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RESEARCH ARTICLE

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Long-term changes in the frequency of exceptionally cold and warm months in Europe (1831–2020)

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Abstract

The onset of periods with very high or low air temperatures has aroused general interest for a long time, which is understandable since it has many dangerous effects directly affecting humans. Such perilous climatic phenomena include exceptionally cold and exceptionally warm months, which this study investigates for all Europe and for its five physico-geographic regions over the 190-year period of 1831–2020. Therefore, the research in this paper includes two periods characteristic of the history of climate – the late Little Ice Age (LIA) and present-day warming. The studies are based on average monthly air temperature values from 40 weather stations in Europe. In this paper, exceptionally cold months (ECMs) or exceptionally warm months (EWMs) are considered to have occurred when the average air temperature at a station differed from the respective long-term average by at least two standard deviations. The highlights of the study include the identification of a drop in the number of ECMs by 20 over the entire 190-year period, and a highly statistically significant increase in EWMs by 44 between 1980 and 2020. These changes proceeded with different intensities from one physico-geographic region of Europe to another.

KEYWORDS

climate warming, Europe, exceptionally cold months, exceptionally warm months, little ice age, thermal anomaly

1 | INTRODUCTION

Given that we live in a period of rapid climate warming (Kundzewicz *et al.*, 2020; IPCC, 2021), we are inundated with publications addressing the problem, which is fully understandable given the dangerous effects it causes (Vicedo-Cabrera *et al.*, 2016; Campbella *et al.*, 2018). The greatest warming of the climate has been noted on the European continent (van der Schrier *et al.*, 2013; Luterbacher *et al.*, 2016), and the scenarios of change imply that the warming will increase (Vautard *et al.*, 2014; Christensen *et al.*, 2015). Recent research has shown that the average temperature in Europe is rising by varying degrees in different parts of the continent (Krauskopf and Huth, 2020; Twardosz *et al.*, 2021). This is an obvious consequence of the increase in the frequency and intensity of heat waves (Twardosz and Batko, 2012; Zhang *et al.*, 2020), as well as monthly periods or even whole seasons with temperatures considerably increasing the long-term average (Twardosz, 2019; Twardosz and Kossowska-Cezak, 2021), which were felt particularly strongly in the early 21st century (Coumou and Rahmstorf, 2012; Liu *et al.*, 2020; Twardosz and Kossowska-Cezak, 2021). Notably, long-lasting hot or cold weather conditions lead to more dangerous biometeorological, economic and natural impacts than short spells of hot (heat waves) or cold (cold waves) weather. The occurrence of such thermally anomalous months may pose a direct threat to human health and lives, cause hindrance to transport and reduce the performance of the economy (Blazejczyk and Twardosz, 2010). The most extreme events in Europe's climate to date have included the extremely cold February1929 (Gumiński, 1931) and 1956 (Dizerens *et al.*, 2017), the January 1963 (Hirschi and Sinha, 2007), and the unusually warm August 2003 (Chase *et al.*, 2006), 2010 (Sidorenkov and Sumerova, 2012), as well as the June 2019 (Blazejczyk *et al.*, 2022).

The awareness of the above facts prompted the authors to undertake research in order to answer the question about the frequency of exceptionally cold and exceptionally warm months in Europe based on the longest possible series of air temperature measurements. Such research may be used to enrich knowledge about the evolution of the present-day warming process and compare it with an earlier characteristic climatic period – the end of the Little Ice Age, that is, a period of discernible drop in temperature. Research on temporal changes and spatial differentiation of ECMs and EWMs in Europe and its immediate surroundings was carried out by Twardosz and Kossowska-Cezak (2021). It spanned a short period, that is, the 68 years between 1951 and 2018. The present study covers the 190-year period of 1831–2020 and stations at other locations, which will be discussed below. Thus, the beginning of the study period coincides with the end of the Little Ice Age. Notably, there is no consensus among researchers as to when the period ended. According to Lamb (1977), it lasted until 1850, Grove (1988, 2001) set the end date at 1860, and Trepińska (1994) maintained that it continued until as late as the end of the 19th century.

The purpose of the paper is to learn about changes in the occurrence of exceptionally cold and exceptionally warm months in Europe over the centuries. The research period covers 190 years 1831–2020. The paper consists of three sections. The results section of the paper consists of six sub-sections. The starting point in the analysis is a general characterization of the occurrence of unusually cold and unusually warm months, that is, their number, annual variation, and spatial variation (sub-section 3.1). Subsequent subsections describe the multi-year course (long-term variation) of unusually cold and unusually warm months sequentially for Europe as a whole as well as regionally (sub-section 3.5). The final section is a discussion of the results and conclusions.

2 | DATA AND METHODS

2.1 | Series of air temperature values used in the study

In Europe, temperature started to be measured as early as the mid-seventeenth century, but this was only done at a few places. Even though the number of sites grew considerably in the 18th century, the measurements were not carried out on a continuous basis. Systematic measurements began many years later. Up until the end of the 18th century, temperatures were measured at a total of 62 sites in Europe, and the data is currently available in various climatology databases (Michalik, 2016). What is known as the Manley series, which started to be compiled for mid-England in 1659, has been the longest series of temperature measurements (Parker *et al.*, 1992). In the 18th century, the longest reconstructed series are those from De Bilt (from 1706) and Saint Petersburg (from 1743). By 1831, another 15 weather stations that measured temperatures had been established, including sites in Eastern Europe.

Data from the 77 stations referred to above were retrieved from the KNMI Climate Explorer (www.climexp.knmi.nl), HISTALP (www.zamg.ac.at), RIHMI-WDC (www.meteo.ru), ECA&D (www.ecad.eu) online databases, and obtained directly from some researchers (see the acknowledgements section) who deal with the reconstruction and homogenisation of air temperature series in Europe. It transpired that series from some stations had serious gaps (even exceeding 5%), therefore the sites were reviewed to select those which offered air temperature series that were complete and had already been fully verified for homogeneity. This is an obvious prerequisite for climatological studies. The most complete data were obtained from the HISTALP database, consisting of monthly homogenized records for the 'Greater Alpine Region' (Auer et al., 2007). In addition, there was data from the ECA&D database, where the data are also subject to verification for homogeneity based on four statistical tests (Wijngaard *et al.*, 2003), and the results of this verification are directly available on the project website. Ultimately, 40 sites which met this criterion (completeness and uniformity of the series) were selected

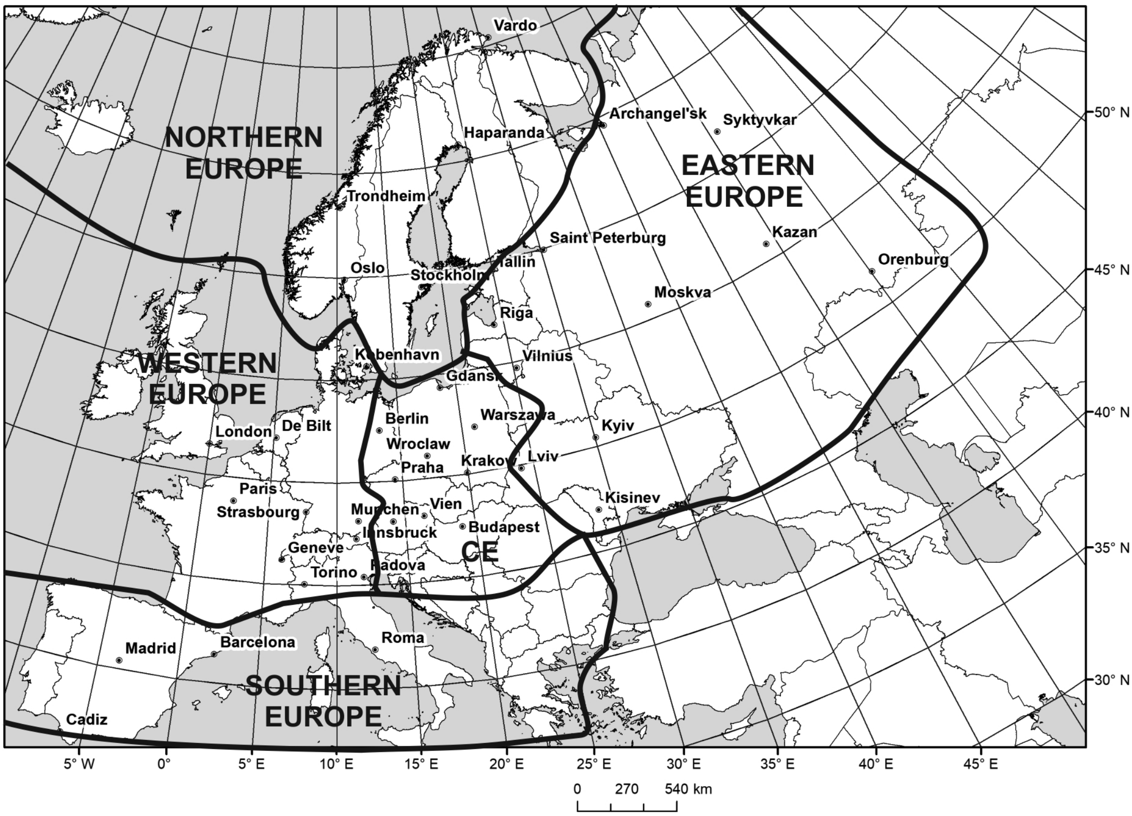

FIGURE 1 Locations of the meteorological stations used in the study within the physico-geographic regions according to Krąż *et al.* (2020; revised)

(Figure 1). Of these, the longest series is available for London (from 1,659) (Manley, 1974), while the shortest were for seven stations: Kazan, Orenburg, Syktyvkar, Lviv, Vardo, Kishinev and Strasbourg (from 1831). Thus, the period that involves all the 40 stations spans the 190 years between 1831 and 2020, and this is the period studied in this paper. This provided the most extensive available and reliable database of monthly air temperature values in Europe in terms of the number of locations and the length of time series.

Most of the stations (32) included lie in lowland areas, that is, up to 300 m·a.s.l., of which 19 are located at up to 100 m·a.s.l., five at an altitude of 301–500 m·a.s.l. and five above 500 m a.s.l.

2.2 | Methods of investigating the study material

The research concerns extremely cold and extremely warm months and seasons, which are generally referred to as thermally anomalous or abnormal periods, that is periods when air temperature deviates considerably from the mean during that time and in a given month (Twardosz and Kossowska-Cezak, 2021).

In this study, extremely cold or extremely warm months are considered to be those when the average air temperature at a station diverges from the corresponding long-term average (t_{av}) by at least two standard deviations (*SD*): exceptionally cold – EC: $t \le t_{av.}$-2 *SD*; and exceptionally warm – EW: $t \ge t_{av} + 2\ SD$. The multi-year average air temperature as well as the standard deviation was calculated from the entire 190-year period 1831–2020, which is statistically correct, since the sum of positive and negative deviations of the monthly air temperature values will reset to zero. The use of such statistical methods in research to identify exceptionally cold and exceptionally warm periods is a relative method, a method which is commonly used in climatology (e.g., Kamae *et al.*, 2014; Twardosz and Kossowska-Cezak, 2021).

Based on the statistical criterion adopted, EC and EW months were identified for each of the 40 stations. Following that, the calendars that were the basis for determining their numbers were compared. The analysis of the frequency of long-term changes was carried out for successive 5-year periods of the 190-year study period of 1831–2020. There were 38 such 5-year periods in total. The analysis also took into account the average number of stations covered by such anomalous months. The study of long-term variations also included those EC and EW

TABLE 1 Number of ECMs and EWMs and average number of stations per ECM and EWM (1831–2020)

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan–Dec
Number of ECMs	50	47	43	49	42	49	51	50	43	45	47	57	573
Average number of sites detected ECMs	4.9	5.6	4.0	3.1	3.5	2.3	2.0	1.7	3.0	3.9	3.7	4.6	3.5
Number of EWMs	41	39	50	51	59	76	71	71	62	58	49	34	661
Average number of sites detected EWMs	1.7	2.0	2.6	2.9	2.9	2.6	3.3	3.2	3.1	2.7	2.6	2.0	2.7

months in which the mean temperature deviation exceeded 3SDs. The statistical analysis of linear trends was completed using the Statistica program.

Europe is an area which shows great variation in geographical terms and, as research shows, also demonstrates considerable variations in the frequency of thermally anomalous periods (Twardosz and Kossowska-Cezak, 2021) and in the trends of changes in mean air temperatures (Krauskopf and Huth, 2020; Twardosz *et al.*, 2021). This study also comprises research on a regional scale, with Europe divided into large physico-geographic units on account of the limited number of sites. Use was made of the division of Europe into physico-geographic regions according to Krąż *et al.* (2020), which draws on the concept proposed by Kondracki (1965), and distinguishes between four regions: Northern, Eastern, Western and Southern Europe. However, this paper adds a subregion to the West Europe region, namely Central Europe, on account of its different (transitional) climate conditions. Ultimately, the study comprises five regions: Northern (N), Western (W), Central (C), Eastern (E) and Southern (S) Europe (Figure 1). The densities of measuring sites are the greatest in Eastern (11 stations), Western (10), and Central (10) Europe, while the lowest are in Northern (5) and Southern Europe (4).

3 | RESULTS

3.1 | General characteristics behind the occurrence of ECMs and EWMs

As Table 1 shows, the years 1831–2020 saw more EWMs (661) than ECMs (573) at 40 sites, but the number of stations where one EWM was detected was clearly smaller (2–3) than that with one ECM (3–4).

The highest numbers of ECMs were observable in December (57) and July (51), while the lowest were in May (42) and in March and September (43 each). Thus, the number of ECMs showed a complex annual pattern – with the main maximum in winter and the secondary one in summer, and with the minimum number in the transitional seasons, lower in spring (134) than in autumn (145) (Table 1). As mentioned above, on average, an ECM extended over 3–4 stations, with the greatest number found in February (5–6) and generally from December to March – 4–5 stations, while July and August saw the lowest number of such months – no more than two stations.

A clear maximum frequency of EWMs was observed in the summer: in June (76), in July and August (71 each). Their number in spring (160) was only slightly lower than in autumn (169). On average, an EWM was detected by 2–3 sites per year, and in individual months the number ranged from 2 from December–February and slightly more, namely 3–4, from July–September. Therefore, the mean coverage of EWMs changed during the year, as did their frequency, but the variations in extreme monthly values were less pronounced than in the case of ECMs (in September less than twice as much as in January).

The regional differences in the frequency of ECMs and EWMs are presented in Table 2. Given that the numbers of stations vary from one region to another, the differences are depicted per station. As is shown by the figures, Central and Eastern Europe have the highest mean number of ECMs over the 190 years (53 each). There were slightly fewer of them in Western (51) and Northern Europe (48), and they were the least numerous in Southern Europe (37). Their greatest number was recorded in winter months, while the lowest was in summer months in each of the regions (Table 2), which corroborates the general trend of these variations for Europe as a whole.

EC winter months clearly predominated in Central Europe, averaging 22 per site over the 190-year period. CE is a region that periodically receives incoming air masses of very variable thermal properties and which cause substantial drops in air temperature during advection of arctic air masses from the north or continental air masses from the east. In Southern Europe, they were nearly two times less numerous (12). This is an obvious consequence of the physico-geographic conditions, namely the latitudinal orientation of mountain ranges, which form a barrier to advection of heavy cold air masses from the north. It should also be emphasized that there are far fewer winter ECMs in Eastern Europe (19), that is.,in a region with a continental climate and low air

TABLE 2 Average number of ECMs and EWMs per station across the physico-geographic regions of Europe (1831–2020)

	ECMs					EWMs				
Europa	**Winter**	**Spring**	**Summer**	**Autumn**	**Year**	**Winter**	**Spring**	**Summer**	**Autumn**	**Year**
Northern (5)	19.2	12.6	5.6	10.8	48.2	4.6	7.6	16.8	9.2	38.2
Western (10)	19.7	10.8	8.1	12.8	51.4	3.7	10.0	15.4	14.3	43.4
Central (10)	22.3	11.7	7.2	11.8	53.0	3.3	8.3	13.1	10.2	34.9
Eastern (11)	18.6	13.4	7.8	12.8	52.8	6.4	10.5	13.0	8.9	38.6
Southern (4)	11.8	8.3	8.1	9.4	37.3	8.8	10.3	16.5	12.8	48.3

Note: The number of stations based on which average values were calculated is given in parentheses.

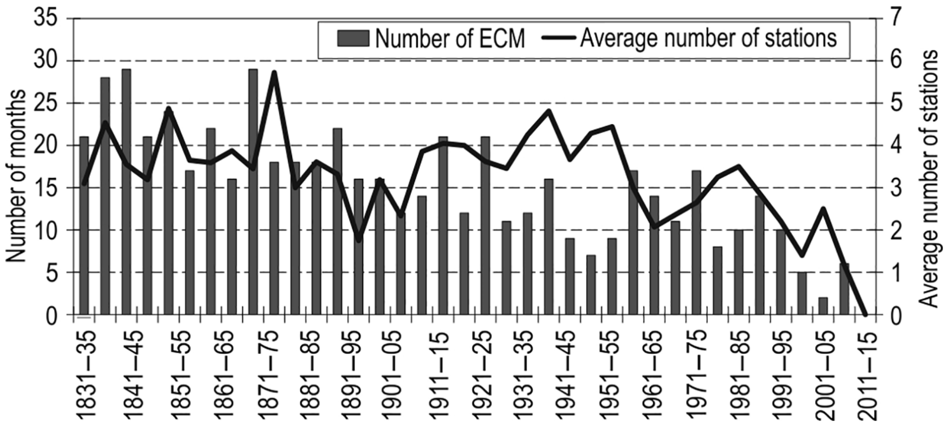

FIGURE 2 Long-term variation in the number of ECMs and average number of stations with such months in the successive 5-year periods of the 1831–2020 timespan

temperature in winter as its inherent feature. This means that, in winter, the average monthly temperatures less frequently reach values qualifying for the anomaly criterion adopted in this study.

Contrary to ECMs, the highest average number of EWMs per station per year was found in Southern Europe (48), with slightly fewer of them in Western Europe (43). The lowest number of EWMs in the 190 years occurred in Central Europe (35). Undoubtedly, summer months were the most frequent months with EW temperatures in all 5 regions (Table 2). Their average number per station varied from 13 in Central and Eastern Europe to 17 in Northern and Southern Europe. Thus, it can be seen that unlike ECMs in summer their spatial variation is not large, which proves that advection of warm air masses from the south may extend far to the north. Orographic barriers do not block such air masses as effectively as they do in the case of cool and heavy masses from the north.

Summing up, there were clear spatial differences in the frequencies of thermally anomalous months and seasons from one region of Europe to another. The changes in the mean frequency of ECMs and EWMs are greater in the north–south direction than in the west–east direction. This confirms the results of earlier studies by Twardosz and Kossowska-Cezak (2021) obtained on the basis of a different division of Europe and a different dataset.

3.2 | Long-term variation in the number of ECMs

As can be clearly seen in Figure 2, the highest number of exceptionally cold months occurred in the earliest period of the 190 years under study, which spans 1831–1895. During that 65-year timespan, there were 283 such months – almost half of all ECMs. The highest frequencies of ECMs were noted in the 5-year periods of 1841–1845 and 1871–1875 (29 each), and in 1836–1840 (27), which constitutes 15% of all ECMs in the whole study period. In the twentieth century, the number of ECMs was gradually decreasing to reach the minimum frequency in the early 21st century (Figure 2). In the last 15-year period of 2006–2020, there were about six times fewer than in the first 15-year period of 1831–1845. In the 2006–2010 5-year period there were only two ECMs, and in the last one, 2015–2020, there were no ECMs at all. The second period with low frequency of ECMs was the 15-year period of 1946–1960. Despite a discernible general downward trend in the frequency of ECMs, the 20th century saw 5-year periods with a relatively high number of ECMs. They were 1916–1920, 1926–1930 (21 ECMs each), and 1941–1945, 1961–1965 and 1976–1980 (16–17 ECMs each) (Figure 2).

The mean range covered by ECMs varies greatly (Figure 2). The largest average range of ECMs occurred

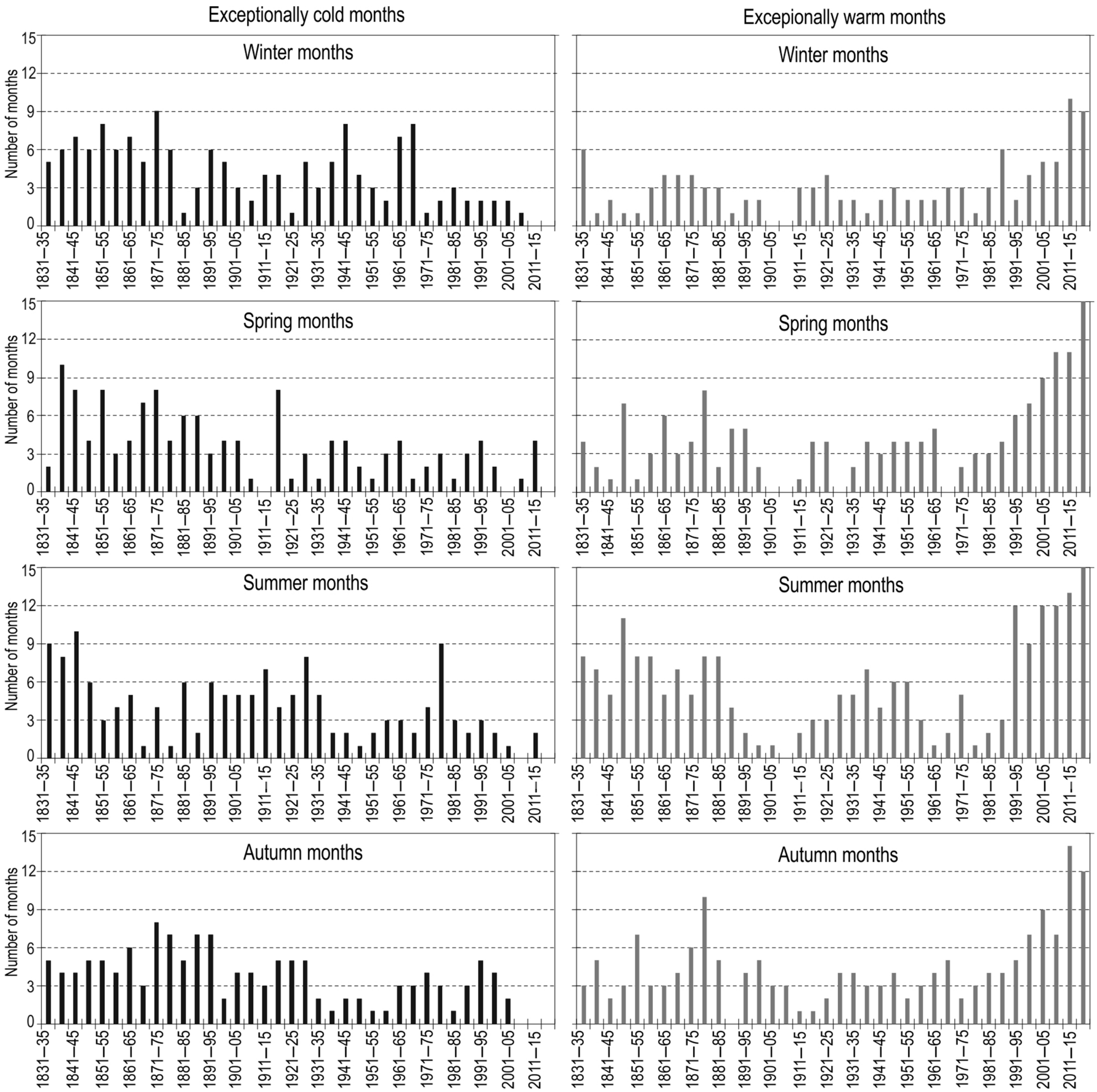

FIGURE 3 Long-term variation in the number of ECMs and EWMs in seasons in the successive 5-year periods of the 1831–2020 timespan

in the 1876–1880 5-year period – 6-7 stations. From the end of the 20th century, the average range of ECMs decreased considerably.

Figure 3 shows the long-term trend in the number of ECMs across the seasons of the year. It can be clearly seen that the beginning of the period under investigation observed a greater frequency of ECMs in all seasons. In particular, this concerns winter, with a long period of high frequency of ECMs in 1831–1880 (65 ECMs, 42% of those in the 190 years), with the maximum (9) in the 5 years of 1871–1875.

In the case of spring ECMs, a period with a high frequency of these lasted until 1905 (60% of the ECMs in the 190 years), with the maximum frequency (10 ECMs) in the 1836–1840 5-year period, followed by 1841–1845, 1851–1855, 1871–1875, each of which saw eight ECMs (Figure 3). In the summer season, ECMs were definitely most numerous in the period up to the middle of the 19th century, that is in the 20-year period of 1831–1850, especially in the 1841–1845 5-year period, when there were 10 of them. The second extended period of relatively high frequency of ECMs in summer

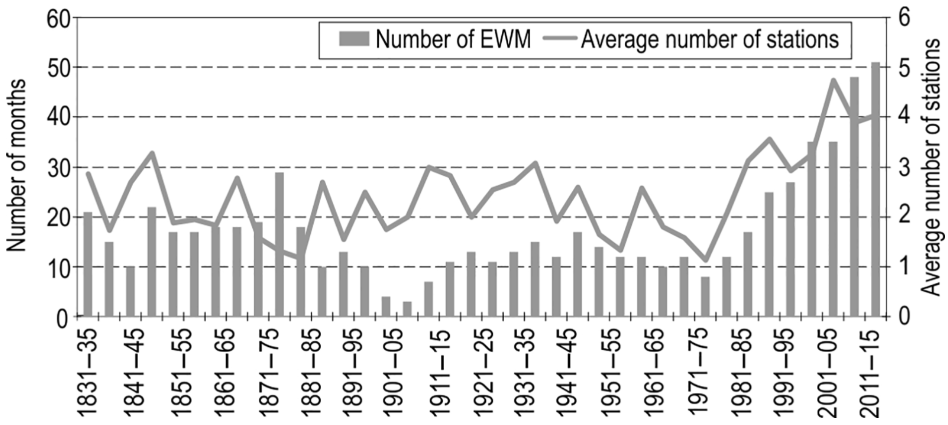

FIGURE 4 Long-term variation in the number of EWMs and average number of stations with such months in the successive 5-year periods of the 1831–2020 timespan

came in the years 1881–1935. In autumn, the highest frequency occurred towards the end of the 19th century, in the years 1871–1895. Overall, the occurrence of ECMs in autumn was characterized by the lowest variability when compared with the other seasons across the entire 190-year period.

The winter season was the first to display a discernible decrease in the number of ECMs – in the 1881–1895 5-year period (1 ECM). For spring, such a major decrease started to be observable from the 1906–1910 5-year period, while in summer from 1936–1940 (2 ECMs), and in the autumn from 1931–1935 (2 ECMs). This means that the warming started earliest in winter. From 1971, the frequency of ECMs in winter dropped sharply, and from 2011 onwards such months ceased to occur at all. In spring, not a single ECM occurred in the 5-year periods of 1911–1915 and 2001–2005, 2016–2020, while in summer there were none in 2006–2010 and 2016–2020. In the last three 5-year periods, there was not a single ECM in autumn (Figure 3).

3.3 | Long-term variation in the number of EWMs

An analysis of the long-term trend of exceptionally warm months clearly shows that the greatest number of them occurred at the end of the 190-year period under study (Figure 4). From 1981, there was a systematic increase in their frequency: from 12 (1981–1985) to 51 (2016–2020). A relatively high frequency of EWMs is also found at the beginning of the period under investigation, that is, in the 55-year period of 1831–1885, (204–35% of all EWMs). That period included a 5-year period (1876–1880) with a high frequency – 29 EWMs, which is similar to that at the end of the 20th century. At the turn of the 20th century, the number of EWMs was the lowest (3 EWMs) in the 5-year period of 1906–1910. Following that, this number was climbing slightly until 1950 to decline again until 1980. In the last 15-year period, namely 2006–2020, the number of EWMs was about three times higher than in the earliest 15 years, that is, 1831–1845. In general, the study has revealed that the number of EWMs showed irregular fluctuations in the years 1831–1980 followed by a strong upward trend from 1981 to 2020 (Figure 4).

Medium-range EWMs display similar regularities, that is, irregular fluctuations until the 1980 s, followed by a steep rise. The largest average range of EWMs (4–5 stations) was seen in the last 15-year period of 2006–2020, while the smallest was in 1881–1885 and 1976–1980, with only 1–2 stations covered (Figure 4).

The variation in annual EWMs corresponds most visibly to the variation in the summer number of EWMs, which is an obvious consequence of their large share (34%). As demonstrated in section 3.1, it is during the summer months that most EWMs occur. The direct cause of the prolonged occurrence of anomalously high temperatures in summer is stationary high-pressure systems, which usually involve advection of hot tropical air. It should also be noted that, in addition to advection, an important factor supporting the increase in temperature in summer is an increase in the amount of sunshine, which is favoured by the low cloud cover on long summer days, typical in high pressure systems. A long summer day, even with high cloud cover, has the effect of limiting the large drop in air temperature, which is reflected in the markedly lower frequency of ECMs (Twardosz and Kossowska-Cezak, 2015).

Figure 4 leaves no doubt that there was a sharp increase in the frequency of summer EWMs from the last decade of the 20th century. In the 5-year period of 1986–1990 there were only 3 EWMs, while in the one that followed – 12 EWMs. Overall, the 30-year period of 1991–2020 saw 73 summer EWMs, which accounts for 32% of all EWMs at that time of year in the entire 190-year timespan. This gave rise to the very large increase in summer temperature in Europe, which

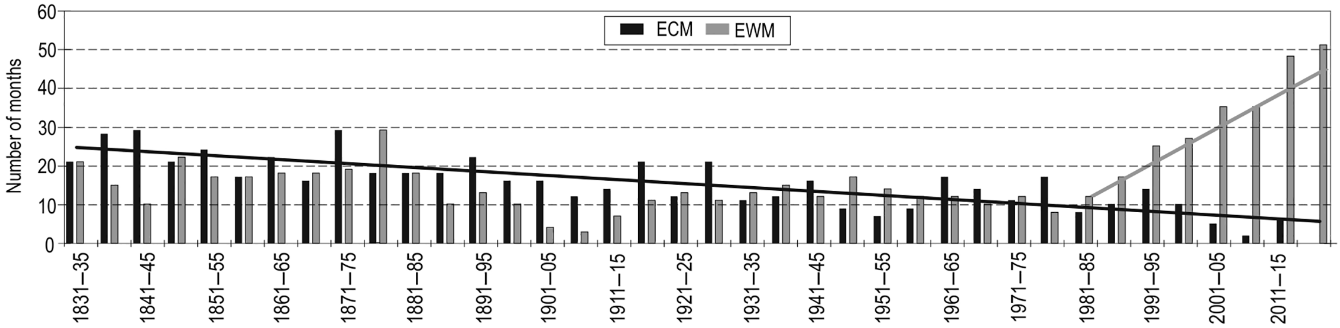

FIGURE 5 Long-term variation in the numbers of ECMs and EWMs and their trendlines in successive 5-year periods of the 1831–2020 timespan

averaged 1.3°C in the years 1986–2018 (Luterbacher *et al.*, 2016). From the 1990 s, spring and autumn EWMs also rose in frequency, but the upward movement was gradual, rather than radical.

The rise in frequency of winter EWMs occurred first – from the 5-year period of 1986–1990, but it is clearly weaker compared with the other seasons of the year. The highest frequency of EWMs in this season also occurred in the 5-year period of 2011–2015.

At the beginning of the period under investigation, EWMs were most frequent in summer. A prolonged period of increased frequency of EWMs continued for 55 years (1831–1885), averaging 7 EWMs per 5 years. Their frequency peaked in the years 1846–1850, reaching as many as 11. This means that the frequency in that 5-year period resembled that in the most recent 5-year periods (Figure 3).

In the 19th century, individual 5-year periods with a high frequency of EWMs would also occur in the other seasons. For winter, this was the 5-year period of 1831–1835 (6 EWMs), for spring those of 1846–1850, 1876–1880, and for autumn those of 1851–1855 and 1876–1880 (Figure 3).

3.4 | Comparison of long-term trends in the number of ECMs and of EWMs

This section provides a comparative analysis of EC and EW months in Europe. The differences are best illustrated if the numbers of ECMs and EWMs in the successive 5-year periods are shown in a single figure. First of all, this reveals the years when ECMs were more frequent than EWMs and vice versa. As can be seen in Figure 5, up until 1980, ECMs were more frequent in most of the 5-year time intervals. Starting from the 5-year period of 1981–1985, this relationship began to change, that is, the EWMs began to become more frequent, and from the mid-1990 s to become dominant in fact. The changes in the numbers of ECMs and EWMs also went hand in hand with changes in their mean ranges (Figure 6). In nearly all the 5-year periods in the 1831–1990 timespan, the range of ECMs was greater than that of EWMs. In the last 30 years (1991–2020), the opposite has been true. This is noticeable particularly strongly in the 5-year period of 2011–2015, when, on average, an EWM covered an area over 2 times larger than that of an ECM (EWM 3–4 stations, ECM 1–2) (Figure 6).

The regularities of long-term changes (1831–2020) in the frequency of EC and EW months described above are confirmed by a statistical regression analysis (Table 3). Over the entire 190-year period, the decrease in the number of ECMs is highly statistically significant, and was 20 ECMs (−0.103 ECMs/year).

There are 2 periods in the EWM timeline: 1831–1980, with irregular fluctuations masking a downtrend, and 1981–2020, with a very statistically significant linear increase. Thus, an actual trend can only be identified towards the end of the 190 years in question, namely from 1981. The choice of this year has some statistical justification, based on the quality of the fit of the linear regression. In the last 40 years, the number of EWMs increased by 44 (1.1 EWMs per year).

In Table 3 the least significant result is that for the period 1831–1980, since the p-value is 'only' 0.012. That is the reason why the normality of residuals has been tested here. The result of the Shapiro–Wilk normality test is: $W = 0.942$ which results in a p-value $= .102$ which means that there is no reason to reject the hypothesis of data normality.

One interesting fact from the perspective of long-term developments in the frequency of EC and EW months is the emergence from among these months of cases where temperature (Δt) anomalies reached extremely high values. In this paper, such anomalous months are considered to be those when the average temperature differed by at least three SDs from the long-term average at least within one site. Typically, such phenomena extend over

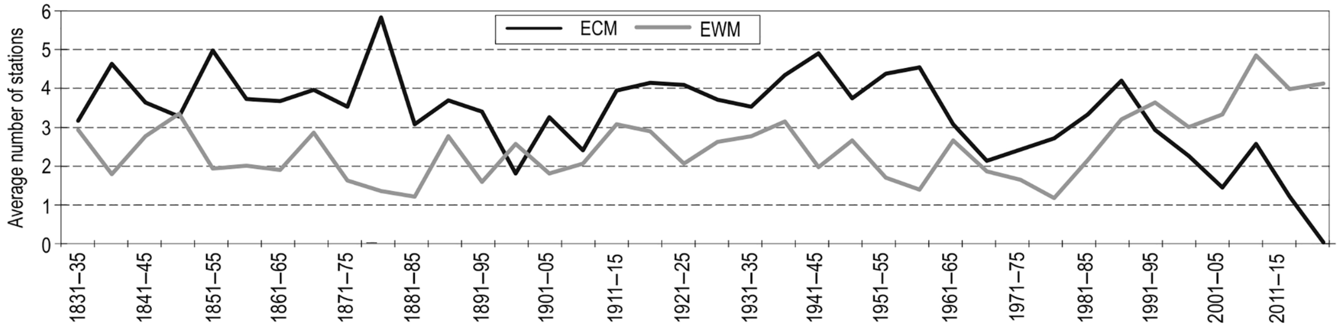

FIGURE 6 Average number of stations with an ECM and an EWM in the years 1831–2020

TABLE 3 Coefficient of linear regression (slope) of ECMs and EWMs. The slope uncertainty is standard deviation (1σ)

ECMs/ EWMs	Slope (number/year)	R^2	*p*-value	95% confidence interval
ECMs 1831–2020	−0.103 ± 0.011	.67	.0000000028	−0.127, −0.078
EWMs 1831–1980	−0.055 ± 0.020	.20	.012	−0.097, −0.013
EWMs 1981–2020	1.1 ± 0.08	.97	.00012	0.922, 1.296

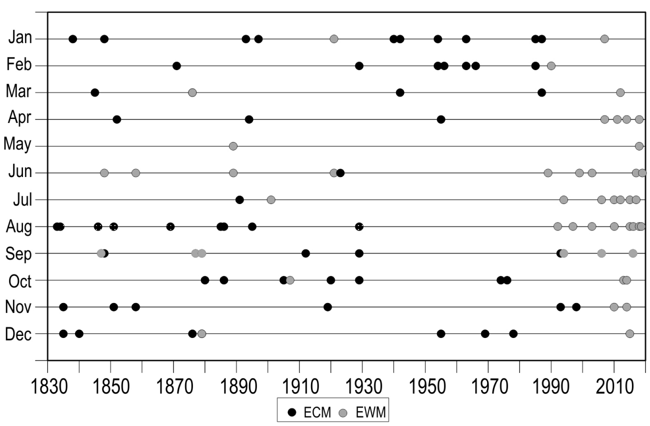

FIGURE 7 Occurrence of ECMs and EWMs in the years 1831–2020

large areas and have the most dangerous biometeorological and economic implications (Twardosz and Kossowska-Cezak, 2021). The months that satisfied such a tightened statistical criterion were selected from the database of all 573 ECMs and 661 EWMs (Table 1). There were 54 and 51 of them respectively. Their development in the long term is illustrated by the months involved (Figure 7). First of all, it can be noted that the majority of ECMs with Δt > 3SDs occurred in the first half of the 190-year timespan, mainly up until the end of the 19th century, except for January and February, which were most frequent around the middle of the 20th century. By contrast, even though EWMs with Δt > 3SDs also occurred in the nineteenth century, mainly in summer, they were most frequent at the end of the 190-year study period. Most of them (65%) occurred after 1986, with half only in the last 15-year period of 2006–2020. This is a clear sign of the rapid warming of the climate in Europe since the beginning of the 21st century, manifested not only by an increase in the frequency, but also by a growing severity of air temperature anomalies. One noteworthy observation is a long 55-year period (1931–1985) without an EWM with Δt > 3SDs within the area of Europe studied.

3.5 | Long-term variation in the number of ECMs and EWMs in the regions of Europe

The overall picture of the temporal changes in the number of extremely cold months in Europe is mirrored by the trends observable in most of the physio-geographic regions of Europe. As can be seen in Figure 8, there was a decrease in the frequency of ECMs in the 190-year period, but it varied in intensity from one region to another. The greatest decline is recorded in Northern Europe, as there was not a single ECM here after 1985.

There were definitely more ECMs in the 19th century than in the 20th and early 21st centuries, with the exception of Southern Europe, where ECMs were not only least numerous, but also followed a different trend, that is, there were more of them in the 20th century, with the maximum frequency (9) in the 5-year period of 1991–1995. The rest of Europe saw a general downward trend, but there were also short-term periods with high rates of ECMs. In the 19th century, these were the years 1891–1895 (20 ECMs) in Eastern Europe, which were

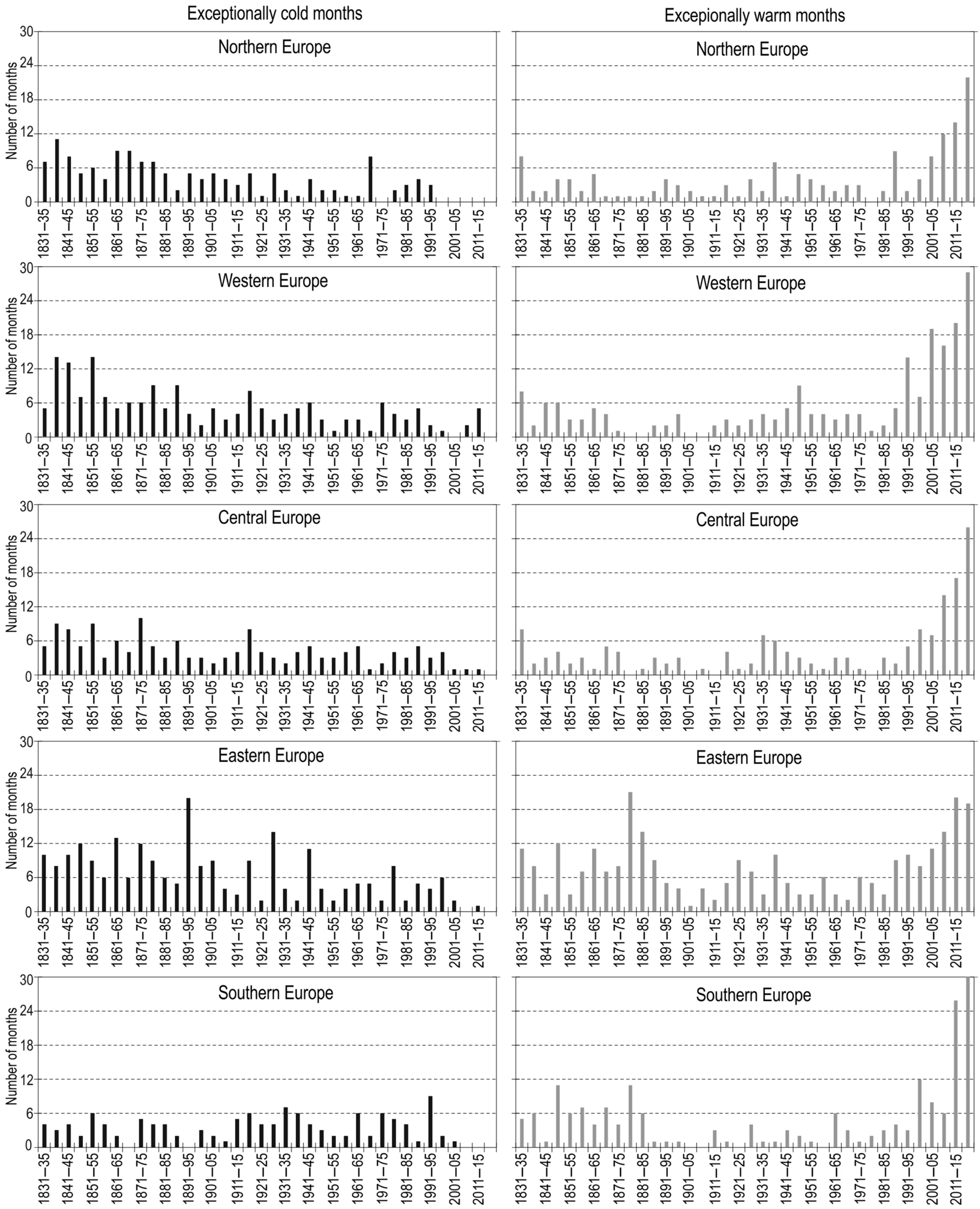

FIGURE 8 Long-term variation in the number of ECMs and EWMs in European regions in successive 5-year periods of the 1831–2020 timespan

unusually cold mainly in Russia (Lokoshchenko and Vasilenko, 2009; Jones *et al.*, 2012), as well as 1836–1840 (14 ECMs), 1841–1845 (13 ECMs), and 1851–1850 (14 ECMs) in Western Europe (Figure 8).

The twentieth century did not observe such large increases in the frequency of ECMs, with the greatest frequency of them found for Eastern Europe in the 5-year periods of 1926–1930 (14 ECMs) and 1941–1945 (11 ECMs). In other regions, they did not exceed 10 ECMs.

In the 21st century, ECMs occurred sporadically and 7 out of 14 of all the ECMs observable in that 15-year period occurred in Western Europe. No ECM was observed in Southern Europe from 2006 onwards, and in Northern Europe none were even detected from 1996 onwards (Figure 8).

The increase in the frequency of EWMs at the turn of the 21st century, which was mentioned in section 5 above, was experienced by all physico-geographic regions of Europe (Figure 8). In the last 5 years, each of the regions had the highest number of EWMs, with a record number (27) in Southern Europe. In Northern, Western and Central Europe, the EWMs in the years 1986–2020 accounted for over 1/3 of all the EWMs in the 190-year period under investigation. In the preceding years, the frequency of EWMs in these 3 regions varied greatly: from their complete absence to several in the 5-year period. EWMs were relatively numerous in the first 5-year period of 1831–1835. It was different in Eastern and Southern Europe, where from the beginning of 1831 to the 1880 s, EWMs accounted for 40% of all EWMs. In Eastern Europe, the 5-year period of 1876–1880 even saw their greatest number in all the 190 years.

4 | DISCUSSION AND CONCLUSIONS

Based on 40 series of monthly air temperature values, the study examines changes in the frequency of exceptionally cold and exceptionally warm months in the 190-year period 1831–2020 for the entire area of Europe and its individual physico-geographic regions. Such anomalous months were identified against a strict statistical criterion (±2 SDs).

There is a clear spatial differentiation in the frequency of ECMs and EWMs. Most ECMs occurred in Central Europe, while EWMs occurred in Southern Europe. These frequency distributions are geographically conditioned. Generally, it can be said that changes in the mean frequency of ECMs and EWMs are greater in the north–south direction than in the east–west direction.

The key observations are those regarding the long-term evolution of the frequency of exceptionally cold and exceptionally warm months.

The highest number of ECMs occurred at the beginning of the 190-year period, that is, in the years 1831–1895, following which their number gradually decreased to reach a minimum frequency in the early 21st century. EC winter months were the first to disappear, starting from the 1970 s, notably in Northern Europe. The situation differed diametrically in Western Europe, where they kept occurring until the end of the study period, but with a reduced frequency.

Despite a discernible general downward trend in the frequency of ECMs, the 20th century also saw 5-year periods with a relatively high frequency of them.

For EWMs, the study found that most occurred at the end of the 190-year period. In the years 1831–1980, the number of EWMs displayed irregular fluctuations, while from 1981 to 2022, there was a discernible highly statistically significant upward trend. This increase was noted across the seasons. This first appeared in winter, but was much weaker than in the other seasons in the following years. In the summer, starting from 1991, the frequency of EWMs rose sharply – a 4-fold increase in frequency between the 5-year period of 1986–1990 and that of 1991–1995.

The observed increase in the frequency of EWMs is an obvious consequence of climate warming. Since the 1980 s, a highly statistically significant linear increase in air temperature has been observed on the European continent and in its immediate vicinity. As was shown by a study of Twardosz *et al.* (2021), in the years 1985–2020, the average annual temperature increased by 0.051°C/year. The late 20th century and the early 21st century have been the warmest periods in the last 2000 years (Luterbacher *et al.*, 2016). Warming in Europe has intensified towards the northwest of the continent (Krauskopf and Huth, 2020; Twardosz *et al.*, 2021). As has been shown above, the frequency of ECMs decreased the most in Northern Europe, and the increase in EWMs was not as strong as in other regions of Europe. Thus, research confirms that the warming is a driving factor increasing the occurrence of extreme climatic phenomena, such as EC and EW months.

The question of what are the causes of exceptionally warm months is, in fact, one about the causes of present-day climate change. It would be easiest to explain them by global warming, that is, a growing concentration of greenhouse gases (Stott *et al.*, 2004; Jones *et al.*, 2008; IPCC, 2021). However, there are certainly other drivers. The ones pointed to most frequently include circulation systems (Van den Besselaar *et al.*, 2010; Hoy *et al.*, 2016), ocean surface water temperature (Black and Sutton, 2007), changes in the amount of cloud cover (Tang *et al*., 2012) and solar radiation (Trigo *et al*., 2009; Samukova *et al*., 2014).

It must be remembered that ECMs continue to appear. One such month was January 2017 in the Balkan Peninsula, which, according to Anagnostopoulou *et al*. (2017), was one of the coldest and snowiest Januaries recorded in this area. So it can be concluded that contemporary warming in Europe is a complex process, which is largely caused by a growing frequency of EWMs rather than by a decline in ECMs. This means that the warming is asymmetric in nature, which means an increase in temperature variance.

The studies into the frequency of ECMs and EWMs that have been completed have proven that the late Little Ice Age was not a uniform period in terms of thermal conditions, since there were spells with a very high frequency of ECMs and spells with a considerable frequency of EWMs. This reflects the very high variability of air temperatures in Europe, most of which is found in the temperate zone, an area with great variability of atmospheric circulation.

AUTHOR CONTRIBUTIONS

Magdalena Skrzyńska: Conceptualization; formal analysis; writing – original draft. **Robert Twardosz:** Conceptualization; methodology; supervision; writing – review and editing.

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CONFLICT OF INTEREST

There are no conflicts of interest in this paper.

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