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RESEARCH ARTICLE

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Using early extremes to place the 2022 UK heat waves into historical context

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Abstract

As global surface temperatures continue to rise, both the duration and the intensity of heat waves across most land areas are expected to increase. The 2022 European summer broke a number of temperature records where a new record daily maximum temperature of 40.3°C was reached on 19th July making it the hottest July heat wave event in the UK. This paper aims to detect and analyse historical heat wave events, particularly prior to 1927 and compare these with recent events, particularly, 2022, which featured four summer heat wave events in the UK. This allows us to understand how noteworthy historical extremes are in comparison to those in recent decades, to place modern events into historical context, and to extend the sample of extreme events. Summer heat wave events have been detected between 1878 and 2022 from long station data in the UK. Heat wave extent, duration, and intensity have been analysed to compare past heat waves to the recent 2022 heat waves. For each of the summer months at least one of the top 10 most intense events between 1878 and 2022 occurred in the earliest third of the dataset (before 1927) emphasising the value of analysing early heat events. In all detected events, the anomalous UK heat was part of large-scale European extreme heat when examining 20th-century reanalysis data, associated with a high-pressure system. The 2022 July event resembles in pattern of warming and circulation some earlier events, for example, in 1925. While there is a clear trend in the monthly data and the overall frequency of anomalously hot days, heat wave activity on daily scales even in the period 1878 and 1926 is considerable and in some cases comparable to modern heat wave events in the UK. The most intense events detected led to societal impacts based on UK newspaper articles from the period including impacts on the agricultural sector, health impacts, and travel disruptions, broadly comparable to impacts from recent events.

KEYWORDS

heat waves, impacts, mechanisms

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1 | INTRODUCTION

The magnitude and the frequency of heat wave events in Europe and around the world are expected to increase as the globe continues to warm (Fischer & Schär, 2010; Masson-Delmotte et al., 2021; Perkins, 2015; Russo et al., 2015; Schär et al., 2004; Seneviratne et al., 2021). The National Weather Service in the USA regards heat waves as the major cause of weather-related fatalities most years (Robinson, 2001) and in Europe, the 2003 heat wave resulted in the loss of life of up to 70,000 people (García-Herrera et al., 2010; Robine et al., 2008). The heat throughout summer of 2022 has been estimated to have led to the death of 15,000 people in Europe and 3200 in the UK (Henri & Kluge, 2022). There are race, class, and gender disparities in heat extremes and who is most heavily impacted by them (Benz & Burney, 2021; Chakraborty et al., 2019; van Steen et al., 2019). These disparities can relate to the heat island effect, the level of tree cover and green spaces in high versus low-income areas as well as to the density of the built environment amongst other factors. While a single day of heat will not generally result in increased mortality, 2·days of consecutive heat can lead to a substantial increase, particularly when night-time temperatures are high (Perkins, 2015).

Heat waves are normally defined as an extended period of unusually high temperature. Previous studies of heat waves have used definitions with a variety of time and spatial scales (National Academies of Sciences, Engineering, and Medicine (US) and National Academies of Sciences, Engineering, and Medicine (US), 2016; Xu et al., 2016). Definitions are usually based on the exceedance of fixed absolute values or a deviation from the normal such as from a daily mean or maximum value (Cowan et al., 2014; Donat et al., 2016; Robinson, 2001).

In this paper, heat wave events that occurred in the 19th and 20th centuries in the UK are detected and analysed. A more detailed analysis of early observed events can help to understand decadal variability in heat wave activity (Beckett & Sanderson, 2022; Burt, 2004; Hegerl et al., 2019; Sanderson et al., 2017) and improve the sampling of conditions that lead to rare extreme heat, and with that improve preparedness for events with similar mechanisms in the future. While many studies focus on recent heat wave events, including attribution (National Academies of Sciences, Engineering, and Medicine (US), 2016; Stott et al., 2016), for example, past events in the early instrumental record contain useful information and can provide samples of heat waves to learn more about the mechanisms behind them and anticipate future heat waves that may not always be well captured by climate models (Van Oldenborgh et al., 2022). By analysing past events we ensure that the study of extreme events is not limited to today's climate state, and we extend the sample of analysed extreme events to be used in future studies. They can also be used to place modern events, such as the 2022 European summer heat waves, into a historical context (Hawkins et al., 2022; Hegerl et al., 2019).

We focus on summer events due to the impact of such events on human health. How events have changed from past to present is investigated in terms of their frequency, and individual events from the past are compared to more recent heat wave events, such as the 2022 heat events in the UK. We detect 19th and early 20th-century heat waves using temperature data from central England where there are existing long observational records. The definition of a heat wave used here has been designed to work best for the central England region. This paper also makes use of reanalysis data to determine the spatial extent and synoptic situation that was involved in generating the heat wave, and to understand if long regional datasets can be used to detect large-scale heat waves.

Heat waves are generally described using daily data; however, monthly data are available to further back in time and with better spatial coverage than daily data for many time periods and regions. We investigate to what extent monthly data can capture anomalous heat by understanding if monthly temperature is indicative of a heat wave event occurring at the daily level. In addition, testing for overlaps between heat waves detected on a monthly basis versus daily could push the study of heat waves further back in time. To allow for this, the daily heat wave events are detected for each month of summer separately.

Lastly, archival documentary data is used to understand if any impacts were felt during the events detected and selected from the station and gridded data sets. This illustrates whether these early heat waves had consequences for the UK population at the time.

2 | DETECTING HEAT WAVES USING STATION DATA

2.1 | Datasets used

The instrumental data used for this analysis include the Met Office Hadley Centre Central England Temperature Data (HadCET) (Parker et al., 1992) as well as the station data from the Radcliffe Observatory site in Oxford (Burt & Burt, 2019). These datasets were selected due to their long instrumental record of temperature as well as due to the fact they have been homogenised and corrected, including for the introduction of the Stevenson screen, and they are regularly updated. The HadCET dataset is the longest instrumental temperature record in the world with the monthly temperature series dating back to 1659, the daily-mean series beginning in 1772 and the daily maximum series dating back to 1878. The dataset is representative of a triangular area of the UK which encloses Lancashire, London, and Bristol. The data has been adjusted for urban warming from 1974 with a correction of −0.2°C applied to mean temperatures. HadCET has been used in other recent heat wave studies (King et al., 2015). The Radcliffe Observatory site in Oxford has monthly mean data dating back to 1813 and daily maximum and minimum values from 1815.

Maximum daily temperatures were used from the HadCET dataset in order to detect and analyse early heat wave events in this paper. The Oxford dataset was analysed as an independent verification as it was not used as a station in the HadCET daily maximum temperature record from 1878 (Parker & Horton, 2005) and is based on a single station measurement. We use data between 1878 and 2022 where data are available from both datasets. The 2022 heat broke many temperature records across Europe and the UK. The UK exceeded 40°C for the first time on record on 19th July 2022 (UK MET Office, 2022) and records for maximum daily temperatures were set at the Radcliffe Observatory site in Oxford (Burt & Burt, 2019) and for the Met Office Hadley Centre Central England Temperature Data (HadCET) (Parker et al., 1992) on the 19th July 2022.

The 20th-century reanalysis version 3 (20CRv3) was used to examine pressure patterns linked to selected early heat events and to understand the spatial extent of the events detected (Compo et al., 2011; Slivinski et al., 2021). NCEP/NCAR Reanalysis 1 (Kalnay et al., 1996) was used to determine the pressure pattern and spatial extent of the July 2022 event as 20CRv3 does not have data for this time period. A comparison of 20CRv3 with HadCET for monthly means of daily maximum temperature (1878–2015) for each month of summer is provided in Figure A1. While 20CRv3 is cooler than CET overall it shows very similar interannual variations and trends to the observations.

To understand any societal impacts that resulted from the past heat wave events, the Times newspaper archives (The Times Archive, n.d.) were used. The online archives hold newspaper articles from 1785 to 1985 and allow the user to search for keywords, related to heat and specific impacts from heat. The term ‘heat’ was used in this search which uncovered impacts relating to human health, agriculture, and impacts on sports. These are noted in section 5 and, although not an exhaustive list of impacts, shows that the events detected using station data had associated societal impacts in the majority of cases.

2.2 | Defining heat waves

The definition used in this paper is at least three consecutive days of daily maximum temperature above the 90th percentile, where the 90th percentile is calculated based on a 15-day calendar window using daily data from 1878 to 2022. We have not detrended the data in our main study in order to treat past heat waves the same as more recent events, but we evaluate sensitivity to doing so. The 90th percentile was used as this is a commonly used percentile threshold in the research of heat wave events (Perkins, 2015; Russo et al., 2015). Other windows were tested with the Oxford and HadCET datasets including 1, 5, and 15-day windows (see Figure A2).

Heat waves are usually defined as at least three consecutive days above a certain temperature threshold although this definition can be extended to four or more consecutive days of heat (Horton et al., 2016; Perkins, 2015). In order to understand if there is a relationship between intensity of a heat wave and its length, the maximum temperature reached during events and the mean temperature of events is plotted in Figure 1. The Pearson's correlation between the maximum temperature reached during a heat wave and mean heat wave temperature reached is large (0.91). In contrast, the correlation between heat wave length and maximum event temperature is relatively weak (0.32) and even weaker with mean event temperature (0.15). Thus, while there is a tendency for low-intensity events to be shorter events, there are some short events with high intensity. In order not to miss such events with potential health consequences (Cowan et al., 2014; Horton et al., 2016; Perkins, 2015), we require only three or more days of anomalous daily maximum temperature when defining a heat wave.

2.3 | Detecting heat wave years

Heat wave years are defined as years where at least one heat wave occurred in the summer (June, July, or August) of that year. A heat wave is considered to have taken place in a particular summer month if at least 3-days of consecutive heat fall within that month (Figure 2). This approach is used for the remainder of the paper in order to understand if monthly temperatures are generally indicative of a heat wave occurring based on daily data. In June, out of the 145 years between 1878 and 2022, 49 heat wave years were detected from the Oxford dataset and 51 from the HadCET dataset. Out of the 51 heat wave years detected in HadCET, 28-years were prior to 1975, and 12-years were between 1878 and 1926. In July, 47 heat wave years were detected between 1878 and 2022 in both the Oxford dataset and HadCET with 25 prior to 1975 and 14-years between 1878 and

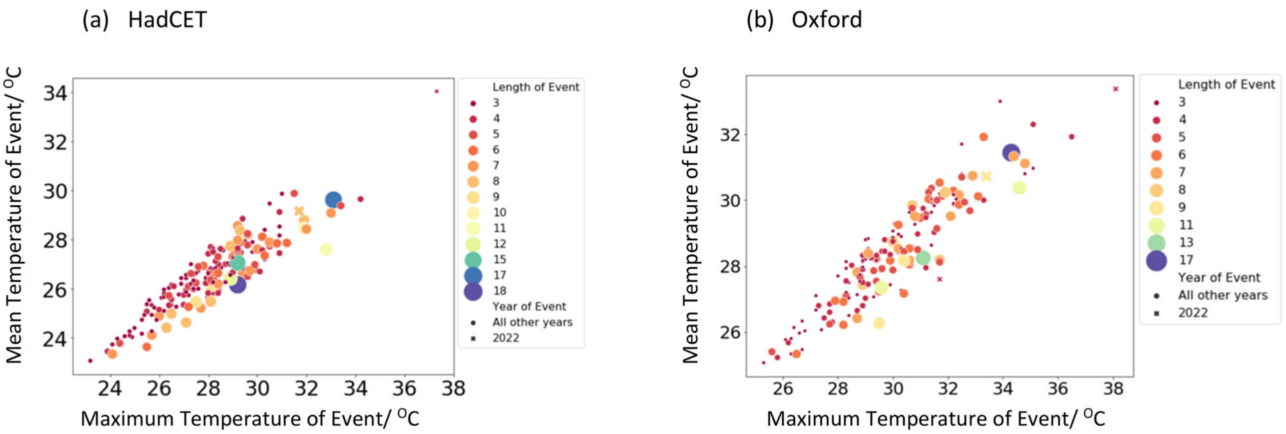

FIGURE 1 Comparison of maximum temperature reached during events and mean temperature of heat wave events in Central England from the HadCET dataset (a) and the Oxford dataset. (b) Note the exceptional nature of 2022 (top right corner).

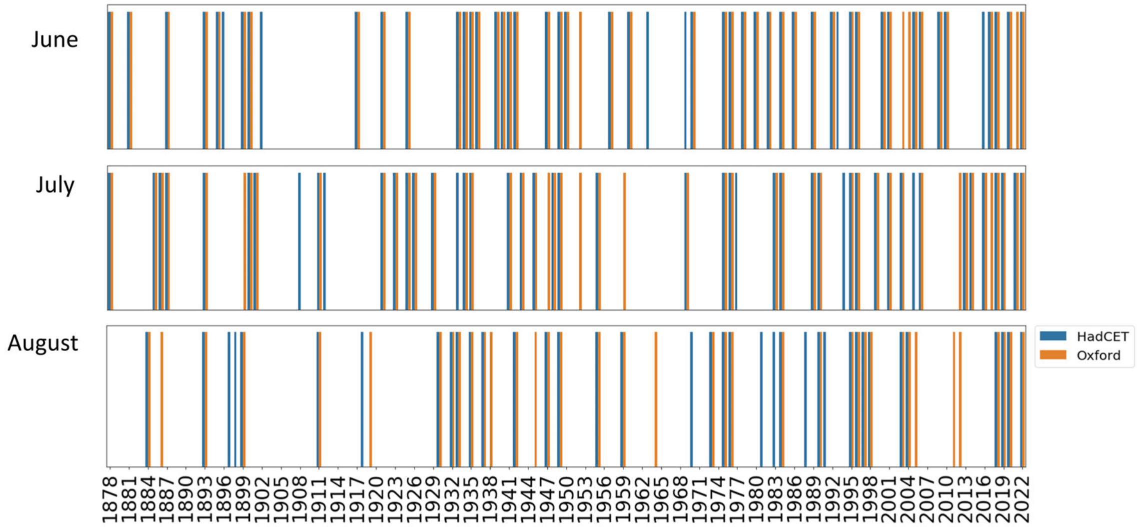

FIGURE 2 Comparison of heat waves detected in HadCET (blue) and Oxford (orange). A bar is used to represent a year where at least one heat wave occurred that month—split into the months of June, July, and August. If a heat wave was detected in both HadCET and Oxford both blue and orange bars are plotted. In June, 93% of heat wave years detected occurred in both time series, in July 91.7% and in August 89%.

1926 and for August, 19 out of 37 heat wave years were prior to 1975, emphasising the added sampling gained by studying early heat events. If the analysis uses detrended data, the fraction of early heat waves is even higher: Based on HadCET, the number of heat wave years prior to 1975 in June increases from 28 to 30, in July this increases from 25 to 27, and in August this increases from 19 to 26 (see Figure A3). Using HadCET, in June, 9.8% of the heat wave years had more than one heat wave occur that year, while that number was higher in July (27.7%) and more so in August (32.4%). For June, the Oxford and HadCET datasets agree for 135 out of a total of 145·years, that is, 93.1% agreement. For July they agree for 91.7% of years and for August they agree for 89% of years. The Pearson's correlation between the maximum monthly temperatures for the HadCET and Oxford datasets varies between 0.93 and 0.95 for the months of June, July, and August (Figure 2). Due to this similarity, and since HadCET dataset covers a larger land area, we use HadCET for the remainder of the analysis in this paper.

3 | A COMPARISON OF PAST AND MODERN HEATWAVES

3.1 | Heat wave trends from past to present

Figure 3 shows an increase in the number of days above the 90th percentile and the number of heat wave events

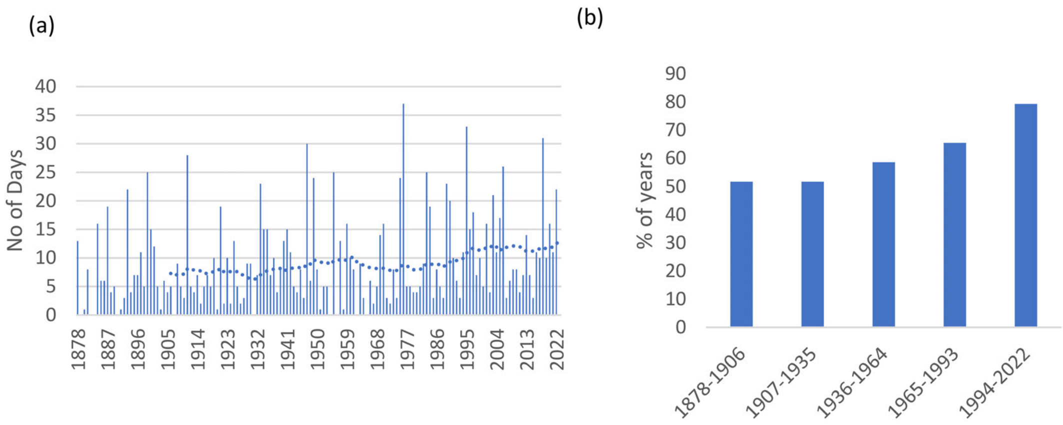

FIGURE 3 (a) A total number of days above the 90th percentile using HadCET in June, July, and August per year between 1878 and 2022 with a 29-year running mean shown by the dashed line (b) the percentage of years per 29-year period from 1878 to 2022 where at least one heat wave occurred that summer (these years were selected to allow five equal bins for comparison).

per year from 1878 to 2022. The summer with the highest number of days above the 90th percentile in central England was 1976 with 37-days during June, July, and August. During the summer of 1911, there was a total of 28-days above the 90th percentile and in 2022 there were 22-days. Figure 3 shows the percentage of years in each 29-year period between 1878 and 2022 in which at least one heat wave occurred. In the most recent period, between 1994 and 2022, at least one heat wave occurred in 79% of years which is higher than the previous 29-year periods (51%–65% of years).

3.2 | Comparing past and modern heat wave events

To compare past heat wave events to those that have occurred more recently, individual heat wave events have been ranked (Figure 4). Intensity of an individual event is defined as an equally weighted average of the mean temperature of the event and the maximum temperature reached during the event, and only the single hottest event for each month was used. Based on our ranking, the highest intensity events in June between 1878 and 2022 occurred in 1947 and 1976, the highest intensity event in July in 2022, and the most intense event in August was in 1990. While recent years contain many strong and highly ranked heat wave events, there are also some strong past events that occurred in the year 1926 or earlier (Figure 4). Overall, in each of the summer months one of the top 10 events, in terms of intensity, occurred before 1927, emphasising the value of analysing early heat events. While there is an increasing trend in the number of days above the 90th percentile and number of heat wave events, there is less of an increase over time in terms of individual heat wave characteristics including mean and maximum temperatures of heat wave events and length of heat wave events.

The UK 2022 summer heat waves broke daily maximum temperature records across the country. The most intense event occurred between the 17th and 19th of July, 2022. This event was ranked as the most intense in any July between 1878 and 2022 in the HadCET dataset. The maximum temperature reached during this event was 37.3°C and the mean temperature across the event was 34°C. In comparison, the second most intense July event, 11–13th July 1976, reached a maximum temperature of 33.1°C and the mean temperature across the event was 31.2°C (see Table 2). The August 2022 heat wave between 8 and 15th was ranked as the second most intense August heat wave between 1878 and 2022 behind a 1990 heat wave event and the 2022 June event between 15 and 17th was ranked 24th most intense, behind some early heat waves including 1878, 1925, and 1893.

4 | DAILY VERSUS MONTHLY TEMPERATURES

4.1 | Are monthly data suitable to detect heat waves?

While we use daily data to define heat waves, monthly data are available to further back in time and could therefore be used to investigate heat waves prior to 1878. We explored to what extent the occurrence of a heat wave event (defined on a daily level) can be indicated by using monthly data alone. Figure 5 plots the monthly means using the HadCET dataset since 1878 and their coincidence with heat waves detected from the daily data.

Summer months with at least one heat wave detected (red bars) show a significantly different distribution of monthly temperatures compared to those without (blue bars). This was verified with the use of the two-sample Kolmogorov–Smirnov test where the *p*-value was below 0.05 for each month of summer. Thus, summer months with heat waves tend to show significantly higher monthly averages.

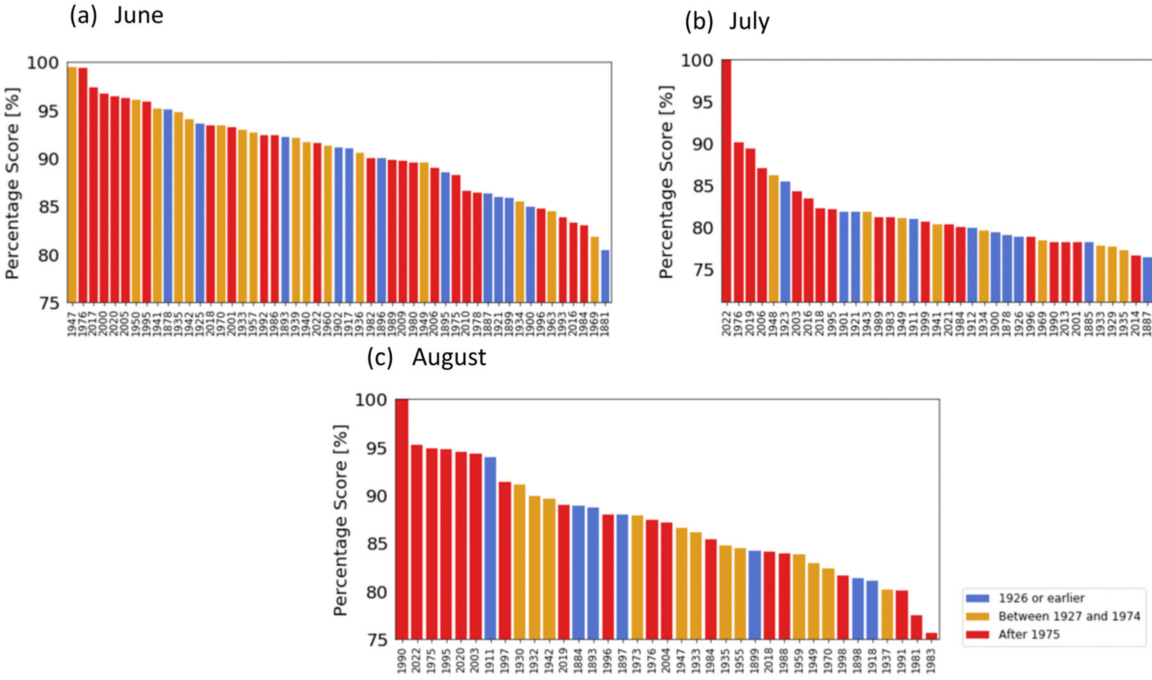

FIGURE 4 Rank of heat wave events based on intensity metrics (choosing the most intense event per year) in (a) June, (b) July, and (c) August split between heat waves that occurred in 1926 or earlier (blue), between 1927 and 1974 (orange) and those occurring after 1975 (red). Percentage Score $=\left(\frac{\overline{T_i}}{\max \overline{T_i}}+\frac{T^x_i}{\max T^x_i}\right)0.5$. Where $T_i=$ mean temperature of event and $T^x{}_i=$ maximum temperature of event. For June $i\in\{1,\ldots,47\}$, for July $i\in\{1,\ldots,45\}$, for August $i\in\{1,\ldots,38\}$.

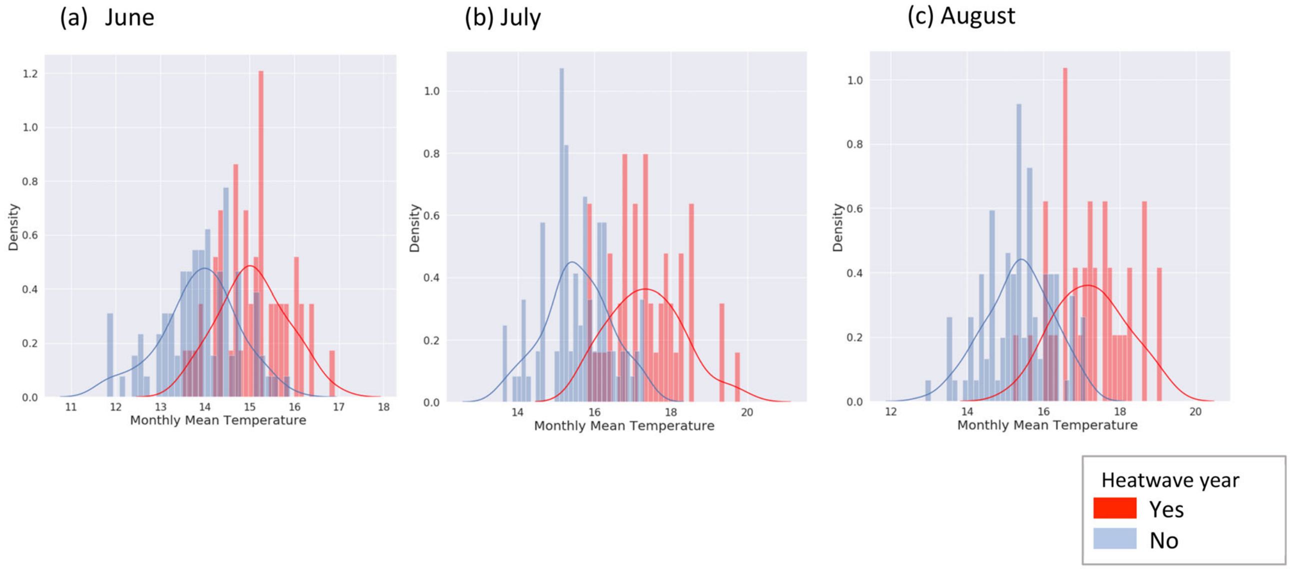

FIGURE 5 The monthly mean temperature from HadCET plotted against their occurrence. Red represents a month where a heat wave occurred that year and blue if a heat wave that did not occur that year for years between 1878 and 2022. As a reference, the monthly mean temperatures for 2022 are June, 14.9°C; July, 18.2°C, and August 18.7°C.

How indicative are high monthly temperatures of the presence of heat waves? To address this, we calculate the percentage of months containing at least one heat wave (based on the earlier defined daily criteria), for all months, and the upper and lower terciles of monthly mean temperatures (Table 1). The likelihood of a heat wave having occurred in a warm month compared to an average month increases by more than a factor of two in June, July, and August, with between 64.6% and 77.1% of months in the upper tercile also showing the occurrence of at least one heat wave. One striking result is that in July, no heat wave events were detected in months in the lower temperature tercile. This suggests that the longer HadCET monthly temperature time series starting in 1659 can be used as a proxy for the presence of heat waves before daily data were available, although not a perfect one. June 1676, for example, is the second warmest June on record and August 1747 is the seventh warmest August on record and may hold interesting heat waves to compare with more recent heat waves. This could extend the record and samples of extreme temperature events in order to place contemporary events, like 2022, into an even longer historical context.

TABLE 1 Percentage of summer months containing at least one heat wave (Total (expected)) compared to the percentage of heat waves in the warmest and coldest months (based on the monthly mean) from 1878 to 2022. The fraction of months with a heat wave is more than twice that in a warm month compared to an average month in June, July, and August.

% of heat wave years	Total (expected)	Warmest months (top third)	Coldest months (bottom third)
Jun.	35.2%	70.8%	6.3%
Jul.	32.4%	77.1%	0%
Aug.	24.8%	64.6%	2.1%
% of heat wave years	Total (expected)	Warmest months (top third)	Coldest months (bottom third)
Jun.	35.2%	70.8%	6.3%
Jul.	32.4%	77.1%	0%
Aug.	24.8%	64.6%	2.1%

5 | CASE STUDIES OF HEATWAVE YEARS

How representative are early heat waves detected in HadCET of large-scale European heat, and what were the atmospheric circulation anomalies that lead to them? The 20CRv3 was used to analyse the weather conditions under which the heat waves occurred and the spatial extent of anomalous heat, focusing on two heat wave events for each summer month that are ranked highest in Figure 4 and occurred prior to 1927. While extreme temperatures from reanalysis are more uncertain than from station data, 20CR has successfully been compared to station data for the US dustbowl heat events (Cowan et al., 2017). The heat wave events shown are compared to the highest intensity July 2022 heat wave. The highest intensity heat wave events in June were in 1878 and 1925, in July 1923 and 1901, and in August 1911 and

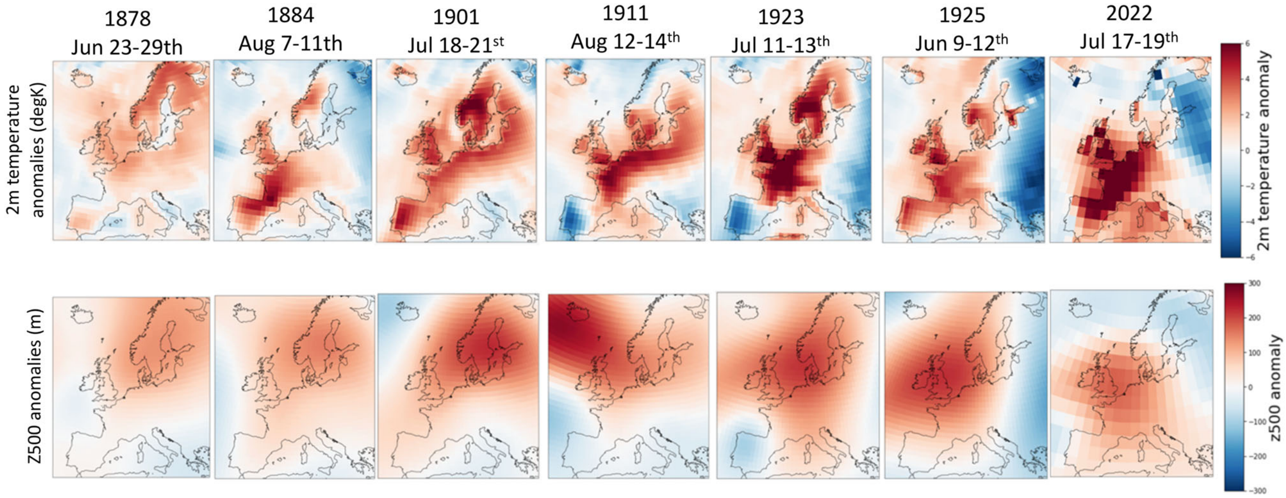

FIGURE 6 Monthly 2·m temperature and Z500 anomalies for the six most intense early events (with reference to Figure 4) and the highest intensity 2022 event. Reference period for anomalies is 1981–2010. 20th-century reanalysis v3 data and NCEP-NCAR Reanalysis 1 data provided by the NOAA/OAR/ESRL PSL, Boulder, CO 20CRv3 was used for the early heat waves and NCEP-NCAR was used for 2022, a similar model to 20CRv3.

TABLE 2 Highest intensity early heat wave years compared to 2022, and their associated characteristics including the number of days reached above the 90th percentile per month; the maximum temperature reached during the event; the mean temperature reached during the event; other events that occurred in the summer of that year and the ranking of the month compared to all years from 1878 to 2022 (145·years) using monthly mean temperature.

Year	Month	Event dates	No of days above 90th percentile	Max temp reached (°C)	Mean temp reached (°C)	Heat wave event ranking (heat wave years between 1878 and 2022 per month)	Monthly mean ranking(all years between 1878 and 2022 per month)	UK impacts (reported in the times archives for 1878–1926)
	Events from early period (1878–1926)							
1878	Jun.	23–29th	7	29.4	26.7	10	31	Health/agriculture/sports
	Jul.	17–2nd	6	29.0	27.3		48	Sports
1884	Aug.	7–11th	11	29.3	27.5	13	18	Health/sports/agriculture
		22–24th	11	28.0	26.7			No direct impacts found
1901	Jul.	18–21st	6	29.4	28.9	11	12	Health/sports
1911	Jul.	6–8th	13	27.1	26.6		8	Health
		11–14th	13	28.0	27.4			Health/fire
		27–29th	13	29.8	27.9			Health/drought
	Aug.	8–10th	10	30.9	28.2		7	Health/drought/agriculture
		12–14th	10	30.5	29.5	7		Health/drought/agriculture/ sports
1923	Jul.	5–7th	7	29.5	27.9		20	No direct impacts found
		11–13th	7	31.0	29.9	6		No direct impacts found
1925	Jun.	9–12th	7	28.4	26.8	13	37	Health
	Jul.	12–14th	6	25.6	25.5		40	No direct impacts found
2022	**Jun.**	**15–17th**	**5**	**28.2**	**25.8**		**42**	
	Jul.	**10–12th**	**7**	**29.9**	**27.3**		**10**	
	Jul	**17–19th**	**7**	**37.3**	**34.0**	**1**		
	Aug.	**8–15th**	**10**	**31.7**	**29.2**		**3**	

Note: Red rows indicate the most intense events per year and the ranking of these heat wave events compared to other years from 1878 to 2022 have been included in Figure 4. Where further heat waves occurred in the same summer, these are also listed in the table.

1884. Temperature anomalies during the heat wave events in these years are shown in Figure 6, together with the co-occurring geopotential height at 500·hPa (Z500). All six events analysed, in common with the July 2022 heat wave, show a positive temperature anomaly and a positive Z500 anomaly over central England. The highest temperature anomaly over central England was during the event in 2022 followed by July 1923 (see Table 2). The analysis shows that the most intense heat waves detected in central England are part of much larger scale extreme heat events linked to extensive high-pressure systems and that long homogeneous station data can be used to find events with impacts across Europe, although some strong early European heat waves with weak extension into the UK may not have been detected in HadCET. Figure 6 also illustrates that the location of extreme heat varies between heat waves, and is closely linked to the circulation anomaly associated with them.

5.1 | Did detected early heat events cause impacts?

The Times newspaper archives were used to determine if any impacts of extreme heat were reported during the most intense events detected using instrumental data. This is done to evaluate if early events were considered impactful at the time and provides a further, indirect evaluation of the detected early heat.

The term 'heat' was used in a keyword search across the days of each of the events detected in the instrumental data. This was completed for all the heat waves across each summer month of the six selected years with reference to Table 2. The top 10 results in the archive search, which tend to be most relevant, were analysed in order to note any impacts. In addition, the term 'sunstroke' was searched across the entire summer season for each of the 6·years as a proxy for severe health impacts. This term was generally used in the time period to discuss heat and health impacts rather than similar terms such as 'heat stroke'. This allowed for delayed impacts to be detected following a heat wave event.

The UK impacts before 1927 included disruption to travel and sporting activities, agricultural impacts, and health impacts. Deaths from sunstroke were reported during or shortly after the June 1878 heat wave, the July 1901 heat wave, and the July 1911, and July 1923 heat waves. Other reported impacts include mentions of heat heavily impacting smells from sewage systems and drains in London as well as vermin infestations that were blamed on heat affecting hop markets in the UK during the June 1878 heat wave, for example. Health impacts were mentioned in relation to forge and steel workers, and 'agricultural labourers' with reports of work needing to be ceased in the UK in these sectors during heat wave events such as in August 1911. Horses suffering from heat were also reported on during several heat wave events including during 1911 leading to disruption to travel and also impacting the agricultural sector.

This qualitative information illustrates that these early heat waves were associated with local impacts around the UK with some themes, including heat mortality and impacts on agriculture and transport, being similar to those felt by modern society during the 2003 and 2022 heat waves, for example, (Barriopedro et al., 2011; García-Herrera et al., 2010, Henri & Kluge, 2022).

6 | CONCLUSION

The aim of this paper was to detect historical heat waves and compare these to more modern heat wave events to understand if any past events are noteworthy in comparison to more recent events including the 2022 summer heat waves. Between 1878 and 2022, the number of days above the 90th percentile and the number of heat wave events have increased. In the latest 29·year period, between 1994 and 2022, 79% of years had at least one heat wave in the summer months which is higher than any of the previous 29·year periods and consistent with a warming trend of monthly average temperatures. However, some individual heat wave events from the past are comparable to modern heat wave events in terms of the mean and maximum temperatures reached during each event and therefore could be used as case studies alongside more modern events, and are of similar magnitude and consequence as more recent events. When ranked based on the intensity of the event, the 10th strongest event that occurred in June to date was in the year 1878, the sixth most intense event to have occurred in July was in 1923 and the seventh most intense event to have occurred in August was in the year 1911. The most intense heat wave to have occurred in July was in 2022 when a maximum temperature of 37.3°C was reached during the event from 17th to 19th of July. This is the most intense heat wave event on record. The second most intense heat wave event to have occurred in August was in 2022. Analysis of early detected heat wave data in the 20th-century reanalysis shows that these early heat waves were parts of widespread extreme heat over Europe associated with extensive high-pressure anomalies. Historical documentation illustrates that these early heat waves caused impacts on health, food agriculture, and outdoor activities in the UK. Monthly mean temperatures in the HadCET dataset tend to be high for months that contain heat waves defined on the daily level. Between 64.6% and

77.1% of summer months in the upper tercile contained heat waves, and no heat wave years were found in the coldest tercile of monthly anomalies in July, suggesting that prior to availability of daily data, monthly data may be indicative of heat wave conditions which could allow heat waves even earlier in the record to be detected.

AUTHOR CONTRIBUTIONS

Emma Lyndsey Yule: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; software; validation; visualization; writing – original draft; writing – review and editing. **Gabriele Hegerl:** Conceptualization; funding acquisition; methodology; project administration; resources; supervision; writing – review and editing. **Andrew Schurer:** Conceptualization; data curation; funding acquisition; methodology; project administration; resources; software; supervision; writing – review and editing. **Ed Hawkins:** Conceptualization; formal analysis; funding acquisition; methodology; project administration; resources; supervision; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

Datasets used include the Met Office Hadley Centre Central England Temperature Data (HadCET), the Radcliffe Observatory site in Oxford and 20th Century Reanalysis, NCEP/NCAR Reanalysis as well as The Times Archives online.

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APPENDIX A

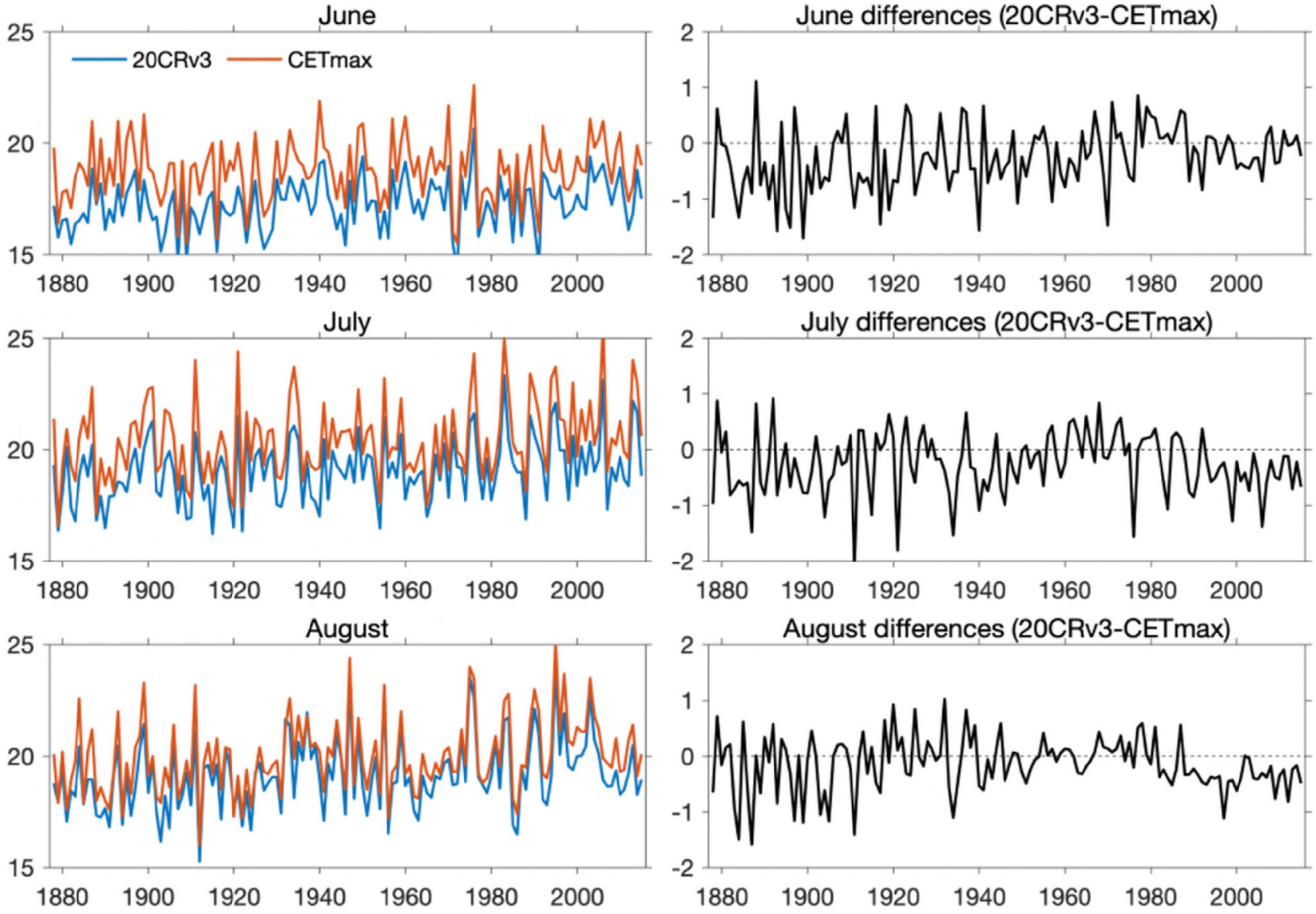

FIGURE A1 Comparison of 20CRv3 with HadCET. Comparing 20CRv3 with HadCET for monthly means of daily maximum temperature (1878–2015) for each month of summer. (Left) Absolute temperatures, and (right) the difference between the series after accounting for a mean bias using a 1961–1990 baseline. 20CRv3 is cooler than CET overall but shows very similar interannual variations and trends to the observations. There are hints that 20CRv3 warms more than the observations before 1961–1990, and warms less than the observations after that period, but these differences are small compared to the size of year-to-year variations. CET does have an urban adjustment applied after 1970 which reduces the observed trend.

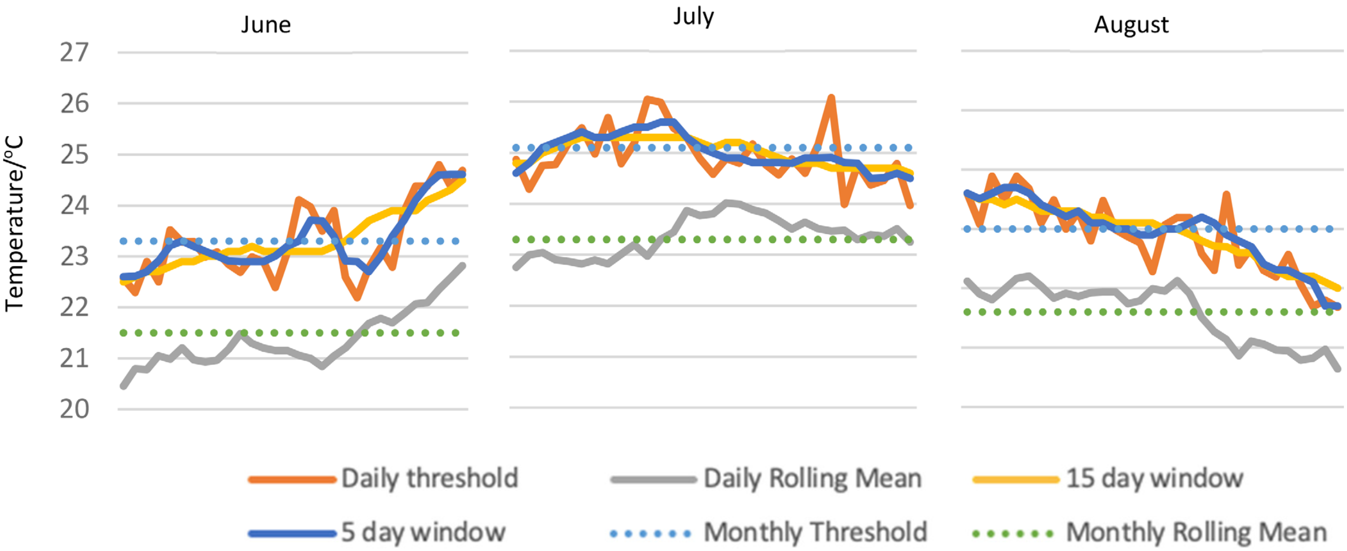

FIGURE A2 Comparison of threshold windows. The monthly threshold (dotted blue) is too low for the end of June and is too high for the end of August and does not take into account the range of temperatures across the month. The daily threshold (orange) is highly variable and is therefore highly dependent on the particular dataset. The 5-day window (blue) is also highly variable whereas the 15-day window (yellow) smooths out any noise in the data and follows the expected climatology for the summer season in Central England. The rolling mean methods were consistently lower than expected. The most appropriate method for calculating the 90th percentile is therefore considered to be the 15-day window method which was used in this paper.

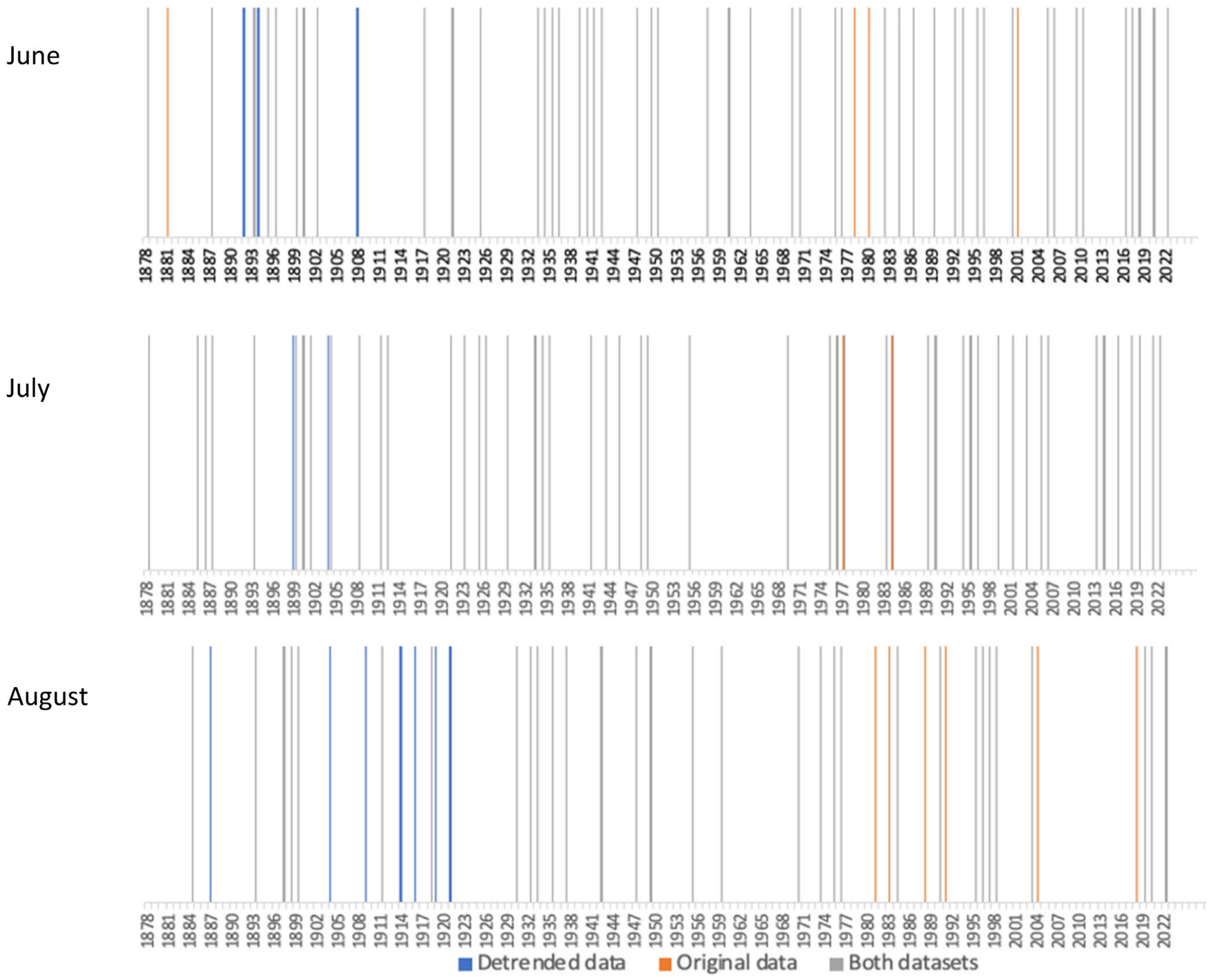

FIGURE A3 Comparison of heat wave years in original (raw) HadCET daily maximum data with detrended data. Grey bars represent heat wave years in both datasets, orange bars represent heat wave years in the original HadCET maximum daily temperature dataset and blue bars represent heat wave years only found in the detrended dataset. In June, the original and detrended datasets agree for 138/145 heat wave years, that is, 95.2% of years, in July they agree for 97.2% of years and in August for 91.7% of years. HadCET maximum daily temperature data was linearly detrended separately for each summer month.