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THE VARIABILITY OF THERMAL WINTERS IN POLAND IN THE YEARS 1960/61–2024/25

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Abstract. This study analyses the temporal and spatial variability of the start and end dates and duration of thermal winters (period <0°C) in Poland from 1960/61 to 2024/25. Mean monthly air temperature values from 55 stations in Poland were used in the study. The start and end dates of thermal winters were calculated using Gumiński's formulas (1950). Winters were classified according to their length (quantiles), and the frequency of years without a thermal winter was calculated. The influence of atmospheric circulation on thermal winters North Atlantic Oscillation (NAO) was also analysed. The analysis revealed significant spatial variation in the start and end dates and duration of winters in Poland. Isochrones are aligned meridionally, and this pattern is disturbed by the influence of the Baltic Sea and the mountains in southern Poland. Thermal winters in Poland are beginning increasingly later and ending earlier, and their duration is rapidly shortening. Thermal winters have been absent from the Baltic coast and western Poland in recent decades. In the rest of the country, years without thermal winters are becoming increasingly frequent. These changes are strongly linked to the NAO. The shortening, or even disappearance, of thermal winters has enormous environmental, social and economic consequences.

Key words: thermal winter, climate change, North Atlantic Oscillation, Poland

Introduction

The functioning of the atmosphere and other elements of the environment exhibits seasonality related to astronomical and geographical factors. Thermal winter is defined as a period with a daily mean air temperature below 0°C (Meteorological Dictionary 2003). Thermal winters are undergoing significant changes due to ongoing global warming (Wang *et al*. 2021). This applies to various regions of the world, including the United States (Higgins *et al.* 2002; Mayes Boustead *et al*. 2015), Asia (Liu *et al*. 2014) and Europe, e.g., England (Chapman *et al*. 2020), Estonia (Jaagus, Ahas 2000), Finland (Ruosteenoja *et al*. 2011, 2020) and Hungary (Domonkos, Piotrowicz 1998). The number of frosty days in the northern hemisphere is decreasing (Yuan *et al.* 2025). In Poland, long and cold winters are becoming increasingly rare (Kejna, Pospieszyńska 2023). There are also mid-winter warming events (Kuziemski 1971; Piotrowicz 2002; Czarnecka, Nidzgorska-Lencewicz 2013). The frequency of above-freezing days (with temperatures >0°C) during winter periods (Szyga-Pluta 2011) is increasing. There is a clear shortening of thermal winter periods, or even their frequent absence (Czarnecka, Nidzgorska-Lencewicz 2013; Ziernicka-Wojtaszek, Zuśka 2016).

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This process is particularly evident in the transitional climate found in Poland. The influence of the Atlantic Ocean is found to be weakening in the west of the country, whereas the frequency of continental air masses is increasing in the east; these trends confirm the growing degree of climate continentality (Gorczyński 1922) and the declining index of climate oceanity (Marsz 1995). In January (being on average the coldest month), the 0°C isotherm runs through Poland, and its location has been shifting eastward in recent decades (Kejna, Rudzki 2021). In Poland, the thermal winter shows significant spatial variability. Czarnecka and Nidzgorska-Lencewicz (2017) identified three regions (western, central and eastern) that differ from one another in their start and end dates and duration of winter. In the mountains, winters are characterised by considerable length and severity, and additional sub-periods can be distinguished within them based on thermal thresholds of -5 and -10°C (Hess 1965; Lewik 1997).

Winters can be classified according to their length and severity. Previous studies have determined, for example, the sum of cold days (days with an average daily temperature above 0°C) or the number of thermally characteristic days: in Poland, those were winter days (mean temperature <0°C), frosty days (tmax <0°C) and very cold days (tmax <-10°C) (Piotrowicz 2000/01). The severity of winter is also evidenced by extreme temperature drops.

In Poland, among the thermal seasons, it is winter that is showing the greatest tendency to shorten (Piotrowicz 2000; Kossowska-Cezak 2005; Nidzgorska-Lencewicz, Mąkosza 2008; Skowera, Kopeć 2008; Woś 2006; Kejna, Pospieszyńska 2023). The rate of winter shortening is twice as fast as the rate of summer and spring lengthening (Czernecki, Miętus 2015). The start dates are delayed, and the end dates occur earlier. This applies to both the western and eastern regions of Poland (Wójcik, Miętus 2014). These changes are caused by atmospheric factors (Niedźwiedź 1993; Falarz 2004, 2009; Bednorz 2006; Czarnecka, Nidzgorska-Lencewicz 2010; Czernecki, Miętus 2017) and – in particular – by the variability of the North Atlantic Oscillation (NAO) (Marsz 1999; Piotrowicz 2000/2001, 2002; Tomczyk, Bednorz 2014; Twardosz, Kossowska-Cezak 2016).

Changes in the seasons, especially winter and the growing season, have various consequences for nature (Sparks, Menzel 2002). The duration of winter and the thermal conditions during this period affect snow cover; snow cover is shortening in duration and decreasing in thickness (Paczos 1982; Bednorz, Falarz 2004, 2006; Czarnecka 2012; Świątek 2014; Tomczyk 2021; Twardosz, Kossowska-Cezak 2021).

The purpose of this article is to analyse the temporal and spatial variability of the start and end dates and duration of thermal winters in Poland in the years 1960/61–2024/25. The frequency of occurrence of mid-winter warming and the occurrence of years without a thermal winter are also examined. These issues are analysed against the background of atmospheric circulation variability.

Source data

Monthly mean air temperatures from 55 stations in Poland from 1960 to 2025 were analysed (Fig. 1). The data came from website of the Institute of Meteorology and Water Management, National Research Institute (IMWM-NRI 2025).

The data were complete for most of the stations. However, during the analysed period, the homogeneity of the data series was occasionally disrupted. Some stations were relocated, e.g., in the case of Elbląg and Płock, corrections were made from neighbouring stations with homogeneous data series. For several stations, it was necessary to supplement the missing data (discontinued operation, station closure, commissioning into operation after 1960). The linear correlation between air temperature and a nearby station was used for this purpose. Detailed information on these data can be found in the articles by Kejna and Rudzki (2021) and Kejna and Pospieszyńska (2023).

The stations used in this study are evenly distributed throughout Poland. Most are lowland stations, and only three stations are located in the mountains: in the Sudetes (Mt Śnieżka – – 1,603 m a.s.l.) and the Carpathians (Zakopane – 852 m a.s.l., Mt Kasprowy Wierch – – 1,988 m a.s.l.), which influences the occurrence of thermal winter (Hess 1965). There are significant climatic differences within Poland due to the greater influence of westerly maritime air masses in the west and the increasing frequency of continental air masses in the east. In northern Poland, the warming influence of the Baltic Sea is noticeable in winter (Woś 1996; Kożuchowski, Marciniak 2002; Kożuchowski 2011).

The analysis of the impact of atmospheric circulation on winter phenomena used monthly values of the North Atlantic Oscillation Index from the University of East Anglia. This index is calc-

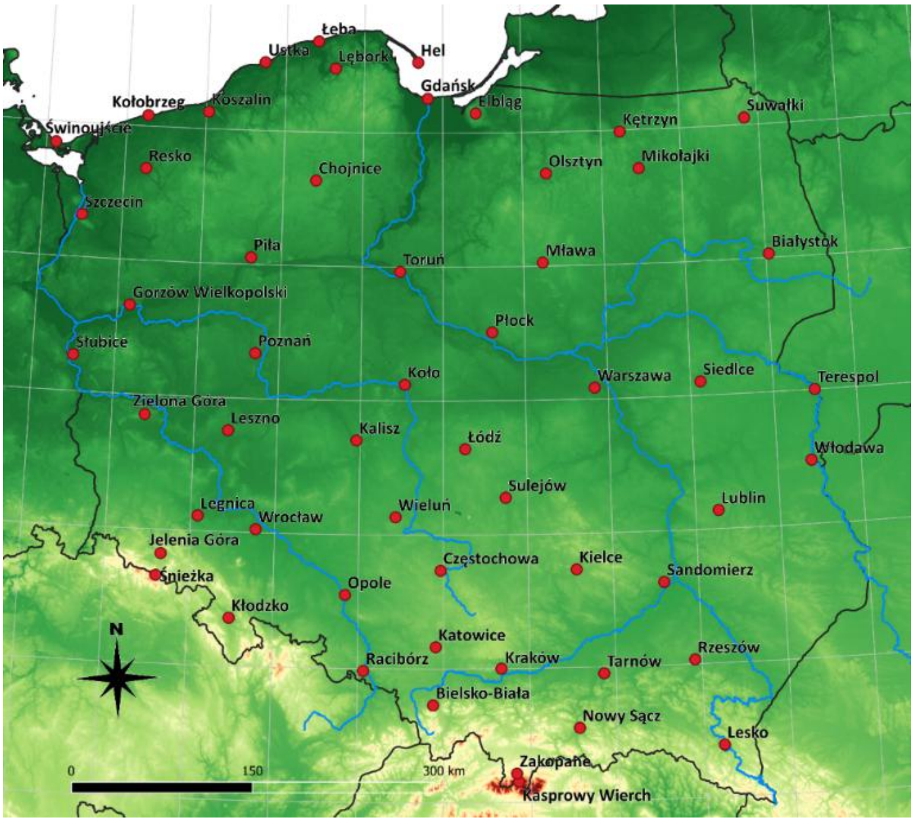

Fig. 1. Location of stations used in the study

ulated from the normalised pressure difference between Gibraltar and Reykjavik (Iceland) (Hurrell 1995, updated Jones *et al.* 1997, UEA 2025).

Research methodology

There are various ways of dividing the year into seasons (Trenberth 1983; Piotrowicz 2002). In this study, it was assumed that thermal winter is a period with an average daily air temperature below 0°C (Meteorological Dictionary 2003). The Swedish Meteorological Institute defines thermal winter as a period of five consecutive days of daily mean temperatures below 0°C (32°F). On the other hand, Wang *et al.* (2021) proposed another method: dividing the year into four thermal seasons based on quantiles, where winter occurs when the mean daily temperature is below the 25th percentile. In this way, winter is not necessarily associated with negative air temperatures.

As part of the research, the start and end dates of the thermal winter and its duration were determined. Next, the spatial distribution of these parameters in Poland in the years 1960/61–2024/25 was analysed. Changes in the onset of winter were also examined by comparing two reference periods: 1961–90 and 1991–2020. Trends for the duration of winter were also calculated for the years 1960/61–2024/25.

The start and end dates of winter can be determined based on daily or monthly values. Various methods are used for this purpose (Piotrowicz 2002) and show some differences (Nowosad, Filipiuk 1998; Bartoszek *et al*. 2012; Kępińska-Kasprzak, Mager 2015). The course of air temperature based on daily data shows significant oscillations, and, in the cold half of the year, the temperature frequently passes through 0°C. Therefore, Kuziemski (1971) proposed that the beginning and end of winter be determined by a sequence of at least three days with a negative daily mean air temperature. Such a concept of winter has been analysed by, among others, Czarnecka and Michalska (2007), Czarnecka (2009) and Czarnecka and Nidzgorska-Lencewicz (2013, 2017). In Sweden, a period of five days of negative air temperature has been adopted. Piotrowicz (1996) proposes to take the middle of a five-day moving average with a temperature <0°C. Nowosad and Filipiuk (1998), on the other hand, proposed an 11-element filter that removes multiple instances of temperature passing through 0°C. Another method was developed by Huculak and Makowiec (1977) and Makowiec (1983), who calculated the cumulative series of deviations of the mean daily temperature below (start) or above (end) the threshold value.

Monthly mean values are a broad generalisation of thermal conditions. Nevertheless, they have been used to identify the start and end dates of thermal seasons, including winter (Romer 1906; Merecki 1915; Gumiński 1950; Wiszniewski 1960). The authors of this method assumed a uniform decrease (or increase) in temperature between months above (or below) the thermal threshold. This method yields good results for long-term mean values, but when analysing winters in individual years, methodological problems arise related to the thermal threshold of 0°C being exceeded several times, i.e. the occurrence of mid-winter warming (referred to as "coreless winters") (Kejna, Pospieszyńska 2023).

In this study, monthly mean temperature values and formulas proposed by Gumiński (1950) were used to define the thermal winter:
For the beginning of winter:

$$x = \frac{t_1 - 0}{t_1 - t_2} \cdot n \quad (1)$$

For the end of winter:

$$x = \frac{0 - t_1}{t_2 - t_1} \cdot n \quad (2)$$

where:
x – number of days to be added to the 15th day of the previous month,
t_1 – mean monthly temperature in a month with positive air temperature,
t_2 – mean monthly temperature in a month with nagative air temperature,
n – 30 days.

The obtained x value was added to the 15th day of the preceding month (beginning or end of winter) to obtain the day when the temperature exceeded 0°C.

The climate in Poland is characterised by significant air temperature variability caused by atmospheric circulation. This is particularly evident in winter, when significant warming can occur, causing a period of positive air temperature after the onset of winter, followed by another cooling period. This phenomenon is called a mid-winter warming. In such a situation, according to Samborski and Bednarczuk (2009), the number of days in periods with temperatures below and above 0°C were determined. Short mid-winter warming periods were included in the thermal winter period. This method is described in detail in the article by Kejna and Pospieszyńska (2023).

Most stations (except for mountain stations) experienced years without a thermal winter, which made it impossible to analyse trends in the start and end dates of this season. However, changes over time were demonstrated by comparing two sub-periods, 1960/61–1989/90 and 1990/91–2019/20; for these periods, monthly mean temperatures were calculated, and, on this basis, the average start and end dates of the thermal winter were determined using the formulas of Gumiński (1950). In addition, trends in the length of thermal winter were calculated for the entire period from 1960/61 to 2024/25. Years without thermal winter were assigned a duration of zero. The statistical significance of the trends obtained was determined using Student's t-test (at a significance level of 0.05).

Standard deviations of the average air temperature have also been used in the classification of winters (Lorenc, Suwalska-Bogucka 1996; Warakomski 1998; Piotrowicz 2000; Filipiuk 2011). This analysis uses a quantile approach (Klein Tank *et al*. 2002; Czernecki, Miętus 2011), where winters were divided by length into:
- short winter – with a length below the 25th percentile,
- normal winter – with a length between the 25th and 75th percentiles,
- long winter – lasting above the 75th percentile.

Percentile values were calculated only for years with a thermal winter. The occurrence of years without a thermal winter was also analysed. The frequency of mid-winter warming with a positive mean temperature between months with negative values was also identified.

The present study also examined the relationship between the length of winters in Poland and the North Atlantic Oscillation (NAO) according to Hurrell (1995). Atmospheric circulation oscillation related to the air pressure gradient between the Azores High and the Icelandic Low. The period of 1960/61–2024/25 was taken into account. The analysis showed that the relationships between winter length and the index are strongest for the period from November to March. Next, we examined the spatial distribution of Pearson's linear correlation coefficient between NAO_{NDJFM} and (each individually) the start, end and duration of winter in Poland. Correlations of NAO with duration of winter was performed for all years, including those with no thermal winter, for which a duration of 0 days was applied. However, for correlations of start and end dates, "winter-free" years were necessarily excluded from calculations.

A custom script developed in R language was used to calculate the start and end dates of the thermal winter, as well as the trend parameters and their significance. The kriging method (Childs 2004) was used in the spatial analyses of the start and end dates and duration of the thermal winter.

Results

Thermal conditions of winter months in Poland

In the years 1961–2020, negative average air temperatures occurred in lowland Poland in December, January and February (Fig. 2). Only at mountain stations (Śnieżka and Kasprowy Wierch) did this period last from November to April. In Poland, a meridional isotherm pattern occurred during the winter months. Only in the north did the isotherms run parallel to the coast due to the warming influence of the Baltic Sea (Woś 1996; Kożuchowski 2011).

In December, the lowest mean air temperatures occurred in north-eastern Poland (Suwałki -2.1°C), and the highest in western Poland and on the Baltic coast (Świnoujście 1.5°C). The 0°C isotherm ran through central Poland. In the mountains, the temperature decreased with altitude above sea level and amounted to -5.2°C on Mt Śnieżka and -6.5°C on Mt Kasprowy Wierch. In January, almost all of Poland, except for its north-western edge (Świnoujście 0°C), had a negative average temperature. It was coldest in the north-east of the country (Suwałki -4.4°C) and in the mountains: -6.5°C on Mt Śnieżka and -7.9°C on Mt Kasprowy Wierch. In February, the area affected by frost decreased. The 0°C isotherm covered the coast, the Szczecin Lowland and the Silesian Lowland. The highest mean temperature was recorded in Świnoujście (0.7°C) and the lowest in Suwałki (-3.7°C) and in the mountains: on Mt Śnieżka (-5.2°C) and Mt Kasprowy Wierch (-8.1°C).

Comparing the two periods 1961–1990 and 1991–2020, a meridional isotherm pattern was found to persist in all months analysed (Fig. 3). In December, there was an increase in air temperature, especially in the north of the country (a 1.1°C increase in Koszalin). In southern Poland, the changes were smaller (Lesko 0.3°C). The isotherms also showed a clear shift eastwards (of ~200 km) and, on the coast, towards the inland. On average, positive temperatures were even recorded in Podkarpackie Province (Tarnów). In January, in 1961–1990, negative mean air temperatures were recorded at all stations. However, in 1991–2020, positive values were recorded on the coast and in the Szczecin Lowland, as well as in part of the Silesian Lowland (Legnica).

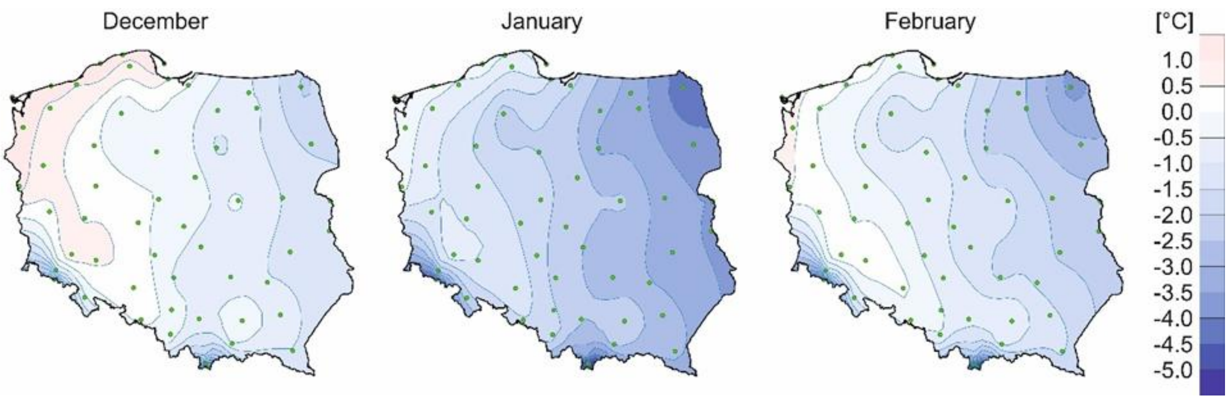

Fig. 2. Spatial distribution of average air temperature in Poland in December, January and February in 1961–2020

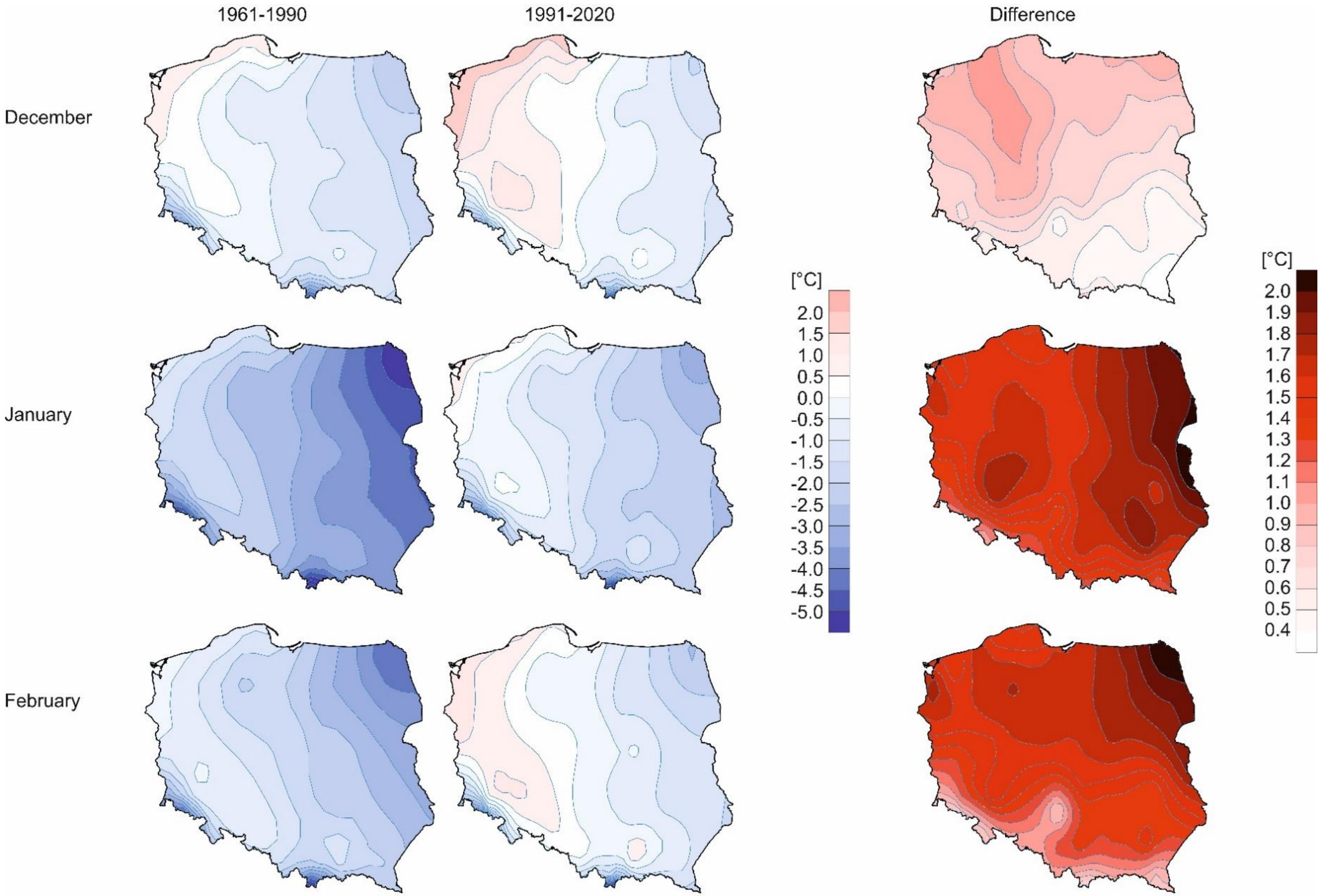

Fig. 3. Spatial distribution of average air temperature in Poland in 1961–1990 and 1991–2020, and the temperature difference between these periods

The air temperature rose by 1.5–2°C, increasing most in eastern Poland (by 2.0°C at Terespol) and least in the south and in the mountains (by 1.1°C at Śnieżka and Kasprowy Wierch). Also in February, in the period 1961–1990, the whole of Poland was characterised by a negative mean air temperature, but by the years 1991–2020, the 0°C isotherm was running through central Poland (an eastward shift of 300 km). The temperature rose by 1–2°C. The increases were greatest in NE Poland (Suwałki, 2.0°C) and smaller in the mountains (Śnieżka and Kasprowy Wierch, 0.6°C).

Spatial variability in the start, end and duration of winter

Period 1961–2020

In the years 1961–2020, on average, winter began earliest in the mountains, as early as October (on 24 Oct on Mt Kasprowy Wierch and on 31 Oct on Mt Śnieżka) and in November in north-eastern Poland (on 30 Nov in Suwałki) (Tab. 1).

In the following days, winter covered increasingly larger areas, reaching the western border of Poland in the first ten days of January (Słubice, 9 Jan). Winter began even later on the Baltic Sea coast (Kołobrzeg, 13 Jan). The difference in the start of this season in Poland (excluding mountain stations) was as much as 44 days. The end of winter came earliest in western Poland (Słubice, 23 Jan). In the east, winter did not end until March (Suwałki, 13 Mar). The difference was 49 days. In the mountains, winter did not end until the second half of April (Mt Śnieżka, 19 Apr; Mt Kasprowy Wierch, 27 Apr). Between 1961 and 2020, there was no winter in Świnoujście, while in the rest of the country winter lasted on average from 15 days in Słubice to 104 days in Suwałki. The isochrone system was meridional; only in the north was it parallel to the Baltic Sea coast. In the mountains, winter was very long, e.g., 171 days on Mt Śnieżka and 186 days on Mt Kasprowy Wierch.

Table 1

Dates of the beginning, end and duration of thermal winter at selected stations in Poland in 1961–2020

Station	Beginning	End	Duration
Świnoujście	No thermal winter		
Gdańsk	19 Dec	25 Feb	68
Suwałki	30 Nov	13 Mar	104
Słubice	9 Jan	23 Jan	15
Warszawa	12 Dec	24 Feb	74
Terespol	7 Dec	2 Mar	86
Wrocław	28 Dec	5 Febr	39
Kraków	10 Dec	21 Feb	73
Lublin	7 Dec	1 Mar	85
Śnieżka	31 Oct	19 Apr	171
Kasprowy Wierch	24 Oct	27 Apr	186

Difference between periods: 1961–1990 and 1991–2020

With rising air temperatures, the onset of winter was delayed (Tab. 5; Figs. 4–5). In western Poland, there was no thermal winter in the years 1991–2020. Where it did occur, the differences between the two 30-year periods reached over 20 days. Smaller differences in the onset of winter occurred in south-eastern Poland (Suwałki, 7 days). The changes were also small in the mountains (Śnieżka, 2 days; Kasprowy Wierch, 1 day). There were also significant differences in the dates of the end of winter. In the east, winter ended earlier, e.g., by 8 days in Suwałki. As a result of these changes, winter became significantly shorter (Fig. 4), disappearing completely in the west. For example, in Kołobrzeg, winter lasted 77 days in 1961–1990 but did not occur at all in the following period. In central Poland (Poznań), winter shortened by 57 days. In the east, the changes were smaller (Suwałki, 16 days).

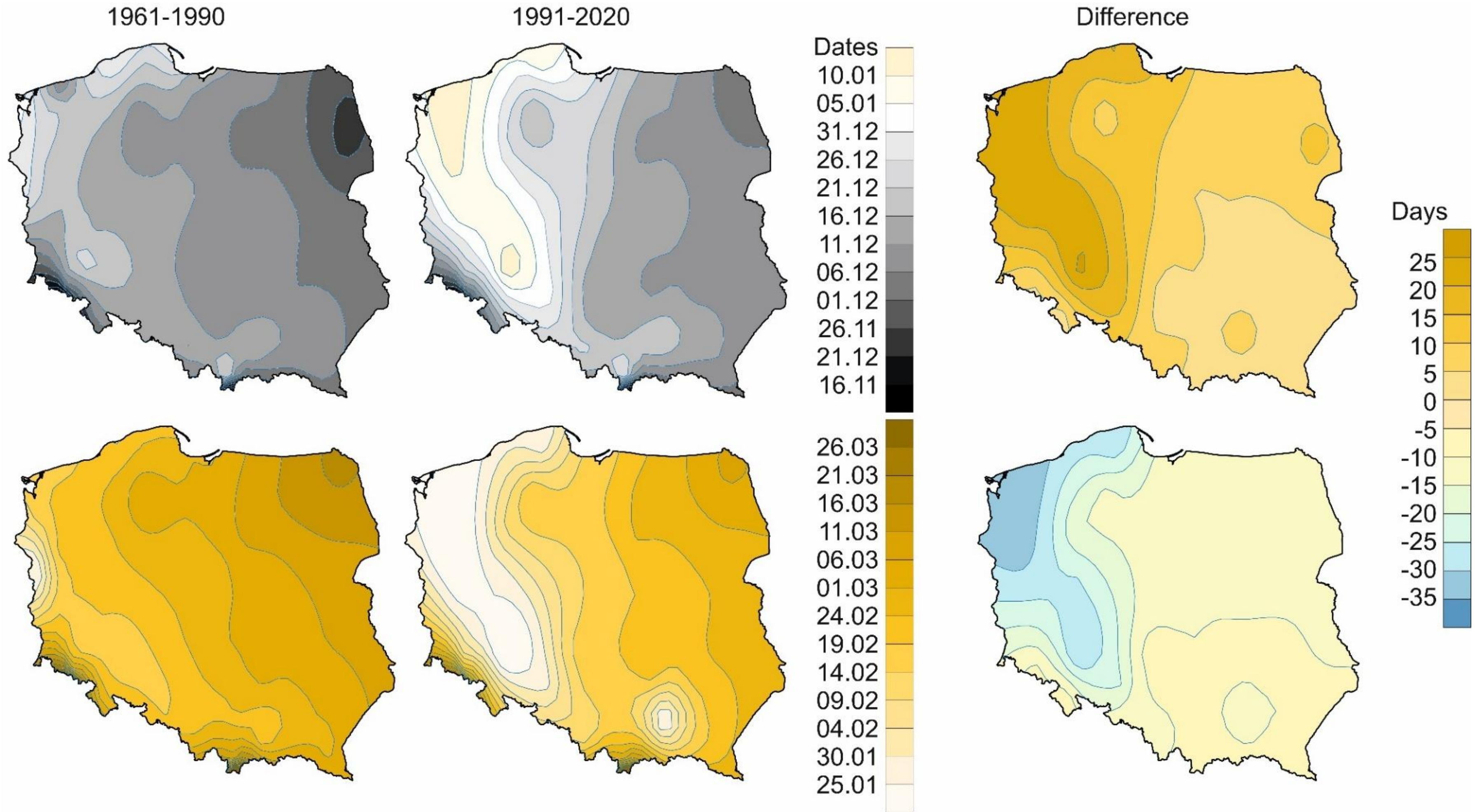

Fig. 4. Spatial distribution of the beginning (upper panel) and end (lower panel) dates of thermal winter in Poland in 1961–1990 and 1991–2020 and differences between these periods

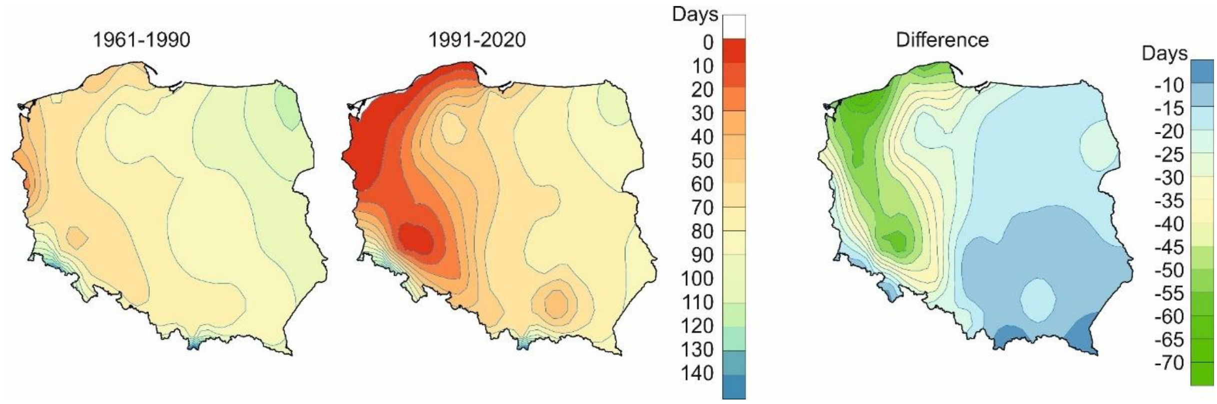

Fig 5. Spatial distribution of the duration of thermal winter in Poland in 1961–1990 and 1991–2020 and differences between these periods

Table 2

Dates of the beginning, end and duration of thermal winter at selected stations in Poland in 1961–1990 and 1991–2020

Station	1961–1990			1991–2020		
	Beginning	End	Duration	Beginning	End	Duration
Świnoujście	4 Jan	14 Feb	42	No thermal winter		
Gdańsk	17 Dec	28 Feb	74	20 Dec	23.Feb	66
Suwałki	27 Nov	16 Mar	110	4 Dec	8 Mar	95
Słubice	28 Dec	15 Feb	50	No thermal winter		
Warszawa	9 Dec	1 Mar	83	15 Dec	17 Mar	65
Terespol	4 Dec	8 Mar	95	10 Dec	25 Febr	78
Wrocław	18 Dec	18 Feb	63	No thermal winter		
Kraków	8 Dec	26 Feb	81	13 Dec	16 Feb	66
Lublin	5 Dec	5 Mar	91	9 Dec	25 Feb	79
Śnieżka	30 Oct	23 Apr	176	2 Nov	14 Apr	164
Kasprowy Wierch	24 Oct	30 Apr	189	25 Oct	24 Apr	182

Temporal variability of thermal winter onsets

The occurrence of thermal winters in Poland is characterised by high temporal variability. Figure 6 shows the occurrence of winters at selected stations in the years 1960/61–2024/25. The stat-ions in western Poland (e.g., Świnoujście, Słubice and Wrocław) are characterised by short winters and a high frequency of years without thermal winter. At stations in eastern Poland (Suwałki, Terespol, Lublin), winters are long, but there are also significant differences in the start and end dates in individual years.

At the stations in mountains (Zakopane, Śnieżka, Kasprowy Wierch), winters are long and show less year-to-year variability (Fig. 7). Only in Zakopane have significant changes been observed, especially in the last two to three decades.

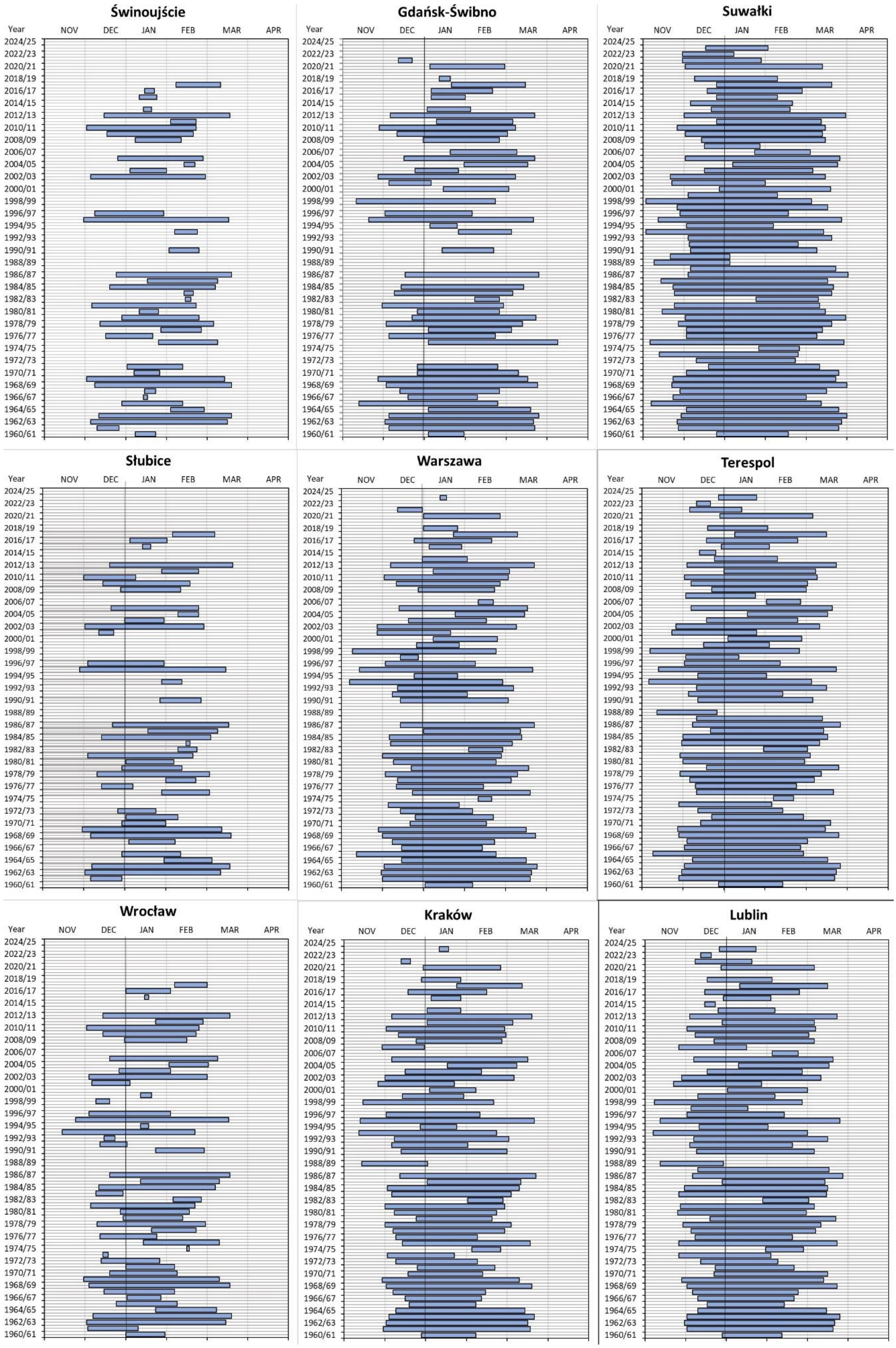

Fig. 6. Occurrence of thermal winters at selected stations in Poland in the years 1960–2025

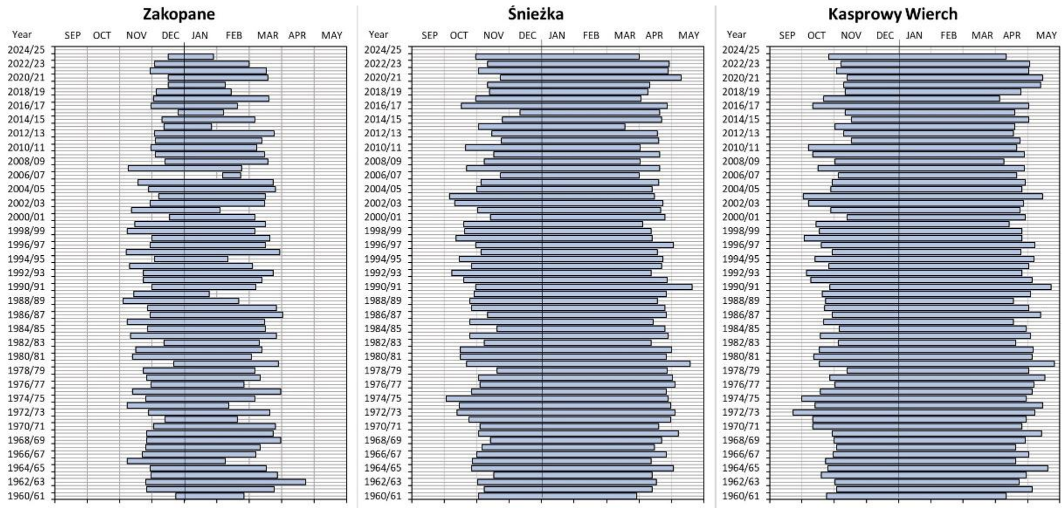

Fig. 7. Occurrence of thermal winters at mountain stations in Poland in 1960–2025

The earliest and longest winters

Thermal winters in Poland can occur exceptionally early – in the lowlands, as early as the beginning of November in the east of the country (Suwałki, 2 Nov; Białystok, 3 Nov) (Fig. 8). In western Poland, the earliest winter began in the third decade of November (Słubice, 27 Nov), and on the coast it began even in December (Hel, 3 Dec). In the mountains, winter arrived earliest in the Carpathians (Mt Kasprowy Wierch, 23 Sep) and in the Sudetes (Mt Śnieżka, 3 Oct). The latest end of winter also showed significant spatial variation. Winter ended latest in the mountains – in May (Kasprowy Wierch, 24 May; Śnieżka, 4 May). In the east, it lasted until 30 March (Suwałki) and in western and central Poland until the second decade of March (Koło, 15 Mar; Szczecin, Słubice and Legnica, 17 Mar).

The longest winters in eastern Poland lasted 143 days (Suwałki). Winters also lasted over 100 days in western Poland and on the coast (e.g., Hel, 102 days). In the years 1960/61–2024/25, the length of winters was characterised by significant temporal and spatial variability. The longest winter (as an average of 52 lowland stations) in Poland was in 1995/96 (Tab. 3). On average, it lasted 120 days, ranging from 100 days on the Baltic Sea coast (Hel, 7 Dec–15 Mar) to 135 days in north-eastern Poland (Suwałki, 12 Dec–25 Mar).

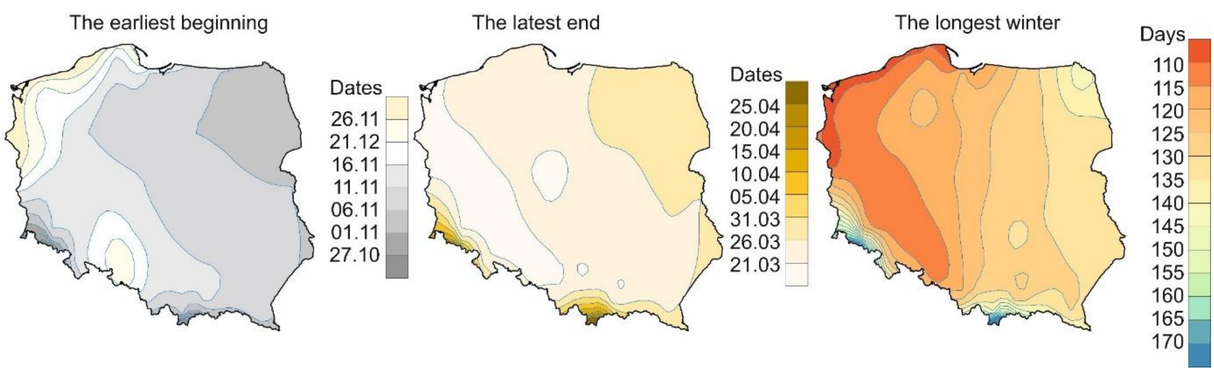

Fig. 8. Spatial distribution of the earliest-starting, latest-ending and longest thermal winter in Poland in 1961–2025

Table 3

Average, maximum and minimum length of the longest thermal winters (in days) in lowland Poland in the years 1960/61–2024/25

Winter	Mean	Maximum	Minimum	Standard deviation
1995/96	120.4	135	100	8.8
1968/69	108.4	129	98	6.2
1963/64	107.7	122	98	5.6
1962/63	107.7	121	99	5.2
1969/70	105.8	120	94	5.5
2012/13	101.1	119	44	10.6
1986/87	97.3	118	61	9.6
2002/03	95.6	114	83	7.3
1961/62	93.6	118	16	31.2
1978/79	92.8	113	79	8.5

Table 4

The longest winters (in days) in mountain areas in Poland in the years 1960/61–2024/25

Śnieżka		Zakopane		Kasprowy Wierch	
Winter	Duration	Winter	Duration	Winter	Duration
1974/75	205	1962/63	148	1972/73	225
1972/73	201	1995/96	142	2003/04	223
1990/91	200	1975/76	137	1979/78	219
1973/74	195	1983/84	135	1973/74	212
1981/82	195	1985/86	127	1974/75	209
2002/03	192	2005/06	125	1990/91	206
1980/81	190	1968/69	124	1991/92	206
2016/17	190	1986/87	123	1964/65	205
2003/04	189	1999/00	121	1994/95	204
1991/92	188	1992/93	120	1980/81	203

That winter was the longest in the analysed period at a total of 46 stations. Winters lasting over 100 days on average occurred in 1962/63, 1963/64, 1968/69, 1969/70 and 2012/13. The longest winters were characterised by little spatial variation (covering the entire country). Only the winter of 1961/62 stood out for the large standard deviation (31.2 days) due to the prolonged winter in eastern Poland (Suwałki, 118 days; Białystok, 116 days) and the short winter on the Baltic coast (Świnoujście, 16 days).

In the mountainous areas, winters became longer with increasing altitude above sea level (Tab. 4). In Zakopane, the longest winters occurred in 1962/63 (from 25 Nov until 21 Apr), in 1995/96 and 1975/76. On Mt Śnieżka in the Sudetes, the longest winters lasted over 200 days; for example, in 1974/75, winter began on 4 October and lasted until 26 April (205 days). The case was similar for 1972/73 (201 days) and 1990/91 (200 days). On Mt Kasprowy Wierch in the Tatra Mountains, which is almost 1,200 m higher, winters were only slightly longer. In 1972/73, winter there lasted 225 days, from 23 September to 5 May. The winter of 2003/04 was similar (223 days, from 3 Oct to 12 May).

A comparison of lowland and mountain stations revealed a temporal disparity in the occurrence of the longest winters. During periods of cold continental air, which is conducive to the formation of long winters, the highest parts of the mountains are often located in warmer air masses, with vertical air temperature inversions occurring (Hess 1965; Wibig 1997; Grajek, Szyga-Pluta 2021).

Mid-winter warming

Based on monthly values, years with mid-winter warming can be identified. The analysis showed that, in the years 1960/61–2024/25, this phenomenon occurred in 20 years, but not simultaneously at all stations. The highest number of such cases was observed during the winter of 1993/94 (43 stations), when December and January were characterised by an positive mean monthly temperature, and November and February had a negative mean temperature. In contrast, during the winter of 1961/62, after a frosty December, January saw a positive mean air temperature at 24 stations, whereas February was frosty. Similarly, during the winter of 1998/99 (January at 22 stations had a positive average temperature). In contrast, during the winter of 1965/66, after a frosty November, December was warm, followed by a significant cooling.

Mid-winter warmings were found to have occurred most often in central Poland (Koło, 9 winters; Zielona Góra, 8 winters; Płock and Poznań, 7 winters each) and in mountain valleys (Jelenia Góra, 8 winters). There were few mid-winter warmings on the Baltic Sea coast (where winters are usually short) and in the east of the country (where temperatures are low and the average monthly temperature rarely exceeds 0°C). At the mountain stations, mid-winter warmings did not occur (Kasprowy Wierch) or occurred exceptionally (1 such winter on Mt Śnieżka and 4 in Zakopane).

Years without a thermal winter

Years without a thermal winter are increasingly common in Poland. This does not, of course, rule out short-term cooling during the winter months. In the years 1960/61–2024/25, the highest number of years without a thermal winter occurred on the Baltic Sea coast (Ustka, 26 years; Kołobrzeg, 24 years; Świnoujście, 23 years; Hel, 22 years) and in the west of the country (Słubice, 23 years; Szczecin, 22 years). Years without winters are very rare in the east of the country (Suwałki, 1; Białystok, Kętrzyn, Lublin, Siedlce and Terespol, 2). Such situations did not occur at all in the mountains (Kasprowy Wierch, Śnieżka and Zakopane). Comparing the two periods 1961–90 and 1991––2020, the phenomenon of years without thermal winters is intensifying. On the Baltic Sea coast and in western Poland, the most recent decades have been dominated by years without thermal winters (Fig. 9).

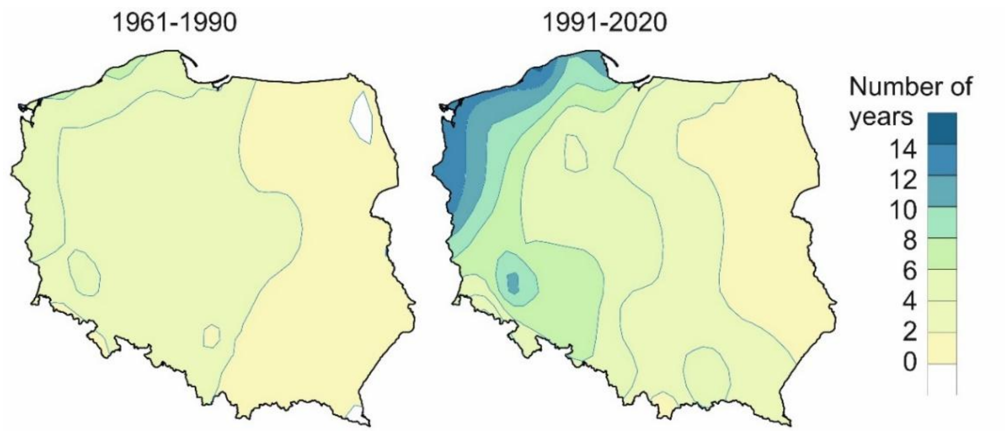

Fig. 9. Spatial distribution of the number of years without thermal winter in Poland in 1961–1990 and 1991–2020

Frequency of winters by duration

When classifying winters according to their duration, the 25th and 75th percentiles of their length in the period 1961–2020 were taken into account. The length of thermal winters in Poland varies over time. Based on the analysis of the two periods, 1961–1990 and 1991–2020, there was a change in the structure of winters at all the stations (Tab. 5).

Table 5

Frequency of winter types in the years 1961–2020 at selected stations in Poland

Station	Percentile		Winter 1961–1990				Winter 1991–2020				Winter 1961–2020			
	<25	>75	X	S	N	L	X	S	N	L	X	S	N	L
Świnoujście	15	80	6	6	12	6	13	4	9	4	19	10	21	10
Gdańsk	45	99	4	5	14	7	7	8	10	5	11	13	24	12
Suwałki	73	118	0	5	17	8	1	9	16	4	1	14	33	12
Słubice	23	78	6	5	13	6	13	6	9	2	19	11	22	8
Warszawa	52	97	3	3	17	7	3	10	12	5	6	13	29	12
Terespol	58	103	1	4	17	8	1	10	14	5	2	14	31	13
Wrocław	27	80	1	7	16	6	8	7	10	5	9	14	26	11
Kraków	49	95	2	4	17	7	4	8	13	5	6	12	30	12
Lublin	57	103	1	4	16	9	1	8	17	4	2	12	33	13
Śnieżka	155	184	0	3	19	8	0	11	13	6	0	14	32	14
Zakopane	89	117	0	5	17	8	0	10	15	5	0	15	32	13
Kasprowy Wierch	172	200	0	5	18	7	0	10	12	8	0	15	30	15

Explanations: X – no thermal winter, S – short winter, N – normal winter, L – long winter

Whereas in 1961–1990 a significant percentage of winters were long (L), in 1991–2020 the number of short winters (S) and years without a thermal winter (X) increased. For example, in western Poland, in Słubice, there were 19 years without winter throughout the entire period, 13 of which were between 1991 and 2020. The number of long winters decreased from 13 between 1961 and 1990 to two between 1991 and 2020. In eastern Poland, in Terespol, there were only four short winters between 1961 and 1990, and as many as ten such winters in the following sub-period. The number of long winters decreased from eight to five. In the mountains, on Mt Kasprowy Wierch, there were five and ten long winters and eight and seven short winters, respectively, and the number of winters of normal length decreased from 18 to 12.

Winter duration trend

The average length of winter for 52 stations in lowland Poland varied greatly over time (Fig. 10). There were sequences of years with long winters and periods of several years with very short winters. In addition, during the analysed period, there was a statistically significant trend (p=0.001) towards shorter winters, reaching -7.3 days/10 years at lowland stations. This means that winter shortened by as much as 47 days between 1960 and 2025.

There is also a tendency for winters to become shorter in the mountains, but the trend is smaller, amounting to -5.2 days/10 years in Zakopane (p=0.001), -3.2 days/10 years on Mt Śnieżka (p=0.02) and -2.9 days/10 years on Mt Kasprowy Wierch (p=0.01) (Fig. 11). Thus, this trend decreases as altitude above sea level decreases. This is due to the lack of a significant trend in winter in the Tatra Mountains (Żmudzka 2011). Similarly, in the Sudetes, the trend for winter is smaller compared to those for other seasons (Migała *et al*. 2016).

The lack of thermal winters makes it impossible to analyse trends at their beginning and end. However, calculations were made for the duration of winter (Fig. 12).

The analysis showed that, in the years 1961–2025, there was a statistically significant trend in eastern Poland towards a shortening of winter at a rate of more than seven days per decade (e.g., Siedlce, -7.4 days; Mława, -7.3 days; Terespol, -7.2 days; Suwałki, -7.0 days). In central Poland, this shortening ranged from -5 to -6 days. The trend was smaller in the south of the country (less than -5 days), and no significant trend was found in the mountains. In western Poland, thermal winter occurred, but the fact that the last few decades have been without this phenomenon means that the trend is not significant.

The absence of thermal winter is becoming more frequent and covering an increasing area of

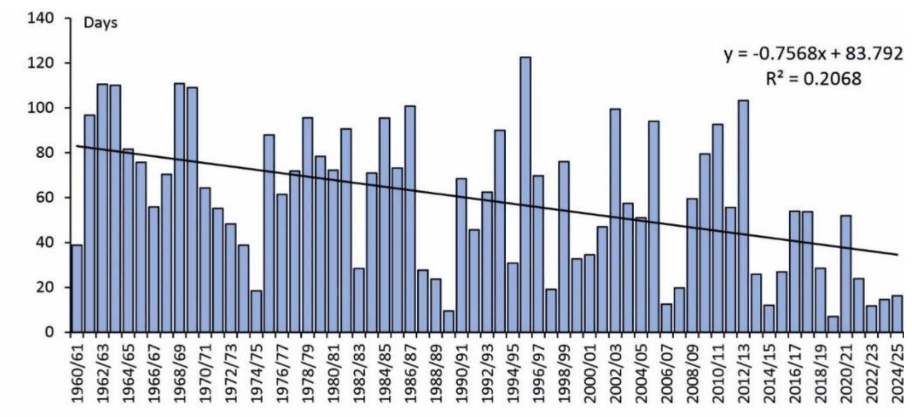

Fig. 10. Course of average length of thermal winter in Poland (52 lowland stations) in the years 1960/61–2024/25

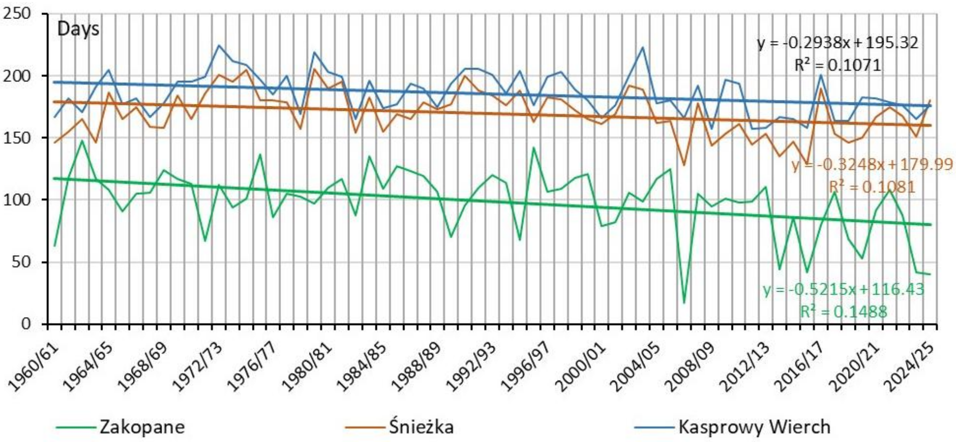

Fig. 11. Course of thermal winter duration on Kasprowy Wierch, Śnieżka and Zakopane in the years 1960/61–2024/25

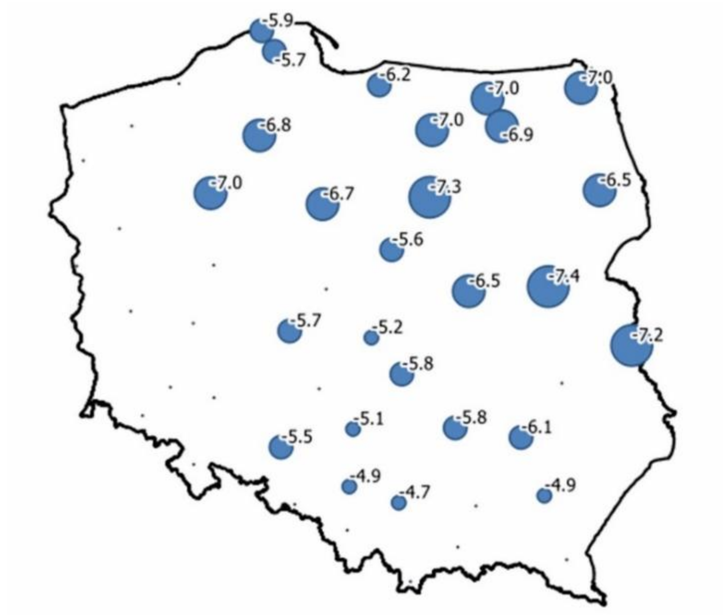

Fig. 12. Trend in thermal winter duration (days per 10 years) in Poland in 1961–2020
Stations with a significant trend (p<0.05) are marked

Poland (Fig. 13). Until the mid-1980s, it occurred sporadically, mainly in western Poland and on the Baltic coast. In the following decades, its frequency increased and covered almost the entire country. For example, in the winter of 2019/20, of all stations, it occurred only at the three stations located in the mountains (Zakopane, Śnieżka, Kasprowy Wierch). In the rest of the country, even in the east, no thermal winter was observed, and all winter months had a positive mean air temperature. The winter periods of 1989/90 (87% of stations without winter) and 2014/15 and 2022/23 (72.7% each) were also characterised by a small area of thermal winter occurrence.

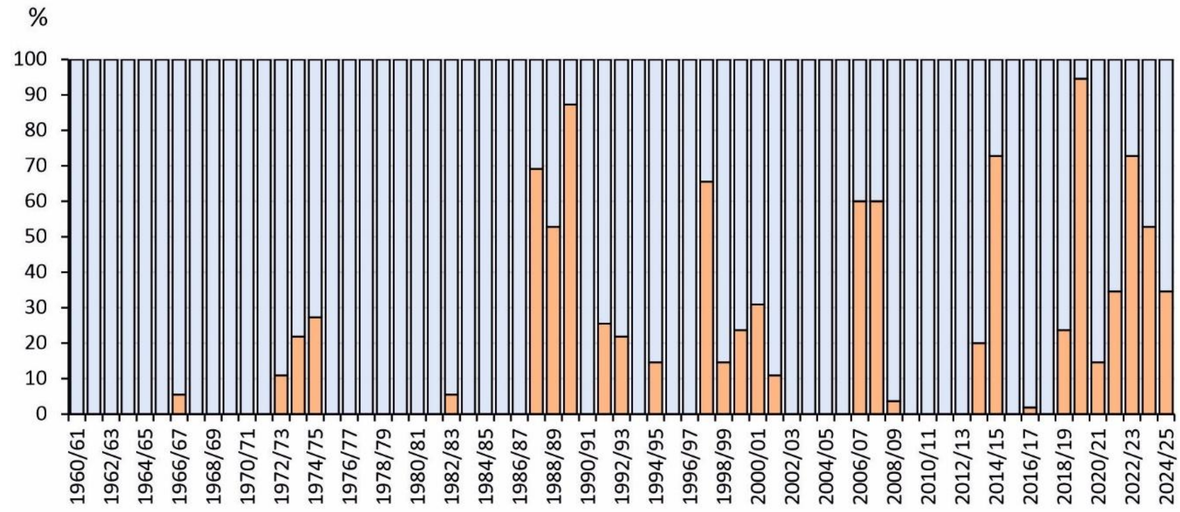

Fig. 13. Percentage share of stations without thermal winter in Poland in 1960/61–2024/25

The relationship between thermal winters and the NAO

In central Europe, thermal conditions in winter depend on the type of air masses flowing in. The barometric gradient between the Azores High and the Icelandic Low is important in this respect. The relationship between these centres changes, as described by the North Atlantic Oscillation (NAO) circulation index. This is the major mode of variability in atmospheric circulation in Europe. An increase in the pressure gradient (NAO^+) intensifies westerly circulation with an influx of maritime air masses. In winter, this brings significant warming and contributes to the occurrence of thermal winters. A weakening of the westerly circulation (NAO^-) favours the expansion of high-pressure systems in eastern Europe and the influx of continental air masses with long and cold winters. In the analysed period, NAO_{NDJFM} did not show a statistically significant trend. However, there were years with exceptionally low values of this circulation index. For example, 1962/63 (-1.22), 1968/69 (-2.07), 1995/96 (-2.40) and 2010/11 (-1.83). These are the years in which Poland experienced cold winters. On the other hand, positive values occurred in 1982/83 (1.94), 1988/89 (1.99), 1992/93 (2.04), 1994/95 (2.28) and 2015/16 (2.17). These were the years with mild winters.

Many studies have confirmed a correlation between air temperature in winter and the NAO in Europe (Hurrell 1995; Hurrell, van Loon 1997) and in Poland (Niedźwiedź 1993; Marsz 1999; Marsz, Styszyńska 2001; Kejna, Rudzki 2021). In Poland, in the years 1961–2025, the strongest correlation occurred in the northern and western parts of the country (Fig. 14), e.g. in Świnoujście R=0.63 (Fig. 15).

The impact of the NAO on air temperature translates into the onset of thermal winter (Fig. 16). The beginning of winter in Poland is associated with the NAO_{NDJFM}, especially in the western part of the country and on the Baltic Sea (e.g., Szczecin R=0.639). No significant correlation was found in the south-eastern part of the country. The end of thermal winter also depends on NAO_{NDJFM}. The correlations are negative, with the strongest relationships occurring in central and eastern Poland (e.g., Suwałki R=-0.522). In the west, the correlations are weaker, but this is due to the increasingly frequent absence of thermal winters. The length of winter is negatively correlated with the NAO. The intensification of atmospheric circulation from the west (NAO^-)

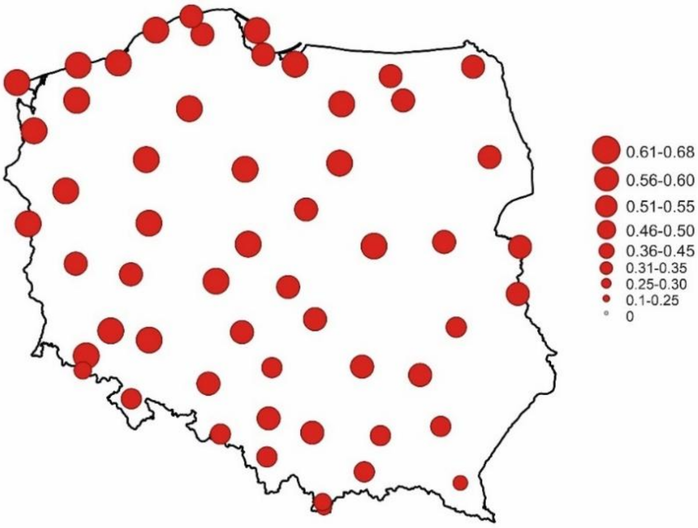

Fig. 14. Relationship between the air temperature of winter months (DJF) in Poland and the NAO_{NDJFM} index in the years 1961–2025

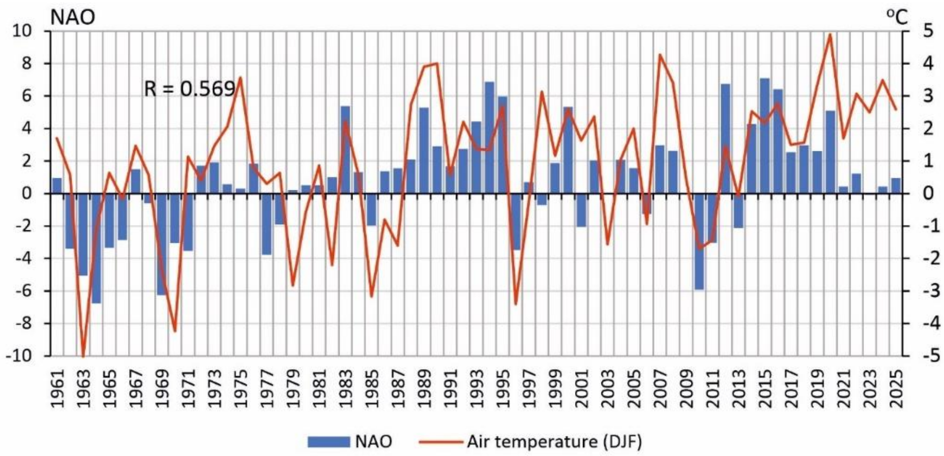

Fig. 15. Relationship between the temperature of winter months (DJF) in Świnoujście and the NAO_{NDJFM} index in the years 1961–2025

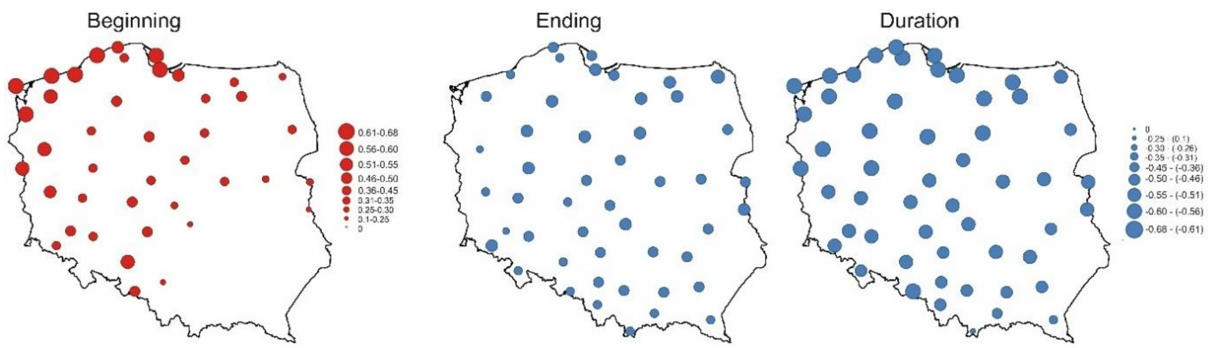

Fig. 16. Linear correlation coefficient of winter occurrences (beginning, end and duration) in Poland with NAO_{DJFM} in Poland in the years 1961–2025

shortens winters. This is evident throughout Poland, with the strongest correlation occurring especially in western and northern Poland (Gdańsk R=-0.629).

The increasingly frequent lack of thermal winters is caused by the dominance of maritime air masses at NAO+. This is found in, for example, Świnoujście in north-eastern Poland (Fig. 17).

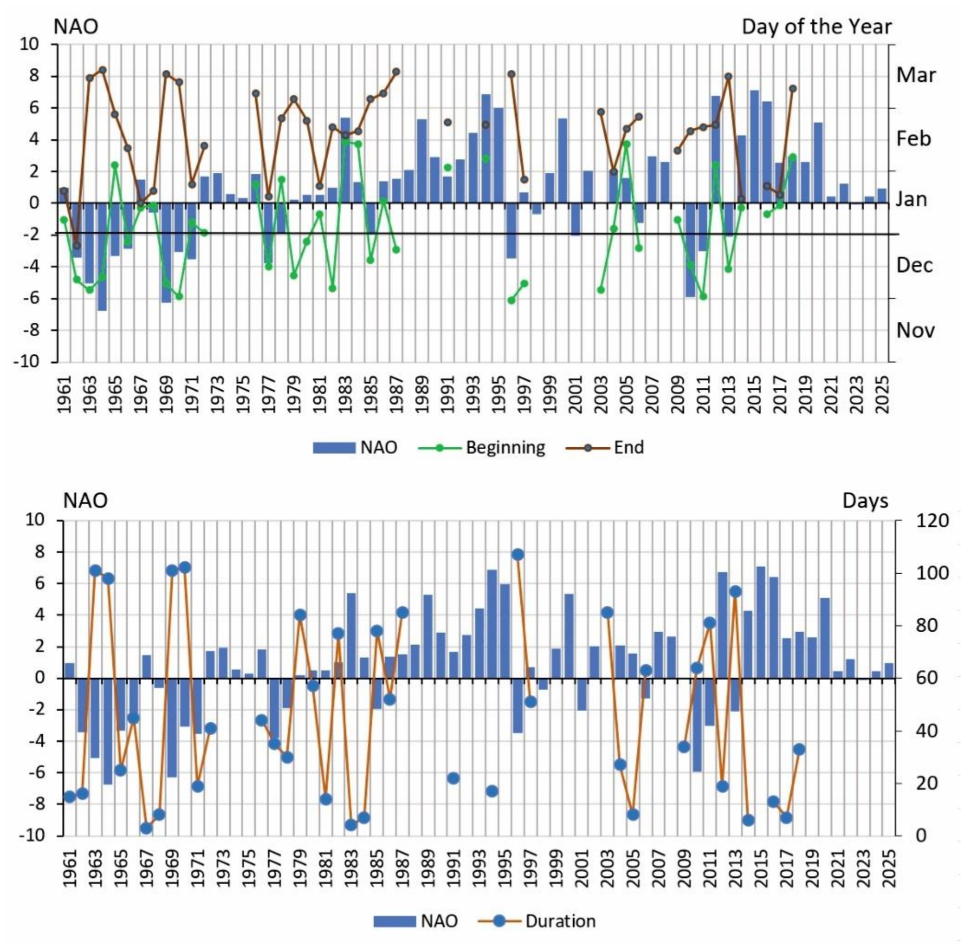

Fig. 17. The course of the beginning and end dates (upper panel) and duration of the thermal winter (lower panel) in Świnoujście against the background of the NAO_{DJFM} index in the years 1961–2025

At this station, between 1961 and 2025, there were 23 years without a thermal winter, including there having been no thermal winter since 2019. The NAODJFM index for these years was 0.61, with an average of 0.21 for the entire period.

Discussion of results

Progressive global warming is causing changes in the occurrence of thermal seasons (Wang *et al.* 2021). This problem affects various regions of the world, such as the United States (e.g., Higgins *et al.* 2002; Mayes Boustead *et al.* 2015), Asia (Liu *et al.* 2014) and Europe. For example, England is experiencing an increasing frequency of warm spells during winter (Chapman *et al.* 2020). In Estonia (Jaagus, Ahas 2000), there has been a significant shortening of winter. In Finland, the shortening of winter by 2099 may reach 2–4 months, progressing at a rate of 10–24 days per 1°C of local warming (Ruosteenoja *et al.* 2020). The Severity Winter Index in Central Europe has decreased (Domonkos, Piotrowicz 1998). However, there are cold spells associated with the advection of continental air masses from the east, with low North Atlantic Oscillation values (Lhotka, Kyselý 2015).

Poland is also undergoing a rapid increase in air temperature, especially in the summer and winter seasons (trend of up to 0.3–0.4°C/10 years in 1951–2018) (Ustrnul *et al.* 2021). In western Poland, even in the coldest month, the mean temperature was above zero. The range of the 0°C isotherm is shifting eastward (Kejna, Rudzki 2021). The climate is becoming less continental, and climate oceanity is increasing (Gorczyński 1922; Marsz 1995; Kożuchowski, Marciniak 2002). This affects the occurrence of thermal seasons, especially winter (Czernecki, Miętus 2015).

The analysis of the start, end and duration of thermal winter in Poland from 1960/61 to 2024/25 revealed considerable spatial variability. Winter occurred earliest in the mountains, as early as October. In the lowlands, it arrived on 30 November in north-eastern Poland and latest on the Baltic coast (13 Jan). The end of winter was progressively later along an east-to-west gradient (between 14 Mar and 25 Jan). On the highest peaks of the Sudetes and Tatra Mountains, winter did not end until the end of April. The isochrones of the beginning and end of winter were meridional, and in the north parallel to the Baltic Sea coast, which confirms earlier analyses (Lorenc 2005; Tomczyk, Bednorz 2022). However, compared to the results obtained by Czarnecka and Nidzgorska-Lencewicz (2017), which identified three regions (western, central and eastern) that differed from one another in winter patterns, a coastal region should also be distinguished, where the warming influence of the Baltic Sea causes a delay in the beginning and end of winter and a shortening of the winter season. This is confirmed by the results of other studies (Kitowski *et al.* 2019). The sea was found to exert a similar influence on winter in Estonia (Jaagus, Ahas 2000). In contrast, mountainous areas are characterised by an early and long winter (Kasprowy Wierch, 188 days). The specificity of the mountain climate has been described by Hess (1965), Lewik (1996) and Migała *et al.* (2016). However, the analysis showed that exceptionally cold and long winters in the mountains do not coincide with those in lowland areas – due to frequent vertical air temperature inversions (Grajek, Szyga-Pluta 2021). In large cities, the urban heat island effect is noticeable, with winter arriving later and being shorter than in suburban areas (Majewski 2014).

Winter periods in Poland are characterised by high year-to-year variability, especially in the west of the country (Czarnecka, Nidzgorska-Lencewicz 2017). This was confirmed by analyses of winter types. Short winters or the absence of a thermal winter are becoming more frequent. Long winters (with a length >75th percentile) are becoming less frequent. It has been found that the longest winter in Poland was in 1995/96 (an average of 120 days for the lowland stations). A series of long winters occurred in the 1960s (1961/62, 1962/63, 1963/64 and 1969/70). The winter of 1962/63 was not only cold but also covered a significant area of Europe (Twardosz, Kossowska-Cezak 2016). In the 21st century, Poland has witnessed only one winter of longer than 100 days (2012/13).

A characteristic feature of Poland's climate is mid-winter warming. This phenomenon occurred especially in the 20th century, e.g. during the winters of 1961/62 and 1993/94. They are characterised by a large number of days atypical for winter, with a mean temperature above 0°C. In the 20th century in Kraków, such days accounted for as much as 47% of the winter period (Piotrowicz 2002). It has been found that such winters occur most often in central Poland, rarely on the coast and in the east of the country, and not at all in the mountains. The phenomenon of winter warm spells is intensifying not only in Poland; for example, in England, their number has increased two- to three-fold since the late 1800s (Chapman *et al.* 2020).

Comparing the years 1961–1990 and 1991–2020, it was found that the onset of thermal winter occurred later, on average by 27 days in the west of the country and 10 days in the east. This trend has already been observed. For example, in Krakow, progressively over the period from 1792 to 1995, the onset of winter occurred 17 days later and the end 16 days earlier, and its length increased by one month (Piotrowicz 2000). Similarly, Niedźwiedź and Limanówka (1992) found that, in 1951–80, winter was 10 days shorter than in 1881–1930. This is the result of both a delay in the onset of winter and its earlier end (Wójcik, Miętus 2014). Winter has also shortened in other European countries, e.g., in Estonia, by 30 days between 1946 and 1998 (Jaagus, Ahas 2000). Across Poland, winter has shortened by up to two months in central Poland, while in the east of the country the changes have been smaller (by 16 days). On the Baltic Sea coast and in western Poland, thermal winter has frequently failed to occur. In the winter season of 2020/21, there was no thermal winter in the entire lowland region of Poland. The area without winter is covering increasingly larger areas, moving rapidly eastward.

These changes are confirmed by trend analyses covering the period 1960/61–2024/25. The changes reach 7 days/10 years, which means a change of 45 days in the analysed period. In the years 1951–2010, this trend was 0.64 days/year and was twice as high as in years and in spring seasons (Czernecki, Miętus 2017). The severity of winter has decreased in Poland and Hungary (Domonkos, Piotrowicz 1998). In the years 1961–2009, the trend averaged 11 days with very high spatial variability (Czarnecka, Nidzgrodzka-Lencewicz *et al.* 2010).

The variability of thermal winters is related to air mass advection. In Europe, atmospheric circulation in winter is controlled by the Azores High, the Icelandic Low and the East Siberian High. The strength of advection from the west depends on the pressure gradient in the North Atlantic (NAO) (Hurrell 1995; Riaz *et al.* 2017).

Research on the impact of atmospheric circulation on climate (Niedźwiedź 1993; Marsz 2001; Falarz 2004, 2009; Bednorz 2006; Czernecki, Miętus 2017), and in particular the NAO (Marsz 1999; Piotrowicz 2000/2001, 2002; Tomczyk, Bednorz 2014; Twardosz, Kossowska-Cezak 2016; Tomczyk *et al.* 2021), has also been conducted in Poland. This analysis also showed significant correlations between winter length and the NAO_{NDJFM}, with the correlations being highest in western and northern Poland (e.g., Gdańsk -0.63). Positive NAO values correspond to years without a thermal winter or winters of short duration, whereas negative values are accompanied by long and cold winters. Central Europe often undergoes cold spells, e.g., in February 1956 and the winter of 1962/63, and in January 1987, associated with low NAO values (Lhotka, Kyselý 2015).

The disappearance or shortening of the thermal winter affects the functioning of the environment (Sparks, Menzel 2002). In the Northern Hemisphere, there is a significant reduction in the number of frosty days due to rising temperatures, especially in autumn (Yuan *et al.* 2025). In Poland, the duration and thickness of snow cover have decreased, which affects the water balance, especially in spring, when the growing season begins (Paczos 1982; Falarz 2004; Bednorz 2006; Czarnecka 2012; Świątek 2014; Tomczyk 2021; Twardosz, Kossowska-Cezak 2021). With the winter getting shorter, the growing season has become significantly longer (Kejna, Pospieszyńska 2025). Bioclimatic conditions are also changing, with the lack of a thermal winter being particularly noticeable; in Szczecin, it has not occurred in one third of years (Mąkosza 2021). Despite this, there are cold spells with severe cold stress (UTCI – Universal Thermal Climate Index), but the frequency of such situations has been decreasing in recent years (Wereski *et al.* 2020).

Climate scenarios based on Global Climate Models (GCMS) indicate further warming and shorter winter periods, e.g., 2–4 months shorter in Finland in 2070–2099. A temperature increase of 1 °C causes winter to shorten by 10–24 days (Ruosteenoja *et al.* 2011, 2020). In Poland, if the current winter-shortening trend continues, thermal winter will occur sporadically in the coming decades, except in the eastern regions of the country and in the mountains.

Conclusions

1. Poland is undergoing a significant increase in air temperature, especially in the winter months, which is causing the 0°C isotherm to shift eastward. An increasingly large area of the country is characterised by a positive average air temperature in the winter months.
2. Based on an analysis covering the years 1960/61–2019/20, significant differences were found in the start and end dates and duration of thermal winters in Poland:
- The isochrones of the beginning of thermal winter differ by more than 40 days between the coast and western Poland and its easternmost parts. Winter ends earliest in the west and latest in the north-east of the country. There is no thermal winter on the Baltic Sea coast. The duration of winter increases from west to east.
- In the mountains, with increasing altitude above sea level, winter becomes longer, starting earlier and ending later than in lowland areas. The longest winters in the mountains are often not synchronous with those in lowland areas.
- The thermal influence of the Baltic Sea delays the onset of thermal winter, its duration is insignificant, and, in the western part of the coast, thermal winter is becoming increasingly rare.
3. Comparing the period 1961–1990 and 1991–2020, significant changes in the characteristics of winters were found:
- In western Poland and on the Baltic Sea coast, thermal winters do not occur or have significantly shortened by up to two months. Winters start later and end sooner. In eastern Poland, with its continental climate, the changes are less pronounced.
- The longest winter occurred in 1995/96 and lasted from 100 days on the coast to 135 days in the east of the country. A series of long winters occurred in the 1960s. In the 21st century, only the winter of 2012/13 was long. Long winters are becoming increasingly rare.
- The phenomenon of mid-winter warming is becoming increasingly rare. During short winters, its probability of occurrence is lower.
- The frequency of years without a thermal winter is increasing, with the most frequent occurrences on the Baltic Sea coast and in western Poland.
4. The winter trend in 1961–2025:
- In Poland, there has been a downward trend in the length of winters, of even -7.3 days/10 years, resulting in an average shortening of winter by 47 days. This is the result of both a later onset and an earlier end to thermal winter.
- In the mountains, the rate of winter shortening decreases with altitude above sea level, e.g., on Mt Kasprowy Wierch the trend was -2.9 days/10 years.

- If these trends continue, thermal winters will disappear in the 2040s on the coast, in the 2060s–70s in central Poland, and at the beginning of the 22nd century in the east of the country.

5. The correlation of the occurrence of winters and atmospheric circulation:

- The influence of atmospheric circulation on the occurrence of thermal winters in Poland has been confirmed. The length of winter showed the strongest correlation with the North Atlantic Oscillation (NAO_{NDJFM}). With NAO^+, winters are mild and short. With the weakening of the western circulation (NAO^-), the length of winters increases due to the weakening of Atlantic influences and the greater frequency of continental air masses.

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