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Using analogues to predict changes in future UK heatwaves*

Emma L Yule[1,**], **Gabriele C Hegerl**[1], **Andrew Schurer**[1], **Andrew Ballinger**[1] and **Ed Hawkins**[2]

[1] School of GeoSciences, University of Edinburgh, Edinburgh EH9 3FF, United Kingdom
[2] National Centre for Atmospheric Science, Department of Meteorology, University of Reading, Reading, United Kingdom
** Author to whom any correspondence should be addressed.

E-mail: emma.yule@ed.ac.uk

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Abstract

The intensity and frequency of extreme heat events is increasing due to climate change, resulting in a range of societal impacts. In this paper, we use temporal analogues to analyse how past UK heatwave events, such as during the summer of 1923, may change if they were to occur under different global warming scenarios. We find that the six most intense early heat events are caused by circulation patterns similar to that of 1923, which can cause intense heat over the UK and parts of NW Europe. Circulation analogues for the 1923 heatwave are also linked to intense heat events in the future, although not all analogues are anomalously hot. At 4 °C of global warming, mean summer temperatures in England over the duration of the 1923 heatwave are between 4.9 and 6.4 degrees warmer than pre-industrial levels across the three models used. At that global mean warming level, future heat events with similar circulation as 1923 over England are estimated to be on average 6.9 °C–10.7 °C hotter than those at pre-industrial levels. Exploring how the intensity of events similar to past events may change in the future could be an effective risk communication tool for adaptation decision making, particularly if past events are stored in society's memory, for example, due to high impacts.

1. Introduction

Extra-tropical summer heatwave events consist of prolonged periods of high temperatures, and tend to occur during periods of anticyclonic atmospheric circulation (Krueger *et al* 2015, Perkins 2015, Kornhuber *et al* 2017, Yiou and Jézéquel 2020). Heatwaves cause a variety of societal impacts including on agriculture, biodiversity and human health (Ebi *et al* 2021, Shivanna 2022). During the summer months of 2003 in Europe, over 70 000 excess deaths are estimated to have occurred and over 60 000 heat related deaths have been estimated in Europe during the summer of 2022 (Robine *et al* 2008, Ballester *et al* 2023). Impacts of heatwaves on society are not felt equally, there are race, class, and gender disparities in who is most heavily impacted by them (Gallo *et al* 2012, Chakraborty *et al* 2019, Benz and Burney 2021). Globally, heat extremes have increased in frequency and in intensity and are expected to increase further due to global warming (Fischer and Schär 2010, Russo *et al* 2014, Perkins-Kirkpatrick and Lewis 2020, Masson-Delmotte *et al* 2021). Furthermore, heat in Europe is projected to increase at a disproportionate rate compared to the global mean temperature (Russo *et al* 2015, Rousi *et al* 2022). Currently, warming in Europe compared to pre-industrial is almost 1 °C higher than the average global increase, higher than on any other continent (Copernicus 2022, Simmons 2022, Ballester *et al* 2023). It is therefore vital that adaptation measures are put in place to reduce the societal impacts associated with heatwave events and to reduce vulnerability to such events. Using past or historical events to serve as analogues of potential future events has been identified as an approach for analysing future impacts under a changing climate, aiding adaptation decision making (Rosenzweig *et al* 2021). Past extreme events, particularly those with high societal impacts, can be stored in a society's collective

* Datasets used include 20th Century Reanalysis, NCEP/NCAR Reanalysis, CMIP6 models: UKESM1-0-LL, CanESM5 and MPI-ESM1-2-LL.

memory and understanding how these events may change due to global warming could raise the level of concern, a requirement for adaptation action (Vasileiadou and Botzen 2014, Hazeleger *et al* 2015). Temporal analogues use data from past events to serve as analogues of expected future conditions. It is a way to estimate temperatures observed during similar pressure or atmospheric conditions to a past event. Using this approach means that events that actually occurred are used to characterise potential future events. This could be useful for local-based adaptation and be a useful way to study extremes that could be missed using statistical models alone.

Our research uses a temporal analogue method, similar to that developed by Yiou *et al* (2007). We define 'analogues' as days with a similar atmospheric circulation pattern to the heatwave days we are interested in exploring. This is based on the premise that circulation patterns influence local temperatures. Therefore, examples of past relationships between atmospheric circulation and temperatures can be used to analyse potential future temperature anomalies with similar atmospheric flow, but different external forcing and climate. This allows for the separation of the thermodynamic and dynamic contributions to an event. A similar approach has been used in a number of other studies (Yiou *et al* 2007, 2017, Cattiaux *et al* 2010, 2012, Jézéquel *et al* 2018a, 2018b, 2018c, Harrington *et al* 2019, Cowan *et al* 2020) where the circulation patterns during an event are used to find analogous circulations in other time periods and a variable such as temperature or rainfall is compared between the two. While originally used in fields including weather forecasting, analogues have recently been used in attribution and storyline-based research to understand how extreme events are impacted by climate change and to decompose the dynamical and thermodynamical impacts on such events (Trenberth *et al* 2015, Otto *et al* 2016, Shepherd *et al* 2018, Harrington *et al* 2019, Shepherd 2019). Storylines, defined as plausible, physically self-consistent unfolding of past events (Shepherd *et al* 2018) could be a powerful tool in risk related decision making and could be linked with the human aspects of climate change to create effective adaptation plans.

In this paper, we aim to understand how past heatwave events in the UK could look in the future under different degrees of global warming. We identify the circulation patterns of several past UK heatwaves in reanalyses and models to find heat anomalies associated with analogous situations to them in the future. While many studies, including attribution studies, focus on recent events, past events can provide case studies of high impact heatwaves, while improving storylines that may be used to increase preparedness for similar events in the future (Otto *et al* 2016, Stott *et al* 2016, Harrington *et al* 2019, Hegerl *et al* 2019). We therefore use the heatwaves occurring in the summers of 1911 and 1923, from which we aim to find analogues in the present and the future in order to explore any differences in the frequency in which similar circulation patterns are found, as well as in the heat anomalies associated to the analogues. Heatwaves in 1911 and 1923 are both examples of early heatwaves detected in Yule *et al* (2023). Heatwaves in 1911 and 1923 in the UK and Europe were associated with societal impacts and reached a similar intensity in terms of maximum and mean temperatures across the event as more recent heatwave events such as 2003 (although not as intense as the 2022 heatwave) (Yule *et al* 2023).

We aim to explore the limitations of using circulation analogues to examine potential future heatwave events as well as discussing different methodological approaches to identifying analogues. We also explore if this approach could form a 'tale' or storyline (Hazeleger *et al* 2015) that is relevant for decision makers. We examine what the 1923 heatwave could look like at different degrees of global warming, particularly at 2 °C and 4 °C which is the UK Climate Change Committee recommendation for adaptation planning (Climate Change Committee 2021).

1.1. Datasets and models used

The 20th-century reanalysis version 3 (20CR) was used to explore the circulation patterns and large-scale temperatures associated with the heatwave events in 1911 and in 1923 (Compo *et al* 2011, Slivinski *et al* 2019). While other datasets such as the NCEP reanalysis I dataset (Kalnay *et al* 1996) has been used in previous studies (e.g. Jézéquel *et al* 2018b), it only provides data starting from 1948 and therefore earlier occurrences of heat extremes cannot be studied. 20CR also has the advantage of being a longer dataset and therefore increases the sample from which analogues can be searched within and has been used in other similar studies (Cowan *et al* 2017, Hawkins *et al* 2023).

Five ensemble members were used from three different CMIP6 models (Eyring *et al* 2016), UKESM1-0-LL (UKESM), CanESM5 (CAN) and MPI-ESM1-2-LL (MPI) in order to find analogues under different warming scenarios. SSP5-8.5 was used between 2015 and 2100 as well as their associated historical runs. This scenario was chosen as we are interested in exploring analogues at higher degrees of global mean warming, including 4 °C. These three models were selected as they have been used in previous studies that sampled model uncertainty to first order as well as having relatively many ensemble members for the

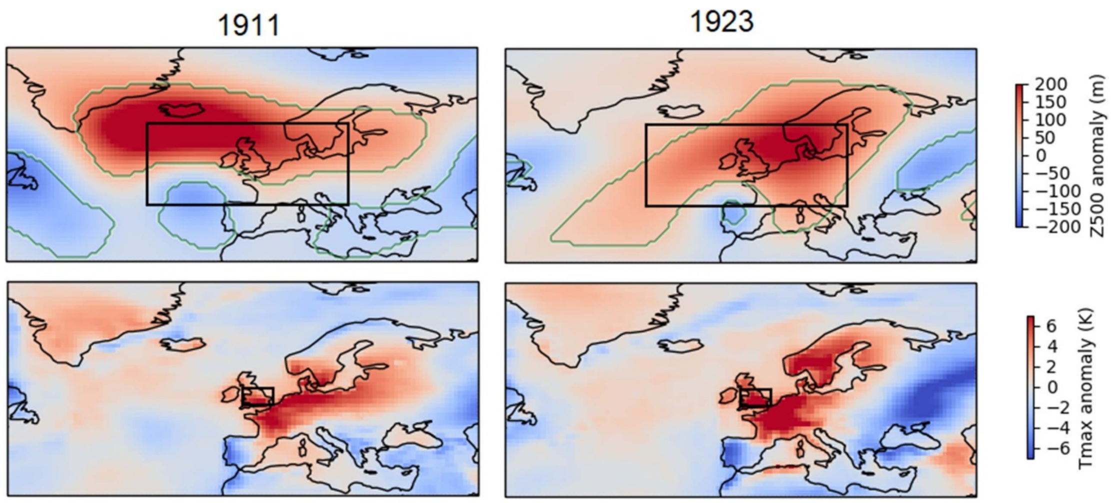


Figure 1. Maximum temperature anomalies (bottom row) and Z500 anomalies (top row); reference period for anomalies is 1850–1900) using 20th-century reanalysis v3 data. Provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, US. The Z500 anomaly patterns were used to search for analogues for the 1911 and 1923 events. These heatwave events have been selected as they represent the two most intense early heatwaves in August and July respectively (based on HadCET data) with different circulation patterns. The black boxes represent the areas used to find analogues (top row) and to analyse temperature anomalies over England (bottom row). The mean of 20CR ensembles are used, with the green contours showing the regions where anomalies are significant among 20CR ensemble members (2 standard deviations do not encompass zero), showing the main features of the pattern searched for to find analogues is robust.

variables of interest (daily maximum temperature and Z500) that were available at the time of writing (Slater *et al* 2021).

1.2. Choice of heatwave events

We have selected past heatwave events that occurred in 1911 and 1923 due to their intensity, associated impacts and because they show some differences in their circulation patterns (Yule *et al* 2023). Between 12 and 14 August 1911 an intense heatwave event occurred in UK and across the European continent. Impacts associated to this event include sunstroke in the UK and the need to cease work outdoors including forge and steel work and agricultural work. When using HadCET (Met Office Hadley Centre Central England Temperature) dataset, the maximum temperature reached in the Central England region was 30.5 °C, and August 1911 is the 7th warmest month on record in Central England between 1878 and 2022 (Parker *et al* 1992, Yule *et al* 2023). In Yule *et al* (2023), the definition of heatwaves used is at least three consecutive days of daily maximum temperature above the 90th percentile based on a 15 d calendar window between 1878 and 2022 (note that in this study, the data have not been detrended for determining climatology in order to treat past events in the same way as more recent events). In 1923, a heatwave occurred between 11 and 13 July, which reached 31.0 °C in Central England and was the 6th warmest July heatwave occurring between 1878 and 2022. Based on the maximum temperature reached and the mean temperature across the event, this was a stronger event than the July heatwave during 2003 in Central England which reached a maximum temperature of 30.9 °C during the most intense 3 d event. This therefore allows us to explore past July heatwaves and add to the sampling record with events that would still be considered intense in today's climate. Both events show positive temperature anomalies over the UK in 20CR that stretch over large parts of Northwest Europe. By studying both the 1911 and 1923 events we can comment on the effectiveness of the analogue technique by comparing the results for these two events. Yule *et al* (2023) identified six more early heat events which we will use in comparison to 1911 and 1923.

The circulation patterns and temperature anomalies associated with the 1911 and 1923 heatwave events are shown in figure 1. Both are associated with high pressure over the UK, however they have different circulation patterns, and a different pattern of heat over the rest of Europe. Anomalies of geopotential height at 500 hPa (Z500) relative to 1850–1900 are shown with the maximum temperature anomalies. The black boxes show the area used to find analogues (top row) and the area over which the England Temperature anomaly was calculated (bottom row). The two heatwave events are different, with the highest pressure being over Iceland in 1911 and being over Scandinavia during the 1923 event. The temperatures for both events are comparable over most of Europe with the exception of Iceland, which is warmer during the 1911 event than 1923, while in Northern Scandinavia the inverse is true.

2. General method

The circulation patterns and temperature anomalies associated with the heat events were taken from 20CR for both 3 d events in July 1923 and August 1911. The average Z500 height and maximum daily temperature anomalies were calculated across each event, with anomalies (relative to 1850–1900). The 3 d mean Z500 anomalies were used to find analogue circulation conditions both in 20CR, and in UKESM, CanESM5 and MPI using historical runs between 1850 and 2015 and using SSP5-8.5 ensembles between 2015 and 2100. This provided a large sample from which to detect analogues. Results were similar if searching for analogues for individual days but using 3 consecutive days allows for a build-up of heat. Analogues were searched for within a 31 d window (15 d before the event and 15 d after) centred on the heatwave event.

To search for analogues in the model space, the Z500 heights from 20CR were regridded to match the grid resolution of each model. The ensemble means for Z500 heights were used from 20CR. We calculate the spread of ensemble members available in 20CR in comparison to the mean. We show that the pattern used to search for analogues is robust as the areas of high pressure have absolute anomalies that are within the spread of the ensemble members to two standard deviations, see appendix figure A1.

The 3 d rolling mean of Z500 was used to search for analogues. Z500 was used as a diagnostic of circulation as opposed to SLP, which aligns with previous studies (Jézéquel *et al* 2018b) that suggest that Z500 analogues perform better compared to SLP due to processes related to thermal lows. SLP patterns can be blurred by warm air masses causing local depressions which makes the identification of an anticyclone sensitive to warming and more difficult to detect.

When selecting the area from which we compare the circulation patterns, we aimed to include an area large enough to contain the distinct features (areas of low and high Z500 height) of the circulation pattern which control the weather over the UK, while being small enough not to give weight to features that are less important. We have selected areas that include the most relevant features of the circulation patterns, as shown in figure 1 as has been done in previous studies. (Jézéquel *et al* 2018b).

We used a smaller region from which to extract the temperature anomalies associated with the analogues (circulation patterns). We used a region over England (with a land-sea mask applied) as the original events used were selected due to their high temperatures over central England. We use a 3 d rolling mean of the daily maximum temperatures associated to the analogues.

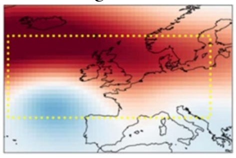
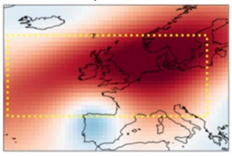
We have used several metrics to define an 'analogue' to the 1911 and 1923 heatwave events. We select suitable analogues by maximising the Spearman correlation between the Z500 maps denoted by rho (ρ), named Spearman's rho. It is a measurement of the strength and direction of the monotonic relationship between the geopotential height values of the event of interest and those that occur in the model or dataset of interest. It is used as a way to analyse the degree of similarity in Z500 spatial patterns, hence a method for finding analogues. Rho is a value between -1 and 1 with a value close to 1 indicating a strong, positive relationship between the event of interest and the potential analogue event. As rho is determined based on rank only, the amplitude of the spatial pattern is not considered.

Minimising the Euclidean distance is another method of finding analogues as a measure of similarity or dissimilarity between the geopotential height values of the event of interest and potential analogue events. It is a representation of the straight-line difference between two sets of values in a multi-dimensional space accounting for amplitude as well as pattern. The differences between methods and further reasoning are discussed in section 4.1.

We define analogues as the top 10% of days with Z500 patterns most similar to the event based on the value of rho. We also explored using a cut-off value for rho and found that the results do not change greatly but could lead to analogues being inconsistently sampled. If we used the top 5% rather than top 10% of days to find analogues, results did not change qualitatively. The 10% cut off varies in rho between 0.45 and 0.73 and the 5% cut off varies between 0.59 and 0.78 between models and decades.

The circulation pattern of the 1923 event appears to be a more common high-pressure system linked to heat in central England. When we calculate the correlations to other observed heat events (to get an idea of the similarity in circulation pattern between 1911, 1923 and other previous heatwave events in Europe) we see that more heatwave events are similar to 1923 than to 1911 (see table 1). We compare the 1911 and 1923 summer heatwaves to those of other similarly intense heatwaves over the UK from 1878 to 2022. We see that the correlation between all other tested events and 1923 is over 0.5 whereas only two of the other events have a correlation above 0.5 when compared to the 1911 event, while the correlation between the 1911 and 1923 event is 0.36. The recent intense heat in 2022 is similar to 1923, but not 1911, while 2003 is slightly more similar to 1911 conditions.

Table 1. Correlations between the 1911 and 1923 events and a sample of other intense early heatwave events within the rectangle in figure 1. Events have been selected for their strength; heatwaves occurring 1878, 1884, 1901, 1911, 1923 and 1925 are the strongest 'early' heatwaves occurring in the late 19th and early 20th century (Yule *et al* 2023). 2003 and 2022 have been included as examples of recent strong heatwave events in the UK. This gives an idea of the level of similarity between heatwave events in terms of their circulation pattern, including the difference between the heatwave in 1911 and 1923.

	Correlations (ρ) of z500 pattern of event with other events						
Heatwave events	23–29 June 1878	7–11 August 1884	18–21 July 1901	9–12 June 1925	13–16 July 2003	17–19 July 2022	12–14 August 1911 relative to 11–13 July 1923
12–14 August 1911 	0.38	0.53	0.28	0.18	0.58	0.04	0.36
11–13 July 1923 	0.65	0.71	0.71	0.52	0.75	0.55	

3. Results

Figure 2 shows the climatology around the events for each decade (in a 31 d window) compared to the temperature anomaly associated with analogues of each event (the 1911 event and the 1923 event). Decadal distributions of the rolling 3 d average maximum temperature anomalies are shown from 5 ensemble members from UKESM using the historical runs for the 1850–2014 period and the SSP5-8.5 scenario for the time period from 2015 to 2100. The orange box and whiskers plots show the entire maximum temperature distribution of all sampled days around the events (in a 31 d window) centred on 12–14 August 1911 (left) and 11–13 July 1923 (right) for each decade. We can see how the decadal climatology changes through the decades between 1850 and 2100 as the England temperature anomaly increases with global warming.

The red dashed lines in figure 2 represent the England temperature anomaly during the heatwave of interest, from 12 to 14 August (left) and 11–13 July (right). A red star shows the decade in which the heatwave took place. Both the 1911 and 1923 heatwave events were relatively extreme for their respective time periods, both being outside the 95th percentile for their respective climatologies, consistent with their detection as particularly extreme events over the 20th century. However, the temperatures reached during the 1911 event fall within the 25–75th percentile of the climatology distribution during the 2040–49 period and below the 25th percentile in the time period 2070–79. The 1923 event shows a similar progression, the event that was extreme during the time it occurred only just falls into the 25–75th percentile of climatology by the end of the century.

The blue box and whisker symbols in figure 2 show analogue events (top 10% days with most similar circulation based on their Spearman correlation) and are selected as a subset of the climatology with a geopotential height that most closely matches that of the original event. The decadal distribution of analogues has a higher median England temperature anomaly value than the climatology for each decade, however there is a large spread in the England temperature anomaly values. In most cases, analogues of the 1923 heat event capture the most extreme simulated events with some exceptions, similar to the historical record. This suggests that using geopotential height (Z500) alone to find analogues does not provide a strong constraint for selecting 'hot' events.

The observed events were still relatively extreme compared to the analogues from their respective decades (both outside the 25–75th percentile), but by the end of the century both are outside the distribution for analogues and even cool for a summer period.

Figure 2 also illustrates the difference between the 1911 and 1923 heatwave event. The 1923 event tends to have analogues with a temperature distribution over England that is more clearly separated from that of all days, (note the separation of the central 50% of the distributions between analogues and all days), which identifies analogues as hot days, and with all hot days identified in the climatological values captured as

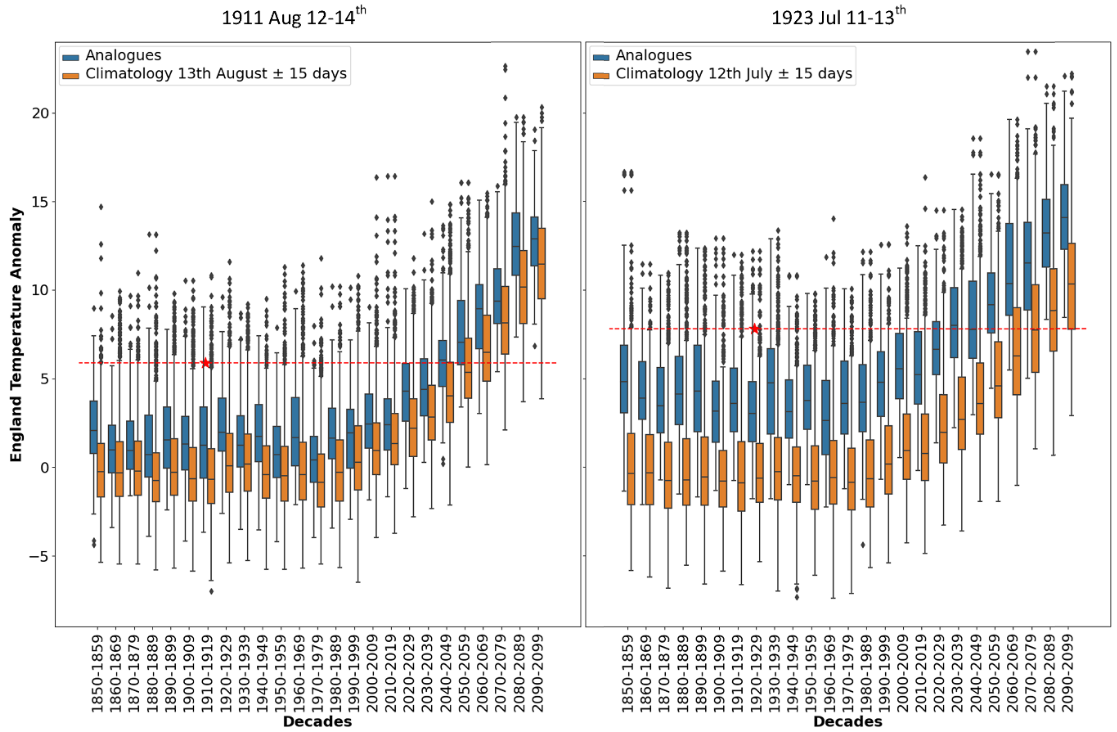


Figure 2. Decadal distributions of rolling 3 d average maximum temperature anomalies from UKESM1.0 [5 ensemble members; historical (1850–2014) and SSP5-8.5 (2015–2100) experiments] for 11–13 July (+−15 d) (right) and for 12–14 August (±15 d) (left), averaged over England. The orange box and whiskers show the complete distribution of sampled days ($n = 1510$; 31 d × 10 years × 5 ens. members), and blue shows the distribution of the subset chosen such that the associated geopotential height (Z500) anomalies most closely match the event from 20CR (the top 10% of analogue 3-day periods, as measured by the Spearman's rank correlation coefficient over pan-European sector). Coloured boxes span the 25th–75th percentiles of the distribution, with the whiskers showing the 5th and 95th percentiles; individual outliers are shown by black dots). Red dashed line indicates the equivalent temperature anomaly over England for the original event from 20CR.

analogue days. In contrast, for the 1911 event the analogues are on average less hot than in 1923. The 1911 event is discussed frequently in literature and many impacts were felt at the time including loss of life e.g. (Ancestry 2020). The event was also associated with drought (UK Centre for Ecology & Hydrology 2020) and therefore an analogue that considers rainfall deficit and heat together, as a compound event (Zscheischler *et al* 2018), may provide more information in this case. Going forward we focus our analysis on the 1923 event since this is more indicative of a range of other heatwaves in the UK including in 2003 and 2022 (see also table 1).

In figure 3, the UKESM climatology and analogues are plotted, with the same from two other models, namely CanESM5 and MPI. Figure 3 shows the England temperature anomalies for the climatology and the analogues compared to global warming levels rather than plotted against time to allow a better comparison. Global warming levels are defined here as the decadal mean anomaly with respect to 1850–1900. Analogues are calculated for the decade where the mean global warming crosses each respective global warming level i.e. 1 °C, 1.5 °C, 2 °C, 3 °C and 4 °C for each model's decadal ensemble mean, relative to the 1850–1900 period. For each model, the analogues have a higher mean temperature value than their respective climatologies for each level of global warming.

We have compared the climatologies and analogues found using UKESM, CanESM5 and MPI to those found using 20CR from 1850 to 2009 in order to validate the models used (results are shown in appendix figure A2). All three models are more variable than 20CR which could be partially explained by the fact that models sample also the variability in sea surface temperatures in their ensembles, while 20CR is driven with observed SSTs. UKESM shows the most variability in the period 1970–2009, the period where we begin to see the impacts of global warming, CanESM5 seems to be most similar to results using 20CR in terms of the mean value of England Temperature anomaly for analogues (see appendix figure A2).

The climatological temperature of a 31 d period around 12 July increases with global warming. At 4 °C of global warming the mean temperature increase in England is between 4.9 and 6.4 degrees warmer than pre-industrial levels with UKESM showing the largest increase, while MPI shows the smallest. Average temperatures of the analogues, events of similar circulation patterns as 1923, over England during this period range from 6.9 °C to 10.7 °C with highest temperatures reached ranging from 11.7 °C to 19.6 °C higher than

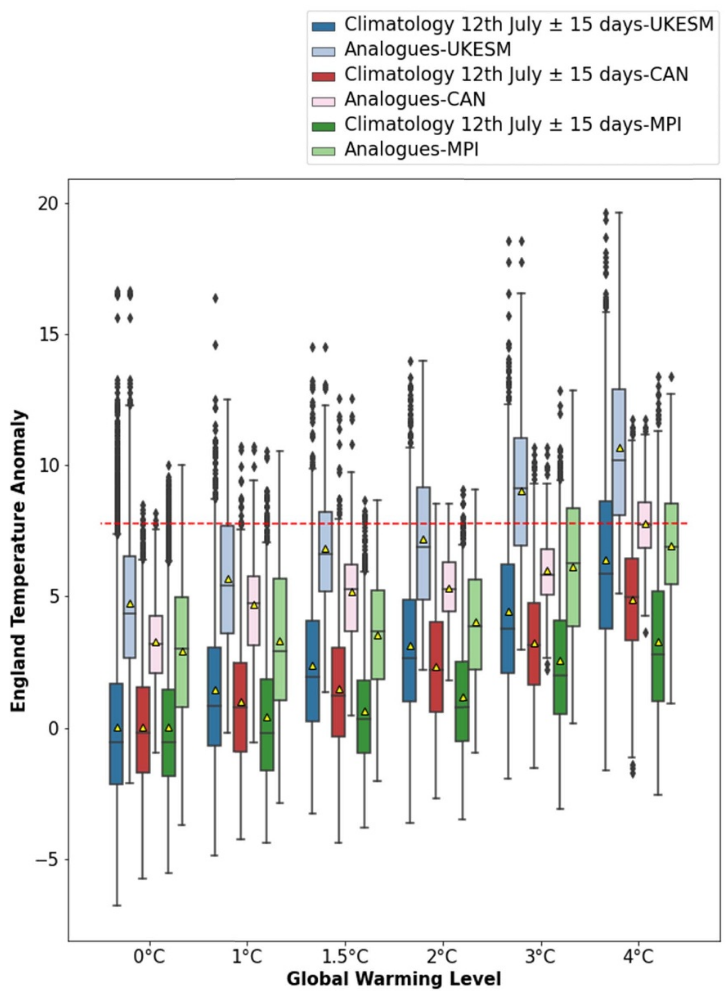


Figure 3. Boxplots showing analogues (lighter colours) and climatology (darker colours) of the period around the 1923 event for the decade where the global warming levels (1 °C, 1.5 °C, 2 °C, 3 °C and 4 °C) are reached for three climate models, UKESM, CanESM5 and MPI. Values are given as anomalies with respect to the average summer maximum temperatures during the heat event period between 1850 and 1900 in the models. Coloured boxes span the 25th–75th percentiles of the distribution, with the whiskers showing the 5th and 95th percentiles; and outliers shown by black dots). The red dashed line indicates the England Temperature anomaly during the 1923 heatwave.

pre-industrial levels. The 1923 event reached 7.8 °C above pre-industrial levels over England. It is evident from figure 3 that there is a significant difference between models, particularly when looking at the extremes in temperature. This highlights the dangers of using a single model for exploring extreme events and to input into adaptation decision making. For example, if a decision maker aims to focus on high risk or an example of a worst-case scenario, this changes per model selected.

Figure 4 shows the rates of change of climatology and analogues compared to Global Annual Temperature. The orange lines represent the climatology (around 11–13 July) for each model. The black lines in figure 4 represent a 1:1 rate of change between global annual temperature and England temperature anomaly. We can see that for UKESM and CanESM5 the summer climatology over England around the period of the 1923 heat event is warming at a faster rate than global warming (at a rate of 1.53 and 1.29 respectively; tables 2 and 3). However, MPI shows a rate of warming of England temperature anomaly that is below the global average. To summarise, at 2 °C of global warming the warming in the three models for England temperature varies between 1.78 °C and 3.06 °C.

Figures 2 and 3 show that not all analogues are anomalously hot, we therefore separately investigate the 'Top 10% hottest analogues'. This is the top 10% of temperatures over England from the analogues, a subset of analogues. This allows us to explore analogues that lead to particularly hot extremes over England by providing this additional constraint.

In UKESM, the rate of change of the top 10% hottest analogues is 1.56 (standard error = 0.06), only slightly higher than the climatology. For UKESM, when comparing the climatology rate with that of the analogues and with top 10% hottest analogues, we find that we cannot reject the null hypothesis that these rates are different using a 5% threshold (table 1).

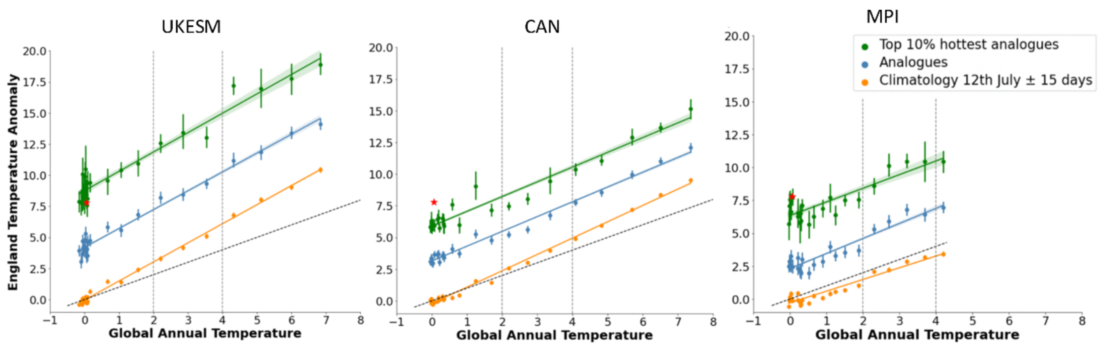


Figure 4. Scatter plot showing the climatology for the period around the 1923 event (orange) compared to the temperature over England of similar circulation patterns to the original event (in blue) and the top 10%of temperatures from those with similar circular patterns (green). Dark grey dashed vertical lines show warming levels of 2 °C and 4 °C. The light grey line represents a 1:1 trend. A red star represents temperature over England during the original heatwave event in 1923 from 20thCR. Climatology (orange) ⊂ Top 10%Analogues (blue) ⊂ Top 10% England temperature anomaly (green).

Table 2. Table of warming rates of England temperatures during the 2023 event window relative to global mean warming, with the standard error associated with each value in brackets, for climatological data, for all analogues selected by similarity of Z500 pattern, and the top 10% hottest analogues. The black lines in figure 4 show a rate of 1 between global annual temperature and England temperature anomaly.

Model/metric	Climatology	Analogues	Top 10% hottest analogues
UKESM	1.53 (0.01)	1.52 (0.02)	1.56 (0.06)
CAN	1.29 (0.01)	1.17 (0.01)	1.16 (0.03)
MPI	0.89 (0.01)	1.14 (0.04)	1.04 (0.08)

Table 3. P-value table testing the hypothesis that climatology warms at the same rate as the analogues and hottest 10% of analogues, (using t-test). Green boxes indicate where the null hypothesis of identical trends can be rejected at a 5% significance level.

Model/metric	Climatology vs analogues	Climatology vs top 10% hottest analogues
UKESM	0.4250	0.764
CAN	0.01	0.0214
MPI	0.01	0.162

In CanESM5 the rate of change of both the analogues and the top 10% hottest analogues are slightly lower than that of climatology, and we find that when comparing the rate of change in decadal climatology between that of the analogues and the top 10% hottest analogues all are significantly different at the 5% threshold level. In contrast, for the MPI model, the analogues show a higher rate of change than the climatology at 1.14 (standard error = 0.04). The rate of climatology to analogues is significantly different but we cannot reject the null hypothesis that the rates are significantly different between the climatology and the top 10% hottest analogues. This emphasises model uncertainty at the rate at which hot extremes increase with warming, despite all models being compared at the same global mean warming level.

Overall, we would expect the climatology to increase at a higher rate than 1:1 as Europe is currently warming at a higher rate than the global average (Russo *et al* 2015, Rousi *et al* 2022) although England may warm less than more continental regions in Europe. The rates for the top 10% hottest analogues, i.e. regimes with similar circulation patterns to the 1923 event that show the highest temperature anomalies over England, seem to be similar to that of climatology, particularly for UKESM and MPI.

4. Discussion

4.1. Methodological choices

Figure 5 shows the correlation thresholds (the cut off value of rho) when considering the top 10% (based on rho value) to be analogues. The rho threshold or cut off values varies between models with CanESM5 tending to have a higher threshold than UKESM or MPI, indicating more similarity of its events to the observed events. The 10% cut off varies between 0.45 and 0.73 and the 5% cut off varies between 0.59 and 0.78 between models and decades. In terms of the associated temperatures over England, taking the 5% or

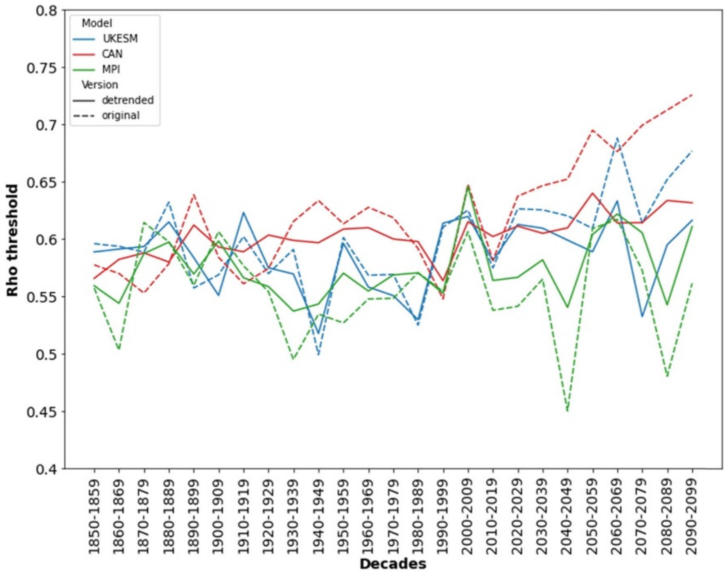


Figure 5. Correlation cut off value/threshold of analogues per decade for each model and the comparison to correlations using detrended z500 patterns.

10% cut-off did not significantly impact results. We therefore have chosen a 10% cut-off to increase our sample size. Using a cut off/threshold value for rho of 0.5 as opposed to 10% yields similar results.

Figure 5 shows that the rho threshold increases over time in both UKESM and CanESM5. This is mainly due to an increase in the mean Z500 height from 1850 to 2100, since the atmosphere thickens as the global temperature increases. Appendix figure A3 shows this increase in Z500 height from pre-industrial times to the end of the century. The largest increase in Z500 is in CanESM5 which is expected as this is the model that warms the most by 2100, by 7.4 °C compared to pre-industrial. The areas of highest Z500 increase for both UKESM and CanESM5 are in the locations of highest pressure during the 1923 event, namely over Scandinavia. Therefore, this aligns with an increased rho cut-off value from 1850 to 2100. MPI in comparison only warms by 4.2 °C at 2100 and therefore the mean Z500 height does not increase by the end of the century as much as for UKESM and for CanESM (see appendix figure A3). Interestingly, the area over Scandinavia seems to be the area of least height increase in MPI in contrast to UKESM and CanESM5. Figure 5 also shows the rho thresholds after being corrected for this height increase from 1850 to 2100. The correction removed the mean Z500 increase for each decade from that decade's values leaving the underlying pattern. As expected, we see that the rho thresholds for UKESM and CanESM5 are corrected downwards towards the end of the century. When MPI Z500 heights are corrected this moves the rho threshold upwards, aligning with different Z500 tendencies between the models over the areas of highest pressure during the 1923 event.

Correcting for the increase in Z500 height makes little difference to the analogues found and their associated England temperature anomaly values (see appendix figure A4). However, this correction is vital if Euclidean distance is used to identify analogues instead of maximising the Spearman correlation (see appendix figure A5). This is because the Spearman correlation method is less sensitive to the magnitude of the difference between the two data sets when compared to using the Euclidean distance and focuses more on the underlying pattern. The Spearman correlation considers the rank order of values as opposed to directly considering the magnitude of differences between values and therefore may be less influenced by increasing geopotential height. Due to this higher sensitivity to removing Z500 trends this analysis focuses on Spearman correlation, but as indicated, results are broadly similar if using Euclidean distance, particularly after detrending Z500 values. This correction is also important when exploring any changes in frequency of occurrence of events similar to 1923 between 1850 and 2100.

4.2. Limitations of analogues

Analogues have been used in many studies to successfully place events into historical context as well as to attribute anthropogenic warming to particular heatwaves or extreme events (Cattiaux *et al* 2010, Otto *et al* 2016, Jézéquel *et al* 2018b, Harrington *et al* 2019). This research aims to determine the effectiveness of using the analogue methodology to explore potential future heat events. A key limitation of using this approach is the dependency on models and their ability to get the circulation patterns right in the future under different warming scenarios. Results will also depend on how many instances there are of a particular event in the model. Both temperature and Z500 height will increase as the globe warms. This may lead to different types of weather regimes unlike those that are currently experienced or that have been witnessed in the recent past (e.g. Rousi *et al* 2022, Yang *et al* 2022, Rousi *et al* 2023). For example, increased heatwave activity in Europe has been linked to atmospheric dynamical changes including an increase in the frequency and persistence of states including double jet streams over Eurasia (Rousi *et al* 2022 a). This could impact the frequency and severity of heatwaves and would not be picked up in an analogue based study such as this one, unless these future changes are reflected in the models. However, the most 'extreme' analogues in terms of England temperature anomaly in the climatology do tend to be picked up when focusing on the analogues only, suggesting that future heatwave circulation patterns do not change strongly in the models used.

We are also limited by the definition of what an analogue actually is and how to define it most effectively. The choice of spatial extent over which analogues are detected can influence results for example. We find that when taking the top 10% of analogues based on their rho value that these lead to a wide range of temperatures over England. For example, with reference to figure 4, at 2 °C the analogues from UKESM range from 2.21 °C to 13.97 °C above pre-industrial over England. We therefore sub-selected analogues based on heat (taking the top 10% of temperatures over England from the top 10% of analogues based on rho value) to explore how analogues that lead to particularly extreme heat over the UK compare to all analogues and climatology. The fact that using circulation patterns alone to find analogues does not always lead to severe heat events over the UK is a limitation of this technique, and was not addressed by using different metrics for detecting analogues. Figure 6 illustrates that analogue events that are not particularly hot tend to have very shallow circulation patterns on average, which illustrates a weakness of the correlation metric, and they also seem to have slightly lower rho values.

In addition, our method does not take into account compound events such as drought and heat which is likely to have played a role in the 1911 event for example. This could be considered by taking into account soil moisture deficit which can play a key role in heatwaves particularly at the local level (Seneviratne *et al* 2010, Vogel *et al* 2017) and so analogues found are only based on the circulation pattern. Our method could potentially be expanded to include analogues for more than one variable with more of a focus on a number of preceding conditions to the event of interest, although this may severely affect sample size. Additionally, we find analogues based on a snapshot of past events, in other words, the mean value over a heatwave event. A future study could investigate finding analogues by using the evolution of the event as the days leading up to an event could also be important.

For two of the models used here, the rate of change of global temperature is slightly lower than that of England summer temperature anomaly, which is similar for climatology and the extremes (the top 10% hottest analogues). However, observational studies suggest that in North–West Europe, the hottest summer days are warming approximately twice as fast as summer days of mean temperatures between 1960 and 2021, a trend that is not captured by climate models (Patterson 2023). Other studies focused on the UK also conclude that extremes of temperature in the UK are changing faster than average temperatures using mean daily data (Kendon *et al* 2023). Since this is not captured in the models used here, this could be due to a missing process and hence a limitation of the analogue methodology and more generally the use of model data in this context. This does however require further investigation as daily maximum temperatures were used in this study.

4.3. Can analogues be used as storylines?

It can be shown, particularly with reference to figure 4, that different models lead to different results and temperature ranges for potential future heatwaves. Figure 6 shows the hottest and coldest 10% analogues at 1 °C, 2 °C and at 4 °C of global warming for each model used. Figure 6 shows that while our method captured the hot analogues, it failed to remove the less suitable candidates in some cases where only Z500 is used with no constraints on the temperature of analogues found. At 2 °C the hottest analogue temperatures over England range from 8.5 °C to 14.0 °C above pre-industrial levels and for 4 °C the range is between 11.7 °C and 19.6 °C. This large range between models highlights the danger of only using one model to make adaptation decisions related to future heatwave events. This also provides challenges when communicating results to decision makers and how ranges and uncertainties in future extreme events should most effectively be communicated and used to make adaptation decisions. The use of workshops or serious games are considered effective methods for making decisions under uncertainty where a storyline approach could be used (Rumore *et al* 2016, Shepherd *et al* 2018, Undorf *et al* 2020). In this case, an organisation could discuss their resilience level to heatwaves reaching the different temperature ranges calculated in this research as a form of 'stress-testing' adaptation strategies. Analogues give the additional benefit of being based on an historic heatwave event, perhaps one that lives in shared societal memory or one that a population has lived through, and therefore could help motivate adaptation action (Garcia *et al* 2022).

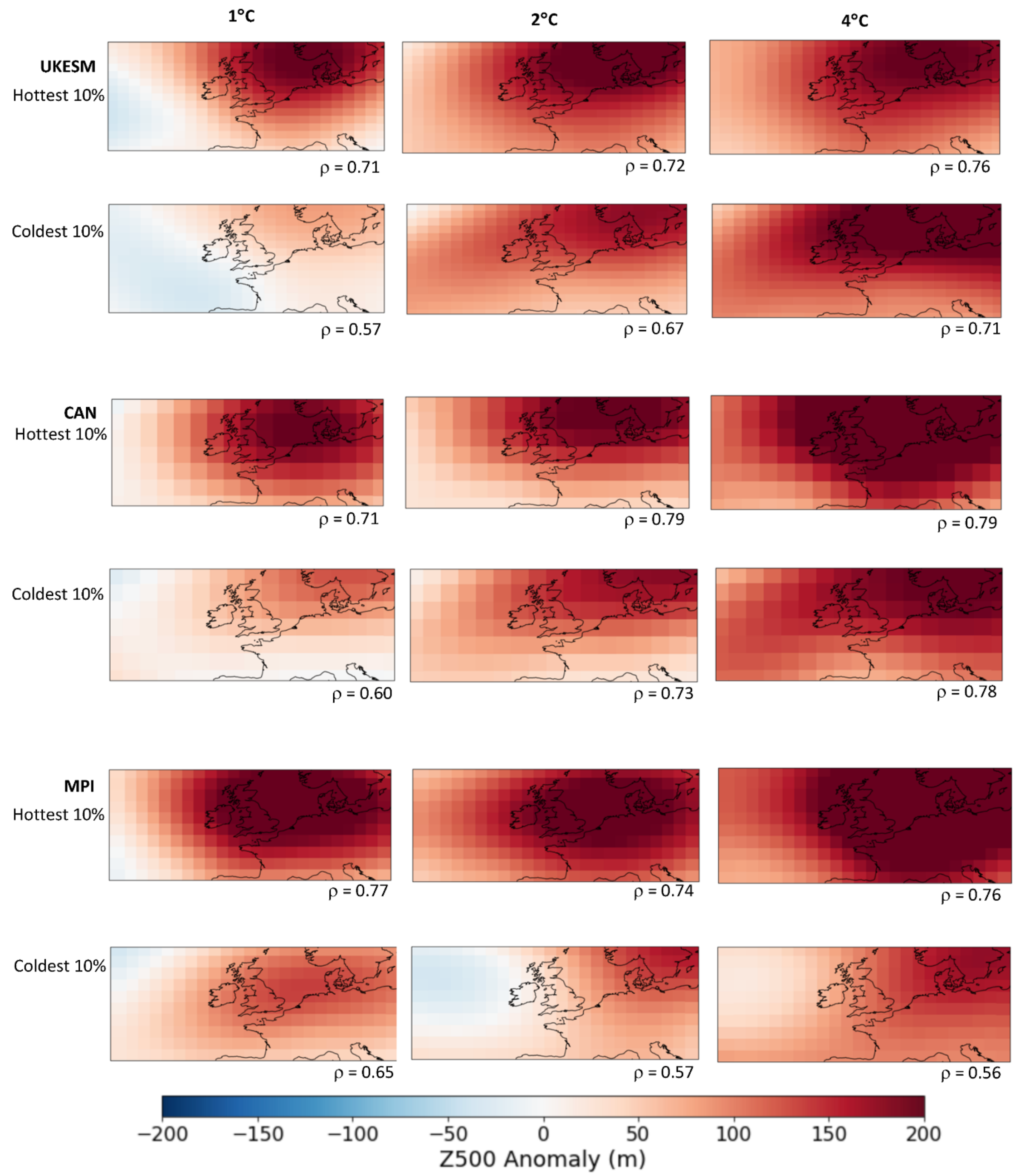


Figure 6. Spatial plots showing z500 anomalies relative to pre-industrial (1850–1900) for the most extreme heatwave analogues found (in terms of their England temperature anomaly) for each warming level (1 °C, 2 °C and 4 °C)—the top 10% hottest for each model on the top row and the coldest 10% on the bottom row. The average rho values associated to each are included below each plot.

5. Conclusion

In this paper, we use an analogue methodology based on atmospheric circulation to analyse how past heatwave events may change under different global warming scenarios. While many studies use the analogue methodology to characterise recent events based on their analogues in the past, less studies use this method to search for analogues in the future, which identifies most of the future hot events and puts them into the context of what was experienced in the past. We comment on methodology choices and the limitations of using this method. For example, we are using Z500 to search for analogues without taking into account preceding conditions, such as drought. Therefore, for compound events such as drought and heat in 1911 this may lead to less effective analogue selection than if using a method that includes drought (e.g. Cowan *et al* 2020). We are also limited by the frequency of the high-pressure system of interest in the dataset and to what extend models can reliably construct potential future events. 1923 seems to be a more common high-pressure circulation pattern over Europe that leads to heat and therefore leads to clearer results than

1911. On the other hand, 1923 is similar to the pattern involved in other strong heat events in the record, making it relatively less distinct and again querying to what extent atmospheric circulation alone is suitable to select the best analogues, as not all analogues provide strong heat events, and all strong heat events seem to be captured by similar circulation patterns. As strong future heat events are captured by 1923 analogues, this suggests that future heatwave events will be similar, in terms of their circulation patterns, to past heatwave events from the early 20th century. Using additional information, such as drought preconditioning, strength of the atmospheric anomaly (which is neglected in correlation statistics) or prior build-up of heat might be necessary to identify analogue events that sample preferentially intense heat.

The 1923 event was an extreme heat event at the time it occurred (above the 75th percentile of the analogue distribution in models), whereas at 4 °C of global warming the same event would be at the lower end of the distribution of the analogue distribution, with much hotter events possible, although with a large model uncertainty illustrated by the three models used here.

We compare the analogues found before and after detrending for increasing pressure levels as the global temperature warms. We find that there is little difference in the analogues found when maximising the Spearman correlation but considerable difference when minimising the Euclidean distance to identify analogues. Despite its limitations analogues could be an effective method of communicating climate risk, particularly to demonstrate the need to adapt to changing extremes. This method takes an event that people are aware of from the past and gives an idea of what we may need to prepare for in the future which could aid in discussions about future preparedness and resilience building.

Future research could take into account other variables or preceding conditions, such as drought, as well as the pressure which could create more realistic or reliable analogues to past events as well as being able to inform adaptation decision making for compound events. In addition, this paper focused on summer heatwaves in the UK. Looking at different types of events or heatwaves in other regions or in different seasons could lead to different results and conclusions. Future work could extend this research to compare with other seasons or to events in other regions.

Data availability statement

No new data were created or analysed in this study.

Acknowledgments

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Conflicts of interest

The authors have no conflicts of interest to declare.

Appendix

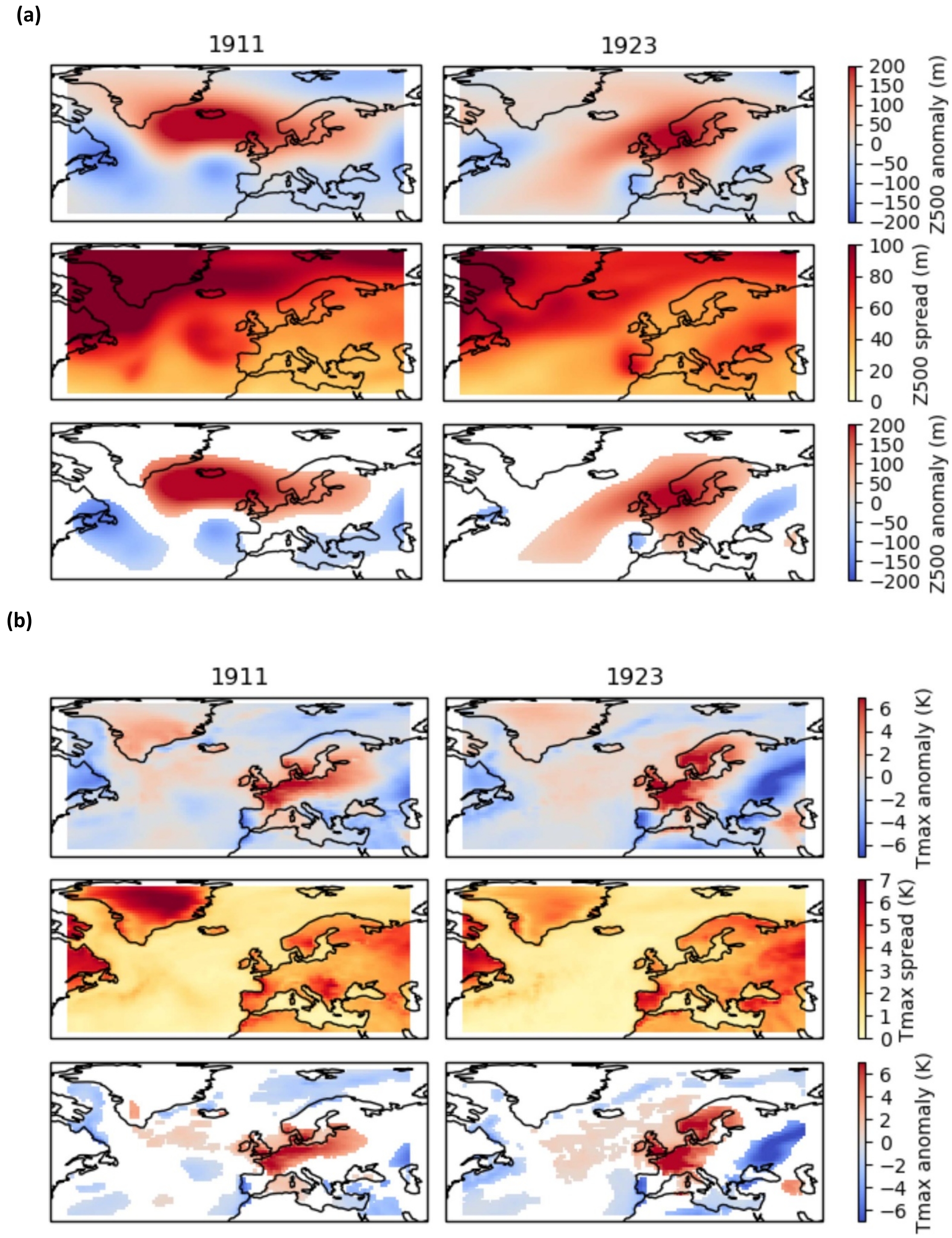

Figure A1. (a) and (b) Robustness of circulation captured in 20CR during early heatwave events. The top rows of both (a) and (b) show the Z500 anomalies and the maximum temperature anomalies respectively, reference period for anomalies is 1850–1900) using 20th-century reanalysis v3 data. Provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, US. The second row in (a) and (b) shows the spread in ensemble members from 20CR for each variable respectively and the bottom rows show the anomalies masked where there is no significance in sign of change, where the absolute anomalies are within the spread of ensemble members to two standard deviations.

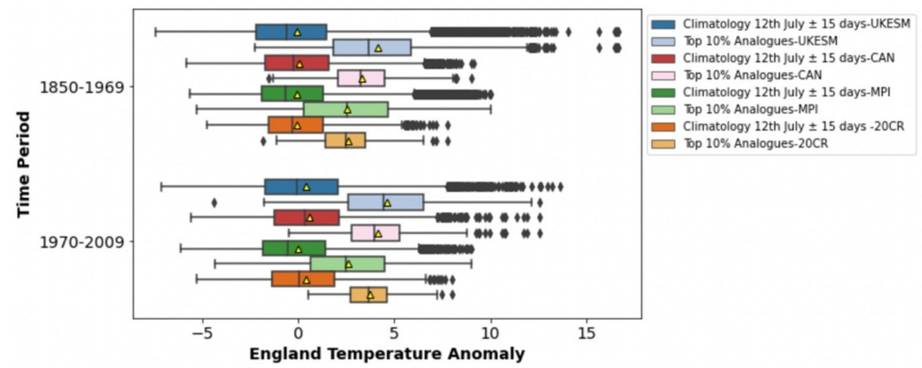

Figure A2. Climatology and top 10% analogues and their associated England temperature anomaly for UKESM, CanESM5 and MPI as well as for 20CR. This plot demonstrates the higher variability in models when compared to 20CR. UKESM exhibits the most variability.

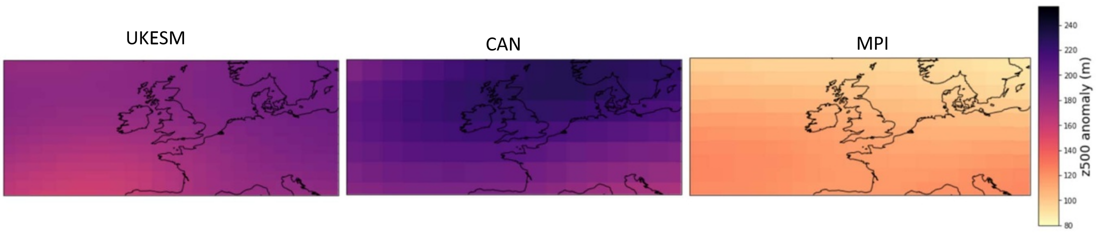

Figure A3. Z500 anomalies in 2090–2100 relative to 1850–1900 for climatology period 12 July ±15 d for UKESM, CanESM5 and MPI. The areas of higher pressure increase tend to be in North-Eastern Europe in UKESM and CanESM5 whereas this is not the case for MPI. MPI shows the lowest increase in pressure out of the three models which is expected as it is also the model that warms the least by the end of the century.

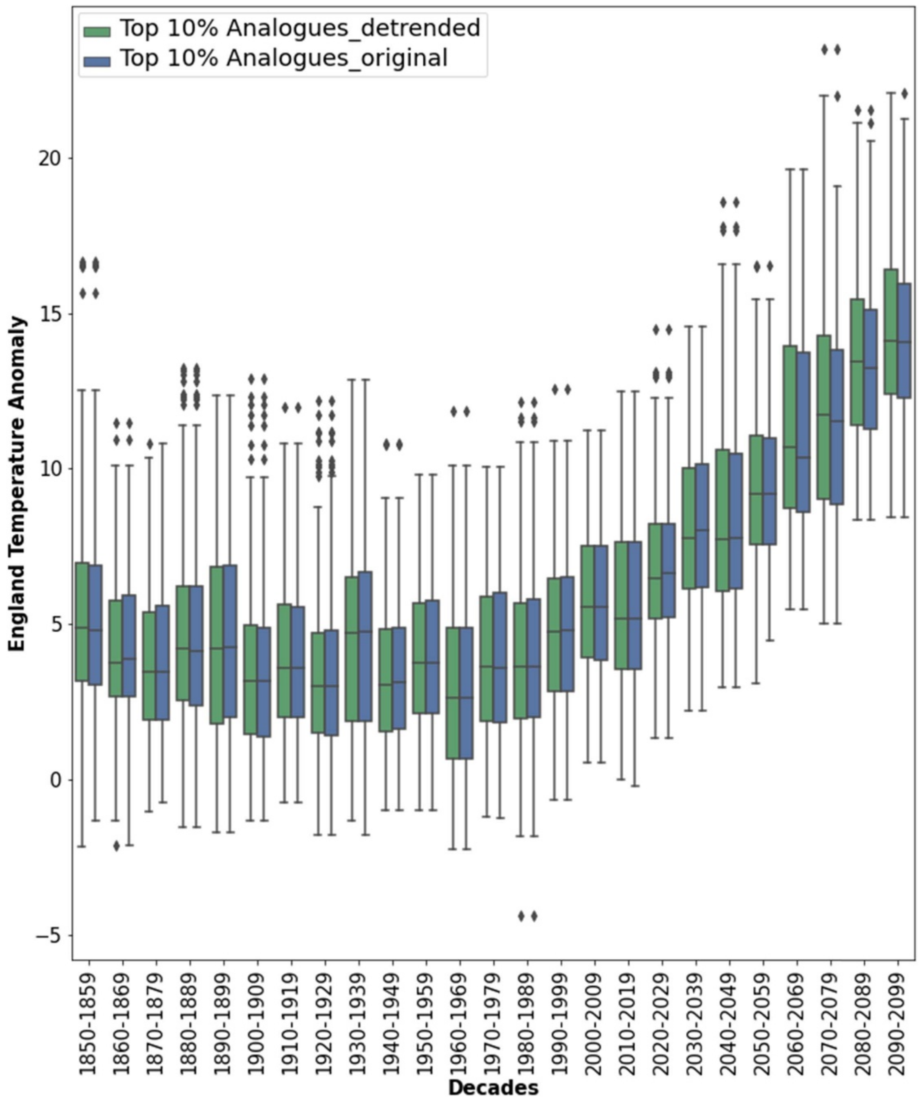

Figure A4. Comparing the analogues found when correcting for Z500 height differences between 1850 and 2100 using Spearman correlation. This plot highlights the similarity in analogues found with and without detrending for the increasing pressure between 1850 and 2100.

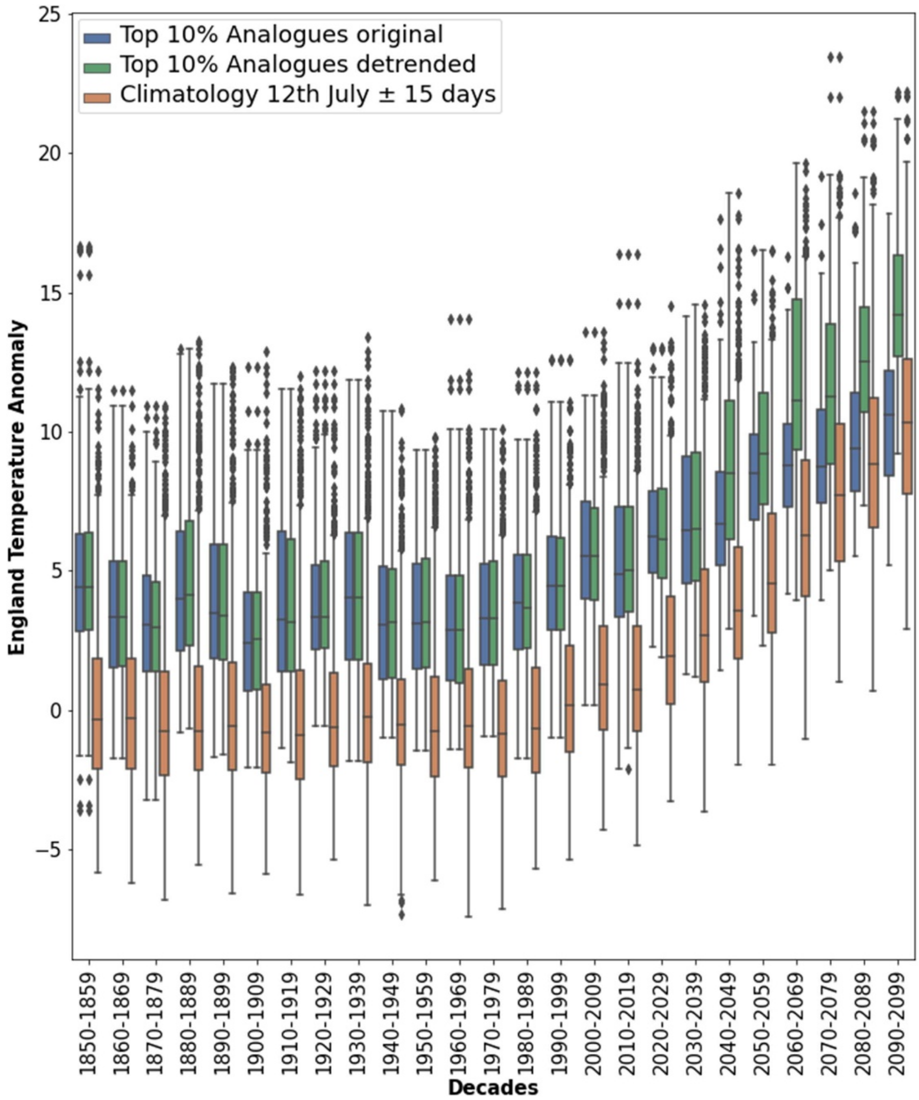

Figure A5. Comparing the analogues found when correcting for Z500 height differences between 1850 and 2100 using minimum Euclidean distance. This plot highlights the difference in analogues found with and without detrending for increasing pressure when using Euclidean distance to identify analogues.

ORCID iDs

Emma L Yule https://orcid.org/0000-0002-5492-2217
Gabriele C Hegerl https://orcid.org/0000-0002-4159-1295
Andrew Schurer https://orcid.org/0000-0002-9176-3622
Andrew Ballinger https://orcid.org/0000-0003-3704-1976

References

Ancestry 2020 England heatwave 1911 (available at: www.ancestry.co.uk/historicalinsights/england-heatwave-1911)

Ballester J, Quijal-Zamorano M, Méndez Turrubiates R F, Pegenaute F, Herrmann F R, Robine J M, Basagaña X, Tonne C, Antó J M and Achebak H 2023 Heat-related mortality in Europe during the summer of 2022 *Nat. Med.* **29** 1857–66

Benz S A and Burney J A 2021 Widespread race and class disparities in surface urban heat extremes across the United States *Earth's Future* **9** e2021EF002016

Cattiaux J, Vautard R, Cassou C, Yiou P, Masson-Delmotte V and Codron F 2010 Winter 2010 in Europe: a cold extreme in a warming climate: cold winter 2010 in Europe *Geophys. Res. Lett.* **37** 20

Cattiaux J, Yiou P and Vautard R 2012 Dynamics of future seasonal temperature trends and extremes in Europe: a multi-model analysis from CMIP3 *Clim. Dyn.* **38** 1949–64

Chakraborty T, Hsu A, Manya D and Sheriff G 2019 Disproportionately higher exposure to urban heat in lower-income neighborhoods: a multi-city perspective *Environ. Res. Lett.* **14** 105003

Climate Change Committee 2021 *Independent Assessment of UK Climate Risk: Advice to Government For the UK's Third Climate Change Risk Assessment (CCRA3)*

Compo G P *et al* 2011 The twentieth century reanalysis project: the twentieth century reanalysis project *Q. J. R. Meteorol. Soc.* **137** 1–28

Copernicus 2022 Climate indicators: temperature (available at: https://climate.copernicus.eu/climate-indicators/temperature)

Cowan T, Hegerl G C, Colfescu I, Bollasina M, Purich A and Boschat G 2017 Factors contributing to record-breaking heat waves over the great plains during the 1930s Dust Bowl *J. Clim.* **30** 2437–61

Cowan T, Undorf S, Hegerl G C, Harrington L J and Otto F E L 2020 Present-day greenhouse gases could cause more frequent and longer Dust Bowl heatwaves *Nat. Clim. Change* **10** 505–10

Ebi K L *et al* 2021 Hot weather and heat extremes: health risks *Lancet* **398** 698–708

Eyring V, Bony S, Meehl G A, Senior C A, Stevens B, Stouffer R J and Taylor K E 2016 Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization *Geosci. Model Dev.* **9** 1937–58

Fischer E M and Schär C 2010 Consistent geographical patterns of changes in high-impact European heatwaves *Nat. Geosci.* **3** 398–403

Gallo V *et al* 2012 Social inequalities and mortality in Europe—results from a large multi-national cohort *PLoS One* **7** e39013

Garcia M, Yu D, Park S, Yousefi Bahambari P, Mohajer Iravanloo B and Sivapalan M 2022 Weathering water extremes and cognitive biases in a changing climate *Water Secur.* **15** 100110

Harrington L J, Otto F E L, Cowan T and Hegerl G C 2019 Circulation analogues and uncertainty in the time-evolution of extreme event probabilities: evidence from the 1947 Central European heatwave *Clim. Dyn.* **53** 2229–47

Hawkins E *et al* 2023 Rescuing historical weather observations improves quantification of severe windstorm risks *Nat. Hazards Earth Sys. Sci.* **23** 1465–82

Hazeleger W, Van Den Hurk B J J M, Min E, Van Oldenborgh G J, Petersen A C, Stainforth D A, Vasileiadou E and Smith L A 2015 Tales of future weather *Nat. Clim. Change* **5** 107–13

Hegerl G C, Brönnimann S, Cowan T, Friedman A R, Hawkins E, Iles C, Müller W, Schurer A and Undorf S 2019 Causes of climate change over the historical record *Environ. Res. Lett.* **14** 123006

Jézéquel A, Cattiaux J, Naveau P, Radanovics S, Ribes A, Vautard R, Vrac M and Yiou P 2018a Trends of atmospheric circulation during singular hot days in Europe *Environ. Res. Lett.* **13** 054007

Jézéquel A, Yiou P and Radanovics S 2018b Role of circulation in European heatwaves using flow analogues *Clim. Dyn.* **50** 1145–59

Jézéquel A, Yiou P, Radanovics S and Vautard R 2018c Analysis of the exceptionally warm december 2015 in France using flow analogues *Bull. Am. Meteorol. Soc.* **99** S76–S79

Kalnay E *et al* 1996 The NCEP/NCAR 40-year reanalysis project *Bull. Am. Meteorol. Soc.* **77** 437–71

Kendon M, McCarthy M, Jevrejeva S, Matthews A, Williams J, Sparks T and West F 2023 State of the UK climate 2022 *Int. J. Climatol.* **43** 1–83

Kornhuber K, Petoukhov V, Karoly D, Petri S, Rahmstorf S and Coumou D 2017 Summertime planetary wave resonance in the Northern and Southern Hemispheres *J. Clim.* **30** 6133–50

Krueger O, Hegerl G C and Tett S F B 2015 Evaluation of mechanisms of hot and cold days in climate models over Central Europe *Environ. Res. Lett.* **10** 014002

Masson-Delmotte V *et al* (eds) 2021 *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press)

Otto F E L, Van Oldenborgh G J, Eden J, Stott P A, Karoly D J and Allen M R 2016 The attribution question *Nat. Clim. Change* **6** 813–6

Parker D E, Legg T P and Folland C K 1992 A new daily Central England temperature series, 1772–1991 *Int. J. Clim.* **12** 317–42

Patterson M 2023 North-West Europe hottest days are warming twice as fast as mean summer days *Geophys. Res. Lett.* **50** e2023GL102757

Perkins S E 2015 A review on the scientific understanding of heatwaves—their measurement, driving mechanisms, and changes at the global scale *Atmos. Res.* **164–165** 242–67

Perkins-Kirkpatrick S E and Lewis S C 2020 Increasing trends in regional heatwaves *Nat. Commun.* **11** 3357

Robine J-M, Cheung S L K, Le Roy S, Van Oyen H, Griffiths C, Michel J-P and Herrmann F R 2008 Death toll exceeded 70,000 in Europe during the summer of 2003 *C. R. Biol.* **331** 171–8

Rosenzweig C, Parry M L and De Mel M (eds) 2021 *Our Warming Planet: Climate Change Impacts and Adaptation* (*Lectures in Climate Change*) (World Scientific)

Rousi E *et al* 2023 The extremely hot and dry 2018 summer in central and northern Europe from a multi-faceted weather and climate perspective *Nat. Hazards Earth Sys. Sci.* **23** 1699–718

Rousi E, Kornhuber K, Beobide-Arsuaga G, Luo F and Coumou D 2022 Accelerated western European heatwave trends linked to more-persistent double jets over Eurasia *Nat. Commun.* **13** 3851

Rumore D, Schenk T and Susskind L 2016 Role-play simulations for climate change adaptation education and engagement *Nat. Clim. Change* **6** 745–50

Russo S, Dosio A, Graversen R G, Sillmann J, Carrao H, Dunbar M B, Singleton A, Montagna P, Barbola P and Vogt J V 2014 Magnitude of extreme heat waves in present climate and their projection in a warming world *J. Geophys. Res. Atmos.* **119** 12,500–12,512

Russo S, Sillmann J and Fischer E M 2015 Top ten European heatwaves since 1950 and their occurrence in the coming decades *Environ. Res. Lett.* **10** 124003

Seneviratne S I, Corti T, Davin E L, Hirschi M, Jaeger E B, Lehner I, Orlowsky B and Teuling A J 2010 Investigating soil moisture–climate interactions in a changing climate: a review *Earth Sci. Rev.* **99** 125–61

Shepherd T G *et al* 2018 Storylines: an alternative approach to representing uncertainty in physical aspects of climate change *Clim. Change* **151** 555–71

Shepherd T G 2019 Storyline approach to the construction of regional climate change information *Proc. R. Soc.* A **475** 20190013

Shivanna K R 2022 Climate change and its impact on biodiversity and human welfare *Proc. Indian Natl Sci. Acad.* **88** 160–71

Simmons A J 2022 Trends in the tropospheric general circulation from 1979 to 2022 *Weather Clim. Dyn.* **3** 777–809

Slater R, Freychet N and Hegerl G 2021 Substantial changes in the probability of future annual temperature extremes *Atmos. Sci. Lett.* **22** e1061

Slivinski L C *et al* 2019 Towards a more reliable historical reanalysis: improvements for version 3 of the twentieth century reanalysis system *Q. J. R. Meteorol. Soc.* **145** 2876–908

Stott P A *et al* 2016 Attribution of extreme weather and climate-related events *WIREs Clim. Change* **7** 23–41

Trenberth K E, Fasullo J T and Shepherd T G 2015 Attribution of climate extreme events *Nat. Clim. Change* **5** 725–30

UK Centre for Ecology & Hydrology 2020 Drought inventory (available at: www.ceh.ac.uk/our-science/projects/1911-drought)

Undorf S, Tett S F B, Hagg J, Metzger M J, Wilson C, Edmond G, Jacques-Turner M, Forrest S and Shoote M 2020 Understanding interdependent climate change risks using a serious game *Bull. Am. Meteorol. Soc.* **101** E1279–300

Vasileiadou E and Botzen W J W 2014 Communicating adaptation with emotions: the role of intense experiences in raising concern about extreme weather *Ecol. Soc.* **19** art36

Vogel M M, Orth R, Cheruy F, Hagemann S, Lorenz R, Hurk B J J M and Seneviratne S I 2017 Regional amplification of projected changes in extreme temperatures strongly controlled by soil moisture-temperature feedbacks *Geophys. Res. Lett.* **44** 1511–9
Yang H, Lu J, Wang Q, Shi X and Lohmann G 2022 Decoding the dynamics of poleward shifting climate zones using aqua-planet model simulations *Clim. Dyn.* **58** 3513–26
Yiou P and Jézéquel A 2020 Simulation of extreme heat waves with empirical importance sampling *Geosci. Model Dev.* **13** 763–81
Yiou P, Jézéquel A, Naveau P, Otto F E L, Vautard R and Vrac M 2017 A statistical framework for conditional extreme event attribution *Adv. Stat. Climatol. Meteorol. Oceanogr.* **3** 17–31
Yiou P, Vautard R, Naveau P and Cassou C 2007 Inconsistency between atmospheric dynamics and temperatures during the exceptional 2006/2007 fall/winter and recent warming in Europe *Geophys. Res. Lett.* **34** L21808
Yule E L, Hegerl G, Schurer A and Hawkins E 2023 Using early extremes to place the 2022 UK heat waves into historical context *Atmos. Sci. Lett.* **24** e1159
Zscheischler J *et al* 2018 Future climate risk from compound events *Nat. Clim. Change* **8** 469–77