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North-West Europe hottest summer temperatures rising much faster than the mean

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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 faster than the mean summer day. The magnitude of the difference in maximum and mean temperature trends cannot be explained by natural variability alone. Worryingly, this trend difference is not captured by comprehensive climate models. The dynamics of conditions leading up to the hottest days are investigated using lagged composite analysis. It is suggested that the difference in maximum and mean trends can be explained by a differential rate of warming between subtropical and mid-latitudes. That is, hot extremes over North-West Europe are often driven by advection of warm air from further south. Subtropical latitudes are warming faster than the mid-latitudes, hence the difference in temperature between ambient mid-latitude air and air advected from lower latitudes, is increasing. These findings suggest that North-West Europe will continue to experience ever more extreme summer temperatures and the findings provide motivation for further research into understanding differences between North Atlantic temperature / circulation trends in models and observations.

1 Background

Human-induced global warming is shifting the distribution of possible temperatures towards 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 and 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 and Huth, 2022), while increased temperature variability is necessary to account for the magnitude of the 2003 European heat wave (Schärf et al., 2004). On the other hand, McKinnon and Simpson (2022) and Thompson et al. (2022) found no evidence for faster warming of extremes, relative to the mean for the Pacific North-West.

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 (Meehl and Tebaldi, 2004; Kornhuber et al., 2019; Teng and Branstator, 2019). For example, Rousi et al. (2022) highlighted Europe as a region of increasing heatwave activity and linked this to more persistent double-jet regimes. Moreover, Cournou et al. (2014) and Mann et al. (2017) argued that climate change is increasing extremes through ‘Quasi-resonant amplification’ (QRA), though the mechanisms driving
QRA and evidence for it are topics of considerable debate (e.g. Screen and Simmonds, 2013; Petoukhov et al., 2013; Barnes and Screen, 2015).

On the other hand, land-atmosphere interactions may also be important. Model simulations of future climate project an increase in European summer temperature variability (Giorgi et al., 2004; Fischer and Schär, 2008; Fischer et al., 2012; Bathiany et al., 2018) 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). This process is likely to have considerably amplified several high impact heatwaves this century (Fischer et al., 2007).

Many countries in western Europe have experienced severe heat extremes in recent years. The record temperature in France, set during the 2003 heatwave, was broken on 28th June 2019, reaching 46.0°C (Mitchell et al., 2019; van Oldenborgh et al., 2019). A few weeks later the United Kingdom (UK) temperature reached 38.7°C for the first time (Vautard et al., 2020). A mere three years later, in July 2022, the UK recorded its first temperatures over 40°C, setting a new record of 40.3°C and 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 and 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 analysed. In this article I seek to investigate the wider context to this mean/extreme trend difference and understand its cause.

2 Results

How do trends in heat extremes and trends in the mean summer temperature differ over Europe? To investigate this, figure 1a,b) shows the trend in the mean daily maximum temperature (tasmax) in boreal summer (June-July-August, JJA) and the trend in the highest summer 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 0.2-0.3K/decade since 1960, though southern countries have warmed slightly more and northern countries, slightly less (figure 1a). This pattern differs in figure 1b) with a higher rise in the highest 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 figure 1a) and figure 1b) that the hottest days have 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 max/mean trend difference pattern is shown even more clearly in the difference plot (figure 1c) and the trend differences across much of North-West Europe are statistically significantly different following a t-test (see methods). The warmest days are also warming faster in the Baltic states, but the differences are not statistically significant.

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. This is clearly in contrast to the trend difference seen here, as there is no obvious difference in max/mean warming rate over southern Europe. One might anticipate that a drying trend could allow for additional heating during extreme events due to a larger amount of the surface energy budget being available for sensible, rather than latent, heating. It might be supposed that this could in turn result in a difference in max / mean temperature trends. However, while most of Europe is becoming drier in summer, soil moisture trends over the UK are positive (supplementary figure S1). Consequently, the observed pattern of soil moisture trends appears unlikely to explain the max/mean trend difference. 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 and Schär, 2008).

Intriguingly, the difference between mean tasmax and highest tasmax/ trends is larger in North-West Europe than anywhere else in the Northern hemisphere (figure 1d). The warmest temperatures in northern Russia are increasing more slowly than the mean, but few other areas show significant differences over a large area. 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, though the magnitude
The report of Zachariah et al. (2022) found that Coupled Model Intercomparison Project phase 6 (CMIP6, Eyring et al., 2016) models underestimate the magnitude of the observed trend in UK heat extremes. Figure 2a), showing the CMIP6 multi-model mean max/mean trend difference, confirms that this is the case for North-Western Europe more widely. The observed trend difference also falls outside of the 95% confidence range 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 max/mean trend difference is simply a result of natural variability. To test this, I first define the ‘trend maximum minus trend 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 in figure 2a). The TMTM index for the 50-member MIROC6 large ensemble is shown alongside ERA5 in figure 2b). The MIROC6 models range from TMTM values of about -0.2 to 0.1 K/decade, whereas ERA5 shows a value of 0.35 K/decade, well outside this range. This suggests that the trend difference is not just the result of natural variability. Interestingly, ERA5 is also outside the range of all CMIP6 models (figure 2b), in agreement with Zachariah et al. (2022). The model with the largest TMTM index is CanESM5 (figure 2c) and interestingly shows a similar, albeit weaker, pattern of the trend difference is lower (supplementary figure S2). Furthermore, such a max/mean trend difference is present for the hottest 5-day mean tasmax (supplementary figure S3).
Figure 2: Evaluation of the max/mean tasmax trend difference in models. a) The multi-model mean of the JJA-maximum tasmax trend minus the JJA-mean tasmax trend. b) The spread of values for the TMTM index (see text) calculated for the CMIP6 model runs (red), MIROC6 ensemble (blue) and ERA5 (black cross), c) as in a) but for the model CanESM5 which has the highest TMTM index of the CMIP6 models and d) is the same but for NorESM2-LM, which has the lowest TMTM index of the CMIP6 models. Note the smaller contour interval in a). Stippling in a) indicates where ERA5 falls outside the 95% confidence interval of the multi-model ensemble and hatching in c,d) shows where max/mean trends are statistically significantly different, as in figure 1c,d)
What is causing the hottest days over North-West Europe to warm faster than the mean in summer? To better understand the dynamics of hot days in the North-West Europe, I plot composites on days leading up to the hottest summer day. The timing of the hottest day may differ between the different locations within the North-West Europe box (defined in figure 2a), hence as an example, I take the date of the highest tasmax over southern England (averaged over the box in figure 3). 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 and cover an area including the UK, France and parts of Spain and Germany. On the hottest day, daily-mean near-surface temperature values are, on average, 5-6K higher than the long-term summer-mean over southern England and northern France. The spatial and temporal scales associated with these anomalies are consistent with a typical baroclinic Rossby wave timescale. This is confirmed by daily-mean 500hPa geopotential height (Z500) composite anomalies (figure 3e-g) which show downstream development of a Rossby wave between 4-6 and 1-3 days before the hottest day and strengthening anticyclonic conditions over the UK and the North Sea.

The strong ridge east of the UK is particularly clear in the hottest summer day of 2019 (25th July), with a large extension of the 5840m Z500 contour towards Scandinavia (figure 3h). This northward excursion of the mid-troposphere air brings warm air up from the subtropics, contributing to the hotter temperatures over North-West Europe (figure 3l). For instance, examining the 850hPa temperature (T850) field the 290K contour of extends from approximately 30N at 30W to 55N at the Greenwich
meridian and the 295K contour from around 20N at 30W to 50N at the meridian (figure 3l). This same pattern is seen for the lagged composites of T850 (figure 3i-k). The 285K and 289K contours, drawn in black, move northwards up to the hottest day, again dragging warm air northwards, consistent with the idealised study of Jiménez-Esteve and Domeisen (2022). This is not to say that horizontal advection is the only process generating anomalous warming during North-West Europe heat extremes, as other factors like adiabatic compression associated with high pressure and diabatic heating will also be important (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.

2.2 Enhanced meridional temperature gradient hypothesis

Given the role of movement of warm air from the subtropics in the hottest North-West Europe days, it is possible that either an increase in the amplitude of Rossby wave events, thereby carrying more warm air from the subtropics towards North-West Europe, or a warming of subtropical air, could increase the magnitude of heat extremes over North-West Europe. On the other hand, an increase in the amplitude of Rossby waves appears unlikely to be the driving factor for the increase in North-West Europe extremes, as Fragkoulidis (2022) finds a decrease in North Atlantic summer wave amplitude since 1979.

Therefore, I hypothesise that the primary reason for the max/mean tasmax trend difference is a differential rate of warming between mid- and subtropical latitudes. Figure 4a) shows the ERA5 trend in zonal-mean temperature, averaged across the Atlantic between 50W and 10W. In the subtropics, air has warmed considerably faster than in the mid-latitudes and indeed there is no statistically significant
Figure 5: Trends in a,c) SSTs and b,d) 300hPa zonal wind are shown for a) HadISST2, b) ERA5 and c,d) multi-model means of model trends. Hatching in a,b) indicates where trends are significant at the 95% level following a Student’s t-test, while stippling in c,d) indicates where the HadISST2 / ERA5 trend falls outside of the 95% confidence interval of the ensemble of model trends.

trend between 45N and 55N (roughly the latitudes at which the max/mean trend difference occurs). Consequently, air advected northwards from the subtropics by Rossby wave packets will tend to be warming faster each year than air over North-West Europe. Hence, advection will drive temperature anomalies over North-West Europe which are more and more extreme relative to the ambient European air.

Why then do climate models fail to capture the magnitude or even the sign of the max/mean trend difference? Figure 4b) shows that the structure of the trend in zonal-mean Atlantic temperature is not captured by the CMIP6 models, particularly the lack of warming in mid-latitudes. In particular, stippling in figure 4b) highlights that the reanalysis trend lies outside the 95% confidence level of the CMIP6 ensemble. Without the temperature difference between subtropical and mid-latitudes, the air advected northwards will be warming at a similar rate to that over North-West Europe, meaning that this mechanism cannot create a max/mean trend difference. To confirm this link, I define a meridional temperature gradient index as the difference in the mean warming trend between the subtropical and mid-latitude boxes shown in figure 4a). A scatter plot showing the MTMT index against the temperature gradient index indicates that models with a more positive Atlantic meridional temperature gradient show a greater max/mean trend difference (R = 0.56, p < 0.01), providing further evidence for this hypothesis (figure 4c). Extrapolating the best fit line towards the temperature gradient trend index value for ERA5, it can be seen that ERA5 lies slightly above the line and hence it may be that there are other differences between the models and observations generating this larger difference. It is also notable that more models have a negative temperature gradient trend than have a positive trend, again in contrast to ERA5.

3 Discussion

The observed trend in the Atlantic meridional temperature gradient raises a number of questions including ‘what is driving the Atlantic temperature trend?’ and once again, ‘why do the models fail to capture this?’ Definitive answers to these questions are beyond the scope of the article, but I discuss some hypotheses here. One potential explanation is the presence of the North Atlantic warming hole, a
region of reduced sea surface temperature (SST) warming, which is present in observations (e.g. figure 5a, Drijfhout et al., 2012; Robson et al., 2016; Caesar et al., 2018). This lack of SST warming in the mid-latitude North Atlantic may reduce the rate of warming in the mid-latitude atmosphere relative to lower latitudes. On the other hand, the North Atlantic warming hole is absent in historical model simulations with its formation delayed by approximately 30 years due to aerosol forcing (Dagan et al., 2020). In particular, models show a stronger warming from 30N to 50N than in observations (figure 5c). Nevertheless, the observed SST trend largely lies within the model spread over the North Atlantic (stippling in figure 5c).

Relatedly, large-scale atmospheric temperature is tightly coupled to winds via thermal wind balance and hence any trends in zonal temperature should be balanced by corresponding zonal wind trends (Harvey et al., 2014). The increasing northward temperature gradient between the sub-tropics and mid-latitudes is linked to a southward shift of the summer jet stream (figure 5b). Hence, if the enhanced temperature gradient mechanism is correct, the jet shift will be related to the max/mean trend difference. The southward jet shift could be related to the increase in double jet regimes found by Rousi et al. (2022), as a mean southward jet will likely project onto a ‘split’ or double jet configuration. Intriguingly, the observed jet trend lies outside the range of model trends and the multi-model mean shows no overall trend (figure 5d). Moreover, the observed southward shift of the jet is perplexing as models generally project a poleward shift with future climate change (Harvey et al., 2020). However, Dong and Sutton (2021) have recently argued that aerosol forcing may explain the observed trend. In any case, the discrepancy in jet and temperature trends between models and observations requires further research. For example, it would be of interest to quantify the magnitude of natural variability and the extent to which this may have contributed to jet trends.

The suggested link between the observed pattern of tropospheric warming over the North Atlantic and the difference in max/mean temperature trends over Europe demonstrates how large-scale patterns of change can impact trends on a regional scale. This underlines the importance of understanding the southward jet trend over the North Atlantic and the drivers of the North Atlantic warming hole. Furthermore, the failure of current models to capture the observed Atlantic trends and consequently, the trend in summer North-West European extreme temperatures, may reduce one’s confidence in models’ abilities to represent current and future near-surface temperature variability for this region in summer. For example, this could be a concern for extreme event attribution studies as the models may not be able to adequately represent the probability of extremely hot events, such as the UK exceeding 40C in July 2022 (Zachariah et al., 2022).

Finally, the enhanced temperature gradient hypothesis as a mechanism to explain max/mean temperature trend differences, has been evidenced through lagged composite analysis and the correlation with the temperature gradient trend across the CMIP6 model ensemble. This idea could be further tested using a model experiment in which the model is nudged towards the observed trends in North Atlantic tropospheric temperature and zonal wind and examining whether this leads to a pronounced max/mean temperature trend difference over North-West Europe. Additionally, multiple ensemble members could be employed to test for the role that natural variability may have played in these trend differences.

4 Conclusions

In this paper I have shown that trends in the highest summer temperatures over North-West Europe exceed trends in the mean. I have argued that the primary driver for this trend difference is due to the higher rate of warming in the subtropical North Atlantic relative to the mid-latitudes. Therefore, when subtropical air is advected north towards Europe, it leads to increasingly extreme temperature anomalies, relative to the ambient air. Therefore, this work links large-scale climate trends to the occurrence of extreme heat events. Worryingly, CMIP6 models generally fail to capture either the max/mean trend difference or Atlantic tropospheric temperature trends. Further research is needed to understand why models fail to capture these trends and secondly, whether the higher rate of warming of hot extremes relative to the mean will persist into the future.
5 Data and methods

5.1 Data

In this study I utilize ERA5 reanalysis data on a 1x1 degree grid spanning the period 1960-2021 (Hersbach et al., 2020). Most of the variables in this study are daily-means with one notable exception being the maximum daily 2m air temperature, known here as tasmax. The HadISST2 dataset (Titchner and Rayner, 2014) is also used for calculating observed trends in sea surface temperatures (SSTs).

I compare the observations and 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 ssp585 scenario run to 2021. These 26 models were chosen because they each provided daily tasmax data for both historical and ssp585 simulations.

In order to quantify internal variability I have also investigated the 50-member MIROC6 large ensemble (Tatebe et al., 2019). Similar to the other CMIP6 simulations, historical (1960-2014) and ssp585 (2015-2021) model runs have been combined for each MIROC6 ensemble member. All model data have been interpolated to a common 1x1 degree horizontal grid. A full list of model simulations used in this study can be found in the supplementary material.

5.2 Significance testing

To test whether trends are statistically significant (such as in figure 1a,b), a two-tailed t-test is used, with the null hypothesis being that the trend is zero.

To test whether trends are statistically significantly different from one another (such as in figure 1c), I again use a t-test. Following Paternoster et al. (1998) the test statistic, \( Z \), is defined

\[
Z = \frac{b_1 - b_2}{\sqrt{\sigma_{b_1}^2 + \sigma_{b_2}^2}},
\]

where \( b_1 \) and \( b_2 \) are the trends and \( \sigma_{b_1}, \sigma_{b_2} \) are the standard errors on the trends. The number of degrees of freedom in the t-distribution when comparing two trends is given by \( n_1 + n_2 - 4 \), where \( n_1, n_2 \) are the numbers of years in the sample. Note that year-to-year autocorrelations for European summer near-surface temperatures are low at less than 0.1 (Patterson et al., 2022, supplementary figure S2) and hence the numbers of years is roughly equivalent to the true sample size.

6 Data availability

No new data was created as part of this study. ERA5 data is available via the climate data store (https://cds.climate.copernicus.eu/), HadISST2 from the Met Office website (https://www.metoffice.gov.uk/hadobs/hadisst/) and CMIP6 data is available on the Earth System Grid Federation servers (e.g. https://esgf-node.llnl.gov/search/cmip6/).

7 Code availability

Computer code used to produce the plots can be obtained from the author on request.

8 Competing interests

The author declares no competing interests.

References


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Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplementarymaterial.docx