

Communicating changes in the intensity of UK heatwaves

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Sutton, R. ORCID: <https://orcid.org/0000-0001-8345-8583> and
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Communicating changes in the intensity of UK heatwaves

Ed Hawkins¹ ,
Rowan Sutton^{1,2}  and
Mike Kendon²

¹National Centre for Atmospheric Science, Department of Meteorology, University of Reading, UK

²Met Office, Hadley Centre, Exeter, UK

Introduction

Communicating how we personally experience changes to the weather could help highlight how we are already affected by climate change, especially during extreme weather events. This is one motivation for near-real-time event attribution which aims to discuss how a particular weather event would have had different consequences or have occurred with a different frequency in the past (van Oldenborgh *et al.*, 2021).

Heatwaves are often studied in this context due to their serious impacts on human health and ecological systems. Maximum temperatures during heatwaves are projected to warm faster than the rate

of global temperature change in many regions in climate model simulations (e.g. Fischer *et al.*, 2014; Seneviratne *et al.*, 2016; Zhang and Boos, 2023). In observations, Vautard *et al.* (2023) and Patterson (2023) have shown that, across northwest Europe, hot days are warming much faster than the global average. Dynamical influences have been suggested as one factor (although not over the UK according to Vautard *et al.*, 2023) with other mechanisms including land-atmosphere interactions, soil moisture feedbacks or thermal advection (see Patterson, 2023 for more details). For the UK, Kendon *et al.* (2024) highlighted two related aspects of how observed temperature extremes have already changed. First, the frequency of hot days is increasing fastest for the hottest temperatures over most UK regions. Second, the UK average of daily temperature has warmed more for extreme days than for more typical days, for both cold minimum temperatures (T_{\min} in winter) and hot maximum temperatures (T_{\max} in summer).

Here, we describe a simple observation-based approach which examines how daily temperatures are substantially warmer now than on a comparable day a century

ago. We mainly consider the context of UK summer heatwaves and focus on how the observed change in intensity might be communicated, but the ideas are more general. The relationships derived between changed heatwave intensity and global temperature change are not a formal attribution to, for example, greenhouse gas emissions, but are still useful communication tools. We use the HadUK-Grid dataset which currently provides daily T_{\max} and T_{\min} for 1931–2024 (v1.3.1; after Hollis *et al.*, 2019). We use the data on a 12km grid, along with the regional (river basin) averages of T_{\max} .

As an example, timeseries of various percentiles of summer daily T_{\max} averaged over the Anglian region of the UK are shown in Figure 1. The hottest summer days (98th percentile) have warmed 3.9°C from 1931 to 2024 (from 26.6 to 30.5°C), which is far more than the coolest summer days (2nd percentile), which have warmed by 1.0°C (from 14.4°C to 15.4°C). An average summer day has warmed by 2.0°C (from 20.2°C to 22.2°C). Over the same period, global temperatures increased by around 1.2°C, so a typical summer day in Anglia is warming around 2 times faster than the global mean, with the hottest days warming more than

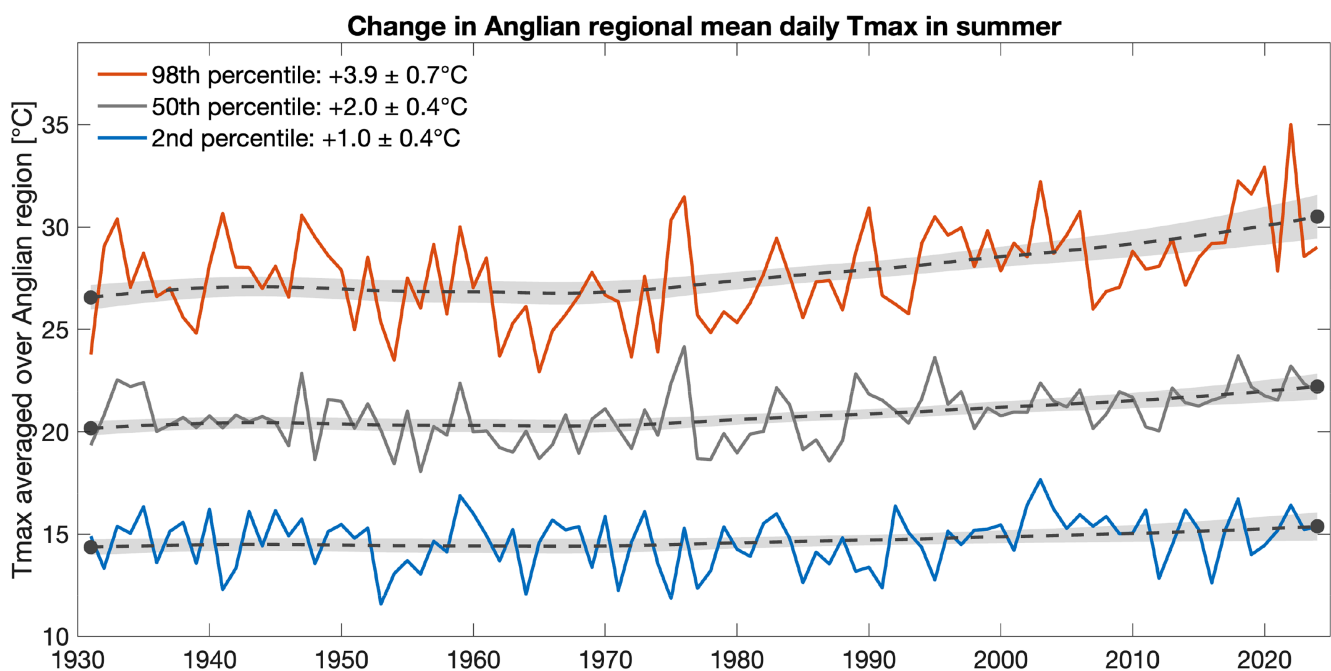


Figure 1. The 98th, 50th and 2nd percentiles of Anglian average daily T_{\max} in summer (JJA) each year from 1931 to 2024. A regression onto a smoothed global temperature time-series (41-year loess smoothing applied to HadCRUT5; Morice *et al.*, 2021) is shown with the dashed black line (following Hawkins *et al.*, 2020). The difference in T_{\max} between the black dots in 2024 and 1931 is shown as the change in the legend for each percentile, with an indication of the uncertainty in this value.

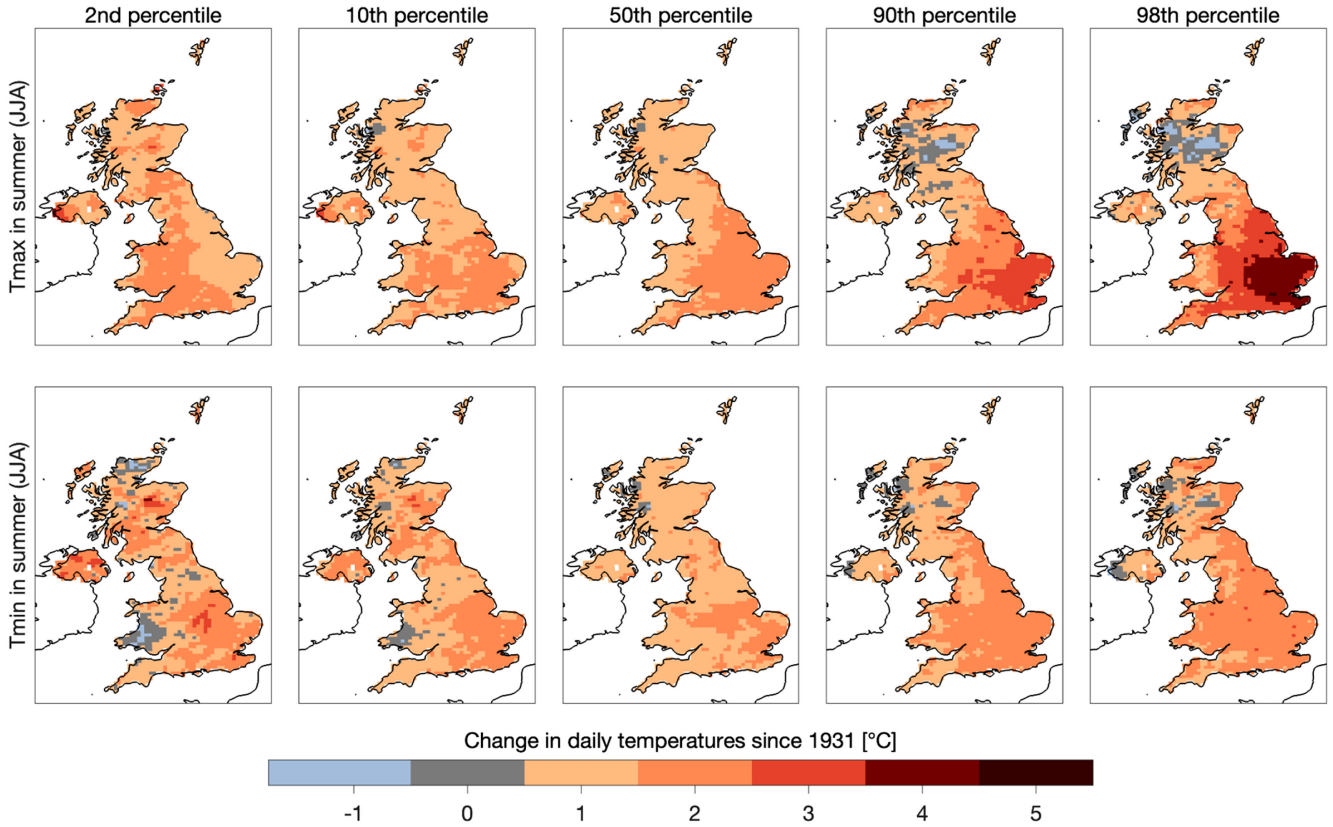


Figure 2. Change in daily temperatures across the UK between 1931 and 2024, for different percentiles, in summer T_{max} (top) and T_{min} (bottom). The hottest summer days are warming fastest, with smaller variations across percentiles for summer nights.

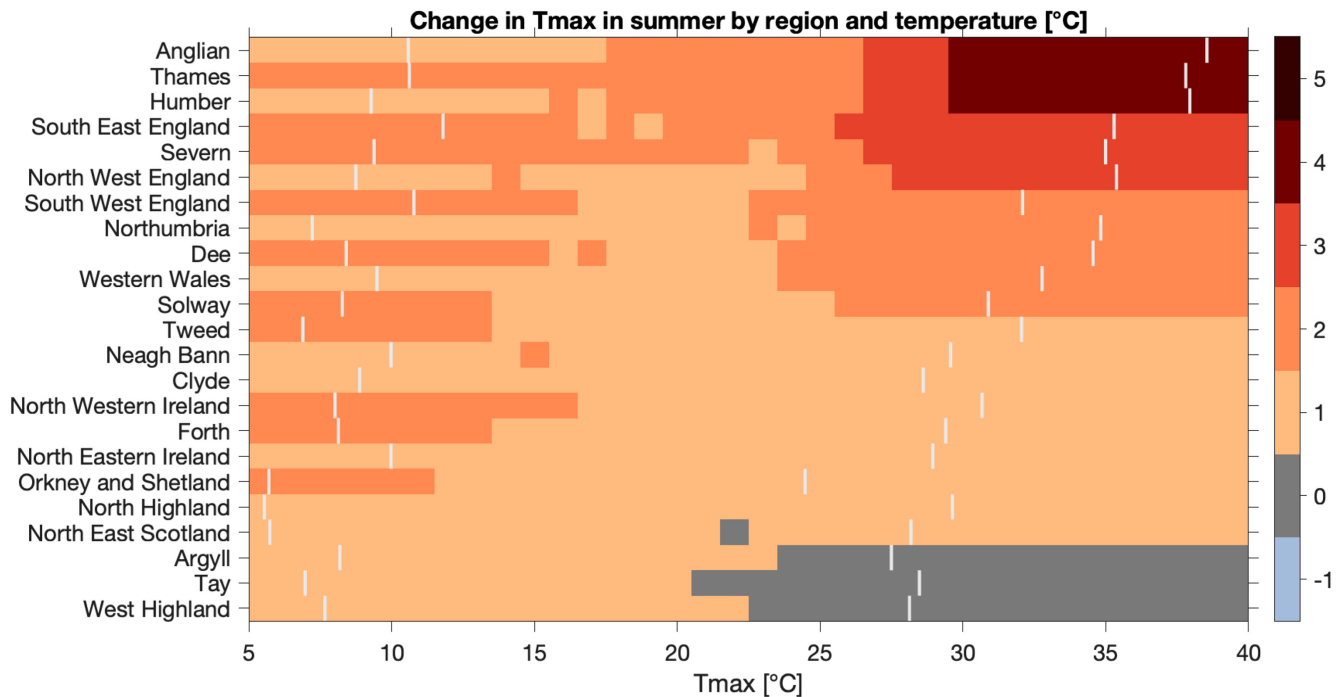


Figure 3. Observed change in regional mean daily T_{max} in summer since 1931 for different absolute temperatures experienced now. The white vertical bars show the lowest and highest observed regional mean T_{max} between 1931 and 2024.

3 times faster. We note that the differences in warming rates between the coolest and warmest summer days are statistically significant and focus the rest of the analysis on communicating the effects.

Those wanting to downplay the risks of climate change sometimes suggest that

global warming is ‘just’ an increase of 1°C or 2°C so the consequences cannot be large. And, on many days, a difference of 1°C would not matter. However, these observed changes in hot summer extremes – which have serious health and other impacts (e.g. Gasparrini *et al.*, 2015; Howarth *et al.*, 2024)

– highlight that how we experience global warming can be considerably amplified from the global average change. Given that heat mortality risk increases ever faster for hotter temperatures in the UK (Gasparrini *et al.*, 2015), this also implies that every 0.1°C of additional global change is more

impactful for summer heat mortality than the previous 0.1°C increase, assuming no adaptation.

Change in UK regional temperature extremes

The analysis presented in Figure 1 can be extended across the UK (using the 12km gridded data), for both T_{max} and T_{min} in summer (JJA). Figure 2 shows the change in temperature between 1931 and 2024 for a range of percentiles, highlighting that different parts of the UK are warming at different rates, particularly for T_{max} .

The southeast of the UK (including the well-observed Anglian region) shows the largest observed summer warming in T_{max} and this is substantially amplified for the hottest days. This pattern may have an urban heat island component, but the amplification is not isolated to just urban areas. Cool summer days have warmed far

less, highlighting that the shape of the daily distributions of temperatures is changing – for summer T_{max} they are generally widening. Those living in Scotland have experienced far less summer warming than other regions and there is less variation in warming rate with percentiles. There are small areas in the Scottish mountains where the hottest days are cooling slightly in this dataset. However, the relative sparseness of observations in these areas will increase uncertainty in the trends which should be interpreted with more caution. For T_{min} , there are smaller variations with percentiles and across different regions of the UK.

Changes across a wider range of seasons, regions and datasets are summarised in the Supplementary Information (Figures S1–S5). In particular, for Central England Temperature (CET), which is based on a small number of reliable long-term weather station observations (Legg *et al.*, 2024), the hottest summer days are still warming fast-

est using data back to 1878 (Figures S1 and S6). This even longer series provides further evidence that a large part of the signal is not related to internal variability.

Moving from percentiles to temperatures

Communicating changes in percentiles of extreme temperatures to the public is likely challenging. Instead, we consider a different way of showing the information in Figure 2 by linking the percentiles to more relatable absolute temperatures.

For each location or region, the percentile associated with a modern day value of T_{max} is calculated using the regression approach shown in Figure 1. Specifically, for each region, we find the percentile that produces a regression that ends in 2024 (black dots in Figure 1) at, say, 30°C and calculate the change in that percentile since 1931. Figure 3 shows that, for example, days in the Anglian, Thames and Humber regions that now reach 30°C are 4°C hotter than comparable days in 1931. We suggest this is an easier way to communicate changes in T_{max} than percentiles. Note that the calculated change in the 99th percentile is used for any temperature above that level, and this could imply that the estimated change is an underestimate for extremely hot days (see Figure S2).

We can use the information in Figure 3 as a ‘look-up table’, providing the estimated observed change in T_{max} for each region for any recently observed T_{max} (or even a forecast of T_{max}). This information could be updated each year as new observations accumulate, although the differences are likely to be incremental. The same information can also be calculated for each grid point and we use that data below.

These estimates of changes in T_{max} are not calculated for individual events but represent an average over a range of different synoptic patterns that produce that temperature in that region in that season, similarly to probabilistic approaches to event attribution. Below we use the term ‘comparable day’ to indicate this average. It is possible that higher or lower temperature differences would be estimated if conditioned on specific events.

Application to individual days

We highlight the potential for using this information using three example days: 19 July in each of 2021, 2022 and 2023 (Figure 4). The observed temperatures were quite different on these 3 days, with 19 July 2022 being the hottest day on record for the UK; 40°C was recorded at a few sites. That heatwave caused a wildfire in London and around 2200 excess deaths during the 2 weeks of the heat period (UKHSA, 2022).

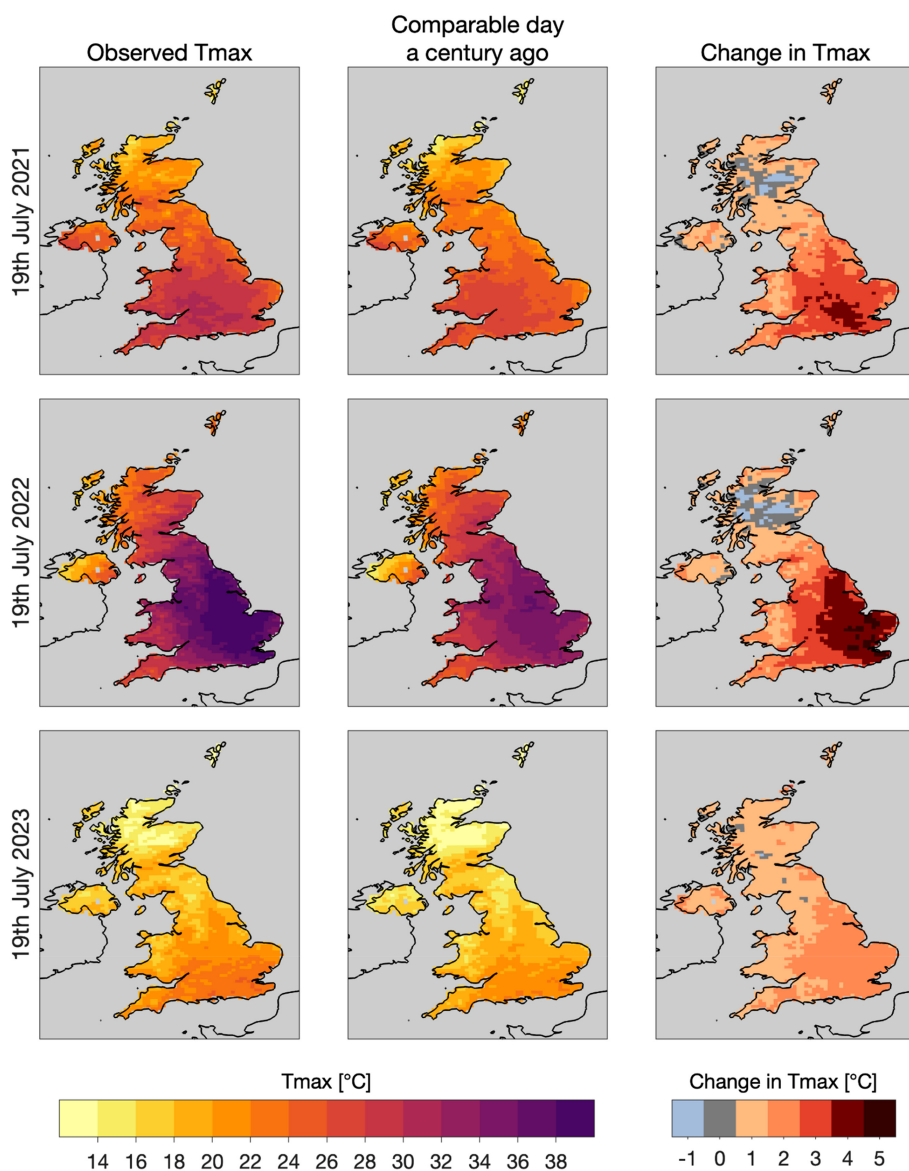


Figure 4. Three example days – 19 July 2021, 2022 and 2023 – showing the observed daily T_{max} (left), a comparable event a century ago (middle), and the change in T_{max} (right).

Daily maximum temperature [°C]

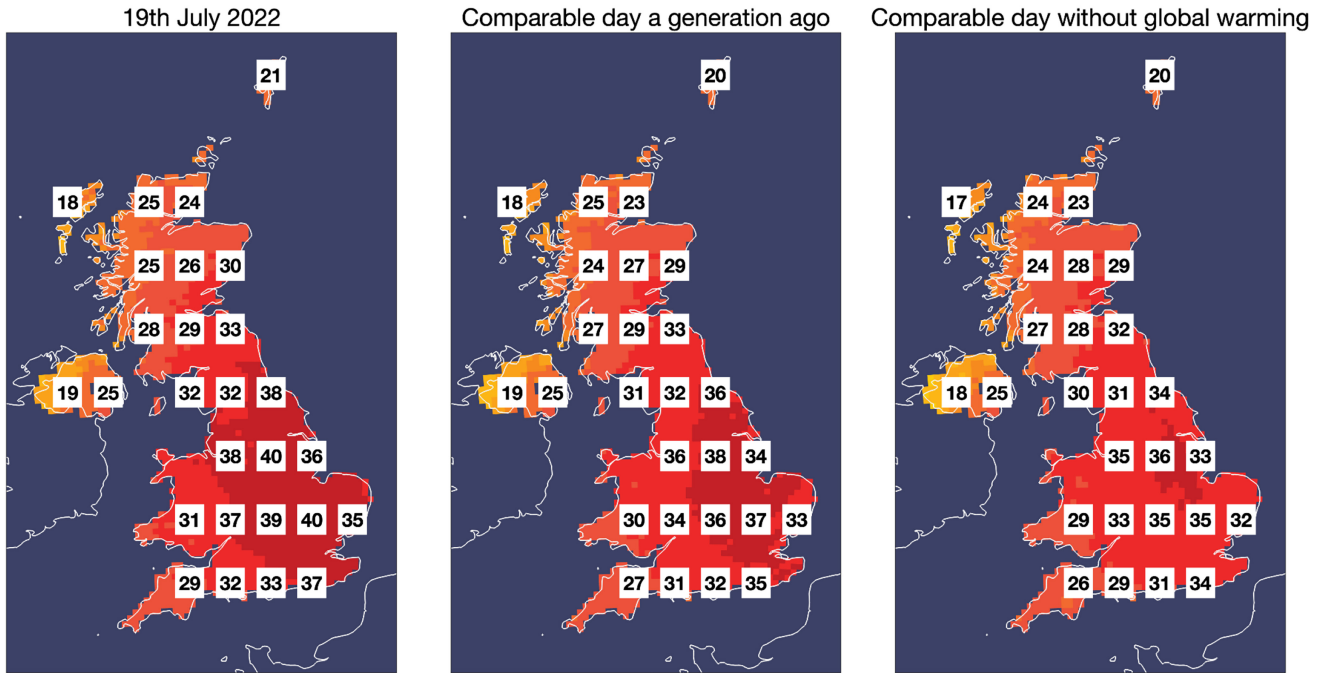


Figure 5. Illustrative example of how the observations (or forecast) of T_{max} [°C] could be communicated to highlight how much hotter a particular day was (or is likely to be) for typical maximum temperatures across the UK. Left: as observed on 19 July 2022. Middle: a comparable day 30 years ago ('in generational memory'). Right: a comparable day nearly a century ago ('without global warming'). Colour scale based on BBC weather graphics.

Gridded (12km) T_{max} for historical events and translated into present

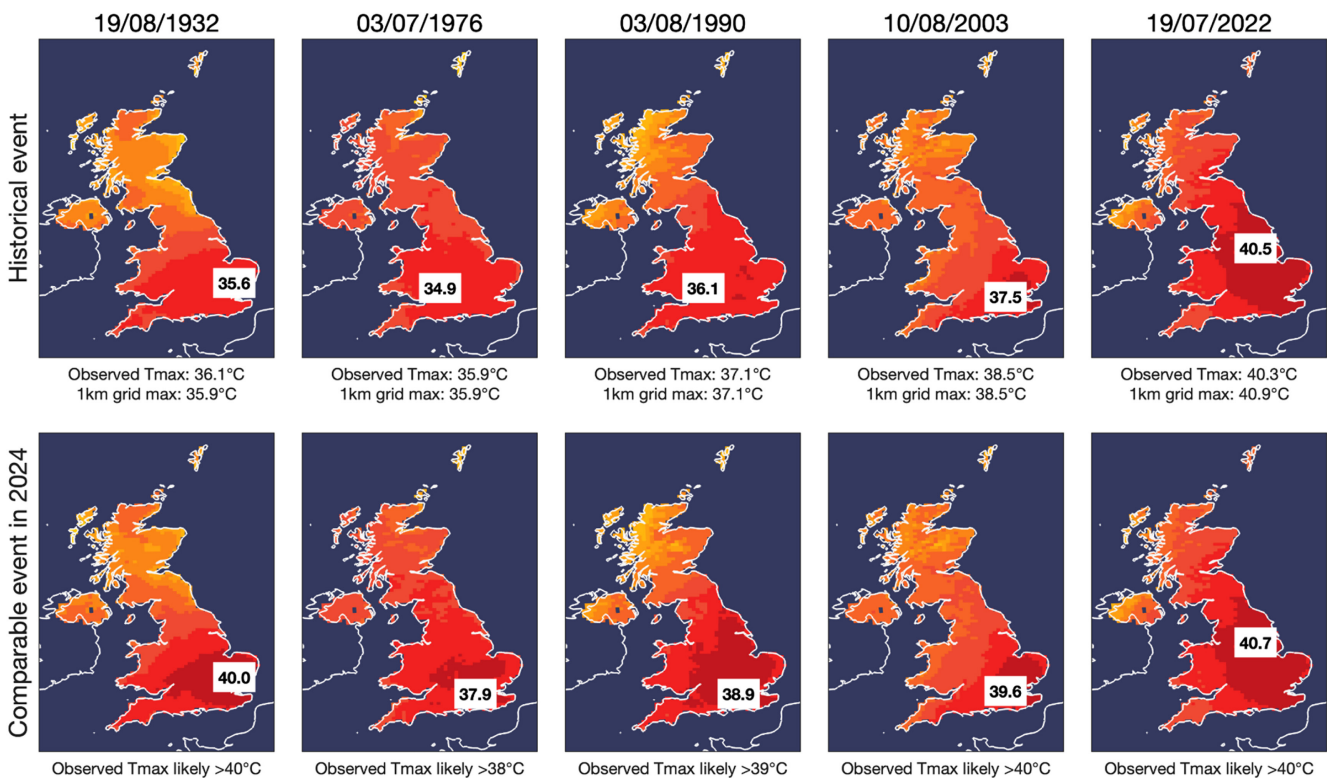


Figure 6. Estimating how extreme historical days would be experienced today. Top: the observed event, with the maximum value on the 12km grid labelled. The station maximum and 1km grid maximum are given below, which are often slightly larger. Bottom: an estimate of how that day would look in the climate of 2024, and an indication of whether the observed station maximum would likely be above 38°C, 39°C or 40°C is given below.

The same day in 2021 was warm, and in 2023 it was relatively cool.

Using the gridded T_{max} data we show that for parts of the southeast of England,

the peak temperatures in 2022 were 4–5°C warmer than would have been expected for a comparable day nearly a century ago. Zachariah *et al.* (2022) reported simi-

lar numbers from an observational analysis based on the methods described in Philip *et al.* (2020). We suggest that the peak temperature on 19 July 2022 would have

been around 36°C on a comparable day a century ago, with likely fewer excess deaths and reduced wildfire risk. Smaller changes are seen in other parts of the country, and on the cooler example days (Figure 4), but in most cases these changes are the same or larger than the equivalent level of global warming over the same time period (around 1.2°C).

How could this information be used during a future heatwave? Imagine a weather forecaster discussing a future day like 19 July 2022. Before the event their primary aim is to inform people about the heat-related risks and so help save lives, but they could consider discussing the effect of climate change after the event when some of the impacts would be known. Figure 5 shows an illustrative example of how the differences could be communicated using a familiar UK weather map. On a comparable day within generational memory (30 years ago), the peak would have been around 38°C, and a century ago it would have been around 36°C.

Discussion

We have considered how the changed intensity of a UK heatwave could be communicated, highlighting that the hottest days are warming faster than typical summer days. This overall approach could also be implemented every day using the forecast temperatures, possibly even within weather forecast apps on mobile phones to broaden communication opportunities. The approach is flexible and could also be implemented for other seasons and both T_{\min} and T_{\max} . We suggest that there are opportunities for weather forecasters and app developers, as trusted messengers on weather and climate, to consider these ideas.

We can also use the approach described above in reverse to consider what the peak temperature might be in a modern climate for an event comparable to notable historical heatwaves (Figure 6). Such storyline approaches to translating extreme events into different climates are becoming more widely used (e.g. Sánchez-Benítez *et al.*, 2022; Hawkins *et al.*, 2023; Callahan *et al.*, 2025).

We first note that the amplification of global warming during UK heatwaves means that the peak temperatures on a comparable day to July 2022 would already be around 0.2°C hotter in 2025. Looking further back, we estimate that the peak observed temperatures on around 4 other historical days in the past century would likely have exceeded 38°C somewhere in the UK in the current climate (Figure 6), two of which would have probably exceeded 40°C. And, although it is not included in the gridded dataset, the earlier UK heatwave of August 1911 had an observed T_{\max} of 36.7°C

at stations in Kent and Northamptonshire – a record which stood for nearly 80 years – and would likely be as hot or hotter than July 2022 if it occurred again today. These findings fit with a recent model-based study suggesting that a >40°C day is now roughly a 1-in-25 year event (Kay *et al.*, 2025).

An alternative approach often used in event attribution is to discuss the increased likelihood of hotter temperatures, rather than the change in intensity. For the Anglian region example shown in Figure 1, two possible statements are: (1) a daily T_{\max} of 25°C would have been around 23°C a century ago, and (2) a daily T_{\max} of over 25°C in summer is now around 4 times more likely than a century ago (this temperature threshold has moved from the 94th percentile in 1931 to the 78th percentile in 2024, based on regression estimates like those shown in Figure 1). We suggest that these two types of statement are complementary. Some modern events are found to be statistically implausible in a pre-industrial climate, and this is a helpful message, but the change in likelihood can be highly uncertain for very extreme days as it is the ratio of two very small numbers.

Last, we note that this analysis is not a formal attribution of the change in temperatures to human influence, but rather examines how extreme temperatures have been observed to change relative to global warming. There may be local amplification (or suppression) of global warming due to, for example, internal variability, variations in sulphate aerosols, cloudiness or land surface conditions such as drying soils, urbanisation or other land use changes (see discussion in Vautard *et al.*, 2023). If these factors were locally important over the past century then it could mean that future changes in hot extremes are not necessarily going to be similarly amplified when compared to global temperature change, that is, the next 1°C of global warming may cause less (or more) than 3°C of warming in the hottest Anglian days. However, we still need to live with, adapt to and suffer through, the changes in extreme temperatures that have already occurred, and those that will occur in future.

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Author contributions

Ed Hawkins: Conceptualization; investigation; writing – original draft; methodology; validation; visualization; writing – review and editing. **Rowan Sutton:** Writing – review and editing. **Mike Kendon:** Writing – review and editing; investigation; methodology.

Data availability statement

The data that support the findings of this study are openly available in HadCRUT5 (<https://www.metoffice.gov.uk/hadobs/hadcrut5/>) and HadUK-Grid (<https://catalogue.ceda.ac.uk/uuid/4dc8450d889a491ebb20e724debe2dfb/>).

Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1.

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Correspondence to: E. Hawkins
e.hawkins@reading.ac.uk

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