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Variability in the occurrence of thermal seasons in Poland in 1961–2020

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Abstract

The article analyses the variability of thermal seasons in Poland in 1961–2020. Based on the average monthly air temperature values from 55 stations, the onset and end dates as well as the duration of the six thermal seasons were calculated. Taking into account the thermal thresholds of 0°C, 5°C and 15°C for each year, early spring, spring, summer, autumn, early winter and winter can be distinguished. A significant spatial differentiation of the dates of the beginning and duration of the thermal seasons in Poland was observed. The influence of continentalism (in the east) and oceanic climate (in the west) and the influence of the Baltic Sea are noticeable, and in mountainous regions, altitude above sea level is the main factor. The air temperature in Poland increases at the rate of 0.3°C–0.4°C/10 years. This causes significant changes in the occurrence and duration of the thermal seasons. An early beginning of early spring and spring was observed. Summer arrives earlier and is significantly longer, becoming the longest season of the year (above 110 days in the south of Poland). Autumn and early winter are delayed and get shorter, whereas winter comes much later. Throughout the country, winter is 44 days shorter, and in the north-west it does not occur at all. Changes in the onset of thermal seasons are a clear indicator of progressing global warming. They have also a decisive impact on the environment and human activity.

KEYWORDS

agrometeorology, climate change, climate change impacts, forecasting, miscellaneous, thermal seasons

1 | INTRODUCTION

Thermal seasonality is an inherent characteristic of climate and is determined by changes in the amount of incoming solar radiation during the year. Due to the inclination of the Earth's axis with respect to the orbital plane, the angle of incidence of solar rays and the length of day change, thereby reducing the amount of solar energy reaching Earth's surface and affecting thermal conditions.

In Poland, thermal seasonality has been studied for over 100 years. Romer (1906) and Merecki (1915) identified six thermal seasons of the year: early spring, spring, summer, autumn, late autumn and winter. To distinguish these seasons, they used thermal thresholds of 0, 5 and 15°C. Wiszniewski (1960) proposed an extra threshold of 10°C, which allows early summer and late summer to be distinguished. In the Carpathian Mountains, the winter season was additionally divided using −5°C and −10°C thresholds (Hess, 1965). The thresholds 0°C and 5°C have a nature-based justification: at 0°C water freezes, and snow and ice melt, which allows the winter season to be identified; meanwhile, a temperature of 5°C marks the beginning and the end of the growing season. Thermal summer depends on geographic location (Woś, 1999). For example, in Estonia, it is a period with a mean temperature above 13°C (Jaak & Rein, 2000), but above 10°C in Finland (Ruosteenoja et al., 2011). A similar threshold is used for other northern European countries (Ruosteenoja et al., 2020). On Spitsbergen in the Arctic, thermal summer is when the mean diurnal temperature exceeds 2.5°C (Kwaśniewska & Pereyma, 2004).

In Poland, a number of studies have been published dealing with thermal seasons for the whole country (Romer, 1938; Bartnicki, 1948; Gumiński, 1948; Czernecki & Miętus, 2010, 2017; Kitowski et al., 2019; Lorenc, 2005; Niedźwiedź & Limanówka, 1992; Tomczyk & Bednorz, 2022; Warszawski, 1971; Wiszniewski, 1960) or individual regions: SE Poland (Gumiński, 1950), in the Tatra Mountain (Hess, 1965); North Poland (Nowak, 1967), the Karkonosze Mountain (Ustrnul, 1986); the Świętokrzyskie Mountain (Olszewski & Jarząb, 1996), SE Poland (Skowera & Kopeć, 2008), the Pieniny Mountain (Łepko et al., 2011), East Poland (Radzka, 2015), the Baltic Sea coast (Tylkowski, 2015), as well as places: Puławy (Mitosek, 1961), Rabka Zdrój (Trybowska, 1963), Katowice (Rozkosz, 1986), Lublin (Nowosad & Filipiuk, 1998), Warszawa (Kossowska-Cezak, 2005; Majewski & Przewoźniczuk, 2014), Poznań (Woś, 2006), Zamość (Samborski & Bednarczuk, 2009) and Szymbark (Bochenek, 2016). The works by Romer (1906), Merecki (1915), Gumiński (1950), Wiszniewski (1960), Mitosek (1961), Makowiec (1983), Nowosad and Filipiuk (1998), Piotrowicz (2002) and Bartoszek et al. (2012) provide an overview of methods for distinguishing thermal periods.

As air temperature is globally increasing, the start dates and durations of seasons are changing. According to the Sixth Assessment Report IPCC (2021), in the most recent decade (2011–2020), the global temperature of Earth's surface was 1.1°C higher than in the pre-industrial age (1850–1900). We also observe a significant air temperature increase in Poland (Kejna & Rudzki, 2021; Ustrnul et al., 2021) and thermal anomalies are increasingly frequent in all seasons (Twardosz, 2017). Regional conditions, and atmospheric circulation above all, lead to variability in the onsets of thermal seasons in different years (Rapp & Schönwiese, 1994). A similar phenomenon is also observed in Poland (Czernecki & Miętus, 2010, 2017; Kitowski et al., 2019; Kossowska-Cezak, 2005; Mager & Kopeć, 2010; Olszewski & Żmudzka, 1997; Radzka, 2015; Żmudzka & Dobrowolska, 2001). The duration of the thermal season changes, and disturbances occur in the functioning of the biosphere and in phenological seasonality (Tomaszewska & Rutkowski, 1999; Tylkowski, 2015). Such changes are apparent in other parts of the world (Jaagus et al., 2003; Jaak & Rein, 2000; Ruosteenoja et al., 2011; Song et al., 2009).

The purpose of this article is to analyse the spatial distribution of the onset and duration of thermal seasons in Poland. It also examines the variability of seasons in the years 1961–2020 as global warming intensifies.

2 | RESEARCH AREA AND METHODOLOGY

The analysis utilized mean monthly air temperatures in Poland in 1961–2020, obtained from 55 weather stations of the Institute of Meteorology and Water Management, National Research Institute (IMGW PIB)—Figure 1.

The data for Gdańsk were sourced from a station situated on the coast (Świbno), and any missing data were supplemented from the Rębiechowo airport station, based on a linear relationship. In the case of Elbląg, the data from the years 2013–2020 were reconstructed to be relevant for the original location of the station (40 m a.s.l.) using data from its new location at Milejewska Góra (189 m a.s.l.) and from the Olsztyn station. In Płock, the meteorological station was relocated in 1978 from the Vistula River valley to a morainic plateau. Older data were recalculated for the new location with a correction resulting from data from Toruń. Some monthly data were missing for Resko and were appended using a linear correlation with the Szczecin station.

Most of the stations used for the analysis are situated in lowlands (i.e. below 300 m a.s.l). In the mountains, which account for a tiny percentage of the country's area, there are climatic regions determined by absolute height (Hess, 1965). The following stations (with heights above sea level) were taken into account in the Sudetes Mountains: Kłodzko (356 m), Jelenia Góra (398 m) and Mt Śnieżka (1603 m), and in the Carpathian Mountains: Bielsko-Biała (398 m), Lesko (420 m), Zakopane (855 m) and Mt Kasprowy Wierch (1991 m).

The analysis employed the division of the year into six thermal seasons proposed by Romer (1906) and Merecki (1915):

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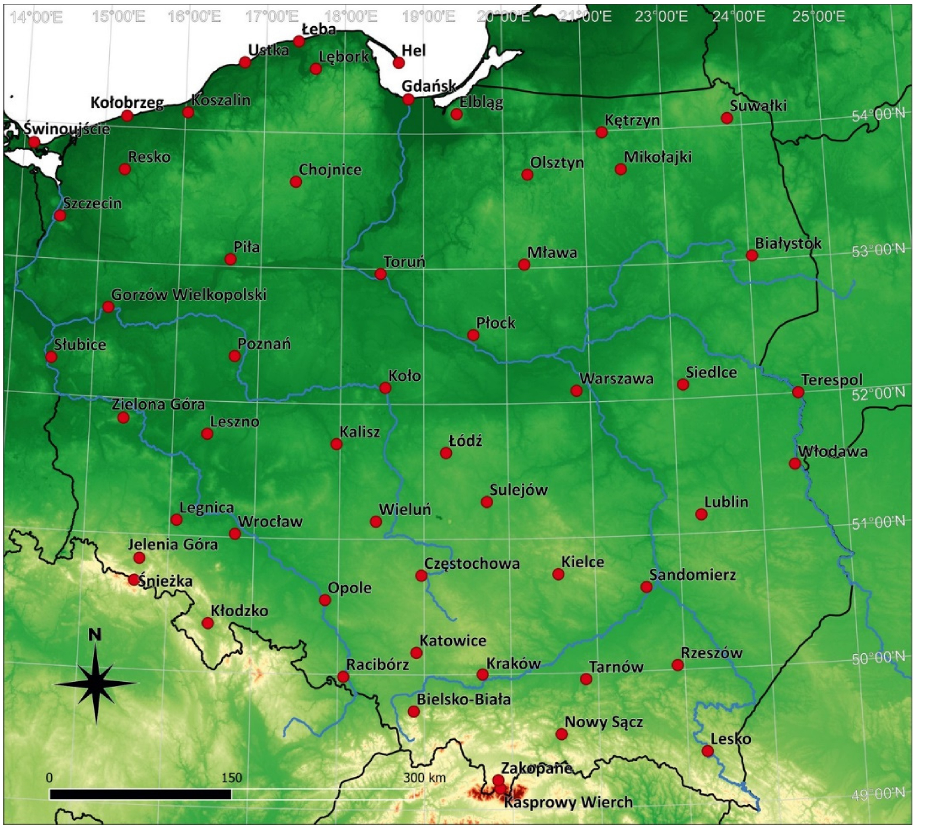

FIGURE 1 Location of stations used in the study.

Thermal season	Air temperature (t_d)
Early spring	$0.0°C < t_d \leq 5.0°C$
Spring	$5.0°C < t_d \leq 15.0°C$
Summer	$t_d > 15.0°C$
Autumn	$5.0°C < t_d \leq 15.0°C$
Early winter	$0.0°C < t_d \leq 5.0°C$
Winter	$t_d \leq 0.0°C$

In order to identify the start and end dates of the seasons, the following formulas by Gumiński (1950) were used:

For temperature increase:

$$x = \frac{t_p - t_1}{t_2 - t_1} .n$$

For temperature decrease:

$$x = \frac{t_1 - t_p}{t_1 - t_2} .n$$

where t_1 is the mean monthly temperature in the month preceding the crossing of the threshold value, t_2 is the mean monthly temperature in the following month, t_p is the threshold value, n is the number of days in the previous month and x is the number of days to be added to the 15th day of the previous month.

The method generally yields good results when multiannual monthly averages of air temperature are used (Figure 2), but in certain years there are occasional problems associated with the temperature frequently oscillating below and above threshold values. This problem was discussed at work by Rapp and Schönwiese (1994). The issue has been tackled by a number of authors. For example, Huculak and Makowiec (1977) proposed a method for unambiguously determining the dates of the growing season (also applicable to thermal seasons) using cumulative series of mean diurnal deviations of air temperature from threshold values. When applied to certain years, the method yields substantially different results from Gumiński's method (Nowosad & Filipiuk, 1998). In the situation where threshold temperatures are frequently passed, Samborski and Bednarczuk (2009) suggested counting the number of days within the periods in which the temperature was above (and, correspondingly, below) the defined thermal thresholds. Czernecki and Miętus (2010) believe that more accurate dates can be obtained on the basis of multiannual daily averages, and they used seven-day rolling averages in their study. On the other hand, Piotrowicz (2002) states that using monthly data instead of diurnal data yields better results. Various methods for identifying thermal seasons have been reviewed by Bartoszek et al. (2012).

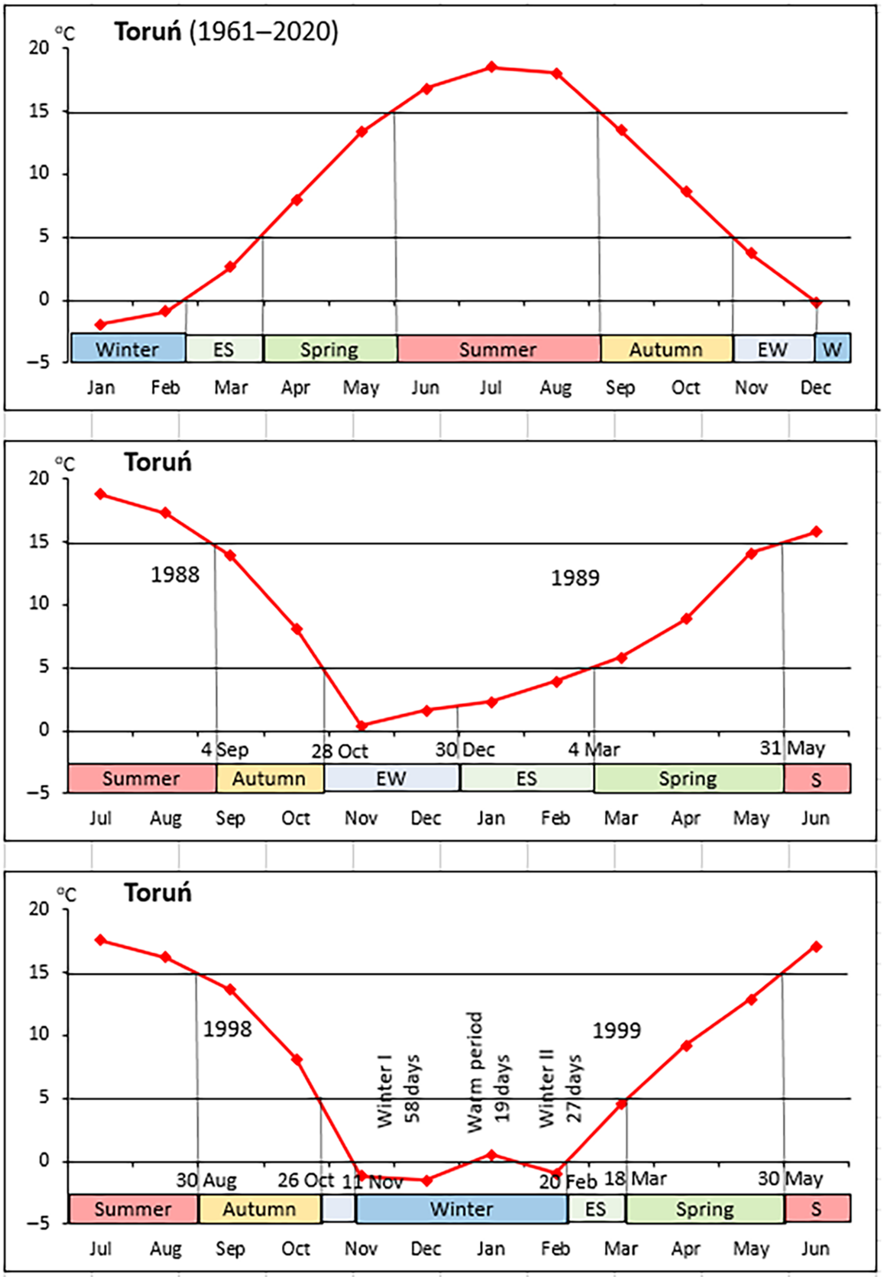

FIGURE 2 Method for distinguishing thermal seasons: for the multiannual period (top panel), for a winterless year (middle), and for a year with midwinter warming (bottom).

The winter season is particularly complex. In this study, in the absence of thermal winter proposed by Skowera and Kopeć (2008), it was assumed that an early winter period transitions into early spring and that the boundary date falls in the middle of the period that aggregates the two (Figure 2—middle panel). A similar solution that involves a symmetrical length of these periods was adopted by Czernecki and Miętus (2010). In the case of a midwinter warming in which temperatures exceeded the threshold value, the number of winter days before and after the warming and the duration of the thaw (with the temperature above zero) were worked out, as proposed by Samborski and Bednarczuk (2009). If the thaw weather lasts shorter than the first and the last cooling, we include the period in winter (Figure 2—bottom panel). A similar approach was used for periods of cool weather in the middle of summer, when the temperature dropped below 15°C.

The calculations of start dates of the thermal seasons were supported by a proprietary script written using the R programming language (R Core Team, 2022). The pattern of contour lines for the start dates and lengths of the seasons in Poland was developed using Gaussian process regression (Childs, 2004), which is often used for climatological analysis (Ustrnul & Czekierda, 2010). Interpolation maps were made in SAGA GIS software (Conrad et al., 2015). The ordinary kriging method was used.

TABLE 1 Average beginning dates (Date) and duration (Days) of thermal seasons at selected stations in Poland in 1961–2020.

Thermal season		SWI	GDA	SUW	SLU	WAR	TER	WRO	KRA	LUB	SNI	KAS
Early spring	Date	19.01	26.02	14.03	24.01	25.02	3.03	6.02	22.02	2.03	20.04	28.04
	Days	67	38	24	58	31	27	45	33	28	35	39
Spring	Date	28.03	4.04	7.04	22.03	27.03	30.03	22.03	26.03	30.03	25.05	6.06
	Day	74	68	63	67	59	58	65	63	62	60	49
Summer	Date	10.06	11.06	9.06	28.05	25.05	27.05	26.05	28.05	31.05		
	Days	90	82	79	102	104	99	106	100	94	0	0
Autumn	Date	8.09	1.09	27.08	7.09	6.09	3.09	9.09	5.09	2.09	23.07	24.07
	Days	67	67	62	66	61	61	63	62	62	59	48
Early winter	Date	14.11	7.11	28.10	12.11	6.11	3.11	11.11	6.11	3.11	21.09	11.09
	Days	67	42	33	57	36	34	47	34	34	40	43
Winter	Date		19.12	30.11	9.01	12.12	7.12	28.12	10.12	7.12	31.10	24.10
	Days	0	68	104	15	74	86	39	73	85	171	186

Note: SWI-Świnoujście, GDA-Gdańsk, SUW-Suwałki, SLU-Słubice, WAR-Warszawa, TER-Terespol, WRO-Wrocław, KRA-Kraków, LUB-Lublin, SNI-Śnieżka, KAS-Kasprowy Wierch.

3 | RESULTS

3.1 | Onset of thermal seasons

The occurrence of seasons in Poland is characterized by a significant spatial variability (Table 1 and Figure 3).

3.1.1 | Early spring

Early spring begins earliest at the Baltic Sea coast (Świnoujście—19 January) and in the west of Poland (Słubice 24 January). This season appears later and later in the hinterland, and, in the east (Suwałki), it does not begin until 14 March. It starts even later in the mountains: on 20 April at Mt Śnieżka (south part of Poland, the Karkonosze Mountains) and on 28 April at Mt Kasprowy Wierch (the Tatra Mountains). The duration of early spring falls from 58 days in the west (Słubice) to 26 days in the east (Białystok). Along the Baltic Sea coast, early spring is very long and lasts from 38 days in Gdańsk to 67 days in Świnoujście. In the mountains, it is quite long (35 days at Mt Śnieżka; 39 days at Mt Kasprowy Wierch).

3.1.2 | Spring

Spring begins in Poland in the last 10 days of March in the Silesian Lowland (SW Poland)—Legnica, 21 March and the Szczecin Lowland (NW Poland)—Szczecin, 22 March. Also, in the Sandomierz Basin and Subcarpathia (SE Poland), it occurs around that time (Tarnów 22 March). In the north-east of the country, the season comes with a substantial delay (Suwałki 7 April), just like at the Baltic seaside (Hel 6 April). In the mountains, it begins even later (Mt Śnieżka 25 May, Mt Kasprowy Wierch 6 June). The duration of spring ranged from 58 days in Terespol (east Poland) to 78 days in Ustka (the Baltic Seaside). In mountain valleys, it reached 73 days in Jelenia Góra and 98 days in Zakopane, but it became shorter high up in the mountains (49 days at Mt Kasprowy Wierch).

3.1.3 | Summer

Summer comes earliest in central Poland—at the end of May (e.g. Warsaw 25 May). The isochrones are latitudinal, and in the northern part of the country, summer begins on 9 June in Suwałki and only on 21 June at the Baltic Sea (Łeba). In the south of Poland, elevation plays a key role: at Mt Kasprowy Wierch and Mt Śnieżka thermal summer does not occur at all. Summer is one of the longest seasons in Poland, exceeding 100 days in the central regions, 106 days in Tarnów and 103 in Opole. In the north, it is short (e.g. 73 days in Łeba, and 79 in Suwałki).

3.1.4 | Autumn

Autumn appears first in the mountains (Mt Śnieżka 23 July and Mt Kasprowy Wierch 24 July). In the lowlands, it begins in the east, on the coast and in Western Pomerania (NW Poland) in the last 10-day period of

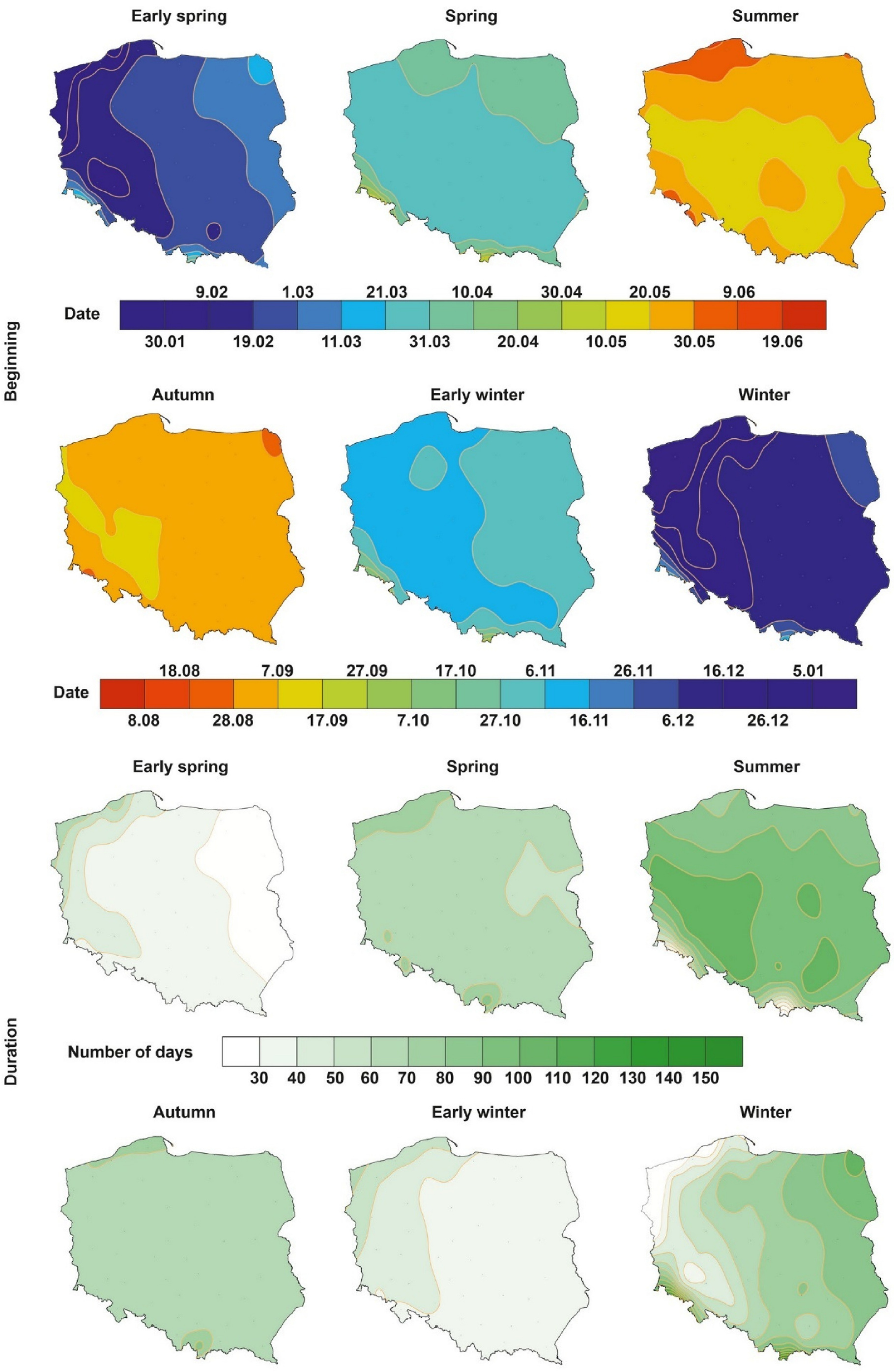

FIGURE 3 Spatial variability of thermal seasons beginning and duration in Poland, 1961–2020.

August (e.g. Lębork 31 August, Suwałki 27 August). The regions where autumn begins latest are Lower Silesia (Opole 9 September) and Subcarpathia (Tarnów 8 September). Except for the mountains, autumn is shortest in the east (61 days in Włodawa, 60 in Sandomierz) and lasts the longest on the coast (74 days in Łeba, Ustka and Lębork). In the mountains, it is short (55 days at Mt Śnieżka and 42 at Mt Kasprowy Wierch) but persists much longer in mountain basins (71 days in Jelenia Góra) and at the Baltic Sea (71 days in Hel and Ustka).

3.1.5 | Early winter

Early winter begins in the mountains in September (Mt Kasprowy Wierch 11 September, Mt Śnieżka 21 September) and at the end of October in the north-east of Poland (Suwałki 28 October). The beginning of the season in the west is more than two weeks later (Legnica 13 November), and it falls as late as on 17 November on the coast (Hel), due to the warming effect of Baltic waters. In the east, early winter lasts for approximately one month (33 days in Włodawa), whereas in the west

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TABLE 2 Average beginning dates (Date) and duration (Days) of thermal seasons at selected stations in Poland in 1961–90 and 1991–2020.

Period			SWI	GDA	SUW	SLU	WAR	TER	WRO	KRA	LUB	SNI	KAS
Early Spring	1961–90	Date	15.02	01.03	17.03	16.02	02.03	09.03	19.02	27.02	06.03	24.04	01.05
	1991–2020	Date	20.01	24.02	09.03	16.01	18.02	26.02	15.01	17.02	26.02	15.04	25.04
	1961–90	Days	47	36	25	37	29	24	35	30	27	36	42
	1991–2020	Days	63	37	25	62	34	29	63	34	30	35	36
Spring	1961–90	Date	03.04	06.04	11.04	25.03	31.03	02.04	26.03	29.03	02.04	30.05	12.06
	1991–2020	Date	24.03	02.04	03.04	19.03	24.03	27.03	19.03	23.03	28.03	20.05	31.05
	1961–90	Days	70	67	61	68	60	57	67	66	62	57	44
	1991–2020	Days	75	69	64	65	58	58	63	61	61	28	53
Summer	1961–90	Date	12.06	12.06	11.06	01.06	30.05	29.05	01.06	3.06	03.06	NA	NA
	1991–2020	Date	07.06	10.06	06.06	23.05	21.05	24.05	21.05	23.05	28.05	NA	NA
	1961–90	Days	83	80	73	94	95	93	94	90	88	0	0
	1991–2020	Days	96	83	86	110	111	105	114	108	100	0	0
Autumn	1961–90	Date	03.09	31.08	23.08	03.09	02.09	30.08	03.09	1.09	30.08	26.07	26.07
	1991–2020	Date	11.09	01.09	31.08	10.09	09.09	06.09	12.09	8.09	05.09	17.06	23.07
	1961–9020	Days	71	69	64	69	63	63	67	65	64	56	43
	1991–2020	Days	67	66	59	64	60	59	63	61	60	97	51
Early Winter	1961–90	Date	13.11	08.11	26.10	11.11	04.11	01.11	09.11	5.11	02.11	20.09	07.09
	1991–2020	Date	17.11	06.11	29.10	13.11	08.11	04.11	14.11	8.11	04.11	22.09	12.09
	1961–90	Days	52	39	32	47	35	33	39	33	33	40	47
	1991–2020	Days	64	44	36	64	37	36	62	35	35	41	43
Winter	1961–90	Date	04.01	17.12	27.11	28.12	09.12	04.12	18.12	8.12	05.12	30.10	24.10
	1991–2020	Date	NA	20.12	04.12	NA	15.12	10.12	NA	13.12	09.12	02.11	25.10
	1961–90	Days	42	74	110	50	83	95	63	81	91	176	189
	1991–2020	Days	0	66	95	0	65	78	0	66	79	164	182

Note: SWI—Świnoujście, GDA—Gdańsk, SUW—Suwałki, SLU—Słubice, WAR—Warszawa, TER—Terespol, WRO—Wrocław, KRA—Kraków, LUB—Lublin, SNI—Śnieżka, KAS—Kasprowy Wierch;
Abbreviation: NA, the season does not occur.

and on the coast, it persists for as long as 57 days (Słubice) and even up to 67 days (Świnoujście). At Mt Kasprowy Wierch, early winter lasts 43 days.

3.1.6 | Winter

In Poland, winter comes from the east. In Suwałki, it begins on 30 November. In central Poland, it starts in the first 10 days of December (Warsaw 12 December, Poznań 24 December), and in the west and on the coast it does not occur until January (Słubice 9 January, Kołobrzeg 13 January). In the mountains, winter begins as early as October (Mt Kasprowy Wierch 24 October). The duration of winter varies throughout the country. Along the Baltic Sea coast, it lasts between 7 days (Świnoujście) and 68 days (Gdańsk). It is longest in the east of Poland (104 days in Suwałki) and in the mountains (171 days at Mt Śnieżka, 186 days at Mt Kasprowy Wierch).

3.2 | Changes in the onset of seasons

Significant changes are observed when comparing the average start and end dates of individual seasons in the years 1961–1990 and 1991–2020 (Table 2, Figure 4).

3.2.1 | Early spring

In the years 1991–2020, early spring started in the west of Poland a month earlier than in 1961–90: for example, in Szczecin on 18 January (previously 17 February), in Legnica on 16 January vs. 17 February. Moving eastwards,

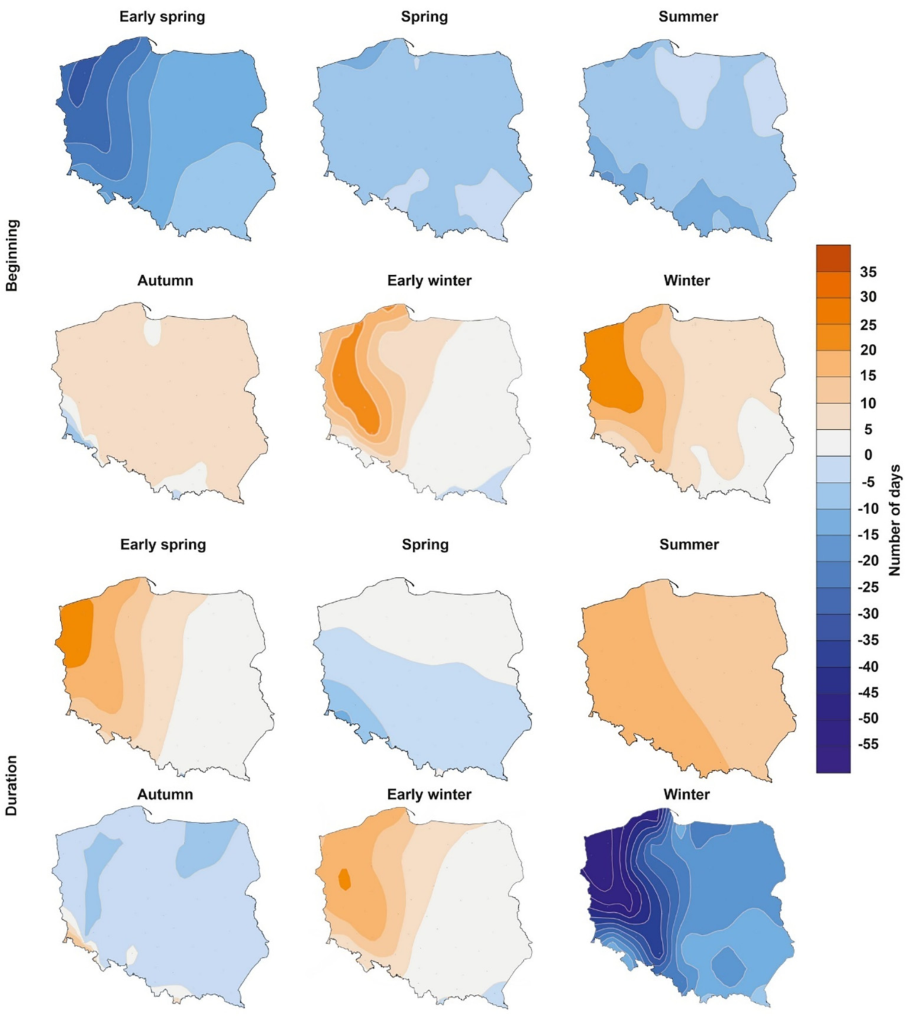

FIGURE 4 Changes in the beginning date and duration of thermal seasons in Poland between 1991–2020 and 1961–1990.

the procession towards earlier onsets becomes less striking, but it is still evident. In recent decades, early spring started on 16 February in Warsaw and on 26 February in Terespol (vs. 2 March and 9 March, respectively). In the mountains, the change is minor, for example, from 1 May to 25 April at Mt Kasprowy Wierch. The isochrones for the acceleration of early spring are meridional. Another observation is that early spring became clearly longer, especially on the coast (from 47 days to 63 days in Świnoujście) and the west of the country (from 37 to 62 days in Świecko). The further eastwards, the lesser the changes, and the duration of early spring has extended from 34 days to 52 days in Poznań, from 29 to 34 days in Warsaw, and to 25 days in Suwałki. In the mountains, on the other hand, the season has become shorter (from 42 to 26 days at Mt Kasprowy Wierch).

3.2.2 | Spring

The coming of spring happens about a week sooner across the entire country. For example, in the years 1961–1990, in Świnoujście, spring started normally around 24 March, whereas in 1991–2020, it happened on 3 April. The case was similar in Suwałki: 3 April (vs. 11 April). In the centre of Poland (Warsaw), spring came on 24 March (vs. 31 March), and at Mt Kasprowy Wierch, it came on 31 May (vs. 12 June). The duration of spring also increased by a few days; for example, in Świnoujście it extended from 70 to 75 days, and in Suwałki from 61 to 64 days. Even greater changes were observed in the mountains: at Mt Kasprowy Wierch, spring lasted 53 days (vs. 44), whereas in Lesko, it shortened from 74 to 68 days. In the west and centre of Poland, the season also shortened, for example, from 68 to 65 days in Świecko, and from 60 to 58 days in Warsaw. In the Sudetes, spring shrank from 57 to just 28 days (Mt Śnieżka).

3.2.3 | Summer

The beginning of summer fell a few days earlier, too. In Świnoujście, in the years 1961–1990, the average start date for summer used to be 12 June, whereas in 1991–2020, it was 7 June. In Suwałki, the procession of onset reached 5 days (from 11 to 6 June). In Warsaw, summer began on 21 May (vs. 30 May). Generally, summer became longer all over Poland. In 1991–2020, most of the country witnessed summer for 100–110 days, which was two weeks longer than in 1961–1990; in Świecko, it lasted 94 days on average in the earlier decades, but 110 days in the latter. The change was from 95 to 111 days in Warsaw, and from 73 to 86 days in Suwałki. On the Baltic coast, summer is about 14 days longer (Świnoujście—96 vs. 83 days; Hel—92 vs. 76 days). High in the mountains (Mt Śnieżka and Mt Kasprowy Wierch), thermal summer did not occur.

3.2.4 | Autumn

Autumn came with a delay across the country. In 1961–90, in Świnoujście, it started on 3 September, but in 1991–2020, it began on 11 September. The case was similar in Suwałki (23 August vs. 31 August) and Warsaw (2 September vs. 9 September). In the Tatras (Mt Kasprowy Wierch), the difference was three days (26 vs. 23 July). Autumn is a season that has become slightly shorter; the reduction is of a few days, for example, in 69–64 days in Świecko, 63–60 days in Warsaw and 64–59 days in Suwałki. The season lasted longer only at Mt Kasprowy Wierch (from 43 to 51 days) and Mt Śnieżka (from 56 to as many as 97 days).

3.2.5 | Early winter

Early winter begins increasingly late. For example, in Świnoujście, it began on 13 November in 1961–1990, but on 17 November in 1991–2020. The shift was from 26 to 29 October in Suwałki, from 4 to 8 November in Warsaw (central Poland), and from 7 to 12 September at Mt Kasprowy Wierch. Early spring was evidently longer on the coast (from 52 to 64 days in Świnoujście) and in the west (from 37 to 56 days in Poznań). The further eastwards, the lesser the changes: e.g. 32 vs. 36 days in Suwałki, and 33 vs. 36 days in Terespol. The season has become shorter even in the mountains (47 vs. 43 days at Mt Kasprowy Wierch).

3.2.6 | Winter

In the years 1991–2020, winter essentially did not occur on the Baltic coast nor in the west of Poland. In recent decades, the mean temperature of the coldest month has not been dropping below 0°C. In 1961–1990, in Świnoujście, winter started on 4 January and lasted 42 days. Winter comes evidently later across the country; in 1961–1990, in Poznań, it used to begin on 14 December, but in 1991–2020, the start date fell on 6 January (23 days later). In Warsaw, the delay was of 6 days (9 and 15 December, respectively), and in Suwałki, it was of 8 days (27 November vs. 4 December). At Mt Kasprowy Wierch, winter appeared at approximately the same time in both analysed multiannual periods (24–25 October). The duration of the season changed a lot, too. In 1961–1990, winter on the coast and in the west of the country lasted between 40 and 50 days (42 days in Świnoujście, 50 in Świecko), whereas, in 1991–2020, typical thermal winter did not happen. In the rest of the country, winter became much shorter, shrinking from 83 to 65 days in Warsaw, and from 110 to 95 days in Suwałki. In the mountains, the reduction was less evident (189 to 182 days, Mt Kasprowy Wierch).

3.3 | Temporal variability

Thermal seasons in Poland are characterized by a substantial year-to-year variability in both their start dates and duration (Figure 5). At some stations, winter did not occur every year. The series of years—1973–1975, 1988–1990, 1998–2002, 2007–2009 and 2019–2020—are particularly prominent, as the mean monthly air temperature observed at many stations then were above zero. At higher elevated stations, along the Baltic Sea coast and in Western Pomerania, thermal summer occasionally did not occur (e.g. 1962 and 1965). In Zakopane, thermal summer occurred only 27 times in the 60 years, but after 1996, it was observed every year.

3.4 | Trends in the onset of seasons

In 1961–2020, seasons of the year showed different trends in terms of durations and onsets (Figure 6).

3.4.1 | Early spring

A statistically significant ($p < 0.05$) increasingly early arrival of early spring was observed at only three stations (Kołobrzeg, Chojnice and Suwałki, −3.1 days/10 years) and at none of the stations considered for this analysis was a significant change in the duration of the season ascertained.

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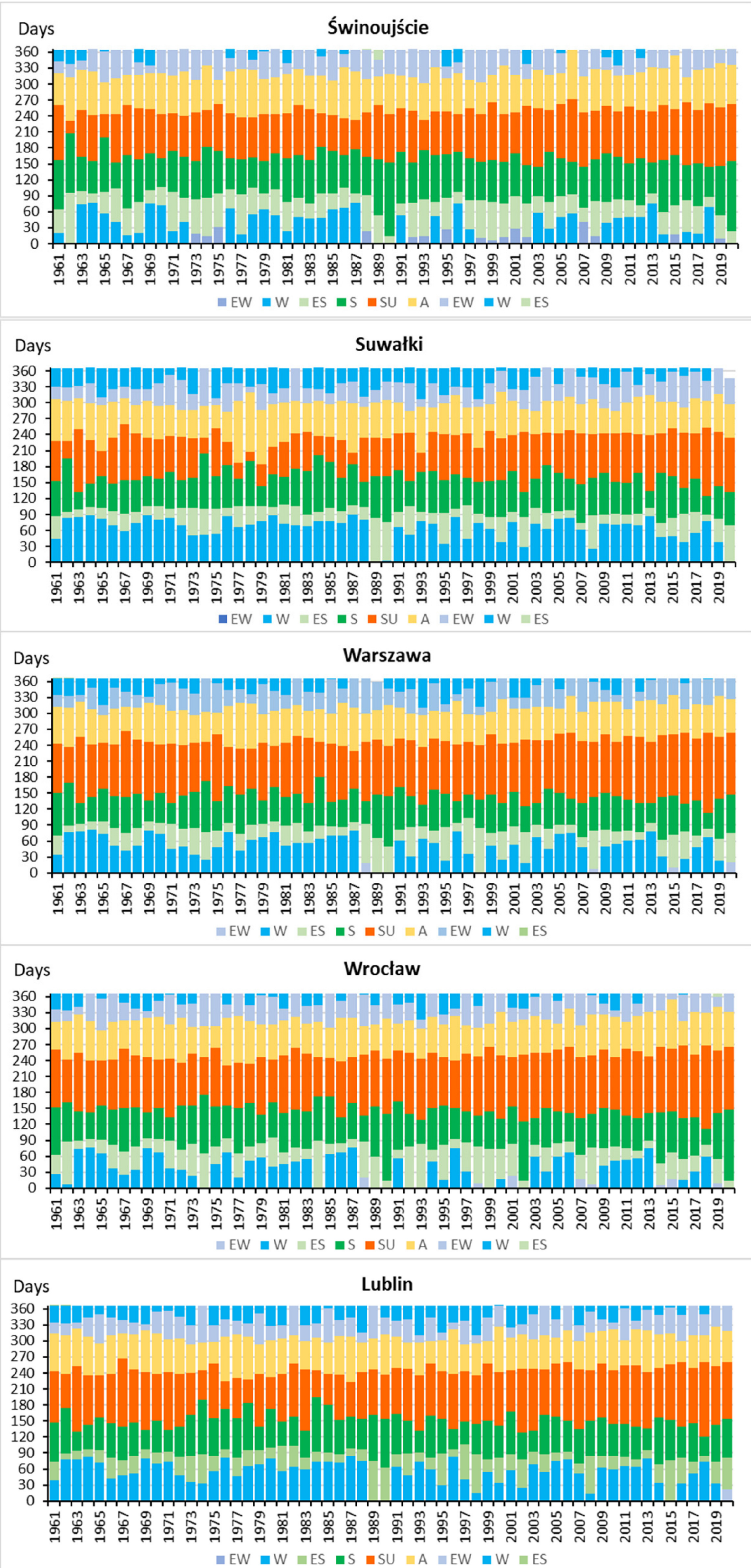

FIGURE 5 Variability of thermal seasons at selected stations in Poland in the years 1961–2020. ES—early spring, S—spring, S—summer, A—autumn, EW—early winter, W—winter.

3.4.2 | Spring

At 84% of the analysed stations, spring exhibits a statistically significant trend towards earlier onset. Especially substantial changes took place in the north of the country (Chojnice, −3.6 days/10 years; Olsztyn, −3.0) and on the coast (Kołobrzeg, −3.6 days/10 years). In the mountains, the Zakopane station showed that spring advanced at a rate of

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FIGURE 6 Trends of the beginning and duration of thermal seasons (days/10 years) in Poland, 1961–2020. Statistically significant trends are marked ($p < 0.05$).

−2.8 days/10 years. On the other hand, the duration of the season changed substantially only at three stations (spring extended most in Leszno: by 3.1 days/10 years).

3.4.3 | Summer

Summer is beginning sooner and sooner. At 73% of the stations, a statistically significant acceleration was observed. It was the greatest in Zakopane (−5.9 days/10 years), Lesko (−4.2), Jelenia Góra (−4.8), and on the coast (Kołobrzeg −4.0). Smaller changes were observed in the central part of the country and in the east, where the trend proved statistically insignificant. At the same time, summer extended by 1.1 days/10 years in Zakopane and 0.8–0.9 days/10 years in Ustka at the sea coast. Changes in its duration at most of the other stations in the east were not statistically significant.

3.4.4 | Autumn

At 93% of the stations, autumn occurred later. Particularly evident delays occurred in Zakopane (5.0 days/10 years), Lublin (4.5 days/10 years), Jelenia Góra (4.2 days/10 years) and on the coast (Ustka 4.0 days/10 years). Smaller changes (below 2 days/10 years) were noted in the east of the country and in Płock and Tarnów. The duration of autumn extended at four stations, and by the greatest amount in Lublin (0.4 days/10 years).

3.4.5 | Early winter

Early winter begins increasingly later at 51% of stations, but at others, the trend is not statistically significant. The greatest delay was observed in Zakopane (3.4 days/10 years). In the north of Poland, no statistically significant trend was found (except for Kętrzyn). The duration of early winter extended at only two stations (Suwałki and Zielona Góra, both over 3 days/10 years).

3.4.6 | Winter

Winter comes later and later, but only at 10 of the stations was the trend statistically significant. The most notable delay was observed in Chojnice (3.7 days/10 years), which means as many as 22 days in the entire period considered (1961–1920). Winter clearly shortened across the country, but statistically significant trends were observed at only 47% of the stations. The greatest changes happened in the north-east of Poland (Siedlce, Mława and Terespol: more than -7 days/10 years). Since 1961, winter has shortened by more than 40 days. In the west of the country, the trends were not significant, due to the absence of thermal winter in recent decades.

4 | SUMMARY AND DISCUSSION

The emergence of thermal seasons is a useful indicator of climate change (Rapp & Schönwiese, 1994). Ongoing climate change leads to environmental disruptions and affects people's lives and the economy. In the years 1951–2018, in Poland, air temperature increased by about 2°C, and the average trend reached 0.2°C–0.3°C/10 years (Ustrnul et al., 2021). The warming was not, however, consistent throughout the year, and in 1961–2018, the greatest rise in air temperature was observed in summer (July 0.48°C/10 years), winter (January 0.46°C/10 years) and spring (April 0.41°C/10 years), whereas in autumn, the warming was not statistically significant. At the same time, the isotherms of winter and summer months are moving eastwards and northwards, respectively (Kejna & Rudzki, 2021). This results in changes in the onsets and durations of thermal seasons. A distinctive feature of Poland's climate is its transitional nature: it lies between maritime and continental types (Kożuchowski, 2011; Woś, 2010) and one of its characteristics is the occurrence of six seasons (early spring, spring, summer, autumn, late autumn and winter). These can be distinguished using three threshold temperatures: 0°C, 5°C and 15°C (Merecki, 1915; Romer, 1906).

The analysis covering the years 1961–2020 demonstrated the following:

1. Substantial spatial variability in the emergence of seasons. Early spring comes to Poland from the west in mid-February and takes as many as three weeks to reach the north-eastern borders of the country. Similarly, spring starts earliest in the west (the last 10 days of March) and reaches the easternmost areas 2–3 weeks later. Summer appears earliest in the centre of Poland (end of May) and a month later comes to the Baltic coast. Autumn starts in the east (the last 10 days of August) and after ~20 days reaches the west of the country. Early winter begins in the north-east (at the end of October), and after two weeks, it covers the west as well. Winter comes from the east (end of November) and is observed latest on the coast (early January). The coast is the area where all the seasons appear notably later, and especially spring, summer, autumn, early winter and winter. The same phenomenon is also observed in Estonia (Jaak & Rein, 2000). In the mountains, seasons occur later as the height above sea level increases; at the highest peaks of the Tatras and Sudetes, there is no thermal summer. The obtained results, as compared with previous analyses, show an evident acceleration of the coming of early spring, spring, early winter and winter (Czernecki & Miętus, 2017; Lorenc, 2005; Woś, 2010; Tomczyk & Bednorz, 2022).
2. The duration of seasons is changeable depending on region, as demonstrated by earlier studies (Czernecki & Miętus, 2015; Tomczyk & Bednorz, 2022). Early spring and spring are clearly becoming shorter from the west to the east. The seasons are particularly long on the coast. Summer is the longest season across most of the country. It is shorter in a northwards direction and depends on absolute height. Autumn is shortening in the east of Poland and becoming clearly longer in the west, especially at the coast. Early winter is very short in the east and longest in the west and on the coast. The pattern of isochrones (duration) of winter proves strong continental influences in the east of Poland, leading to long winters. In the west, thermal winter has been very short or even absent (on the coast) in recent decades (Tomczyk & Bednorz, 2022).
3. Comparing the years 1961–90 to 1991–2020 revealed a significant trend towards the earlier onset of early

spring, by as much as a month in the west and by two weeks in the east. At the same time, the seasons became longer, especially in the west of Poland. Spring came a week sooner and its duration extended by a few days, especially in the east. Summer occurred earlier and lasted up to over 110 days longer in the centre of the country. The arrival of autumn was delayed by about a week, and the season became shorter, except in the mountains, where it got longer. Early winter happened a few days later and its duration extended by a few days, especially on the coast. In recent decades, thermal winter has ceased to occur on the coast and in the west of Poland. In other regions, winter comes 6–23 days later, and its duration has substantially shortened (by as many as 40–50 days in the west, and 15 in the east).

4. The changes are supported by an analysis of the trends. Early spring starts much earlier, but at only three stations was a statistically significant trend observed (up to 3.1 days/10 years). No significant changes in the duration of the season were found. Spring arrives sooner and sooner, by even 20 days over the 60 years, but its duration extended only at three stations (by up to 3.1 days/10 years). Summer starts clearly earlier: 24 days earlier at the seaside and even 27–35 days in the mountains, and it lasts 5–6 days longer overall. Autumn begins later; in the mountains even 30 days later, and 24 days later along the coast. A statistically significant extension of the season was not observed. Early winter begins later, especially in the east (4–5 days), but its duration did not increase notably. Winter, on the other hand, became evidently shorter across the country: even by 44 days in the north-east. In the west and on the coast, thermal winters essentially did not occur. This observation is corroborated by Czernecki and Miętus (2015), who stated that a lack of thermal winter makes this phenomenon non-linear; therefore, no statistically significant values were found for those regions.

The obtained results confirm previous findings (Czernecki & Miętus, 2010, 2017; Kitowski et al., 2019; Kossowska-Cezak, 2005; Mager & Kopeć, 2010; Piotrowicz, 2002; Radzka, 2015). The absence of thermal winter is increasingly observed (Czernecki & Miętus, 2017) and the growing season is becoming longer and longer (Olszewski & Żmudzka, 1997; Żmudzka & Dobrowolska, 2001). In Poland, in the years 1971–2020, growing season was extended by 5–7 days per decade, especially in the west of the country (Koźmiński et al., 2021). This is confirmed by the results of research for a longer period (1792–2020) in Central Europe (Szyga-Pluta et al., 2022). The functioning of the biosphere is being disturbed and changes in phenologic seasonality are occurring (Tomaszewska & Rutkowski, 1999; Tylkowski, 2015). Such changes are observed in other parts of the world, for example in China (Song et al., 2009), in Eastern Europe (Jaagus et al., 2003), where during the period (1946–1995) early spring has started earlier by up to 1 month in Estonia, Latvia and western Russia. In Estonia, in the period 1891–1998, spring has tended to start earlier, while autumn starts later. In conclusion, the summer season has lengthened by 11 days, and winter has contracted by 30 days (Jaak & Rein, 2000). Climate models developed for the coming decades assert that the above-mentioned trends will continue into the future (Carter, 1998). In northern Europe, during the period 2040–2069, the average length of the thermal summer increases by 30 days relative to 1971–2000, and the thermal winter shortens by 30–60 days (Ruosteenoja et al., 2011, 2020).

AUTHOR CONTRIBUTIONS

Marek Kejna: Conceptualization (equal); data curation (equal); formal analysis (equal); methodology (equal); validation (equal); writing – original draft (equal); writing – review and editing (equal). **Aleksandra Pospieszyńska:** Conceptualization (equal); data curation (equal); formal analysis (equal); methodology (equal); software (equal); visualization (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

No potential conflict of interest was reported by the authors.

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