C – Kasprowy Wierch (1991–2023). Data: IMGW-PIB.

in February (40 cm; 21 February 2004. Fig. 12) and also in April (32 cm) and October (31 cm).

There was a slight statistically insignificant negative trend of maximum absolute melt rates day-to-day at all the stations involved in the study in the long-term course in the period 1991–2023 (Fig. 13). Over the entire study period, the decrease in values calculated for a regression line was 1.5 cm in Zakopane (Fig. 13A) and about 4 cm in Hala Gąsienicowa (Fig. 13B) and on Kasprowy Wierch (Fig. 13C). The highest melt rate in Zakopane occurred in the 2016/2017 season (25 cm), with equally high values recorded in the same season in Hala Gąsienicowa (28 cm) and on Kasprowy Wierch (28 cm). The maximum amount of snow melt day-to-day was 40 cm in Hala Gąsienicowa in the 2003/2004 season and 38 cm on Kasprowy Wierch in the 1996/1997 season. The lowest maximum melt was similar for Kasprowy Wierch and Hala Gąsienicowa (10 cm in the 2021/2022 season and 12 cm in the 2022/2023 season, respectively), while the lowest daily melting maximum (7 cm) occurred in the 2007/2008 season in Zakopane.

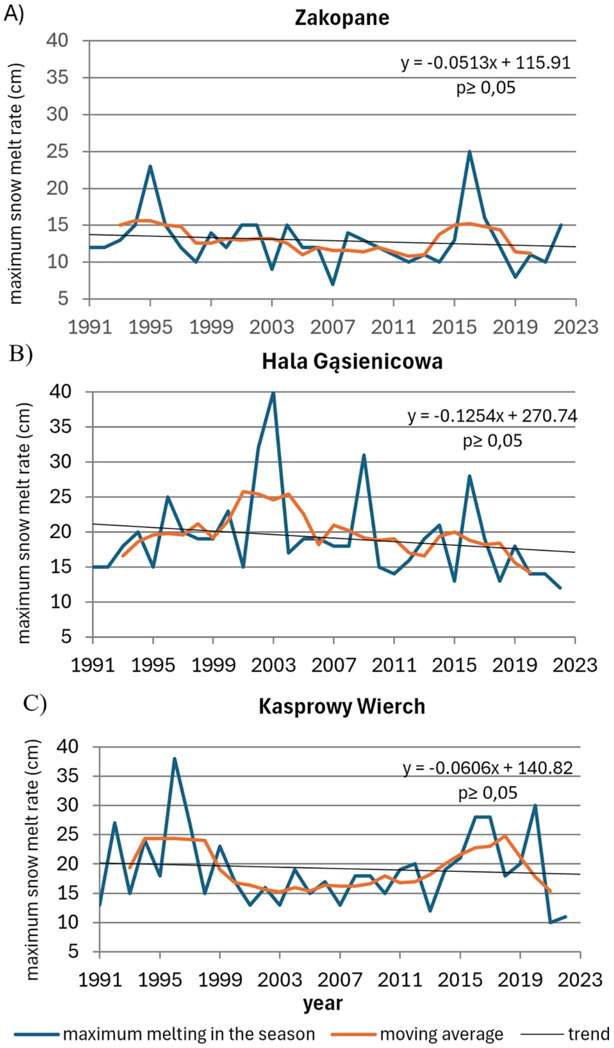

Fig. 13. Long-term course of absolute seasonal maxima of diurnal snow cover melting (cm) for the stations: A – Zakopane, B – Hala Gąsienicowa and C – Kasprowy Wierch (1991–2023). Data: IMGW-PIB.

Impact of atmospheric circulation on rapid melting of snow cover

The threshold values for rapid snow melt were defined as the 90th percentile of the melt rate on all the days with melting at a given meteorological station in the period 1991–2023. These values were ≥7 cm per day in Zakopane, ≥9 cm per day in Hala Gąsienicowa and ≥10 cm per day on Kasprowy Wierch.

The total number of days with rapid snow melt recorded by at least 1 measuring station was 765 days in the period 1991–2023 (i.e. 24 days per year on average). The highest number of days with rapid snow melt occurred in April (251 days over the entire period, i.e. 8 days on average per year) and May (141 days, i.e. 4 days on average each year; Fig. 14). There was also a notably slight increase in days with rapid melting in October (49 days in the entire period) compared with the other autumn months, a slight decrease until January (29 days) and a rapid increase again until April. In July, rapid melting did not occur; in August, it was negligible (1 case).

In the period from October to May, the occurrence of rapid melting was most likely in connection to the inflow over southern Poland of a

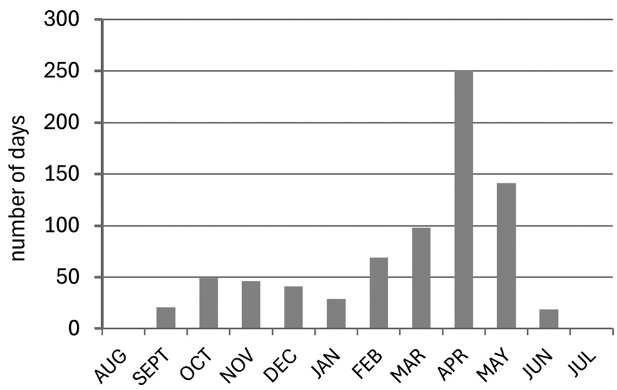

Fig. 14. Total number of days with rapid snow cover melting recorded by at least one meteorological station over the whole study period (1991–2023). Data: The Calendar of circulation types (Niedźwiedź 2025).

tropical air mass (PZ; the conditional probability is 20%; Fig. 15A) and warm polar maritime air (PPmc; 14%). A lower probability of a rapid decrease in snow depth was with the occurrence of various air masses on one day (rmp, 9%). The lowest probability of rapid melting of the snow cover in the Tatras occurred during the inflow over southern Poland of arctic air masses (PA; 2%) and polar maritime air (PPm 4%). In the period from February to May, the conditional probability of rapid melting with tropical air masses increased to 35%. High conditional probability is also observed with warm polar maritime air mass (PPmc; 25%; Fig. 15B). On the contrary, the lowest probability of the occurrence of this phenomenon is during an influx of arctic air mass (4%) and polar maritime air (7%) over southern Poland.

The highest conditional probability of a rapid decrease in snow cover depth from October to May occurred with cyclonic conditions with advection from the south (Sc; 18%; Fig. 16A) and with cyclonic conditions with advection from the south-west (SWc; 14%). A high probability of rapid melting also occurred with unclassified situations and a col over southern Poland (X; 11%). During this period of the year, rapid melting occurred more frequently with cyclonic conditions (52%) compared with anticyclonic conditions (44%). In the period between February and May, the conditional probability of the occurrence of rapid melting with anticyclonic conditions from the south (Sa; 19%; Fig. 16B), the south-west (SWa; 21%) and the south-east (SEa; 14%) as well as the west (Wa; 14%) almost doubled compared with the period from October to May. Like in the period between October and May, the highest conditional probability of rapid melting in the Tatras in the period from February to May was observed with type Sc (cyclonic conditions with advection from the south) and is 31%.

In both the study periods (October–May and February–May), rapid melting occurred with the highest probability with the arrival of a warm front (16% for October–May; Fig. 17A and 26% for February–May; Fig. 17B). In the period from

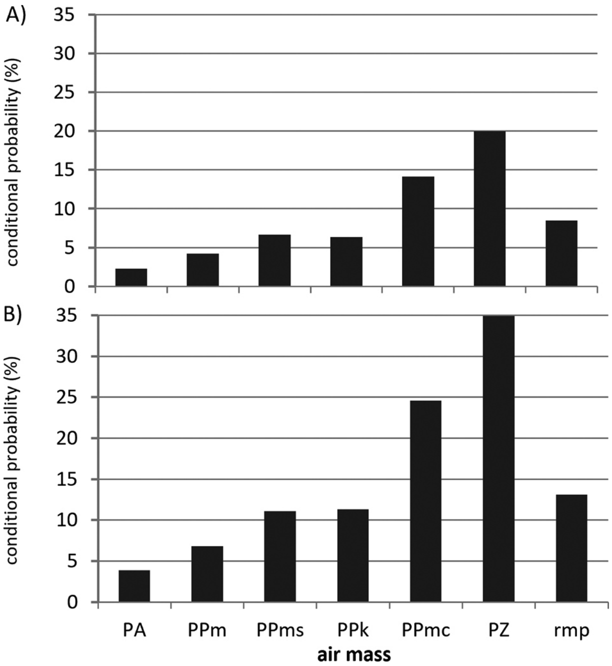

Fig. 15. Conditional probability (%) of occurrence of rapid melt recorded by at least one meteorological station with different air masses A – October–May and B – February–May (1991–2023; air: PA – arctic, PPm – polar maritime, PPms – transformed polar maritime, PPk – polar continental, PPmc – warm polar maritime, PZ – tropical, rmp – different air masses). Data: The Calendar of circulation types (Niedźwiedź 2025).

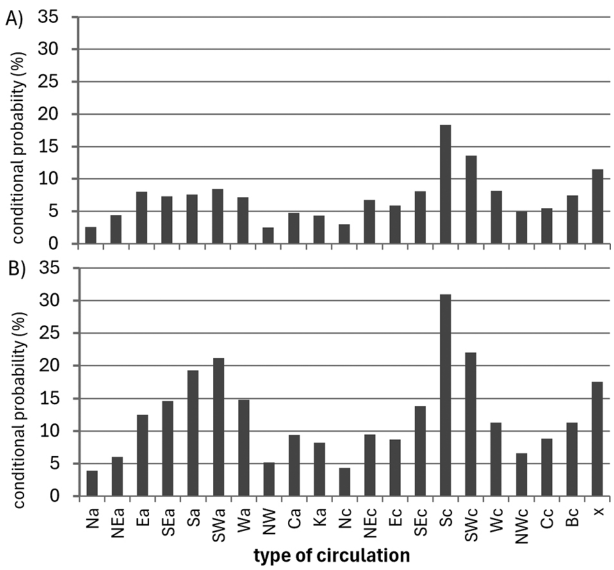

Fig. 16. Conditional probability of occurrence of rapid melting recorded by at least one meteorological station in the Tatras with the individual types of circulation: A – October–May and B – February–May (1991–2023; anticyclonic conditions: Na – northerly, NEa – north-easterly, Ea – easterly, SEa – south-easterly, Sa – southerly, SWa – south-westerly, Wa – westerly, NWa – north-westerly, Ca – centre of high pressure, Ka – highpressure wedge; cyclonic conditions: Nc – northerly, NEc – north-easterly, Ec – easterly, SEc – south-easterly, Sc – southerly, SWc – south-westerly, Wc – westerly, NWc – north-westerly, Cc – centre of low pressure, Bc – cyclonic trough, X – unclassified situations and a col). Data: The Calendar of circulation types (Niedźwiedź 2025).

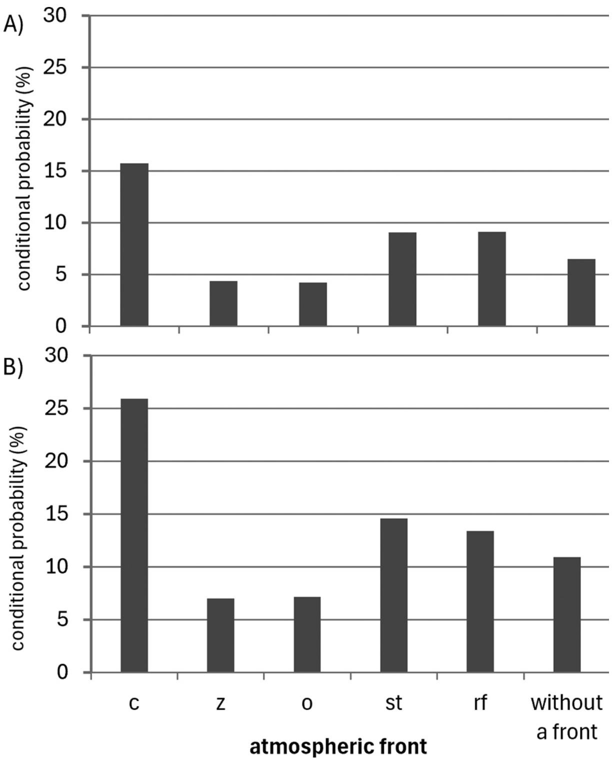

Fig. 17. Conditional probability of occurrence of rapid melting recorded by at least one meteorological station with the occurrence of various weather fronts, A – October–May and B – February–May (1991–2023; fronts: c – warm, z – cold, o – occluded, st – stationary, rf – several different fronts and situations without any front). Data: Calendar of circulation types (Niedźwiedź 2025).

February to May, the conditional probability of rapid snow melts in the Tatras with the occurrence of weather fronts almost doubled compared with the period between October and May. Other fronts with a relatively high probability of rapid melting are a stationary front (9% for October–May and 15% for February–May) and the passage of at least two fronts during one day over southern Poland (rf; 9% for October–May and 13% for February–May). A fairly high probability of a rapid melt also occurred for atmospheric conditions without front (7% for October–May and 11% for February–May). The probability of rapid snow cover loss with a cold front and an occluded front was only a few per cent in both periods.

Discussion of results and conclusions

The study analysed the long-term variability and trends in the number of days with melting and the rate of snow cover melt in the Tatras, focusing on rapid melting and the impact of atmospheric circulation. The most important findings of the study can be summarised in the following statements:

- snow melt on Kasprowy Wierch and in Hala Gąsienicowa was recorded in every month of the year, and in Zakopane only from October to May;
- the highest numbers of days with snow melt were observed in March in Zakopane, in April in Hala Gąsienicowa and in May on Kasprowy Wierch, i.e. in each case in the following month after the highest average snow depth; the highest values of snow melt (cm) were observed in April in Zakopane and Hala Gąsienicowa, and in May on Kasprowy Wierch; the shift of this maximum in the elevation profile of the Tatras (by a month or two, compared with the foothills of the mountains) is the result of the changes in temperature, depending on the altitude above sea level. The decrease in temperature as one moves up the elevation profile of the Tatras causes a significant accumulation of snow cover and a delay in the onset of melting. In both periods (shorter and longer), the seasonal maximum of the number of days with melting and the rate of snow melt fell in the same months and the values are very similar;
- the statistically significant long-term trends were found mainly in the case of melt rate characteristics (in cm) and in the majority of cases in the period 1966/1967–2022/2023; these were: a negative trend of average and maximum melt rate in Zakopane and a negative trend of average melt rate on Kasprowy Wierch. In addition, a positive, statistically significant trend in the number of days with snow cover melting was found on Kasprowy Wierch. In the period 1991/1992–2022/2023, only one statistically significant trend was detected: it was a negative trend of average seasonal snow cover melting in Hala Gąsienicowa; negative melting trends are related to decreasing tendency in the duration of snow cover in the Tatra Mountains and the maximum seasonal snow depth at some measurement points (see Fig. 1). The only positive long-term trend (recorded in both study periods) was found in the case of melt days on

Kasprowy Wierch; it is related to the increasing air temperature and significantly more frequent exceeding the temperature of 0°C at this altitude; in the previous decades, the temperature in winter at the altitude of the Tatra peaks was stable and remained below zero; moreover, the positive trend may be related to a slightly positive change in the depth of snow cover at the top of Kasprowy Wierch (see Fig. 1B);

– the greatest number of days with rapid snow melt in the study period in the Tatras occurred in April (8 days per month on average);
– rapid melting of snow in both study periods of the snow season (October–May and February–May) is favoured by the inflow of tropical air masses over southern Poland (conditional probability for February–May is 35%), advection of air from the southern sector with cyclonic circulation (31% for Sc situation for February–May) and the passage of a warm weather front.

The negative long-term trends in the snow cover melt rate in the Tatras described above are caused by rapid warming conditions (positive air temperature trend in the period 1951–2015 was 0.3°C/10 years, in Zakopane and on Kasprowy Wierch; Błażejczyk 2019) leading to changes in the proportion of liquid and solid precipitation (negative trend of solid precipitation in autumn and positive, statistically significant trend of liquid precipitation in winter in the Tatras; Łupikasza et al. 2024). This, in turn, causes a reduction in the duration and depth of the snow cover (Falarz, Bednorz 2021) and a decrease in the melt rate. Furthermore, in the case of Zakopane, some anthropogenic factors affecting the state of the snow cover due to the effect of the urban heat island as well as the specific landform (Podtatrzański Ditch) may also play a role. Hala Gąsienicowa, which is situated almost 700 m higher than Zakopane, at a distance from the city and surrounded by mountain peaks, is also characterised by decreasing trends in melting over the long-term period. On Kasprowy Wierch, the situation looks slightly different. There was an increase in the number of days with melting, and a decrease in the average melting rate of the snow cover and the absolute maxima of melting. The cause of this phenomenon is the more frequent occurrence of days with positive temperatures, which contributes to slow, not necessarily intense melting (which is also evidenced by a decrease in the melt rate maxima per day) and to a small daily loss of snow cover. The effect of wind deflation or drifting of the snow at the meteorological station on Kasprowy Wierch, as well as the sublimation effect observed at all the meteorological stations, may also be the causative factors.

The occurrence of mostly negative trends in the characteristics analysed in the study may indicate a synergy of changes in the local climatic conditions with the influence of the increased global climate change contributing to the occurrence of milder and shorter winters. This fact is further confirmed by zoophenological phenomena, e.g. earlier than usual awakening of bears from winter hibernation (Pyka 2024). The biological clock of animals depends on broadly understood environmental conditions, e.g. temperature, food availability, climatic and seasonal changes.

Błażejczyk (2019) described long-term trends for, among others, temperature and noted that an increase in the average annual and the maximum air temperature is observed at all meteorological stations included in the study, a decrease in the number of frosty days for Zakopane, a decrease in the number of very frosty days in Hala Gąsienicowa and on Kasprowy Wierch and a decrease in days with rain and snowfall in the Tatras. He also noted a statistically significant decrease in days with snow cover in Zakopane. Gądek et al. (2016) noted that the percentage of melt forms in the profile of snow cover might be increased. Niedźwiedź (1992) also wrote about the possible impact of climate change after 1982 in the areas of the alpine zone, as well as about the increase of the inflow of air masses from the west, and a decrease of those from the southern sector between 1960 and 1980, which might also cause an acceleration of climate change.

Except for their foothills, the Tatras are an area where local anthropogenic impacts on changes in climatic conditions are absent, but the global impact, e.g. through an increase in CO_2 content in the atmosphere, is important. Nevertheless, the study found significant trends describing changes in snow cover melting. This is also evident in other mountains of the world (Vorkauf et al. 2021). Xiong et al. (2019) discovered an earlier onset of snow melt over most of the highest mountain areas of Asia and found a strong correlation between melt and thermal conditions. In most of these areas, snowline altitude at the end of the melting season has shown a rising trend in recent years (Tang et al. 2020). Welch et al. (2016) indicated the effects of earlier melting on the biotic environment and transfer of radiative energy in the mountains of the western United States. The changes are also visible in the Alps, where temperatures have risen by 3°C from June to September since 1880 (Braithwaite, Hughes 2022). This causes mass loss by glaciers: the mean mass balance is about −1.3 ± 0.6 m water equivalent per year. According to Liaqat et al. (2025) in the Naltar Basin in Pakistan, climate change and rising temperatures will cause earlier and more intense melting of snow and glaciers, leading to uncertainty in water availability, reduced river flow during the monsoon season and increased risk of extreme hydrological events.

Mid-winter thaws, which are currently occurring even in the highest parts of the Tatra Mountains, result in changes in the hydrological regime in the basins of streams that originate in these mountains and in the rivers into which they flow. Reducing winter retention will reduce groundwater levels in spring when there is a high demand for moisture by cultivated and wild plants. The increase in mid-winter melting causes a significant deterioration of the conditions for winter sports in the Tatras. The changes referred to herein are undoubtedly an effect of the impacts of global climate change (IPCC 2021, 2023). Further global warming presented in the Intergovernmental Panel for Climate Change (IPCC) scenarios will exacerbate these problems.

Authors' contributions

Conceptualisation: MF; methodology: MF, ZJ; calculations: ZJ, MF, graphics: ZJ, writing – original draft preparation: ZJ; writing – review and editing: MF, ZJ.

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