AGU ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2023GL102757

North-West Europe Hottest Days Are Warming Twice as Fast as Mean Summer Days

Matthew Patterson[1]

[1]Atmospheric, Oceanic and Planetary Physics, University of Oxford, Oxford, UK

Key Points:

- The hottest boreal summer days are warming approximately twice as fast as mean summer days for North-West Europe
- Simulations with comprehensive climate models fail to capture this difference between trends in maximum and mean temperatures
- One possible explanation for the trend difference is an increase in the local meridional temperature gradient

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

M. Patterson,
matthew.patterson@physics.ox.ac.uk

Citation:

Patterson, M. (2023). North-West Europe hottest days are warming twice as fast as mean summer days. *Geophysical Research Letters*, *50*, e2023GL102757. https://doi.org/10.1029/2023GL102757

Received 6 JAN 2023
Accepted 27 APR 2023

Abstract Europe has seen a rapid increase in the frequency and intensity of hot extremes in recent decades. In this study it is shown, using ERA5 reanalysis data 1960–2021, that the hottest summer days in North-West Europe are warming approximately twice as fast as mean summer days. Moreover, this pattern stands out as relatively unusual across the Northern Hemisphere. It is also shown that comprehensive climate models fail to capture this difference in trends. A hypothesis is suggested to explain the differential rate of warming between the mean and hottest days, namely that the hottest days are often linked to warm advection from Iberia and North Africa, areas that are warming faster than North-West Europe. This hypothesis can account for about 25% of the difference between ERA5 and a climate model ensemble and hence further research is needed to understand the drivers of the differing trends in mean and extreme temperature.

Plain Language Summary Extreme heat has a negative impact on society and is becoming more common with climate change. It is shown in this study that, for North-West Europe over the last 60 years, the hottest day in each year has been warming at a faster rate than the average summer day. This suggests that slightly different processes are influencing the trends in the hottest summer days compared to average summer days. Unfortunately, state of the art climate models do not capture this difference between extreme and average summer days which makes understanding this phenomenon more difficult and means that we have to be careful when using these models to study heat extremes. In this article, I suggest an explanation for the difference between the average and hottest summer day trends seen in observations. The hottest summer days in North-West Europe are often linked to transport of warmer air from regions further south, such as from Iberia. These more southerly areas are warming faster than North-West Europe, hence air carried in is ever more extreme relative to the ambient air, leading to a greater trend in the hottest days.

1. Introduction

Human-induced global warming is shifting the distribution of possible temperatures toward higher values, increasing the intensity and frequency of hot extremes globally (Allan et al., 2021). This is concerning as heat extremes are associated with a wide range of negative impacts on society such as in the health (Vicedo-Cabrera et al., 2018), energy (Miller et al., 2008) and agriculture (Lobell & Field, 2007) sectors, while many animal and plant species are vulnerable to heat extremes (Stillman, 2019).

In addition to a simple shift of temperature distributions, there is evidence for recent changes to the width and possibly higher moments of temperature distributions and thus the likelihood of extremes, depending on the region (Huntingford et al., 2013). For instance, Byrne (2021) found that the hottest days on tropical land are warming approximately 20% faster than the mean and linked this to theory via the "drier get hotter" mechanism. The variance in the summer temperature distribution over much of Eurasia has also increased since 1980 (McKinnon et al., 2016). Station data for many parts of Europe show an increase in day-to-day temperature variability within the summer season since the 1960s (Krauskopf & Huth, 2022), while increased temperature variability is necessary to account for the magnitude of the 2003 European heat wave (Schär et al., 2004). On the other hand, recent studies have found no evidence for faster warming of extremes, relative to the mean for the Pacific Northwest (McKinnon & Simpson, 2022; Thompson et al., 2022).

Differing warming trends for mean and extreme temperature values could arise for a number of different reasons. Atmospheric circulation is a key driver of extreme temperatures and hence changes to the frequency of occurrence of certain weather regimes could lead to more extreme temperatures (Coumou et al., 2014; Kornhuber et al., 2019; Mann et al., 2017; Meehl & Tebaldi, 2004; Rousi et al., 2022; Teng & Branstator, 2019). Land-atmosphere interactions could also play a role. Model simulations of future climate project an increase in European summer

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temperature variability (Bathiany et al., 2018; Fischer & Schär, 2008; Fischer et al., 2007, 2012; Giorgi et al., 2004) which has been explained through positive feedbacks between evapo-transpiration and temperature anomalies in regions where soil-moisture is a limiting factor (Seneviratne et al., 2006, 2010; Whan et al., 2015). Additionally, Holmes et al. (2016) argued that changes to thermal advection, such as increases to summertime land-sea contrast, could change European summer temperature variability, while Tamarin-Brodsky et al. (2022) interpreted changes in the skew of temperature distributions as being driven by meridional thermal advection and differing rates of warming with latitude.

Many countries in North-West Europe have experienced severe heat extremes in recent years. The record temperature in France, set during the 2003 heatwave, was broken on 28 June 2019, reaching 46.0 C (Mitchell et al., 2019; van Oldenborgh et al., 2019). A few weeks later the UK temperature reached 38.7 C for the first time (Vautard et al., 2020). A mere 3 years later, in July 2022, the UK saw a new record of 40.3 C, breaking the previous record by 1.6 C (Zachariah et al., 2022). These records are part of a trend in rapidly increasing heat extremes in the European region (Christidis et al., 2015; Perkins-Kirkpatrick & Lewis, 2020).

It has recently been noted that the hottest days in the UK are warming faster than mean summer days (Kennedy-Asser et al., 2021). However, it is unclear whether this trend difference is observed across Europe and indeed further afield or is restricted to the UK. Moreover, the driving mechanism behind this trend difference has not been analyzed. In this article I seek to investigate the wider context to the observed difference between mean and extreme trends and understand its cause. In Section 2 the data sets and model simulations used in this work are detailed. Then, in Section 4, I suggest a potential hypothesis to explain differences between trends in extreme temperatures with respect to mean temperature trends, and finally provide some discussion in Section 5.

2. Data

In this study I utilize ERA5 reanalysis data on a 1 × 1 degree grid spanning the period 1960–2021 (Bell et al., 2021; Hersbach et al., 2020). Most of the variables in this study are daily-means with the exception being the maximum daily 2 m air temperature, referred to here as tasmax.

I compare the reanalysis data to an ensemble of 26 coupled climate model simulations from the Coupled Model Intercomparison Project Phase 6 (CMIP6) archive (Eyring et al., 2016) using historical forcings including variations in greenhouse gases, aerosols and volcanic activity. Historical simulations end in 2014, hence to make up the full period of 1960–2021, historical simulations have been combined with simulations of the high emissions, shared socioeconomic pathway 5-8.5 (ssp585) scenario run (O'Neill et al., 2016) to 2021. Combining the historical results with the ssp585 scenario up to 2021 is justified by the fact that the different ssp scenarios do not strongly diverge from one another in terms of radiative forcing until around 2030 (O'Neill et al., 2016). These 26 models were chosen because they each provided daily tasmax data for both historical and ssp585 simulations.

In order to quantify the extent to which internal variability may influence trends I have investigated the 50-member MIROC6 large ensemble (Tatebe et al., 2019), 25-member CanESM5 ensemble (Swart et al., 2019) and 30-member CNRM-CM6-1 ensemble (Voldoire et al., 2019). Similar to the other CMIP6 simulations, historical (1960–2014) and ssp585 (2015–2021) model runs have been combined for each of the MIROC6 and CanESM5 ensemble members, though only one of the CNRM-CM6-1 members was extended past 2014 and hence only the historical period (1960–2014) is used for this ensemble. All CMIP6 model data have been interpolated to a common 1 × 1 degree horizontal grid. A full list of model simulations used in this study can be found in the Supporting Information S1.

3. Results

How do trends in heat extremes and trends in the mean summer temperature differ over Europe? Figures 1a and 1b shows the trend in the summer-mean tasmax in boreal summer (June-July-August, JJA) and the trend in the summer-maximum tasmax for each year, respectively, evaluated at each grid-point in the European region. Broadly speaking, the mean tasmax over much of Europe has warmed by 0.4–0.6 K/decade since 1960, though southern countries have warmed more than northern countries (Figure 1a). This pattern differs in Figure 1b with a higher rise in the maximum tasmax each year over the UK and other parts of North-West Europe, than in southern Europe. Over southern parts of the UK, it is clear when comparing Figures 1a and 1b that the hottest days have

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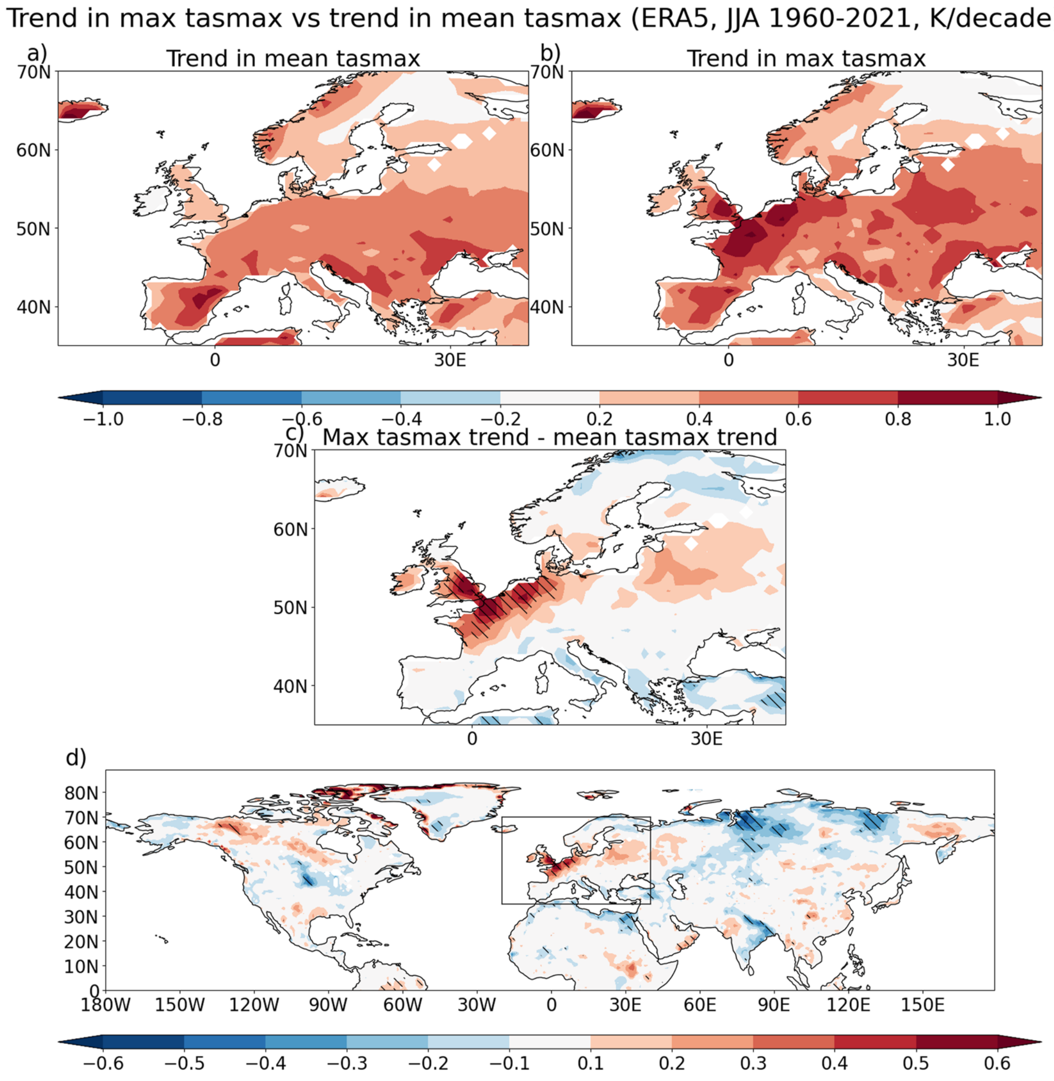

Figure 1. (a) Trend in JJA-mean tasmax (1960–2021), (b) trend in the JJA-maximum tasmax and (c) the trend in the mean minus the trend in the maximum tasmax. Finally, (d) is the same as (c), but for the entire Northern Hemisphere. Hatching in (c, d) shows where trends are statistically significantly different at the 95% level using a *t*-test, following Paternoster et al. (1998). Hatching for statistical significance is omitted from (a, b) for visual clarity as virtually everywhere shaded is statistically significant at the 95% level.

warmed at a substantially higher rate than the mean days, in agreement with Kennedy-Asser et al. (2021). Interestingly, this feature of faster warming of extremes is also present over much of France, Belgium, the Netherlands and northern Germany. The pattern of the difference in maximum and mean trends is shown even more clearly in Figure 1c and the trend differences across much of North-West Europe are statistically significantly different following a *t*-test.

Intriguingly, the difference between maximum tasmax and mean tasmax trends stands out as being particularly large over North-West Europe compared to much of the rest of the Northern Hemisphere (Figure 1d). The warmest temperatures in northern Russia are increasing more slowly than the mean, but few other areas show statistically significant differences over a large area. The ratio of the maximum and mean trends indicates that the hottest days over much of North-West Europe have warmed more than twice as fast as the mean summer day (Figure S1 in Supporting Information S1). Note that the difference pattern over Europe is also seen if one considers the trend in the 95th percentile of summer tasmax rather than the maximum (Figure S2 in Supporting Information S1).

The studies of Zachariah et al. (2022) and Van Oldenborgh et al. (2022) found that CMIP5/CMIP6 models underestimate the magnitude of the observed trend in heat extremes in the UK and de Bilt (Netherlands), respectively,

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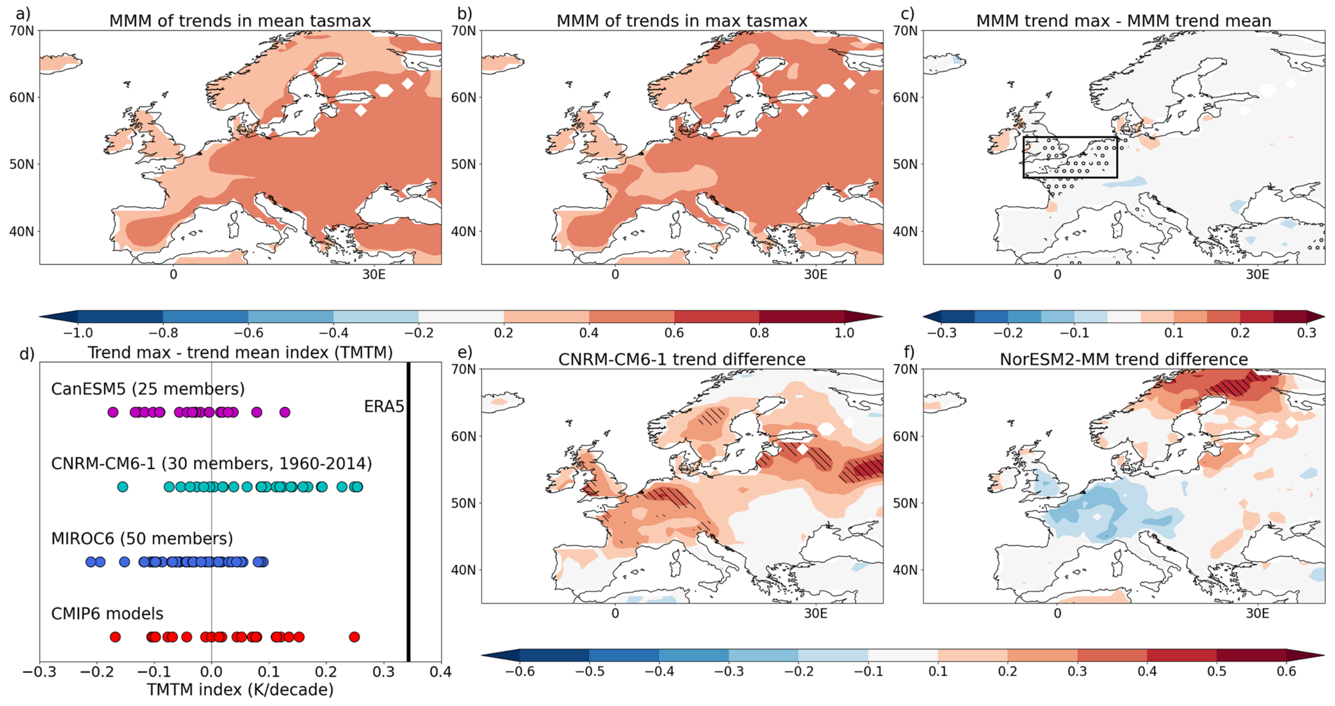

Figure 2. (a) The multi-model mean of the JJA-mean tasmax trend, (b) is the same as (a) but for the JJA-maximum tasmax trend and (c) is the multi-model mean of the JJA-max tasmax trend minus the JJA-mean tasmax trend. In (d), the spread of values for the TMTM index (see text) is shown, calculated for the CMIP6 model runs (red); MIROC6 (blue), CNRM-CM6-1 (cyan) and CanESM5 (magenta) ensembles and ERA5 (thick, black line). Panel (e) is as in (c) but for the model CNRM-CM6-1 (member r1i1p1f2) which has the highest TMTM index of the CMIP6 models and (f) is the same but for NorESM2-MM, which has the lowest TMTM index of the CMIP6 models. Note the smaller contour interval in (c) compared to Figure 1c. Stippling in (c) indicates where ERA5 falls outside the 95% confidence interval of the multi-model ensemble and hatching in (e, f) shows where max and mean trends are statistically significantly different, as in Figures 1c and 1d. The black box in (c) indicates the region used to calculate the TMTM index. Units in all panels are K/decade.

while similar issues have been found in an older generation of regional climate models for North-West Europe (Min et al., 2013). To understand whether this is also the case for the latest models and which locations show this discrepancy, I consider the CMIP6 multi-model means of trends in maximum and mean summer tasmax over the European region. The models generally show a similar trend in mean tasmax over Europe to reanalysis (Figures 1a and 2a), with a magnitude of 0.4–0.6 K and slightly less warming over northern Europe than southern Europe. The multi-model mean trend in maximum tasmax is very similar in magnitude and spatial pattern to the trend in the mean tasmax (Figures 2a and 2b), in contrast to ERA5 where the trend patterns differ markedly (Figures 1a and 1b). This demonstrates that there is no consistent difference between the warming rates of mean and extreme temperatures across the multi-model ensemble, as also illustrated by the difference in maximum and mean warming rates (Figure 2c). Moreover, the observed trend difference also falls outside of the 2.5th and 97.5th percentiles of the multi-model ensemble (stippling in Figure 2a).

However, given that the observational record is just one possible realisation of reality, it is possible that the observed trend difference in this region is simply a result of internal variability. For example, at the end of the time series there could have been several unusually hot days in otherwise average summers, pushing up the maximum tasmax trend by chance. I now test whether any members of three large model ensembles (CanESM5, CNRM-CM6-1, and MIROC6), with historical forcing, can reproduce the observed trend. I first define the "trend in maximum minus trend in mean index" (hereafter TMTM index) as the spatial average of the trend in the summer maximum tasmax minus the summer mean tasmax trend, averaged over the boxed region (48 N–54 N, 5 W–9 E) in Figure 2c). That is, the difference is taken between the maximum tasmax trend and the mean tasmax trend (i.e., Figure 1c for ERA5) and then the TMTM index is the mean of the difference field within the boxed region.

TMTM indices for members of the CanESM5, CNRM-CM6-1, and MIROC6 ensembles range from about −0.2 to about 0.25 K/decade, whereas ERA5 shows a value of 0.34 K/decade, well outside this range. This suggests

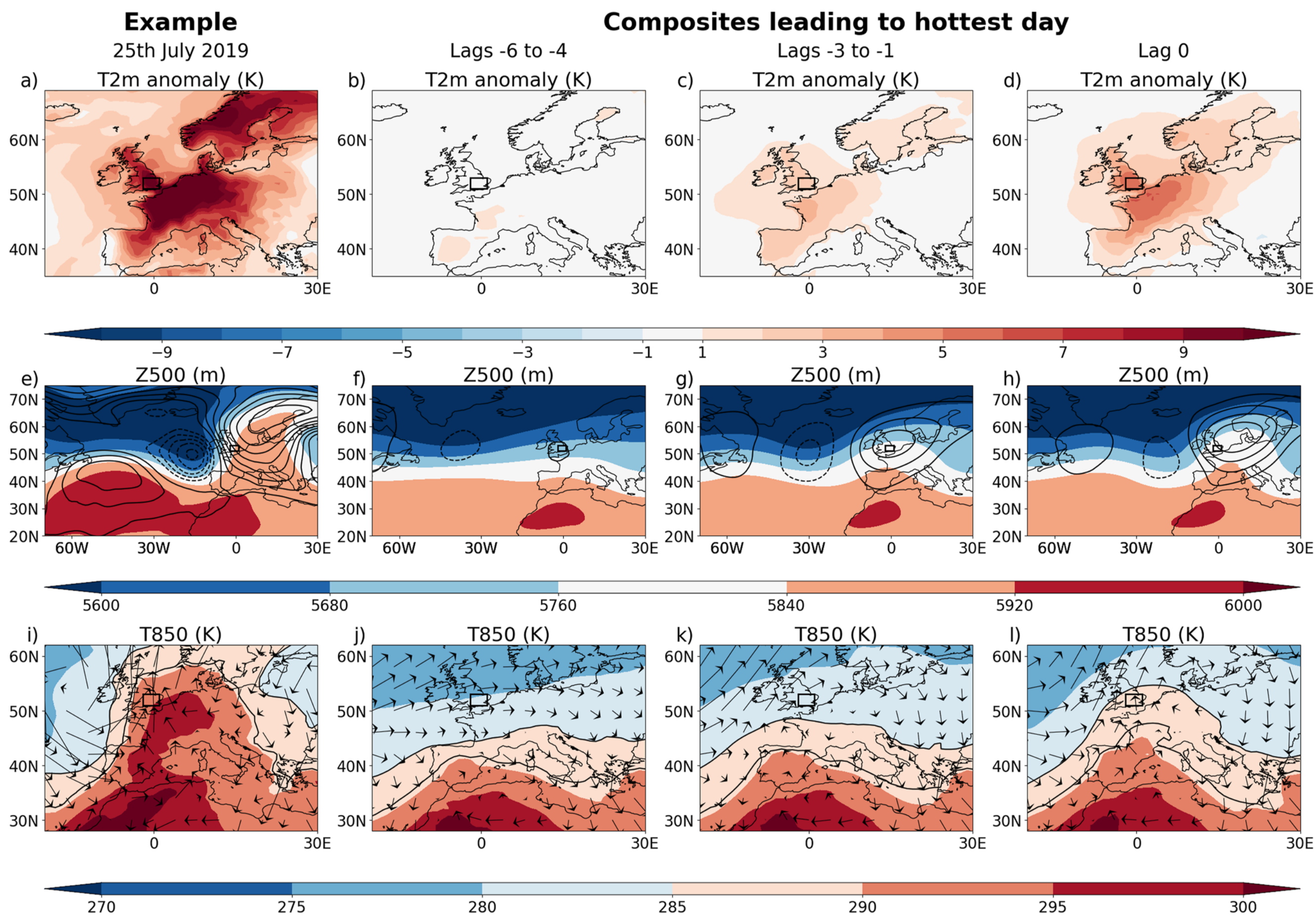

Figure 3. Composites of different variables on the days leading up to the hottest summer day in the south of England (defined by the boxed region shown in each panel) and for the hottest southern England day in 2019 (25th July), all using ERA5 data (1960–2021). The variables shown are (a–d) near-surface air temperature anomalies with respect to the full period; (e–h) 500 hPa geopotential height (colors), with anomalies shown by black, unfilled contours, with contours drawn every 30 m and i–l) 850 hPa air temperature, with 285 and 289 K contours in black, and vectors showing 850 hPa winds. The composites are averaged (b, f, j) 4–6 days and (c, g, k) 1–3 days before the hottest day and d, h, l) on the hottest day.

that the models are incapable of reproducing the observed trend difference considering the models' internal variability and response to historical forcing. Moreover, the ERA5 TMTM index is outside the range of all CMIP6 models (Figure 2d), in agreement with Zachariah et al. (2022). The CMIP6 model with the largest TMTM index is CNRM-CM6-1 (member r1i1p1f2, using 1960–2021, Figure 2e) and interestingly shows a similar, albeit weaker, pattern of trend difference to ERA5 (Figure 1c), with positive differences across France, Germany and also the Baltic states. On the other hand, many models such as NorESM2-MM, which has the lowest TMTM index, show the opposite sign of trend difference (Figure 2f).

4. Enhanced Meridional Temperature Gradient Hypothesis

What is causing the hottest days over North-West Europe to warm faster than the mean in summer? In this section I posit one potential explanation for this finding.

The hottest days in North-West Europe are often associated with large-scale advection of warm air from Spain or the Sahara Desert or other parts of continental Europe (e.g., Black et al., 2004; Burt, 2004; Chiriaco et al., 2014; Miralles et al., 2014; Sousa et al., 2020). For example, while the heatwave which hit the UK and France in June and July 2019 was largely driven by compression from subsiding air (de Villiers, 2020), the hottest days in the UK (25th July) and in France (28th June) were both linked to plumes of hot air from Spain and the Sahara (de Villiers, 2020; Vautard et al., 2020). Figure 3a) shows the 2 m temperature anomaly (with respect to 1960–2021) for 25 July 2019, with high temperatures over much of Europe and temperatures more than 10 C above the climatology over North-

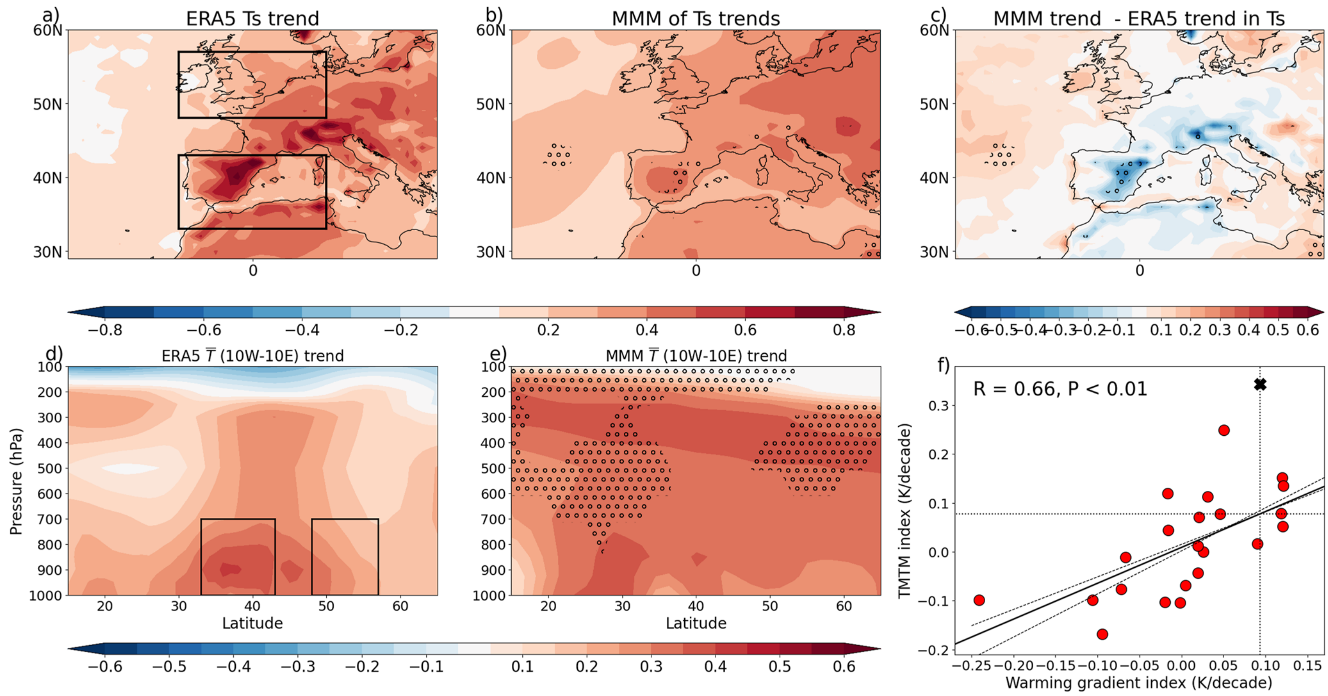

Figure 4. (a) Shows the ERA5 trend in JJA surface temperature and (b) shows the same but for the multi-model mean of all CMIP6 trends and (c) shows the multi-model mean trends minus the ERA5 trend. In (d), the ERA5 JJA trend in air temperature, averaged over 10 W–10 E, is shown, and (e) is the same but for the multi-model mean of all CMIP6 trends. All trends are for the period 1960–2021. In (f), the TMTM index (see text) is plotted for the CMIP6 models (red circles) against the meridional warming gradient index (see text). The ERA5 values are shown by a black cross. The solid line shows the least-squares best fit to the CMIP6 model data and the dashed lines indicate the cross-validated maximum and minimum trend lines if one model is randomly removed. Stippling in (b, c, and e) indicates where the ERA5 trend falls outside of the 2.5th and 97.5th percentiles of the ensemble of model trends. Units in all panels are K/decade.

West Europe. Synoptically, these high temperatures were associated with a ridge to the east of the UK, being fed by a Rossby wave train upstream over the North Atlantic (Figure 3e). The western side of the ridge was linked to southerly flow and advection of warm, subtropical air toward the UK and France (Figure 3i).

This pattern can be seen more generally in composites of the hottest day, and the days leading up to it, in southern England for each year, 1960–2021 (Figures 3b–3d, 3f–3h, and 3j–3l). Specifically, I center the composites on the date of the highest summer tasmax over southern England (averaged over the box in each panel of Figure 3). The composites are only calculated here for one small region rather than the whole of North-West Europe, as the timing of the hottest day may differ between the different locations within a larger area. However, note that the results are very similar for boxes over northern France and northern Germany (not shown). Warm surface anomalies begin to build 1–3 days before the hottest day (Figures 3b–3d). The spatial and temporal scales associated with the circulation anomalies are consistent with a baroclinic Rossby wave timescale (Figures 3f–3h), as seen in 2019 (Figure 3e). In the days leading up to the hottest day, the flow near southern England transitions from being westerly to southerly, advecting warm air up from France and Iberia (Figures 3j–3l). This analysis is not suggesting that horizontal advection is the only process generating anomalous warming during North-West Europe heat extremes, as other factors like adiabatic compression and diabatic heating will also be important (Bieli et al., 2015; Zschenderlein et al., 2019). However, it is clear that the large-scale movement of air from further south is a common factor for the hottest North-West Europe summer days.

Given the role of movement of warm air from the subtropics in the hottest North-West Europe days, it is possible that a warming of subtropical air relative to the ambient mid-latitude air, could increase the magnitude of heat extremes over North-West Europe. That is, both North-West Europe and Iberia/North Africa are warming, but if the latter is warming faster, then northward-moving subtropical air may be more anomalously warm (with respect to mid-latitude air) now than it was previously. This would lead to the hottest days, when warm subtropical air often intrudes into the mid-latitudes, warming faster than the mean summer day. Figure 4a) confirms that Iberia (particularly eastern Spain) and North Africa are indeed warming faster than the UK. This meridional gradient of warming rates is also present in the lower troposphere, as shown by the zonal average air temperature between 10 W and 10 E (Figure 4d). Comparing the boxed regions in Figure 4d), lower tropospheric air is warming at approximately 0.35–0.4 K/decade compared to 0.2–0.3 K/decade at Iberian/North African and North-West European latitudes respectively.

Why then do climate models fail to capture the magnitude of the max/mean trend difference? Whilst the multi-model mean of surface temperature trends does exhibit greater warming over Iberia than North-West Europe, the difference is much smaller than in reanalysis (Figures 4a and 4b). Specifically, the British Isles warm faster in the models, whereas Spain and North Africa warm less than in ERA5 (Figure 4c). This weaker surface warming gradient in models also corresponds with a weaker atmospheric warming gradient (Figure 4e).

If the enhanced meridional temperature gradient hypothesis is correct, a model with a more pronounced warming rate gradient will tend to show more of a difference in temperature trends between average and extreme summer days. To show this, I define a meridional warming gradient index as the difference in the mean warming trend between the subtropical and mid-latitude boxes shown in Figure 4d). A more positive index therefore indicates greater warming in the subtropics than in mid-latitudes. A scatter plot showing the TMTM index against the warming gradient index confirms that models with a more positive warming gradient show a greater max/mean trend difference ($R = 0.66$, $p < 0.01$, Figure 4f). Conversely, the warming rates of the individual boxes are only weakly correlated with the TMTM index (−0.37 and 0.12 for the northern and southern boxes, respectively, $p > 0.05$), suggesting that it is the gradient that is important. Note that none of these results are strongly sensitive to changing definitions of the boxes by up to 5° or extending the southern box to 25 N (not shown).

On the other hand, a comparison of the values of the warming gradient index in models to ERA5 (black cross in Figure 4f) suggests that although ERA5 does have a higher warming gradient than most models, this index cannot fully account for the difference in max/mean warming rates. An emergent constraint analysis (e.g., Hall et al., 2019; Simpson et al., 2021) using the best fit line to the model trends and the observed value of the warming gradient (as shown by the dotted lines in Figure 4f) indicates that this hypothesis can account for 25% of the difference between the TMTM index in reanalysis (0.34 K/decade) and the multi-model mean TMTM index (0.02 K/decade). Therefore, though the meridional warming gradient explains much of the spread of model TMTM indices, this can only explain a portion of the difference between ERA5 and models and hence other factors are likely to be important in the max/mean warming difference.

5. Discussion and Conclusions

This work has shown that the hottest days are warming approximately twice as fast as the mean summer day over North-West Europe. Understanding the warming rate of the hottest days will be important if we are to improve climate model simulation of extreme events and make accurate predictions about how frequently they will occur in future.

I have suggested that this difference can partly be explained by differing warming rates between North-West Europe and Iberia. It is also possible that land-surface feedbacks could play a role. For instance, the study of Fischer and Schär (2010) found that soil moisture feedbacks lead to a larger increase in the temperature variance over southern Europe than for northern Europe in future climate change experiments. On the other hand, this is clearly in contrast to the pattern of the trend difference as there is no obvious difference in the maximum and mean warming rates over southern Europe (Figure 1c). While most of Europe is becoming drier in summer, soil moisture trends over the UK are positive (Figure S3 in Supporting Information S1). Consequently, the observed pattern of soil moisture trends appears unlikely to explain the spatial pattern of trend differences seen here, that is, greater warming of extremes over North-West Europe and little difference elsewhere. Nevertheless, soil moisture variability will undoubtedly play some role in the observed temperature trends and will likely play a significant role in future changes to temperature variability (e.g., Fischer & Schär, 2008).

The enhanced meridional gradient hypothesis suggested in this study raises the question of the mechanisms driving the different warming rates between North-West Europe and Iberia/North Africa. North-West European warming is likely moderated by proximity to the more slowly warming sea surface (Figure 4a) and possibly the North Atlantic Warming Hole (Caesar et al., 2018; Drijfhout et al., 2012; Robson et al., 2016). Furthermore, atmospheric circulation trends, including the southward trend of the summer jet (Dong & Sutton, 2021), may also have played a role, as air temperature is fundamentally linked to winds through thermal wind balance (Harvey et al., 2014). If large-scale circulation trends contribute strongly to the observed pattern of western-European summer warming then this may explain the discrepancy between the meridional warming gradient in models and reanalysis (Figures 4a–4c) as models instead show a northward summer jet trend with climate change (Harvey et al., 2020).

An emergent constraint analysis indicated that the enhanced meridional gradient hypothesis could explain a quarter of the difference between models and reanalysis, suggesting other mechanisms may also be driving this bias. However, this analysis assumed that the hottest days occur for the same reasons in models and the real world. For instance, the relative contributions of warm advection, compressional heating and diabatic heating could be different in models. Hence, further analysis could consider the balance of these different processes in driving heat extremes in models in comparison with observations. Finally, it would be of interest to investigate the role that changes to weather patterns have had on the differential warming rates of maximum and mean summer temperatures. For example, changes to Rossby wave dynamics or jet trends, with climate change, could have increased the occurrence of weather patterns which favor warm temperatures over North-West Europe.

Data Availability Statement

No new data were created as part of this study. ERA5 data is available via the climate data store https://doi.org/10.24381/cds.adbb2d47 and CMIP6 data (including the CanESM5, CNRM-CM6-1, and MIROC6 ensembles) are available on the Earth System Grid Federation servers https://esgf-node.llnl.gov/search/cmip6/. The full list of CMIP6 models is given in Table S1 in Supporting Information S1.

Acknowledgments

I was funded under the WISHBONE project (Grant NE/T013451/1). I acknowledge the World Climate Research Programme, which, through its Working Group on Coupled Modelling, coordinated and promoted CMIP6. I thank the climate modeling groups for producing and making available their model output, the Earth System Grid Federation (ESGF) for archiving the data and providing access, and the multiple funding agencies who support CMIP6 and ESGF. This paper was partly inspired by a Twitter discussion with Robert Rohde and others. I am grateful for helpful discussions with Tim Woollings and Chris O'Reilly on this work. Finally, I thank the two reviewers whose comments helped to substantially improve this manuscript.

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