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ORIGINAL PAPER

Exceptionally cold and mild winters in Europe (1951–2010)

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Abstract Extreme thermal conditions appear to occupy an important place among research subjects at a time of climate warming. This study investigates the frequency, duration and spatial extent of thermally anomalous winters in Europe during the 60 years between 1951 and 2010. Exceptionally cold winters (ECWs) and exceptionally mild winters (EMWs) were identified using the statistical criterion of plus/minus two standard deviations from the long-term winter temperature (January–December) recorded at 60 weather stations. It was demonstrated that ECWs have occurred more frequently and covered larger territories than EMWs and that they may occur anywhere in Europe, while EMWs were limited to its southern and western parts. ECWs are characterised by greater absolute temperature anomalies, as anomalies greater than |6.0 °C| account for 35 % of ECWs, but only for 8 % of EMWs. The greatest anomalies are found in the east of the continent. The largest territory affected by an ECW included 24 stations in 1962/1963, while the equivalent among the EMWs included 11 stations in 2006/2007. The study also confirmed an expected trend whereby ECWs diminished in frequency in favour of EMWs in the second half of the 60-year study period.

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1 Introduction

In the temperate climate zone, which covers most of the European continent, winter has the most variable thermal conditions of all the seasons. These are the result of the typical pattern of atmospheric circulation dominant at the time, which alternates between air mass advection from over the Atlantic Ocean, which favours mild winters, and a build-up of stationary high pressure systems that block such advection and allow inflow of cold air from the north or east and lead to very low temperatures and very cold winters (e.g. Kossowska-Cezak 1997; Jaagus 2006; Bardin 2007; Ugryumov and Khar'kova 2008; Van den Besselaar et al. 2010). The occurrence of such severe winters, as well as shorter winter spells with very low temperatures and, to a lesser extent of very mild winter seasons, has long been the object of universal attention as they have affected all the populations of the territories in question and have had a multifaceted influence on their lives (Błażejczyk and McGregor 2007; Maignan et al. 2008).

Accounts of such exceptional winters can be found in historic chronicles. A study by R. Girguś and W. Strupczewski (*Wyjątki*…, 1965) offers valuable information in this respect, including the following examples:

> In the year of our Lord 1076, a very severe winter befell the lands and their largest rivers, such as the Saone, Rhone, Rhine and Loire in Gaul; the Elbe, Vistula and Danube in Germania; and the Po in Italia which were seized by ice so strong that they fell silent immediately after the smaller ones and the astounded local population went over them as if on solid ground (*Wyjątki*…, 1965, p. 17).
> The winter [1306] was so severe that between the Danish mainland, its islands and Sweden all the seas turned into permanent bridges for fourteen weeks and even longer (*Wyjątki*…, 1965, p. 26).

The winter of 1322/1323:

> Also between Norway, England and France many ships were caught by ice in the open seas, so that merchants walked on the ice to pay visits to each other for entertainment" (*Wyjątki*…, 1965, p. 30).

On the following page:

> During the time between St. Andrew's Day [30 November 1322] and Laetare Sunday [6 March 1323], the weather was so cold that merchants carried their goods on carts across the sea from Norway to Sweden and back and there were inns and taverns on the seas where they consumed their beer and food. Also merchants visited from ports in Prussia and Livonia and there were also taverns in the marketplace (*Wyjątki*…, 1965, p. 31).

Late that year (1556) and at the beginning of the following one, winter [in Poland] was very persistent: great snows and severe colds lasted from St. Hedwig's Day [15 October] without a break until Annunciation Day [25 March] (*Wyjątki*…, 1965, p. 146).

Mild winters were much rarer:

> Winter of that year [1412] was exceptionally warm without ground frost or any frost in general to the extent that even in Lithuania, a cold and frosty land, people already had vegetables to eat and flowers around Presentation Day [2 February], which was regarded as a great wonder and a veritable miracle (*Wyjątki*…, 1965, p. 41).
>
> In that year [1493], the winter in January and February was so mild that trees blossomed in orchards, grass grew tall, birds nested, but in March frost destroyed everything (*Wyjątki*…, 1965, p. 85–86).

These are just a sample of numerous accounts of particularly severe winter seasons, which ceased to occur in Europe due to the period of climate-warming observed since the mid-nineteenth century. Nevertheless, anomalously cold winters still occur with serious consequences ranging from affecting daily life, disorganising the economy to even influencing historic events, such as a series of three exceptionally cold winters during the Second World War. In this last example, in January 1942, the temperature in the war zone in Russia dropped to −56 °C (Brönnimann 2005). On the other hand, exceptionally mild winters can also have adverse effects as they disturb the cycle of natural processes (Maignan et al. 2008).

This study pursues this still current topic and focuses on the frequency, duration and spatial extent of anomalous winter seasons in Europe between the mid-twentieth century and 2010.

The research hypothesis adopted here proposes that the observed increase in winter temperature is expressed by a decline of the frequency of ECWs and an increase in the frequency of EMWs. This paper continues from previous studies by the authors (Twardosz and Kossowska-Cezak 2013a, b, 2015a, b) on exceptionally hot and cold summer seasons in Europe. The intention is to provide comprehensive understanding of thermal anomalies in winter using a single method of their identification, long-term observation data and covering the whole of Europe, as opposed to a wide body of fragmented research targeting different areas and periods (e.g. Baur 1954; Graham et al. 2006; Hirschi and Sinha 2007; Hirschi 2008; Cattiaux et al. 2010; Wang et al. 2010; Ouzeau et al. 2011; Buchan et al. 2014).

2 Data and methodology

The study is based on the average monthly air temperatures recorded at 60 weather stations in continental Europe and the British Isles. Most of the stations are in lowland locations up to 300 m a.s.l. (57 stations, including 35 up to 100 m, 17 stations at 101–200 m, five stations at 201–300 m and one, Astrakhan, in a depression −23 m). Only three stations have higher locations, including Madrid at 667 m a.s.l., Sofia at 595 m and Zurich at 569 m (Table 1). For the purposes of the study, the stations were numbered from 1 to 60 going from west to east in eight belts of 5° of latitude from north to south. Four stations are located below 40° N, 14 stations in the belt 40–45° N, 10 stations each in the belts from 45 to 60° N, seven stations in 60–65° N, four stations in 65–70° N and a single station above the latitude 70° N (Table 1).

The data were sourced from an open database of the European Climate Assessment & Dataset (ECA&D, www.eca.knmi.nl) (Klein Tank et al. 2002).

This database is one of four generally available data sources (Moberg et al. 2006) offering high spatial resolution and large numbers of complete series with high quality data confirmed by homogeneity testing (Wijngaard et al. 2003). The authors, as well as many others, have used this database in the past (e.g. Cony et al. 2008; Van den Besselaar et al. 2010).

In this study, the underlying assumption is that winter lasts between December and February. Anomalous winters are considered to occur when the average air temperature recorded by a given station differs from the corresponding multi-annual average (1951–2010) by at least two standard deviations. Exceptionally cold winters (ECWs)—$t \leq t_{av.} - 2\sigma$ and exceptionally mild winters (EMWs)—$t \geq t_{av.} + 2\sigma$) were distinguished on the basis of this assumption. Exceptionally cold and mild winter months (ECMs, EMMs) were identified using the same method. The standard deviation criterion was adopted by analogy to that used for distinguishing

Table 1 Long-term average winter temperatures and the numbers of ECW and EMW in Europe (1951–2010)

Station No.	Name	WMO no.	$t_{av.}$ (°C)	ECW	EMW
φ<40° N					
1	Lisbon	8535	13.0	1	2
2	Almeria	8487	13.0	1	1
3	Crotone		9.7	1	3
4	Athens	16716	10.9	1	2
φ=40–45° N					
5	La Coruña	8001	10.7	1	2
6	Madrid	8223	6.7	1	1
7	Bordeaux	7510	6.4	1	1
8	Barcelona	8181	9.5	1	1
9	Marseilles	7650	7.4	2	2
10	Rome	16235	8.1	2	1
11	Split	14445	8.4	2	1
12	Belgrade	13274	2.1	4	1
13	Sofia	15614	0.0	2	1
14	Konstanca	15480	2.0	2	1
15	Istanbul	17062	6.9	1	1
16	Simferopol	33990	0.9	2	1
17	Sochi	37099	6.9	1	2
18	Makhachkala	37385	1.4	2	–
φ=45–50° N					
19	Brest	7110	6.7	1	1
20	Paris	7156	5.0	1	1
21	Zurich	6660	0.7	1	1
22	Würzburg	10655	0.8	1	1
23	Vienna	11035	1.0	2	1
24	Debrecen	12882	−0.5	4	–
25	Chernivtsi	33658	−2.7	2	1
26	Zaporozhe	33805	−2.8	1	–
27	Rostov on the Don	34731	−2.9	1	–
28	Astrakhan	34880	−3.8	2	–
φ=50–55° N					
29	Valentia	3953	7.2	2	–
30	London	3776	4.8	1	1
31	De Bilt	6260	2.9	2	1
32	Berlin	10381	−0.8	2	–
33	Warsaw	12375	−1.7	2	–
34	Minsk	26850	−5.0	1	–
35	Kiev	33345	−3.5	2	–
36	Kursk	34009	−6.7	2	–
37	Saratov	31172	−8.3	3	–
38	Orenburg	35121	−11.9	2	3
φ=55–60° N					
39	Edinburgh	3160	3.9	2	2
40	Oslo	1492	−3.2	1	–
41	Copenhagen	6180	1.3	1	–
42	Stockholm	2485	−1.8	2	–
43	Liepaja	26406	−1.5	2	–
44	St. Petersburg	26063	−5.8	1	–
45	Moscow	27612	−7.1	1	–
46	Vologda	27037	−10.2	2	–
47	Kazan	27595	−10.8	3	–
48	Yekaterinburg	28440	−12.4	2	–
φ=60–65° N					
49	Bergen	1317	2.2	4	–
50	Trondheim	1271	−2.1	1	–
51	Vaasa	2911	−6.1	1	–
52	Kajaani	2869	−10.2	2	–
53	Arkhangelsk	2250	−11.5	2	–
54	Syktyvkar	23804	−13.4	3	–
55	Ivdel	23921	−17.1	2	–
φ=65–70° N					
56	Bodo	1152	−1.4	2	–
57	Sodankyla	2836	−13.0	1	–
58	Naryan-Mar	2320	−16.2	1	1
59	Pechora	23418	−17.3	2	1
φ>70° N					
60	Vardö	1098	−4.2	2	1

exceptionally hot months and seasons in Europe (Twardosz and Kossowska-Cezak 2013a, b, 2015a, b). Thus, we are able to compare the results of the present study with our previous research and the research by other authors who applied the same criterion (e.g. Hansen et al. 2012).

Using the above method, the number of ECWs and EMWs was determined at each of the stations, calendars of ECWs and EMWs were compiled, and the geographical coverage of the ECWs and EMWs was determined.

3 Frequency of exceptionally cold winters and exceptionally mild winters

Based on the criterion adopted ($t \leq t_{av.} - 2\sigma$), a total of 103 ECWs were identified in 18 years of the 60-year period between 1951 and 2010 (Table 1).

ECWs were recorded by all the stations, with their number ranging from 1 to 3 per station and reaching 4 at 3 stations only (Table 1); in southern and western Europe, their number tended to be 1–2, whereas the equivalent figure was 2–3 in Northern and Eastern Europe. Isolated cases of large differences between neighbouring stations are perhaps attributable to local circumstances. Overall, the largest number of ECWs recorded in Northern and Eastern Europe is explained by a greater degree of climatic continentalism in these regions entailing much colder winters than those recorded in maritime climates of the southern and western parts of the continent. The number of ECWs and EMWs found at individual stations (3±2) differed from their normal distribution (ca. 5 % or 3). The difference is explained by the fact that as a natural phenomenon, the wintertime distribution of average daily temperature does not follow the normal distribution pattern. Indeed, it is to be expected that a single case of an extremely high or low average temperature may occur thus significantly altering the standard deviation and, consequently, the number of anomalous values identified.

The highest frequency of ECWs was observed in the decade 1960/1961–1969/1970 (Table 2)—the period saw 6 out of the 18 ECWs and nearly half of the cases (48 out of 103). This decade saw the ECW with the widest coverage (24 stations) in 1962/1963. Even though the decade 1980/1981–1989/1990 ranked second in terms of the number of ECWs (4 ECWs, 15 cases), it was the 9-year period 1951/1952–1959/1960 that ranked second in terms of the number of cases (3 ECWs, 28 cases). The 1953/1954 season of the 9-year period recorded the ECW ranking second in terms of coverage (16 stations), but ranking first in terms of the negative air temperature anomaly. Both the frequency of ECWs and the number of cases clearly declined after 1990. Between 1986/1987 and 2009/2010, there were only three ECWs over very limited areas (1–3 stations).

EMWs were much less frequent than ECWs (Table 2) and in the six decades under study, there were altogether 40 EMWs recorded in 13 years. Other researchers also confirm the lower frequency of EMWs compared to ECWs (Dobrovolný et al. 2010). EMWs were recorded by only half of the stations (30) in western and Southern Europe and in its northernmost and easternmost territories. There were no EMWs in the decade 1970/1971–1979/1980 or strictly speaking, between 1966/1967 and 1981/1982. The frequency of EMWs started to increase from the end of the 1980s. Half of the EMWs occurred in the last 20 years of the 60-year period, but among the 22 seasons between 1988/1989 and 2009/2010, as many as nine were EMWs, with the 2006/2007 EMW covering that largest territory in the 60-year period (11 stations).

As can be seen, the number of thermally anomalous winters differs across Europe. This is attributable to the differences in temperature of the air masses carried into Europe in winter. These can be relatively warm maritime polar air masses (mP) and strongly cooled continental polar (cP) or Arctic (A) air masses. The overall predominance of western circulation causes the former (mP) to occur more frequently, in particular over Western and Central Europe, leading to mild winters with temperatures above average but not changing much over time. Meanwhile, the predominance of cP and A leads to very sharp periodic falls in temperature to much below the average. Thus, the statistical distribution of the average temperature in winter is asymmetrical and very large negative deviations are offset by a larger number of more moderate positive deviations, which means that the number of anomalies on both “tails” is different (Dobrovolný et al. 2010). The asymmetry grows eastwards (Fig. 1). This results not only in a higher frequency of ECWs than EMWs but also in greater values of extreme negative anomalies than positive ones, e.g. in the belt stretching between Valentia and Yekaterinburg, they ranged from −2.6 and +1.6 to −8.0 and +4.3 °C. This asymmetry also means that there are more EMWs with no EMMs (due to an accumulation of slight monthly anomalies) than ECWs with no ECMs (due to a higher contribution of very low temperatures in a single month to the average temperature for winter as a whole). It should be noted that the non-symmetry is much more pronounced for individual winter months: The 60-year period saw twice as many ECMs (67) as EMWs (34).

As mentioned above, most of the ECWs (82.5 %) saw exceptionally cold months (ECMs), and in extreme cases, all 3 months were ECMs. By contrast, the EMWs were characterised by less frequent exceptionally mild months (EMMs).

Over the 60 years under study, two winters proved to be ECWs and EMWs at the same time. They were the winters of

Table 2 The number of ECW and EMW and the number of their occurrences

10 years	ECW		EMW	
	No. of years	No. of occurrences[a]	No. of years	No. of occurrences[a]
1951/1952[b]–1959/1960	3	28	2	5
1960/1961–1969/1970	6	48	1	3
1970/1971–1979/1980	2	7	–	–
1980/1981–1989/1990	4	15	3	9
1990/1991–1999/2000	2	2	4	8
2000/2001–2009/2010	1	3	3	15
1951/1952–2009/2010	18	103	13	40

[a] Each occurrence means one ECW/EMW at one station

[b] No data from winter 1950/1951

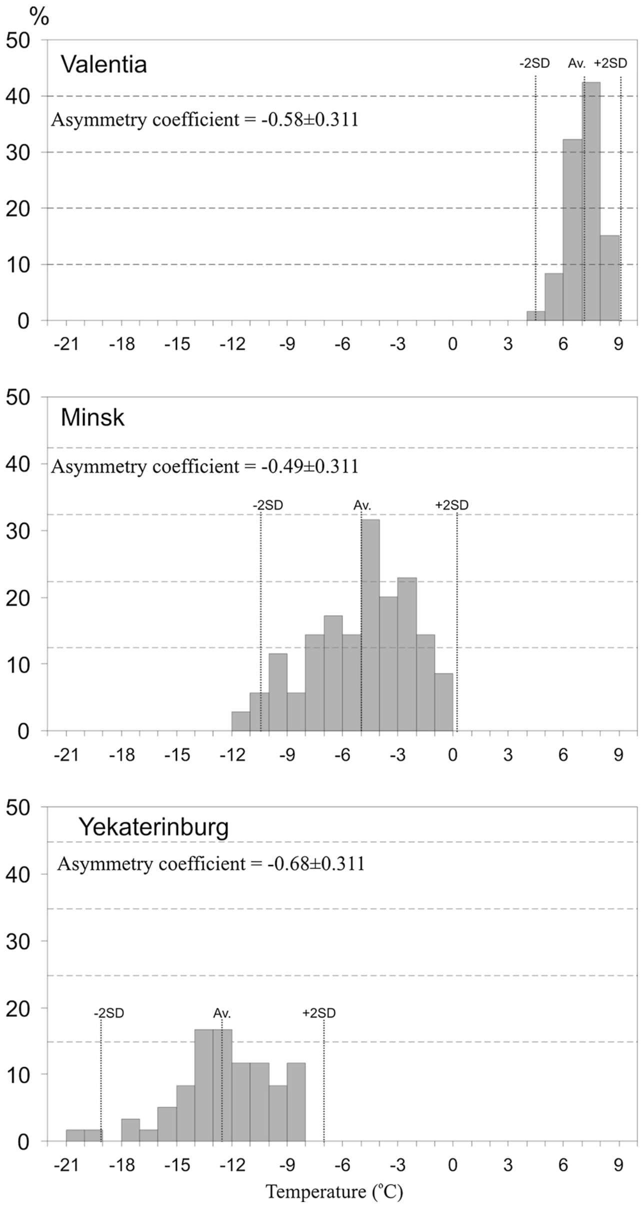

Fig. 1 Frequency (%) of average temperature values in winter at selected stations

1965/1966 which was an ECW in the Scandinavian Peninsula (7 stations) and an EMW in the southeasternmost parts of Europe (3 stations), and that of 1997/1998 which was an ECW in the northeast in Naryan-Mar and an EMW in 3 disparate stations in the west and north of Europe (Tables 3 and 4).

4 Coverage and thermal characteristics of ECWs and EMWs

The years with ECWs and EMWs, as well as the number of the stations with their codes (as listed in Table 1), are shown in Tables 3 and 4 (Calendars of ECWs and EMWs). As mentioned above, ECWs were recorded in 18 years over areas varying in size, i.e. by different numbers of stations—from 1 to 24. However, for the most part, ECWs were recorded by only a single station or by two neighbouring stations; there were seven such winters (Table 3). Those winters which were recorded by 1–2 stations, i.e. fewer than 5 % of all the stations, will be disregarded in this study. The analysis will focus on those winters that were recorded concurrently by at least three stations, i.e. by at least 5 % of the stations). There were 11 such ECWs.

EMWs were identified in 13 years. Most of them were also only recorded by 1 or 2 stations (7 EMWs in total), even though not always by neighbouring ones. As it turned out, there were cases when ECWs were observed by stations distant from each other—three or even more altogether.

This study will focus on those EMWs that were recorded by at least three stations in the same part of Europe. There were four such EMWs. The one covering the largest area was recorded by 11 stations (Table 4).

The characteristics of the ECWs and EMWs described in this study comprise their location in Europe and the indicative area covered, number of stations, average air temperature and degree of anomaly (i.e. air temperature deviation from the corresponding multi-annual average), as well as the average maximum and minimum temperatures and the number of days with a minimum temperature below 0 °C and maximum temperature below 0, −10 and −20 °C.

4.1 Exceptionally cold winters

The *ECW of 1953/1954* was the winter with the second largest coverage (16 stations) and with the greatest negative air temperature anomaly in the 60-year period (the coldest winter in the study area). The winter covered the area of Southeastern Europe (Fig. 2), stretching from Belgrade and Debrecen in the west to Kazan and Orenburg in the east and from the Black Sea and foreland of the Caucasus in the south to Kazan in the north. For most of the stations, January and/or February were exceptionally cold months (ECMs) plus December in the southernmost area (3 ECMs in Istanbul and Simferopol). The temperature anomaly Δt in 5 southern stations exceeded 3 standard deviations; everywhere, except for Sochi, it exceeded −4 °C, reaching −5 to −7.0 °C in the east and −8.6 °C in Rostov-on-Don. It was the greatest negative winter temperature anomaly in the years 1951–2010 in Europe and one of 5 cases when the negative anomaly exceeded −8 °C (Table 5). The entire area saw days with 24-h temperatures below −10 °C (approx. 30 more than on average in the central and eastern parts) and in the east even below −20.0 °C.

The *ECW of 1955/1956* covered the area of northeastern Europe, where it was recorded by ten stations (Fig. 2). It may be presumed that the area of the ECW was not much larger than during the winter 2 years previous to it whereby the clearly lower number of weather stations resulted from the

Table 3 Exceptionally cold winters (ECW) in Europe (1951–2010)

Year	No. of stations	Stations (no. according to Table 1)	Exceptionally cold month (ECM)[a]
1952/1953	2	(2), 9	Jan.
1953/1954	16	12, *14*, *15*, *16*, (17), *18*, 24, 25, *26*, *27*, *28*, 35, 36, 37, 38, 47	Dec.—3 stations, Jan.—10 stations Feb.—15 stations
1955/1956	10	36, 37, 44, 45, 46, 47, 48, 54, 55, 60	Dec.—8 stations Feb.—6 stations
1962/1963	24	(5), (6), 7, (8), (9), (10), 11, 12, 13, *19*, *20*, *21*, *22*, 23, 24, 25, 29, 30, *31*, 32, 33, 39, 41, 49	Dec.—6 stations, Jan.—19 stations Feb.—7 stations
1963/1964	3	12, 23, 24	Dec.—3 stations Jan.—2 stations
1964/1965	1	(1)	–
1965/1966	7	(40), (42), 50, 51, 56, 57, 60	Dec.—1 station Jan.—1 station Feb.—4 stations
1968/1969	9	28, 34, 37, 38, 47, 48, 54, 55, (59)	Dec.—3 stations Jan.—8 stations
1969/1970	4	32, 33, 42, 43	Dec.—3 stations Feb.—1 station
1971/1972	1	18	Jan.
1978/1979	6	31, 43, (49), 53, 54, 59	Dec.—5 stations
1980/1981	3	3, 10, (11)	Dec.—1 station Jan.—2 stations
1984/1985	9	(12), (13), 14, 16, 24, 35, (46), 52, 53	Feb.—6 stations
1985/1986	1	49	Feb.
1986/1987	2	52, (56)	Jan.
1991/1992	1	4	Dec.
1997/1998	1	58	Feb.
2009/2010	3	(29), (39), 49	Jan.

Station numbers printed in italics mean that the average winter temperature at that station met the formula $t \leq t_{av.} - 3\sigma$. A number in brackets means that the station had no single month in the category in that year

[a] This is not a summary of all ECWs, but of just the months that decided that the winter was anomalous

lowest density of the network of stations in that part of Europe. The ECW was recorded by stations from Kursk and Saratov in the south to Saint Petersburg and Ivdel in the north, as well as in Vardö, and from Saint Petersburg in the west to Ivdel and Yekaterinburg in the east. December and February were ECMs. Everywhere, except for Vardö, the temperature anomaly Δt was greater than −5.0 °C, exceeding −7.0 °C in the north and reaching its highest value in Vologda where it was −8.2 °C. In Saint Petersburg, Moscow, Vologda and Kazan, it was the coldest winter in the six decades (Table 5). The entire area, except for Vardö, saw days with 24-h temperatures below −20.0 °C; they were more numerous than on average, between 10 days in Saint Petersburg and 25 days in Ivdel.

Unlike the ECW discussed above, the *ECW of 1962/1963* was recorded in Western Europe by a record number of 24 stations, from Madrid to Rome in the south to Edinburgh and Bergen in the north and from La Coruña and Valentia in the west to Warsaw, Chernivtsi and Sofia in the east (Fig. 2). January was an ECM at nearly all locations. In the northwest, December and/or February were also exceptionally cold months; three ECMs were recorded in Paris, Würzburg and De Bilt. The only areas with no ECM were the Iberian Peninsula and the coast of the Mediterranean Sea.

Even though most of the temperature anomalies in the northeast of the continent reached three standard deviations ($t \geq t_{av.} + 3\sigma$), the absolute value of anomalies was lower than for the above ECWs in the east of Europe with Δt usually ranging between ca. −2.0 and −5.0 °C and its highest value recorded in Warsaw $\Delta t = -6.7$ °C (Table 5). Western Europe owes its lower negative air temperature anomalies in winter to

Table 4 Exceptionally mild winters (EMW) in Europe (1951–2010)

Year	No. of stations	Stations (no. according to Table 1)	Exceptionally mild month (EMM)
1954/1955	4	4, 10, 15, (17)	Jan.—2 stations Feb.—2 stations
1956/1957	1	(30)	–
1965/1966	3	4, (16), 17	Jan. or Feb.
1982/1983	1	(38)	–
1988/1989	1	39	Jan.
1989/1990	7	(1), 5, 6, 7, 8, 9, (25)	Dec.—2 stations Feb.—5 stations
1994/1995	3	(19), (58), 59	Feb.
1995/1996	1	2	Jan. and Feb.
1997/1998	3	(1), *3*, 39	Feb.
1999/2000	1	(38)	–
2000/2001	2	*3*, 9	Dec.—2 stations Jan.—2 stations
2006/2007	11	(3), (11), 12, *13*, *14*, (20), 21, (22), 23, (31), 38	Dec.
2007/2008	2	5, 60	Dec. or Feb.

Station numbers printed in italics mean that the average winter temperature at that station met the formula $t \geq t_{av.}+3\sigma$. A number in brackets means that the station had no single month in the category in that year

the mitigating effect of the waters of the Atlantic Ocean (Hirschi and Sinha 2007), in contrast to the cooled land in central, and even more so, Eastern Europe which is largely responsible for the significant falls in air temperature. Over most of the area, the winter of 1962/63 was the coldest in all the 60 years and was the only anomalously cold winter in the south and west, even though the average temperature in the southern- and westernmost areas remained above zero.

The *ECW of 1963/1964* was observed by three stations in Central Europe: in Vienna, Debrecen and Belgrade. December and January were ECMs. The temperature anomalies ranged between −3.9 °C in Vienna and −5.4 °C in Debrecen (the latter experienced its coldest winter in the six decades).

The *ECW of 1965/1966* covered the Scandinavian Peninsula (7 stations; Fig. 3). In most cases, February was an ECM, with no ECM recorded by the southern stations. It was the coldest winter in the area, with the temperature anomaly Δt between −3.0 °C in Vardö and −7.5 °C in Vaasa (Table 5). In the northern, inner part of the Scandinavian Peninsula, there was not a single winter day when the maximum temperature exceeded 0 °C, with more than 20 days recording 24-h air temperatures below −20 °C (fewer than 10 days on average).

Fig. 2 Stations with ECW: 1953/1954, 1955/1956 and 1962/1963

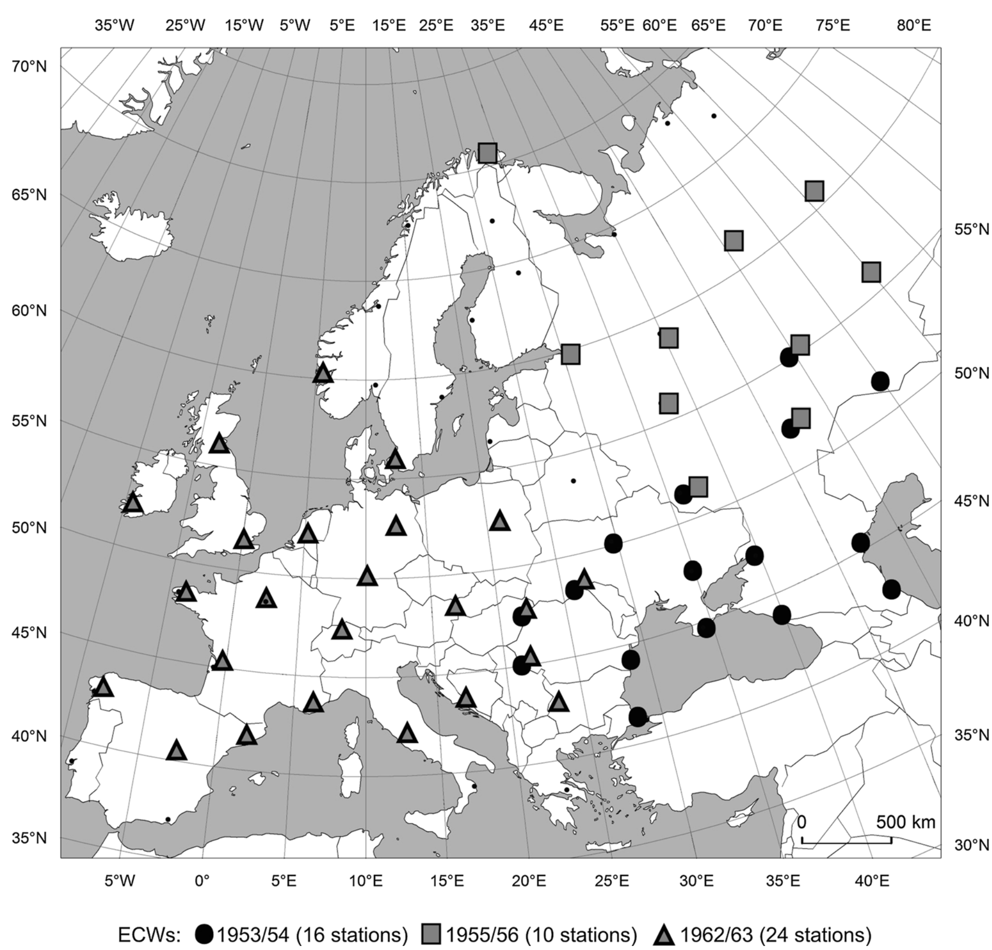

Table 5 Thermal characteristic of the exceptionally cold winters (ECW)

Station		Temperature (°C)				No. of days with temperature			
No.	Name	$T_{av.}$	Δt (°C)	T_{max}	T_{min}	T_{min}<0 °C	T_{max}<0 °C	T_{max}<−10 °C	T_{max}<−20 °C
1953/1954									
12.	Belgrade	−3.1[a]	−5.2	0.1	−6.0	74	47	1	–
27.	Rostov on the Don	*−11.5*[a]	−8.6	−7.9	−14.9	86	77	36	1
35.	Kiev	−9.6*	−6.1	−6.5	−12.7	84	74	29	–
38.	Orenburg	−17.7	−5.8	−13.7	−21.9	90	85	65	14
48.	Kazan	−16.8	−6.0	−13.5	−20.6	90	83	63	21
1955/1956									
44.	St Petersburg	−12.6[a]	−7.0	−8.8	.	.	77	34	11
47.	Kazan	−18.1[a]	−7.3	−14.2	−22.4	91	86	66	20
55.	Ivdel	−23.4	−6.3	−18.5	−28.8	91	91	72	41
60.	Vardö	−7.2[a]	−3.0	−4.7	−9.7	89	80	12	–
1962/1963									
6.	Madrid	5.0[a]	−1.7	8.1	1.8	26	1	–	–
10.	Rome	6.2	−1.9	10.1	1.8	36	–	–	–
12.	Belgrade	−2.5	−4.6	0.2	−5.3	72	43	3	–
20.	Paris	−0.1[a]	−5.1	2.5	−2.7	57	24	–	–
29.	Valentia	4.6[a]	−2.6	7.1	2.1	30	–	–	–
33.	Warsaw	−8.4[a]	−6.7	−5.1	−12.0	86	73	15	–
41.	Copenhagen	−3.2[a]	−4.5	−1.0	−5.3	82	60	–	–
49.	Bergen	−0.8	−3.0	1.4	−3.0	68	31	–	–
1965/1966									
40.	Oslo	−8.5[a]	−5.3	−5.7	−11.2	88	78	14	–
57.	Sodankyla	−19.9[a]	−6.9	−15.3	−25.1	90	90	64	24
60.	Vardö	−7.2	−3.0	−4.7	−9.6	90	78	7	
1968/1969									
28.	Astrakhan	−9.1	−5.3	−4.4	−12.6	88	59	20	–
48.	Yekaterinburg	−20.4[a]	−8.0	−15.9	−24.2	90	88	61	31
59.	Peczora	−25.4[a]	−8.1	−21.5	−29.4	90	90	67	47
1978/1979									
31.	De Bilt	−0.8	−3.7	1.6	−3.4	71	32	–	–
53.	Arkhangelsk	−18.0	−6.5	−13.5	−22.5	90	89	54	20
1984/1985									
12.	Belgrade	−1.6	−3.7	1.3	−4.3	69	43	2	–
35.	Kiev	−9.0	−5.5	−5.6	−11.9	84	69	17	–
53.	Arkhangelsk	−19.5[a]	−8.0	−15.2	−23.6	90	87	59	29

[a] The lowest in 60 years; a value in italics that the temperature meets the criterion $t \leq t_{av.} - 3\sigma$; – no data

The *ECW of 1968/1969* covered the easternmost areas of Europe (8 stations) and Minsk (Fig. 3). January and December were ECMs in Ivdel and Yekaterinburg. The air temperature anomaly Δt was higher than −5.0 °C across the stations, exceeding −8.0 °C in Pechora and Orenburg (Δt=−8.1 and −8.2 °C, respectively). It was the coldest winter in the 60 years for nearly all the stations. The average temperature of −25.4 °C in Pechora was the lowest of all the cases studied here (Table 5) Here too maximum temperatures remained below −20.0 °C for over half the days in that winter (20 days on average). Such a strong decline in air temperature in the area was due to a block caused by a ridge of high pressure over western Russia (Hirschi and Sinha 2007).

The *ECW of 1969/1970* was observed by four stations in central Europe: in Berlin, Warsaw, Stockholm and Liepāja. December was an ECM and February too, but only in Stockholm. The temperature anomaly Δt ranged between −4.6 °C in Vienna and −5.6 °C in Liepāja. In the weather stations on the Baltic Sea, it was the coldest winter in the 60-year period.

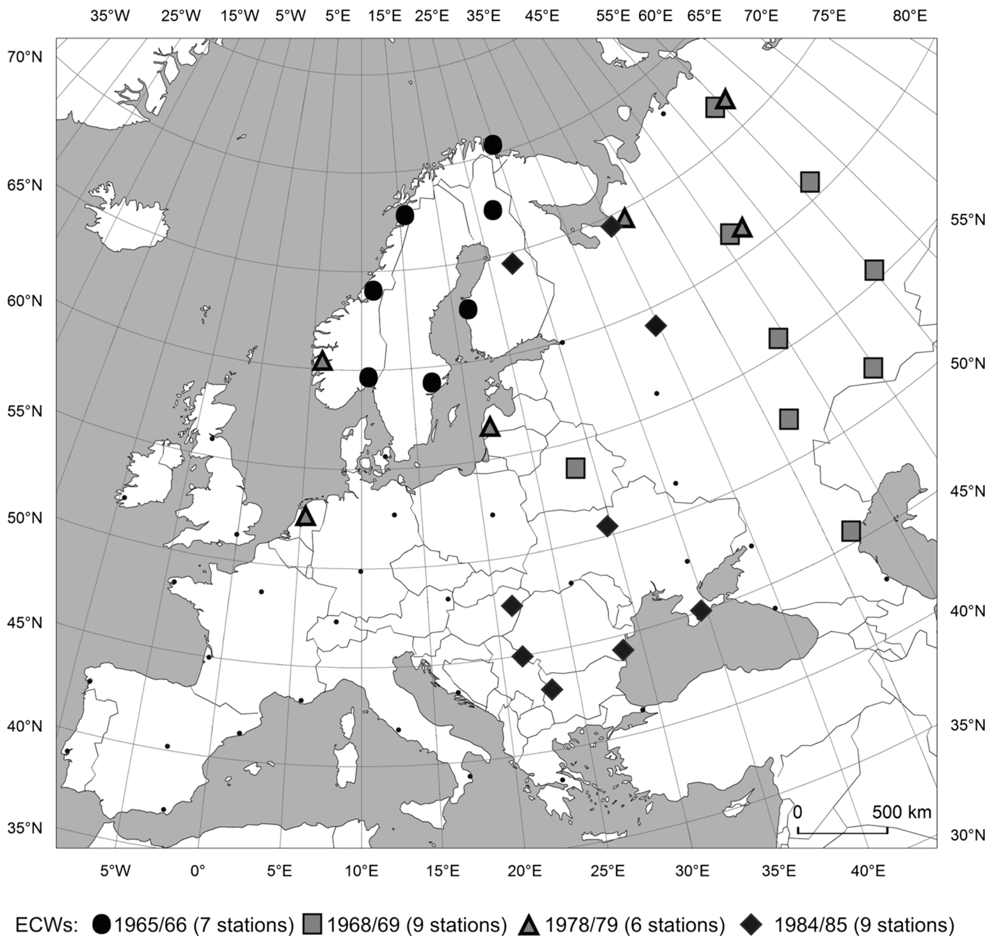

Fig. 3 Stations with ECW: 1965/1966, 1968/1969, 1978/1979 and 1984/85

The *ECW of 1978/1979* was recorded by six stations in the north of Europe: De Bilt and Bergen, Liepāja and Arkhangelsk, Syktyvkar and Pechora. In the last four stations, December was the ECM. Given the high latitudinal span of the ECW, the thermal conditions within its coverage differed greatly: in the westernmost areas, the average air temperature was approx. −1.0 °C (Δt −3.0 to −4.0 °C), and in the easternmost ones, it was lower than −20.0 °C (anomaly Δt −7.0 to −8.0 °C). In the west, there were only 30 days with 24-h temperatures below zero, whereas in the east they were recorded throughout the winter; often, there were days with maximum temperatures below −20.0 °C. For Pechora, it was one of the two coldest winters in the 60 years, with the temperature reaching −25.4 °C on average, i.e. as low as during the winter of 1968/1969 (Fig. 3, Table 5).

The *ECW of 1980/1981* was recorded by three stations on the Italian Peninsula and on the Adriatic Sea: in Rome, Crotone and Split. December and January were ECMs in Crotone, but it was the coldest winter in the 60 years for Rome alone. The air temperature anomaly was approx. −2.0 °C.

The *ECW of 1984/1985* was recorded in two areas: in the south—from Belgrade and Sofia to Kiev and Simferopol (6 stations), and in the north—within the Kajaani-Arkhangelsk-Vologda triangle (3 stations). In Belgrade and Sofia, there were no ECMs, and February was an ECM for the remaining stations. In the two northernmost stations, January was also an ECM. For these last stations, it was the coldest winter in the 60-year period, with the temperature anomaly Δt reaching −7.1 °C in Kajaani and −8.0 °C in Arkhangelsk. For the remaining stations, Δt ranged from −2.6 °C in Sofia to −5.5 °C in Kiev and −6.4 °C in Vologda (Fig. 3, Table 5). Days with 24-h temperatures below −10 °C were observed in both areas: in the south, there were fewer than 20 such days (in the west, even fewer than 5), and in the north, there were up to 60 days, including approx. 30 days with maximum temperatures below −20 °C.

Another ECW recorded by at least three stations appeared only 25 years later—in the *2009/2010* season; it was the only ECW in the twenty-first century, i.e. "a cold extreme in a warming climate" (Cattiaux et al. 2010). It was observed by three seaside stations in the northwest of Europe: in Valentia and Edinburgh (with no ECM, temperature anomaly Δt of −2.1 and −2.4 °C, respectively) and in Bergen (ECM=January, Δt= −3.4 °C; here, it was the coldest winter in the 60-year period).

Strongly negative air temperature anomalies in Western and Northern Europe are observed at the time of negative phases of the North Atlantic Oscillation (Cattiaux et al. 2010; Wang et al. 2010; Ouzeau et al. 2011; Buchan et al.

2014). During such spells, Central and Eastern Europe sees more anticyclonic circulation from the north and east or the formation of highs directly over the area (Kossowska-Cezak 1997).

4.2 Exceptionally mild winters

The *EMW of 1954/1955* was observed at four stations in the southernmost and easternmost parts of Europe: in Rome, Athens, Istanbul and Sochi, with January and/or February providing EMMs. The temperature anomaly was 2.1 °C in the west and from 3.0 °C in the east. It was the warmest winter in the six decades under study.

The *EMW of 1965/1966* was recorded in the eastern part of the same area as the EMW of 1954/1955 by three stations—Athens, Simferopol and Sochi. January was an EMM in Sochi, while February was in Athens. The temperature anomaly ranged from 1.9 °C in Athens to 4.1 °C in Simferopol. In Simferopol and Sochi, it was the warmest winter in the 60 years.

The *EMW of 1989/1990* ranked second in terms of the area covered—it was recorded by six stations in the Iberian Peninsula and Southern France, as well as the distant station of Chernivtsi (Fig. 4). February was an EMM, plus December in the Iberian Peninsula. The temperature anomaly in the main area was between 1.4 °C in Lisbon and 3.0 °C in Bordeaux (Table 6). Apart from Lisbon, it was the warmest winter in six decades across the locations. In the main area, there were nearly no cases of temperatures dropping below 0 °C. These were observed in Chernivtsi, but to a much lesser extent than on average Table 6).

The *EMW of 1994/1995* was recorded by only three stations in two areas far apart from each other: Brest in the west and Naryan-Mar and Pechora in the north-east. However, this EMW is noteworthy because the two last stations recorded the greatest positive air temperature anomaly in the 60-year period, Δt=7.3 and 7.7 °C respectively; these were the only cases of an anomaly greater than 6.0 °C.

The *EMW of 1997/1998* was recorded by three stations in different parts of Europe that were located far apart from one another (Table 4).

The *EMW of 2006/2007* covered the greatest area in the 60 years (Fig. 4). It was recorded by 11 stations across the belt stretching from Paris and De Bilt in the northwest and Crotone, Sofia and Constanța in the southeast, as well as in the distant station of Orenburg. There was no EMM in the western

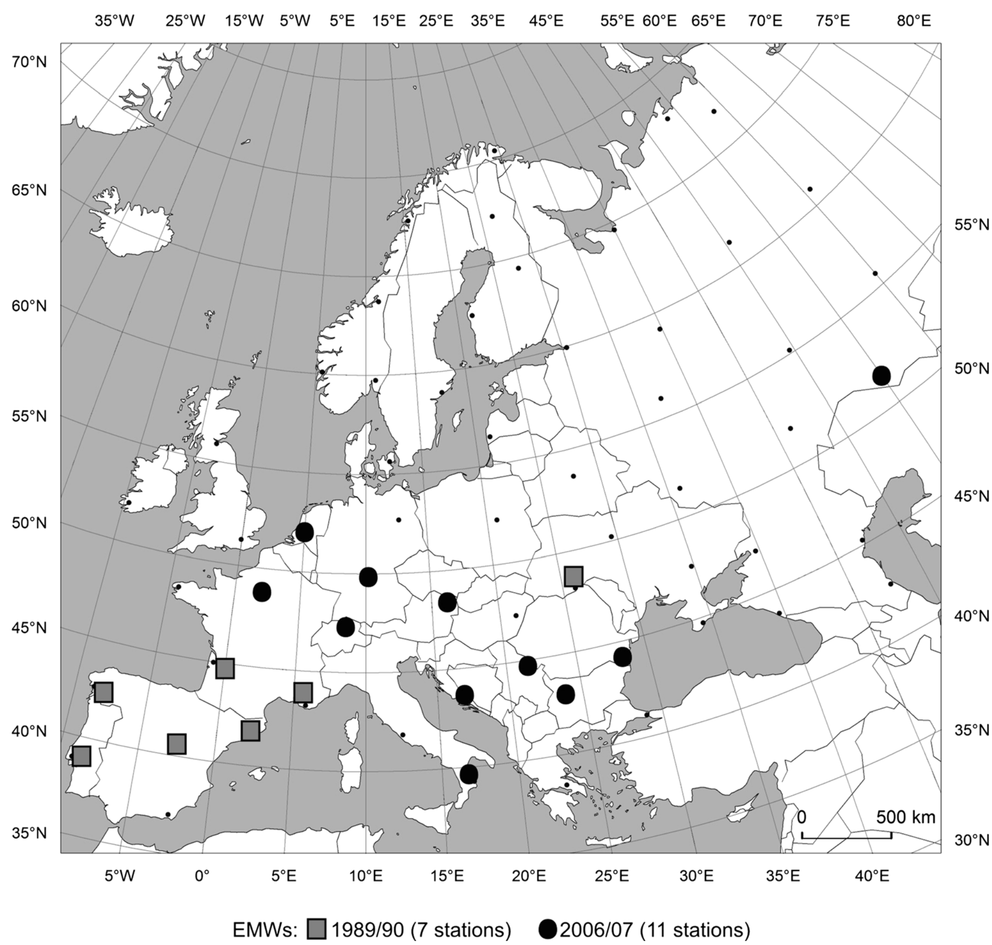

Fig. 4 Stations with EMW: 1989/1990 and 2006/2007

Table 6 Thermal characteristic of the exceptionally mild winters (EMW)

Station		Temperature (°C)				No. of days with temperature			
No.	Name	$T_{av.}$	Δt (°C)	T_{max}	T_{min}	T_{min}<0 °C	T_{max}<0 °C	T_{max}<−10 °C	T_{max}<−20 °C
1989/1990									
1.	Lisbon	13.3	1.4	16.1	10.6	–	–	–	–
6.	Madrid	8.9[a]	2.2	12.1	5.7	1	–	–	–
25.	Chernivtsi	2.2[a]	4.9	5.7	−1.4	54	16	–	–
2006/2007									
12.	Belgrade	6.4[a]	4.3	10.0	3.4	15	–	–	–
20.	Paris	7.9[a]	2.9	10.1	5.5	5	–	–	–
31.	De Bilt	6.5[a]	3.6	9.2	3.9	15	–	–	–
38.	Orenburg	−5.9	6.0	−3.0	−9.2	87	50	10	–

[a] The highest in 60 years

stations, and January was an EMM in the eastern stations. The temperature anomaly Δt ranged between 2.0 °C in Crotone and 4.3 °C in Vienna and Belgrade. It was the warmest winter in the 60 years (Table 6). For some parts of Western Europe, it was the warmest winter since temperature records using instruments began (Hirschi 2008). That winter, there was not a single day with a 24-h temperature below 0.0 °C (except for Orenburg; Table 6). The mild winter was followed by a warm spring, which greatly accelerated the growth of plants (Maignan et al. 2008). As is asserted by many researchers, mild winters in Western and Northern Europe tend to accompany positive phases of the North Atlantic Oscillation (NAO), which is attributed to higher than normal pressure differences between the Icelandic Low and the Azores High. At such times, Central and Eastern Europe sees an increased frequency of cyclonic types of circulation from the west and a fall in or even absence of circulation from the north and the east (Kossowska-Cezak 1997; Jaagus 2006; Isayev and Sherstyukov 2008; Sidorenkov and Orlov 2008; Anisimov et al. 2011).

5 Conclusions

This study is based on the assumption that winter periods (from December till February) are thermally anomalous when their average air temperature differs from the corresponding multi-annual average (1951–2010) by at least two standard deviations. Based on this assumption, exceptionally cold winters (ECW: $t \le t_{av.} - 2\sigma$) and exceptionally mild winters (EMW: $t \ge t_{av.} + 2\sigma$) were identified in the area of continental Europe and the British Isles (60 weather stations) in the seasons of 1951/1952–2009/2010.

Depending on the part of Europe, the terms "cold" and "mild" may denote winters differing substantially in terms of thermal conditions—in the Mediterranean Basin, a "severe" winter may actually be free from temperatures below zero, and in the far north, even "mild" winters may involve prolonged spells of freezing weather. The apparent paradox results from the fact that the identification of temperature anomalies was based on the average temperatures recorded in a given area to which its residents are accustomed.

It was found that there are great differences in the frequency, location and area covered by individual anomalous winters, as well as in the level of air temperature anomaly for both types of anomalous winters.

1. ECWs are more frequent across Europe, while EMWs appear only in the south and west of the continent (they were only recorded by half of the stations).
2. ECWs are recorded more frequently than EMWs—18 and 13 winters respectively in the 60 years.
3. In extreme cases, ECWs cover larger areas than EMWs. Even though a high proportion of anomalous winters are recorded by one or two stations (out of the 60 stations)—this applies to 7 out of 18 ECWs and 7 out of 13 EMWs—the number of anomalous winters recorded by at least 6 stations (i.e. 10 % of the stations) was 7 and 2, respectively, with the most extensive ECW covering 24 stations, while for EMW it was only 11 stations.
4. ECWs are characterised by the greatest absolute temperature anomalies: anomalies up to −3.0 °C apply to 21 % of the cases, and those exceeding −6.0 °C to 35 %, while for EMWs, anomalies up to +3.0 °C represent 68 % of the cases and those exceeding +6.0 °C only 8 %.
5. A vast majority of the ECWs (82.5 %) were characterised by at least one exceptionally cold month, and in extreme cases, as many as three winter months are ECMs (5 cases). During the EMWs, EMMs were less frequent (62.5 %) and were recorded exclusively by a single station (there were only five cases of EMWs with two EMMs and only in the southernmost parts of Europe).

6. The above comparison indicates that the numerous historical accounts of very severe winters and few accounts of mild winters are not accidental but rather indicative, among other things, of a significant characteristic of Europe's current climate. Even though the second half of the six decades saw fewer ECWs and more EMWs (1951/1952–1979/1980: 11 ECWs, 3 EMWs, 1980/1981–2009/2010: 7 and 10, respectively), one may always expect spells of temperature well below zero, short or long lasting, notably in the east and north of the continent. This results from the nature of the circulation of air over Europe which is dominated by advection of warm air masses from over the Atlantic, with intermittent periodic blocks causing the forced descent of cold Arctic or continental polar air from the north or the east (positive or negative NAO phase). In addition, the prolonged presence of high-pressure systems in winter time contributes to further radiative cooling of the air during long cloudless winter nights (especially in the north). This pattern is confirmed by an increased frequency of ECWs in the early part of the study period when the negative NAO phase was also more frequent (Hurrell and National Center for Atmospheric Research Staff 2014).
7. In the light of the authors' previous study on exceptionally hot and cool summers (Twardosz and Kossowska-Cezak 2015b) exceptionally cold winters occurred less frequently than exceptionally hot summers (18 vs. 24 over the 60-year period), but on average covered larger areas (6 vs. 4 stations; exceptionally mild winters and exceptionally cool summers accounted for 3 each). In the second half of the 60-year period, exceptionally cold winters became increasingly rare and their spatial coverage began to shrink, as opposed to exceptionally hot summers, which recorded gains in both frequency and spatial coverage.

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References

Anisimov OA, Borzenkova II, Zhil'tsova EL, Zakharova OK, Kokorev VA, Reneva SA, Strel'chenko YG (2011) Hydrometeorological conditions of the Volga Region and current climate changes. Russ Meteorol Hydrol 36(5):307–314

Bardin MY (2007) Anticyclonic quasi-stationary circulation and its effect on air temperature anomalies and extremes over western Russia. Russ Meteorol Hydrol 32(2):75–84

Baur F (1954) Die Bestätigung bisheriger Ergebnisse der Gro\wetterforschung durch den Winter 1953/54. Arch Meteorol Geophys Bioklimatol A 30(7):188–198

Błażejczyk K, McGregor G (2007) Warunki biotermiczne a umieralność w wybranych aglomeracjach europejskich. Prz Geogr 3–4:401–423

Brönnimann S (2005) The global climate anomaly, 1940–1942. Weather 60:336–342

Buchan J, Hirschi JJ-M, Blaker AT, Sinha B (2014) North Atlantic SST anomalies and the cold North European weather events of winter 2009/10 and December 2010. Mon Weather Rev 142:922–932

Cattiaux J, Vautard R, Cassou C, Yiou P, Masson-Delmotte V, Codron F (2010) Winter 2010 in Europe: a cold extreme in a warming climate. Geophys Res Lett 37, L20704. doi:10.1029/2010GL044613

Cony M, Hernández E, Del Teso T (2008) Influence of synoptic scale in the generation of extremely cold days in Europe. Atmosfera 21(4): 389–401

Dobrovolný P, Brazdil R, Kotyza O, Valašek H (2010) Extreme summer and winter temperatures in the Czech Lands after A.D. 1500 and their central European context. Geografie 3(115):266–283

Graham RJ, Gordon C, Huddleston MR, Davey M, Norton W, Colman A, Scaife AA, Brookshaw A, Ingleby B, McLean P, Cusack S, McCallum E, Elliot W, Groves K, Cotgrove D, Robinson D (2006) The 2005/06 winter in Europe and the United Kingdom: Part 1—how the MetOffice forecast was produced and communicated. Weather 61:327–336

Hansen J, Sato M, Ruedy R (2012) Perception of climate change. Proc Natl Acad Sci U S A 109:E2415–E2423. doi:10.1073/pnas.1205276109

Hirschi JJ-M (2008) Unusual North Atlantic temperature dipole during the winter of 2006/2007. Weather 63:4–11

Hirschi JJ-M, Sinha B (2007) Negative NAO and cold Eurasian winters: how exceptional was the winter of 1962/1963? Weather 62:43–48

Hurrell J, National Center for Atmospheric Research Staff (eds) (2014) "The Climate Data Guide: Hurrell North Atlantic Oscillation (NAO) Index (station-based)." Retrieved from https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based. - See more at: https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based#sthash.umjcln2s.dpuf

Isayev AA, Sherstyukov BG (2008) Mean and extreme characteristics of Moscow climate at the end of the 20th century. Russ Meteorol Hydrol 33(3):151–158

Jaagus J (2006) Climatic changes in Estonia during the second half of the 20th century in relationship with changes in large-scale atmospheric circulation. Theor Appl Climatol 83:77–88

Klein Tank AMG, Wijngaard JB, Können GP, Böhm R, Demarée D, Gocheva A, Mileta M, Pashiardis S, Hejkrlik L, Kern-Hansen C, Heino R, Bessemoulin P, Müller-Westermeier G, Tzanakou M, Szalai S, Pálsdóttir T, Fitzgerald D, Rubin S, Capaldo M, Maugeri M, Leitass A, Bukantis A, Aberfeld R, van Engelen AFV, Forland E, Mietus M, Coelho F, Mares C, Razuvaev V, Nieplova E, Cegnar T, Antonio López J, Dahlström B, Moberg A, Kirchhofer W, Ceylan A, Pachaliuk O, Alexander LV, Petrovic P (2002) Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment. Int J Climatol 22:441–1453

Kossowska-Cezak U (1997) Miesięczne warunki termiczno-opadowe i ich zależność od cyrkulacji atmosferycznej. Pr Stud Geogr 20:125–144

Maignan F, Bréon FM, Vermote E, Ciais P, Viovy N (2008) Mild winter and spring 2007 over Western Europe led to a widespread early vegetation onset. Geophys Res Lett 35, L02404. doi:10.1029/2007GL032472

Moberg A et al (2006) Indices for daily temperature and precipitation extremes in Europe analyzed for the period 1901–2000. J Geophys Res 111, D22106. doi:10.1029/2006JD007103

Ouzeau G, Cattiaux J, Douville H, Ribes A, Saint-Martin D (2011) European cold winter 2009–2010: how unusual in the instrumental

record and how reproducible in the ARPEGE-Climat model? Geophys Res Lett 38, L11706. doi:10.1029/2011GL047667
Sidorenkov NS, Orlov IA (2008) Atmospheric circulation epochs and climate changes. Russ Meteorol Hydrol 33(9):553–559
Twardosz R, Kossowska-Cezak U (2013a) Exceptionally hot summers in Central and Eastern Europe (1951–2010). Theor Appl Climatol 112: 617–628
Twardosz R, Kossowska-Cezak U (2013b) Exceptionally hot summers months in Central and Eastern Europe during the years 1951–2010. In: Dincer I, Ozgur Colpan C, Kaglioglu F (eds) Causes, impacts and solutions to global warming. Springer 17–35
Twardosz R, Kossowska-Cezak U (2015a) Extremely cold summers months in Central and Eastern Europe, 1951–2010. Nat Hazards 75:2013–2026
Twardosz R, Kossowska-Cezak U (2015b) Exceptionally hot and cold summers in Europe (1951–2010). Acta Geophys 63. doi:10.2478/s11600-014-0261-2
Ugryumov AI, Khar'kova NV (2008) Modern changes in St. Petersburg climate. Russ Meteorol Hydrol 33(1):15–19
Van den Besselaar EJM, Klein Tank AMG, van der Schrier G (2010) Influence of circulation types on temperature extremes in Europe. Theor Appl Climatol 99:431–439
Wang C, Liu H, Lee S-K (2010) The record-breaking cold temperatures during the winter of 2009/2010 in the Northern Hemisphere. Atmos Sci Lett 11:161–168
Wijngaard JB, Klein Tank AMG, Können GP (2003) Homogeneity of 20th century European daily temperature and precipitation series. Int J Climatol 23:679–692
Wyjątki ze źródeł historycznych o nadzwyczajnych zjawiskach hydrologiczno-meteorologicznych na ziemiach polskich w wiekach od X do XVI (1965) Girguś R, Strupczewski W, PIHM, WKiŁ, Warszawa