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Warming in Europe: Recent Trends in Annual and Seasonal temperatures

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Abstract—Contemporary climate warming is a key problem faced not only by scientists, but also all by humanity because, as is shown by the experience of recent years, it has multiple environmental, economic and biometeorological implications. In this paper, the authors identify the magnitude of annual and seasonal temperature changes in Europe and its immediate surroundings on the basis of data from 210 weather stations from 1951 to 2020. An analysis of temperatures in the 70-year period shows that air temperature has continued to grow linearly in Europe since 1985. The rate of temperature rise in three seasons of the year, namely winter, spring and summer, does not differ greatly. The highest growth over the 1985–2020 timespan was recorded in spring and the lowest in autumn—0.061 °C/year and 0.045 °C/year, respectively. In winter, the rise in temperature should be considered the least steady, as opposed to the summer when it displays the greatest stability. Overall, the warming intensifies towards the north-east of the continent. Such a strong gradient of change is especially perceivable in winter and spring, and is also marked in autumn. The opposite is true in summer, when it increases towards the south and south-west.

Keywords: Air temperature, Trends, Climate warming, Europe.

1. Introduction

A systematic increase in air temperature on Earth IPCC, 2013; Rahmstorf et al., 2017, Kundzewicz et al., 2020), including Europe (e.g. Chen et al., 2015; Jones et al., 2012; Krauskopf & Huth, 2020; Luterbacher et al., 2004; Schönwiese & Rapp, 1997; Slonosky et al., 2001; Xoplaki et al., 2005; Zveryaev & Gulev, 2009), is the most characteristic feature of contemporary climate change. The latest research by Kundzewicz et al. (2020) shows that the growth was about 0.7 °C/100 years in 1880–2019, reaching about 2.0 °C/100 years in the three most recent decades (1990–2019). However, the intensity of the warming shows clear spatial variations: It is greater over land than over sea, and there are differences between continents (Trenberth et al., 2007). The European continent stands out for the greatest climate warming (Luterbacher et al., 2016; van der Schrier et al., 2013), which—as is evidenced by the change scenarios—is likely to intensify (Christensen et al., 2015; Vautard et al., 2014). This is an obvious consequence of the increase in the frequency and intensity of heat waves, as well as month-long spells, and even whole seasons, with temperatures significantly exceeding the long-term average, especially in the second decade of the twenty-first century (e.g. Błażejczyk & Twardosz, 2010; Hansen et al., 2012; Twardosz & Batko, 2012; Coumou et al., 2013; Kamae et al., 2014; Rahmstorf et al., 2017; Liu et al., 2020; Twardosz & Kossowska-Cezak, 2015, 2016, 2021).

The research conducted so far clearly demonstrates that the increase in air temperature in Europe and its immediate surroundings is not uniform in terms of space and time (Jones & Moberg, 2003; van Oldenborgh et al., 2009; Zveryaev & Gulev, 2009; Anisimov & Zhil'tsova, 2012; Krauskopf & Huth, 2020).

Zveryaev and Gulev (2009) demonstrated on the basis of grid air temperature values in Europe that in summer and autumn over the period 1901–2000 the greatest warming was recorded in western and southern Europe, in winter in the south of the continent and in spring in Scandinavia and north-eastern Europe. Based on air temperatures measured at European weather stations for timespans ranging

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from 100 (1901–2000) to 200 (1801–2000) years, Chen et al. (2015) showed that Southeast Europe is the region with the greatest warming, especially in summer. The upward temperature trend is manifested by the ever more frequent occurrence of large-scale positive air temperature anomalies in this part of Europe (Luterbacher et al., 2016; Twardosz & Kossowska-Cezak, 2019, 2021). In turn, Meleshko et al. (2019) found that the average annual warming in the Arctic since the mid-1990s had been twice as fast as the average on Earth while in northern Eurasia, including European Russia, the frequency of anomalously cold winter months had increased.

From the above, the question arises of how annual and seasonal air temperatures in Europe and its immediate surroundings have evolved from the mid-twentieth century to 2020 against the background of the research results cited above. Therefore the central objective of the present study is to identify changes over a homogeneous timespan and on the basis of a dense and relatively evenly distributed network of weather stations. We pursue this objective in the hope that this article will contribute to a better understanding of recent climate change on the continent. As revealed by the results of recent studies (Anagnostopoulou et al., 2017; Twardosz & Kossowska-Cezak, 2021), Europe still sees extremely cold winter months, some of which in some areas of Europe have been the coldest since the mid-twentieth century. This means that the present-day warming is a complex and spatially diverse process (Ji et al., 2014; Hegerl et al., 2018; Krauskopf & Huth, 2020) that must be monitored on a continuous basis to assess its potential social, economic and environmental impacts.

2. *Data*

The research was based on average monthly air temperature values from 210 weather stations distributed as evenly as possible throughout Europe and its immediate surroundings, from Hopen in the Svalbard Archipelago in the north to the coast of Africa in the south and from Iceland and the western coast of the Iberian Peninsula in the west to the Urals and the Caspian Sea in the east (Fig. 1). The temperatures collected span the period from December 1950 to December 2020. Based on them, the seasonal and annual mean temperatures over the 70-year period were calculated for each station and used as the basis for investigations in the present study. The database was developed on the basis of publicly available online databases of the European Climate Assessment & Dataset (ECA&D., http://eca.knmi.nl/) (Klein Tank et al., 2002), the National Climatic Data Center (NCDC, ftp://ftp.ncdc.noaa.gov/pub/data/gsod/)) and Ogimet (www.ogimet.com), as well as World Weather Records (WWR) publications.

The European Climate Assessment & Dataset was the main source of data employed in the study (Klein Tank et al., 2002). This database is one of the few publicly available sources of meteorological data in Europe (Moberg et al., 2006) and is verified for homogeneity through 4 statistical tests (Wijngaard et al., 2003). Data from the database are commonly used in climatological research (e.g. Cony et al., 2008; Van den Besselaar et al., 2010, Krauskopf & Huth, 2020; Twardosz & Kossowska-Cezak, 2021).

In the ECA&D database, data from some European stations and its immediate surroundings are not publicly available. This applies especially to stations in the UK and the Eastern Mediterranean, including Asia Minor. In such cases, data was sourced from the American National Climatic Data Center (NCDC, ftp://ftp.ncdc.noaa.gov/pub/data/gsod/). In the ECA&D database, there are gaps in temperature values in recent years at many stations, so data from the Ogimet database were used to complete them. Thanks to the use of multiple data sources, data verification was possible in case of doubt as to the actual value of the air temperature. The small amount of missing data (up to 5%) was filled in using data from neighbouring stations (difference method). Of the 210 stations included, most (182) lie below 300 m a.s.l. (Astrakhan is in a depression at − 23 m), and ten stations are situated above 1000 m a.s.l. The use of data from mountain stations is important because, as shown by the results of recent studies, these areas have also seen major temperature increases at the turn of the twenty-first century (Migała et al., 2016). Most of the 210 sites selected, i.e. 164, are located on the European continent, 8 in the British Isles, 11 on North Atlantic and Arctic islands, 1 on a Baltic island and 8 on Mediterranean islands—192 stations in all.

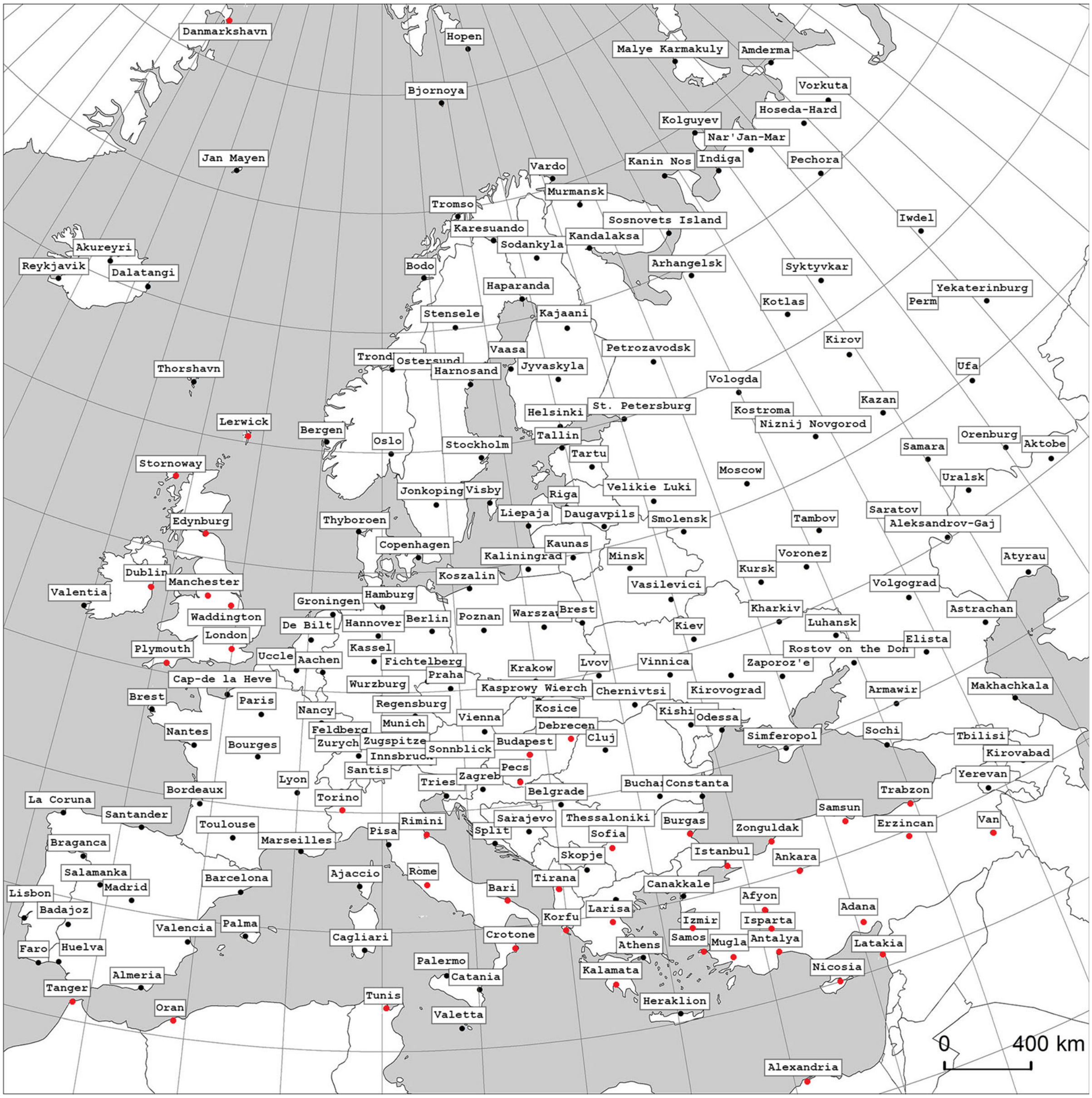


Figure 1

Weather stations included in the study. Black circles represent data sourced from the ECA&D database and red circles represent the NCDC database

In addition, the study was extended to include 14 stations in Asia Minor and four sites on the African coast.

3. Methods

The main statistical method applied is simple linear regression. The slope (a) is, of course, the main result of interest. As a measure of precision/reliability, the standard deviation of the slope (σ_a) was also calculated. The ratio a/σ_a is used as an indicator of statistical significance, however, the p-value was also calculated. In the case of data averaged over all 210 stations, the p-values of the slope are so low that, for clarity, the logarithm was calculated with the negation sign: $-\ \mathrm{Log}_{10}$(p-value).

From the plot of yearly temperatures averaged over all the stations (deeply generalised data), it is evident that the period 1951–2020 is to be roughly divided into half. The period 1951–1985 represents stable temperatures, and 1985–2020 represents a linear rise of temperature. The year 1985 is included both in the calculation of the average temperature in the earlier period as well as in the regression in the later period. The linear regression 1985–2020 is calculated under the assumption of "zero-intercept", i.e. the known starting value of the temperature is assumed.

That value is the average from 1951 to 1985, which is of relatively high precision since the number of points is n = 45 (= 6.7^2). The question of proper choice of the middle year, the one where the model changes (after 1985), is addressed on the basis of the goodness of fit of the linear rise model. As a measure of model quality, the determination coefficient R^2 is applied. For all seasons and the summary yearly data, a search was made for the year which maximizes R^2. The result is not too bad, however it is not unequivocal, so the idea of Occam's razor is additionally applied, and the exact middle year of the 70-year-timespan is accepted: 1985.

Maps of regression slope (a), as well as that of a/σ_a, are calculated based on the 210 stations (data points) which are uniformly distributed over the area. The value calculated for each point on the map is a weighted average of all stations. The weight is, roughly speaking, inversely proportional to the distance. The exact formula is:

$$w_i = 1/\left(d^2 + (x - x_i)^2 + (y - y_i)^2 \right),$$

where (x, y) is the point to be calculated, and (x_i,y_i) is the position of the i-th site, i = 1, 2, 3, …, 210. (The w_i 's are then normalised to sum = 1.) The parameter d is essential for smoothing. Small d, much less than the typical distance between stations, makes the value of each station visible on the map. However, in such a case, the map takes the role of a table. An exceptionally large d would produce a map in only one colour. The value applied is d = 200 km.

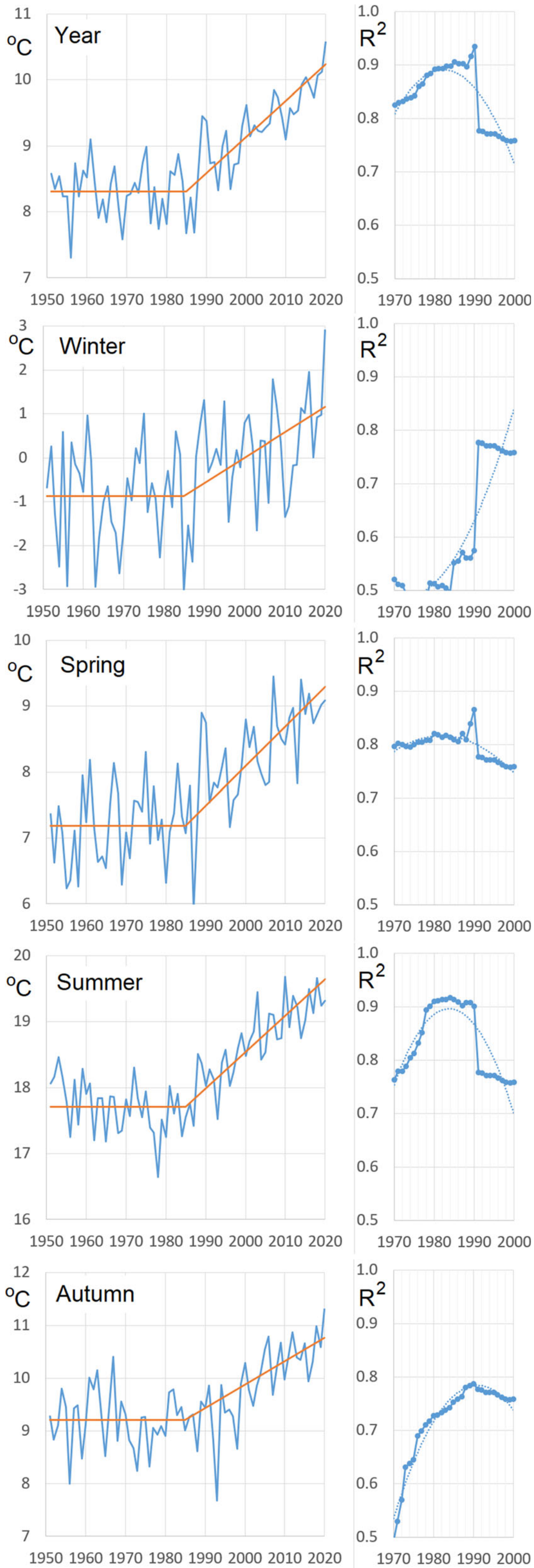
4. Results

4.1. General Characteristics of Air Temperature Changes

In order to gain knowledge about general temperature trends across Europe and its immediate surroundings, area-averaged values of annual and seasonal air temperature were calculated for all 210 stations. How they developed over the entire 70-year period of 1951–2020 is shown in Fig. 2. It is evident from all five plots that in the first half of the 70 years period there is no rise in temperature. That is the reason why the „model" of constant value (the average) is presented. The linear regression model is applied to the second half of the plot.

The year 1985 is exactly in the middle. However that is purely an accident. To check if 1985 is a good starting point for the linear regression, the coefficient of determination (R^2) was calculated as a function of "starting year" in the range 1970–2000 (with 1985 in the middle). The calculations were performed for yearly and seasonal temperatures. Consulting (relatively) independent data is a good way of assessing the reliability of an analysis. The first plot of R^2, for yearly temperatures, is not clear. It is evident that there is a strong influence of two extremely hot years, 1989 and 1990. That fluctuation is ignored, to some extent, by another regression, the fitted parabolic line, giving a maximum around 1981. As a result, 1985 seems to be acceptable. The case of winter, with no R^2 approaching 0.8, can be ignored. The most important case is summer with a group of points with $R^2 > 0.9$, lying between 1980 and 1990. Finally, with no strong statistical evidence, we accepted the year 1985, the one exactly in the middle of our time span.

Table 1 presents a summary of the trends in air temperature over the entire 70-year period and over the last 36 years. As can be seen in the table, the temperature on the European continent has increased, but with different intensity depending on the season, and this increase rate was almost twice as rapid in



◀Figure 2
Overall average temperatures for all 210 stations, with linear regression starting in 1985 from a fixed point defined by the average from 1951–1985. The determination coefficient (R^2) of the linear regression as a function of year chosen as the starting point of the linear increase is also presented (1985 is accepted on the left-hand plots)

1986–2020 than in the whole 7-decade period (Table 1, Fig. 3). The most pronounced trend occurs in spring—0.060 °C/year (0.031 °C/year over the 70 years), with record-high positive temperature anomaly values observed at this time of year in 2007 and 2014 (Fig. 2). The weakest trend, diverging significantly from the spring trend, is found in autumn – 0.045 °C/year (0.022 °C/year over the 70-year period), with the largest positive temperature anomaly at this time of the year recorded during the most recent autumn of 2020. The trends are slightly less noticeable in winter and summer than in spring (0.058 and 0.056 °C/year in 1985–2020, respectively), but they do not display a statistically significant difference (Table 1, Fig. 3). In winter, the air temperature rise is the least stable (the highest standard error 0.009 °C/year = 15% of the slope itself). This is an obvious consequence of the greatest year-by-year variability in temperatures at this time of the year. The last winter in the 70-year period, namely 2019/2020, is at the fore of anomalously warm winters. From a statistical point of view, summer has also shown warming of a similar magnitude after 1985, but due to the smallest standard error of regression, it should be considered as the most stable compared to the other seasons. The two summers of 2010 and 2018 are among the warmest in Europe. The strong upward temperature trends in the seasons translate into a substantial increase in the average annual temperature of 0.055 °C/year (0.027 °C/year in the 7 decades). The small standard error of regression means that this increase is highly stable. 2020 proves to have been the warmest year in the whole 70-year timespan.

The model of the temperature path during the last 70 years discussed above, with 35 stable years and 35 years of linear growth, may not be convincing. So the standard approach is also presented in Table 1. It

Table 1

Coefficient of linear regression (slope) of annual and seasonal air temperatures in Europe during the periods 1951–2020 and 1985–2020

	1951–2020				1985–2020			
	Slope (°C/year)	R^2	p-value	$-\text{Log}_{10}(p)$	Slope (°C/yr)	R^2	p-value	$-\text{Log}_{10}(p)$
Year	0.0267 ± 0.0027	0.58	1E−14	14	0.0551 ± 0.0030	0.91	5E−19	18
Winter	0.0280 ± 0.0065	0.21	6E−5	4	0.0576 ± 0.0089	0.55	2E−7	7
Spring	0.0311 ± 0.0035	0.54	5E−13	12	0.0606 ± 0.0050	0.81	9E−14	13
Summer	0.0251 ± 0.0029	0.53	1E−12	12	0.0556 ± 0.0029	0.91	1E−19	19
Autumn	0.0215 ± 0.0036	0.35	7E−8	7	0.0446 ± 0.0044	0.75	8E−12	11

The slope uncertainty is standard deviation (1σ)

is a typical, simple linear regression. Approaching the question of statistical significance, the coefficient of determination (R^2), as well as the p-value is given in the Table. Additionally, the logarithm of the p-value is presented, which is necessary in face of how exceptional the values obtained are in the sense of significance. The least significant, i.e. the highest p-value is 0.00006, the lowest value is hard to be written conventionally because it requires 19 zeros. Having the simple value of the -Log_{10}(p-value) presented with no excessive precision, it is clearly visible that the model with regression over 1985–2020 is three to seven orders of magnitude more significant than the regression over the full time-span, 1951–2020. The only exception is spring, where a proportion of p-values is 0.2. At the opposite extreme is summer and the year itself.

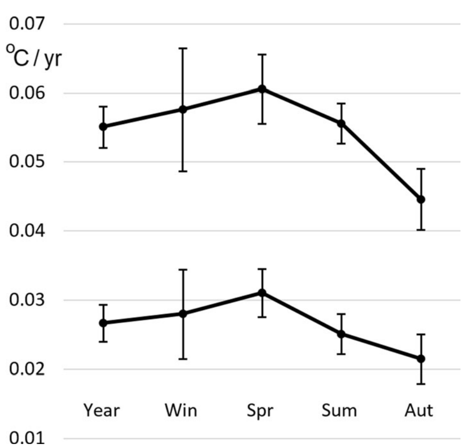


Figure 3
Slopes of the regression lines for the periods 1951–2020 and 1985–2020. The latter are roughly twice as large as the former because the time span is half as long

Linear regressions calculated for all 210 stations for the total time span, 1951–2020, are generally from significant to highly significant. Figure 4 presents histograms of the value of the a/σ_a slope divided by its standard deviation. Generally, values of $a/\sigma_a > 2$ or < -2 indicate statistical significance at the significance level $\alpha = 0.05$. Here, only 10 results are within (− 2, 2), and so on principle are not significant. Two sites have a significant, negative a. The shape of the histogram of a/σ_a is generally Gaussian, with a small, visible, however, non-significant, negative asymmetry equal to − 0.25.

4.2. Spatial Variability of Air Temperature Trends

In order to understand the spatial variations in warming, maps were prepared illustrating the slopes of the linear regressions of annual and seasonal temperatures. As it transpired, the picture of differences of rises in temperature over the 70 years 1951–2020 and the 35 years 1985–2020 is similar

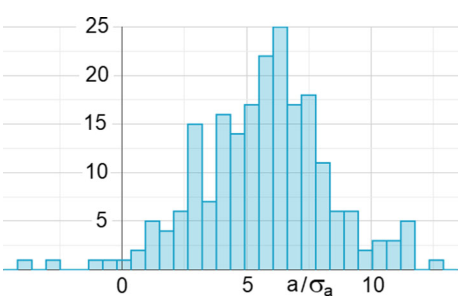


Figure 4
Histogram of the statistical significance of the regression coefficient (slope) for annual average temperature values for 210 stations over the period 1951–2020. The value plotted is a/σ_a i.e., slope divided by its standard deviation

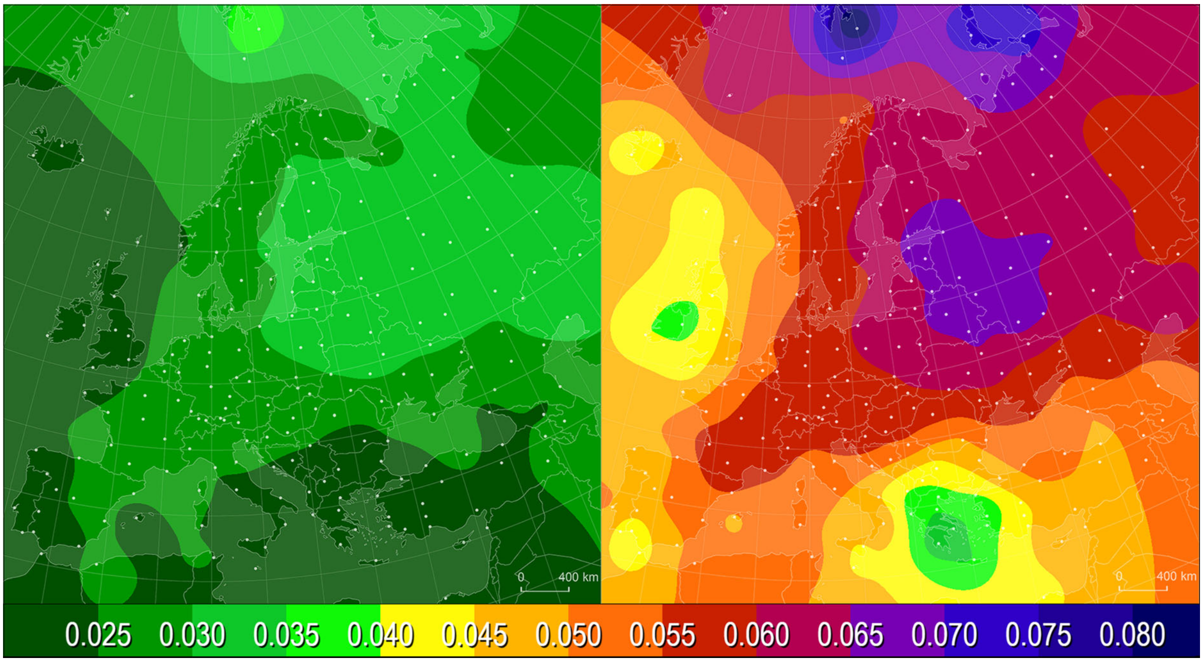


Figure 5
Maps of the annual temperature trends (regression coefficient, slope; unit °C/year), over the time spans 1951–2020 (left) and 1985–2020 (right). Smoothing parameter: d = 200 km

(Fig. 5), therefore further analysis focused on the changes of temperature in the latter period.

The study reveals a strong increase in the annual mean temperature towards the north-east (Fig. 5a, b). In the area from the Baltic and Poland in the west to as far as the vast areas of European Russia in the east and the Arctic in the north, the temperature trend was from 0.060–0.070 °C/year, and even higher in the north. A clearly weaker trend (below 0.050 °C/year) can be observed in the western and south-eastern parts of the study area. The first of these areas extends from Iceland in the north, across the British Isles, to Portugal and the western Pyrenees in the south. The second one covers the central and eastern part of the Mediterranean Basin. The slowest rate of temperature increase is observed over a small area stretching from Greece to Crete—below 0.035 °C/year.

The values of the regression coefficient (slope) quoted above are all statistically significant. However, the trend expressiveness or stability is systematically changing over the area of study. This is the reason for Fig. 6, the map of a quantity of another type. This presents the distribution of the

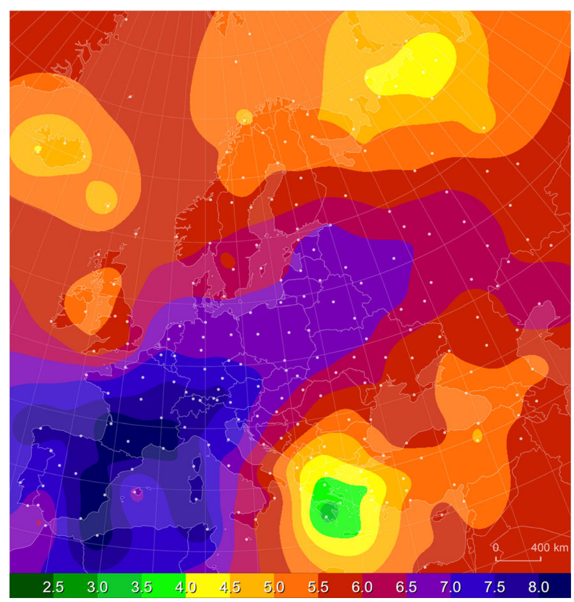


Figure 6
Map of the statistical significance of the regression coefficient of annual temperatures in 1951–2020. The plot is of the slope divided by its standard deviation: a/σ_a (four negative a's included)

quotient a/σ_a, where a is the regression coefficient and σ_a is its standard error. Assuming a normal probability distribution for a, which seems to be acceptable here (not necessitating the t-student distribution because n is not too small; n = 35), the standard probabilities (p-values) may be assigned to $x = a/\sigma_a$: $p(|x|> 1) = 0.32$, $p(|x|> 2) = 0.05$, $p(|x|> 3) = 0.0027$. The physicists even apply a 5σ rule; the scale in Fig. 6 goes beyond 8σ. The map is weakly smoothed, to show details, even single sites. Anyway, the general pattern is clear, while its explanation is not necessarily so.

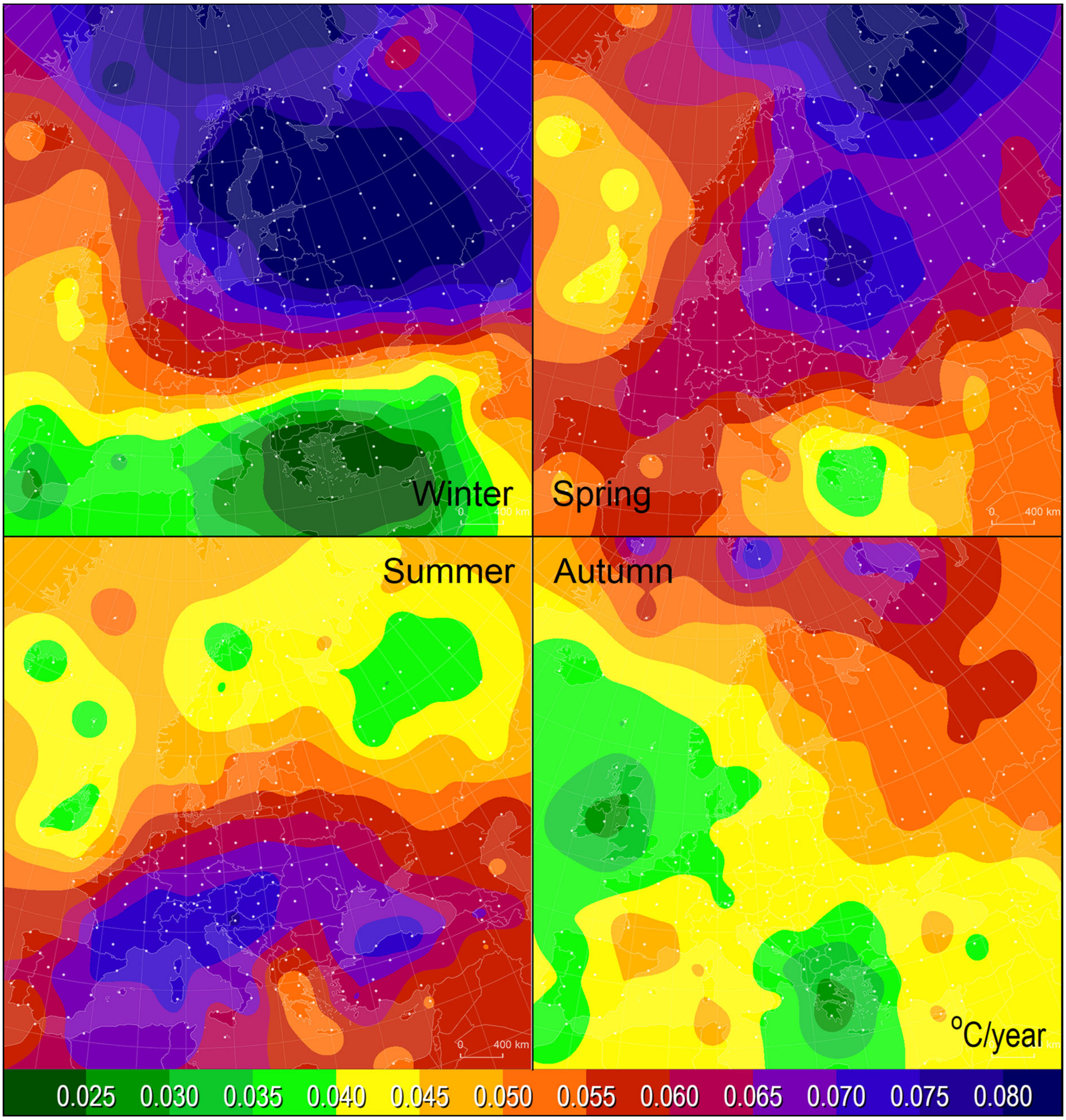


Figure 7
Seasonal temperature trends (°C/year) in 1985–2020. Smoothing parameter: d = 200 km

The greatest spatial variation in air temperature trends is observed in winter (Fig. 7): from below 0.030 °C/year in the east of the Mediterranean Sea to over 0.750 °C/year in the area extending from the North Baltic to the western and central parts of the East European Plain and around Svalbard in the north. Overall, this time of year reveals a marked increase in the warming gradient northwards.

In spring the temperature trends over the whole of Europe and its immediate surroundings exceed 0.060 °C/year, reaching as much as 0.080 °C/year in the north-eastern end. By contrast, the smallest trends (below 0.050 °C/year) are noticeable in the eastern Mediterranean, which reveals clear similarities to the spatial distribution of temperature trends in winter.

In summer, the spatial distribution of trends diverges significantly from that for winter and spring, revealing a decline from the south (over 0.060 °C/year) northwards (0.050 °C/year). In autumn, as in summer, warming shows least spatial variation. Over most of the continent, the temperature trend ranges between 0.040 and 0.050 °C/year. Slightly slower growth is found in the area of the British Isles and in the eastern Mediterranean. In some of north-eastern Europe, the temperature rise is slightly greater.

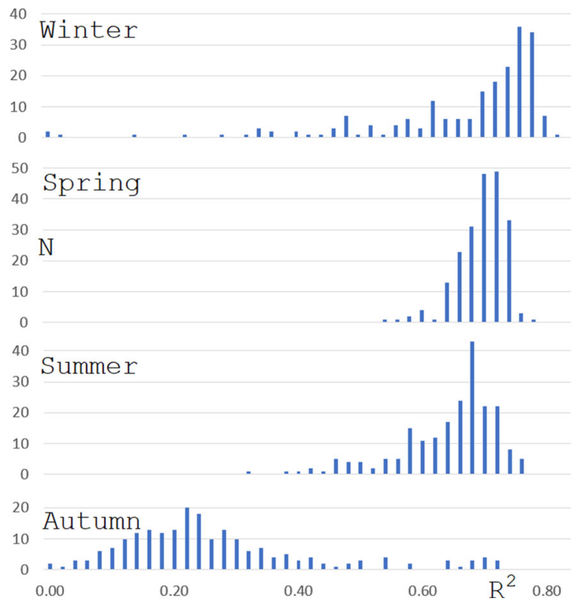


Figure 8
Histograms of the coefficient of determination (R^2) of the linear regression of temperature on time, for the period 1985–2020, calculated for all 210 stations, separately in seasons

Evidently the statistical significance of the trend is weakest in autumn. It is clearly visible on Fig. 8, showing all four seasons. In winter the highest R^2 are obtained, while, at the same time there are stations below standard significance (< 0.11, at alpha = 0.05), which are numerous for autumn. The spring season produces the narrowest range of R^2; almost all stations give a very high coefficient of determination, within 0.6–0.8.

5. *Discussion and conclusions*

The research based on a 70-year (1951–2020) series of annual and seasonal temperature values from 210 meteorological stations in Europe and its immediate surroundings has yielded several important observations.

1. A statistical analysis of the area-average series of air temperature values in the 70-year period of 1951–2020 from the entire area under consideration has revealed the existence of 2 periods: (1) 1951–1985 with a relatively constant temperature, and (2) 1985–2020 with linear growth of high statistical significance. Therefore, an actual temperature trend can be identified from the second half of the seven-decade period under consideration, namely from 1985. The choice of this year is justified statistically in the light of the quality of the fit of the linear regression. The slope of the regression line for both annual and seasonal temperatures in 1985–2020 is about twice as great as in the 1951–2020 period, which is obviously linked to the half as long period on the horizontal axis. For the mean annual temperature it was 0.027 and 0.051 °C/year respectively.

There is a high likelihood that the rise in temperatures observable since the mid-1980s is the greatest warming in the last 2000 years (Luterbacher et al., 2016). The warming is manifested by a rise in maximum temperature, and even more so in minimum temperature, including a growth in the frequency of tropical nights (Dong et al., 2017).

Temperature change trends in mountainous areas (above 1000 m a.s.l.) are the same as in areas outside of the mountains, which aligns with the results of studies by other authors (Migała et al., 2016).

2. The rate of temperature rise does not differ significantly from one season to another, but it displays a specific pattern. The highest growth is recorded in spring and the lowest in autumn, which is illustrated by the regressions for both the 1951–2020 and 1985–2020 periods. Comparing the trend over these two seasons in these two cases gives p-values of 0.056 and 0.016 respectively. The latter value is significant as long as one disregards the fact that the two extreme values were chosen from four available ones. Specifically, the temperature rise rate for spring is 0.031 °C/year over the entire 70-year period and 0.061 °C/year in 1985–2020. For autumn, this is 0.022 and 0.045 °C/year, respectively. In winter, due to the large standard error of the regression coefficient, the temperature increase should be considered the least stable, which stems from the greatest year-to-year temperature variation in this season. The opposite is true in summer, i.e. the most stable rise in air temperature is observed. Similarly, the trend of annual mean air temperature is highly stable, which, however, is associated with the lowest variability of average values.

A strong increase in temperature, especially in spring, has many negative consequences. The early emergence of a long spell of hot weather, as was the case in April and May 2018 invast areas of Europe (e.g. Sinclair et al., 2019; Twardosz, 2019; Twardosz & Kossowska-Cezak, 2021)), has very negative biometeorological consequences, because the human body has not yet adapted to the new conditions after the winter (Muthers et al., 2017). Moreover, early onset of hot and usually dry weather after a mild and snowless winter considerably aggravates drought. This has negative consequences in many areas of the economy, contributing, in particular, to huge losses in agricultural production (Peters et al., 2020; Sinclair et al., 2019; Twardosz, 2019).

3. The rapid increase in temperature leads, above all, to extreme climatic phenomena in Europe, which include month-long spells or even entire seasons with abnormally high temperatures greatly exceeding the long-term average by at least 2 standard deviations (Twardosz & Kossowska-Cezak, 2021)—often 3 or even 4. This was the case, for example, in the summer months of 2003, 2010 and 2015 (e.g. Luterbacher et al., 2004, 2016; Gruza and Ran'kova, 2011; Trenberth & Fasullo, 2012; Hoy et al., 2016; Dong et al., 2017; Twardosz & Kossowska-Cezak, 2021) and 2018 (Sinclair et al., 2019; Twardosz, 2019). Such anomalously warm spells are not local in nature, but instead, tend to cover ever vaster areas of the European continent (Twardosz & Kossowska-Cezak, 2021) and are more and more onerous for society (Hegerl et al., 2018). On the other hand, it should be remembered that although large-scale negative anomalies, such as for example during the extremely cold winter of 1962/1963 (e.g. Hirschi & Sinha, 2007), have not yet occurred in the twenty-first century, spells with steep falls in temperature do occur. This was the case, for instance, in January 2017 in the Balkan Peninsula that was, according to Anagnostopoulou et al. (2017), among the coldest and snowiest ones in this area.

It can be concluded that Europe sees asymmetric warming, which means an increase in air temperature variance.

4. The greatest warming (from autumn to spring) on the continent occurs in north-east Europe. Parts of the area, i.e. the region from the North Baltic to the western and central parts of the East European Plain and around the Svalbard region in the north, saw record-high positive trends of about 0.080 °C/year in winter. By contrast, in summer, the greatest warming of around 0.060 °C/year was recorded in the south and central part of Europe. The above areas with the highest recorded temperature growth are expected to record further upward trends (e.g. Christensen et al., 2015; Vautard et al., 2014). According to Vautard et al. (2014), greater winter warming in the high latitudes of Europe will have both negative and positive effects, one of which will be reduced needs for heating in winter.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability The temperature values used were retrieved from the publicly available websites listed in the text in Sect. 2. Data and methods. European Climate Assessment & Dataset (ECA&D., http://eca.knmi.nl/), NCDC (ftp://ftp.ncdc.noaa.gov/pub/data/gsod/)), Ogimet (www.ogimet.com).

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Consent to participate Not applicable.

References

Anagnostopoulou, C., Tolika, K., Lazoglou, G., & Maheras, P. (2017). The Exceptionally Cold January of 2017 over the Balkan Peninsula: a climatological and synoptic analysis. *Atmosphere, 8*(252), 1–14.

Anisimov, O. A., & Zhil'tsova, E. L. (2012). Climate change estimates for the regions of Russia in the 20th century and in the beginning of the 21st century based on the observational data. *Russian Meteorology and Hydrology, 37*(6), 21–429.

Błażejczyk, K., Twardosz, R. (2010). Long-term changes of bioclimatic conditions in Kraków (Poland). In: R. Przybylak et al. (Eds.) *The Polish Climate in the European Context: An Historical Overview* (pp. 235–246). Springer Science + Business Media B.V. https://doi.org/10.1007/978-90-481-3167-9_10.

Chen, D., Walther, A., Moberg, A. et al. (2015). *European Trend Atlas of Extreme Temperature and Precipitation Records*. Springer Science+Business Media. https://doi.org/10.1007/978-94-017-9312-4_1.

Christensen, O. B., Yang, S., Boberg, F., et al. (2015). Scalability of regional climate change in Europe forhigh-end scenarios. *Climate Research, 64*, 25–38.

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

Coumou, D., Robinson, A., & Rahmstorf, S. (2013). Global increase in record-breaking monthly-mean temperatures. *Climate Change, 118*, 771–782.

Dong, B. W., Sutton, R. T., & Shaffrey, L. (2017). Understanding the rapid summer warming and changes in temperature extremes since the mid-1990s over Western Europe. *Climate Dynamics, 48*(5–6), 1537–1554.

Gruza, G. V., & Ran'kova, EYa. (2011). Estimation of probable contribution of global warming to the genesis of abnormally hot summers in the European part of Russia. *Izvestiya, Atmospheric and Oceanic Physics, 47*(6), 661–664.

Hansen, J., Sato, M., & Ruedy, R. (2012). Perception of climate change. *Proceedings of the National Academy of Sciences of the United States of America, 109*, E2415–E2423. https://doi.org/10.1073/pnas.1205276109

Hegerl, G., Brönnimann, S., Schurer, A., & Cowan, T. (2018). The early 20th century warming: anomalies, causes, and consequences. *Wires Climate Change*. https://doi.org/10.1002/wcc.522

Hirschi, J. J. M., & Sinha, B. (2007). Negative NAO and cold Eurasian winters: How exceptional was the winter of 1962/1963? *Weather, 62*, 43–48.

Hoy, A., Hänsel, S., Skalak, P., Ustrnul, Z., & Bochníček, . (2016). The extreme European summer of 2015 ina long-term perspective. *International Journal of Climatology, 37*, 943–962.

IPCC. (2013). 5th Assessment Report Climate Change 2013. The Physical Science Basis. http://www.ipcc.ch.

Ji, F., Wu, Z., Huang, J., & Chassignet, E. P. (2014). Evolution of land surface air temperature trend. *Nature Climate Change, 4*, 462–466.

Jones, P. D., Lister, H. H., Osborn, T. J., Harpham, C., Salmon, M., & Moric, C. P. (2012). Hemispheric and large-scale land surface air temperature variations: an extensive revision and an update to 2010. *Journal of Geophysical Research, 117*, D05127. https://doi.org/10.1029/2011JD017139

Jones, P. D., & Moberg, A. (2003). Hemispheric and large-scale surface air temperature variations: an extensive revision and an update to 2001. *Journal of Climate, 16*, 206–223.

Kamae, Y., Shiogama, H., Watanabe, M., & Kimoto, M. (2014). Attributing the increase in Northern Hemisphere hot summers since the late 20th century. *Geophysical Research Letters, 41*, 5192–5199.

Klein Tank, A. M. G., Wijngaard, J. B., Können, G. P., et al. (2002). Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment. *International Journal of Climatology, 22*, 441–1453.

Krauskopf, T., & Huth, R. (2020). Temperature trends in Europe: Comparison of different data sources. *Theoretical and Applied Climatology, 139*, 1305–1316. https://doi.org/10.1007/s00704-019-03038-w

Kundzewicz, Z. W., Pińskwar, I., & Koutsoyiannis, D. (2020). Variability of global mean annual temperature is significantly influenced by the rhythm of ocean-atmosphere oscillations. *Science of the Total Environment, 747*, 141256. https://doi.org/10.1016/j.scitotenv.2020.141256

Liu, X., He, B., Guo, L., Huang, L., & Chen, D. (2020). Similarities and differences in the mechanisms causing the European summer heatwaves in 2003, 2010, and 2018. *Earth's Future*. https://doi.org/10.1029/2019EF001386

Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M., & Wanner, H. (2004). European seasonal and annual temperature variability, trends, and extremes since 1500. *Science, 303*, 1499–1503.

Luterbacher, J., Werner, J. P., Smerdon, J. E., et al. (2016). European summer temperatures since Roman times. *Environmental Research Letters, 11*(2), 024001.

Meleshko, V. P., Mirvis, V. M., Govorkova, V. A., Baidin, A. V., Pavlova, T. V., & Lvova, TYu. (2019). The Arctic Climate Warming and Extremely Cold Winters in North Eurasia during 1979–2017. *Russian Meteorology and Hydrology, 44*(4), 223–230.

Migała, K., Urban, G., & Tomczynski, K. (2016). Long-term air temperature variation in the Karkonosze mountains according to atmospheric circulation. *Theoretical and Applied Climatology, 125*(1), 337–351.

Moberg, A., Jones, P. D., Lister, D., et al. (2006). Indices for daily temperature and precipitation extremes in Europe analyzed for the period 1901–2000. *Journal of Geophysical Research, 111*, D22106.

Muthers, S., Laschewski, G., & Matzarakis, A. (2017). The Summers 2003 and 2015 in South-West Germany: heatwaves and heat-related mortality in the context of climate change. *Atmosphere, 8*(224), 1–13.

Peters, W., Bastos, A., Ciais, P., & Vermeulen, A. (2020). A historical, geographical and ecological perspective on the 2018 European summer drought. *Philosophical Transactions of the Royal Society B., 375*, 20190505. https://doi.org/10.1098/rstb.2019.0505

Rahmstorf, S., Foster, G., & Cahill, N. (2017). Global temperature evolution: recent trends and some pitfalls. *Environmental Research Letters, 12*, 054001.

Schönwiese, C. D., & Rapp, J. (1997). *Climate trend atlas of Europe based on observations 1891–1990*. Kluwer Academic.

Sinclair, V. A., Mikkola, J., Rantanen, M., & Räisänen, J. (2019). The summer 2018 heatwave in Finland. *Weather, 74*, 403–409.

Slonosky, V. C., Jones, P. D., & Davies, T. D. (2001). Atmospheric circulation and surface temperature in Europe from the 18th century to 1995. *International Journal of Climatology, 21*, 63–75.

Trenberth, K. E., & Fasullo, J. T. (2012). Climate Extremes and Climate Change: The Russian Heat Wave and Other Climate Extremes of 2010. *Journal of Geophysical Research, 117*, D17103.

Trenberth, K. E., Jones, P. D., Ambenje, P., et al. (2007). Observations: Surface and Atmospheric Climate Change. In S. Solomon (Ed.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 235–336). Cambridge University Press.

Twardosz, R. (2019). Anomalously warm months in 2018 in Poland in relation to airflow circulation patterns. *Weather, 74*, 374–382.

Twardosz, R., & Batko, A. (2012). Heat waves in Central Europe (1991–2006). *International Journal of Global Warming, 4*(3/4), 261–272.

Twardosz, R., & Kossowska-Cezak, U. (2015). Exceptionally hot and cold summers in Europe (1951–2010). *Acta Geophysica, 63*(1), 275–300. https://doi.org/10.2478/s11600-014-0261-2

Twardosz, R., & Kossowska-Cezak, U. (2016). Exceptionally cold and mild winters in Europe (1951–2010). *Theoretical and Applied Climatology, 125*, 399–411.

Twardosz, R., & Kossowska-Cezak, U. (2019). Thermal anomalies in the Mediterranean and in Asia Minor (1951–2010). *International Journal of Global Warming, 18*(3/4), 304–332.

Twardosz, R., & Kossowska-Cezak, U. (2021). Large-area thermal anomalies in Europe (1951–2018). *Temporal and Spatial Patterns. Atmospheric Research, 251*, 105434. https://doi.org/10.1016/j.atmosres.2020.105434

Van den Besselaar, E. J. M., Klein Tank, A. M. G., & van der Schrier, G. (2010). Influence of circulation types on temperature extremes in Europe. *Theoretical and Applied Climatology, 99*, 431–439.

Van der Schrier, G., van den Besselaar, E. J. M., Klein Tank, A. M. G., & Verver, G. (2013). Monitoring European average temperature based on E-OBS gridded data set. *Journal of Geophysical Research: Atmospheres, 118*, 5120–5135. https://doi.org/10.1002/jgrd50444

Van Oldenborgh, G. J., Drijfhout, S., van Ulden, A., Haarsma, R., Sterl, A., Severins, C., Hazeleger, W., & Dijkstra, H. (2009). Western Europe is warming much faster than expected. *Climate of the past, 5*, 1–12. https://doi.org/10.5194/cp-5-1-2009

Vautard, R., Gobiet, A., Sobolowski, S., et al. (2014). The European climate under a 2°C warming. *Environmental Research Letters, 9*, 034006. https://doi.org/10.1088/1748-9326/9/3/034006

Wijngaard, J. B., Klein Tank, A. M. G., & Können, G. P. (2003). Homogeneity of 20th century European daily temperature and precipitation series. *International Journal of Climatology, 23*, 679–692.

Xoplaki, E., Luterbacher, J., Paeth, H., et al. (2005). European spring and autumn temperature variability and change of extremes over the last half millennium. *Geophysical Research Letters, 32*, L15713.

Zveryaev, I., & Gulev, S. K. (2009). Seasonality in secular changes and interannual variability of European air temperature during the twentieth century. *Journal of Geophysical Research, 114*, D02110. https://doi.org/10.1029/2008JD010624

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