Investigating driving factors for the UK-average temperatures in May 2024: A study of the impact of local sea surface temperatures and of climate change

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Introduction

This note explores the temperature of May 2024 and Spring 2024 over the UK. Despite being somewhat cloudier and wetter than average over much of the UK, average temperatures in May and Spring broke previous records in a series dating back to 1884. With the day-time heat in May and Spring focussed in sparsely-populated Northern Scotland, and significant (but not unprecedented) rainfall and cloudiness through the Spring, public perception did not match the recorded temperatures.

In this note we further explore the weather conditions during Spring/May 2024 considering the ranking of the May and Spring temperatures compared to previous years on a regional basis. We then consider the drivers for this unusual event using two separate methods, with a focus on May (as explained below).

Firstly, the impact of the local marine heatwave on UK May temperatures is investigated. Here the focus in on May since this was the period of the peak in the marine heatwave. Recent weather conditions, decadal variability and climate change are all contributing factors that cause marine heatwaves. Therefore, to better understand the role of greenhouse gas emissions alone a second method is used: a rapid attribution study compares the likelihood of the event in a hypothetical pre-industrial world compared to a modern climate period. The method also looks ahead to how temperatures are projected to evolve in the future. Ahead of the attribution study a validation stage is performed. This found that the standard method validated well for studying May, but not for Spring, therefore whilst the validation is presented for both periods the results of the attribution are only provided for May.

The assessment of the impact of the marine heatwave on the weather is carried out following the methodology set out by Berthou et al. (2024). They use a replica of the Met Office regional operational system (UKV) and run it forced at its boundaries with global operational analysis to reproduce the weather of a given month as closely as possible. It is run twice: once with observed satellite Sea Surface Temperatures (ATMostia) and once with 1982-2012 mean climatological SSTs (ATMclim). The difference between the two runs shows how local SST anomalies influence land temperature anomalies. These SST anomalies result from a combination of climate change, decadal variability and weather variability, as shown in Berthou et al. (2024). This assessment quantifies the role of the observed marine heatwave in the magnitude of the record-breaking May air temperatures over the UK, but does not attribute the result between the three causes of the marine heatwave.

The attribution study follows an attribution protocol and methodology similar to that set out by Pirret *et al.* (2023), this note documents a rapid attribution study using

HadGEM3-A (Ciavarella *et al.,* 2018) to assess the changing chance of observing the record high UK May and Spring (March-April-May) temperatures recorded in 2024. To facilitate a rapid study, the attribution study uses a single climate model, which means that it does not fully explore the uncertainty represented by using a range of modelling systems. Specifically, the aims of this study are to:

> a) identify the approximate probability that any May/Spring in the present climate would reach or exceed the 2024 May/Spring average of the daily mean/max/min temperature for the UK (see Table 1) in the present climate (represented by the years 2017 to 2023),
>
> b) compare this to the chance of a May/Spring reaching or exceeding this value in a hypothetical climate that is not influenced by greenhouse gas emissions (so-called, 'natural' climate),
>
> c) illustrate how May/Spring temperatures are projected to evolve in future climate.

As noted earlier, following a validation step, results for aims a) and b) are only presented for the May period. Results are included for both periods for aim c). Here we use a different data source (the UK Climate Projections, UKCP), which has been verified elsewhere (e.g. Murphy et al., 2018) so results are presented for both May and spring.

Examination of temperatures for May and Spring

Using HadUK-Grid, the 2024 provisional observational data for May broke the records for the month-long, UK-wide average of daily mean temperature and daily minimum temperature (Table 1). For daily maximum temperature, 2024 is the second warmest on record, noting that the difference is less than 0.1°C. Over Spring 2024, records were also broken for the HadUK-Grid season-long averages of daily average and daily minimum temperature (Table 2). Note that the HadUK-Grid data are available at 1km resolution, but for comparison with the attribution model we use it on a 60km grid[1].

Table 1. Observed temperatures for the UK, averaged over the month of May. Data from HadUK-Grid, and for May 2024 (1st to 31st) are provisional as of 2nd June 2024.

Temperature variable	May 2024 1km provisional month average (°C) [1dp]	Historic Record for May month average (°C) [year in brackets]
Daily Mean	13.1	12.1 [2008, 2017]
Daily Maximum	17.2	17.2 [2018]
Daily Minimum	9.0	7.8 [2022]

Table 2. Observed temperatures for the UK, averaged over Spring (March-April-May). Data from HadUK-Grid, and for May 2024 (1st to 31st) are provisional as of 2nd June 2024.

Temperature variable	Spring 2024 provisional 1km season average (°C)	Historic Record for Spring average (°C) [year in brackets]
Daily Mean	9.37	9.12 [2017]
Daily Maximum	13.07	13.98 [1893]
Daily Minimum	5.71	5.13 [2014]

Maps of the temperature anomalies alongside those for other variables such as rainfall and sunshine hours can be found in the press release[2] and in the Met Office

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[1] Thresholds for the model were taken from the observed data regridded to the model resolution (60km), with a land-sea mask applied. This results in small numerical differences between 1km and 60km May/Spring 2024 provisional average. The 60km May month averages (to 2dp) were 13.17°C, 17.35°C, and 8.99°C for mean, maximum and minimum, respectively. The 60km Spring season averages (to 2dp) were 9.37°C, 13.12°C, and 5.63°C for mean, maximum and minimum, respectively.

[2] Warm May and Spring for the UK https://www.metoffice.gov.uk/about-us/news-and-media/media-centre/weather-and-climate-news/2024/warm-may-and-spring-for-the-uk [accessed 2023-06-11]

Monthly Weather Report[3]. We note here that conditions were cloudier than usual, which held overnight temperatures up, but likely added to the perception that UK temperature were cool, rather than hot. Additionally, day-time heat was centred in Scotland for this period, with the highly populated south of England (London in particular) being only in the top-third of Mays for temperature. Nonetheless the resulting UK-average daily minimum and daily mean temperatures were record-breaking. While maximum temperatures were persistently well above the average for the first three weeks of May, daily maximum temperatures were record-breaking only in Cumbria and much of Scotland, but still above average across all regions.

A similar geographical distribution was observed for Spring temperatures as for May, with warmth focused over-night and in northern areas of the UK. During this period significant (although not unprecedented) rainfall and cloudiness experienced by much of the UK may be responsible for the mismatch between public perception and the recorded official observed temperatures.

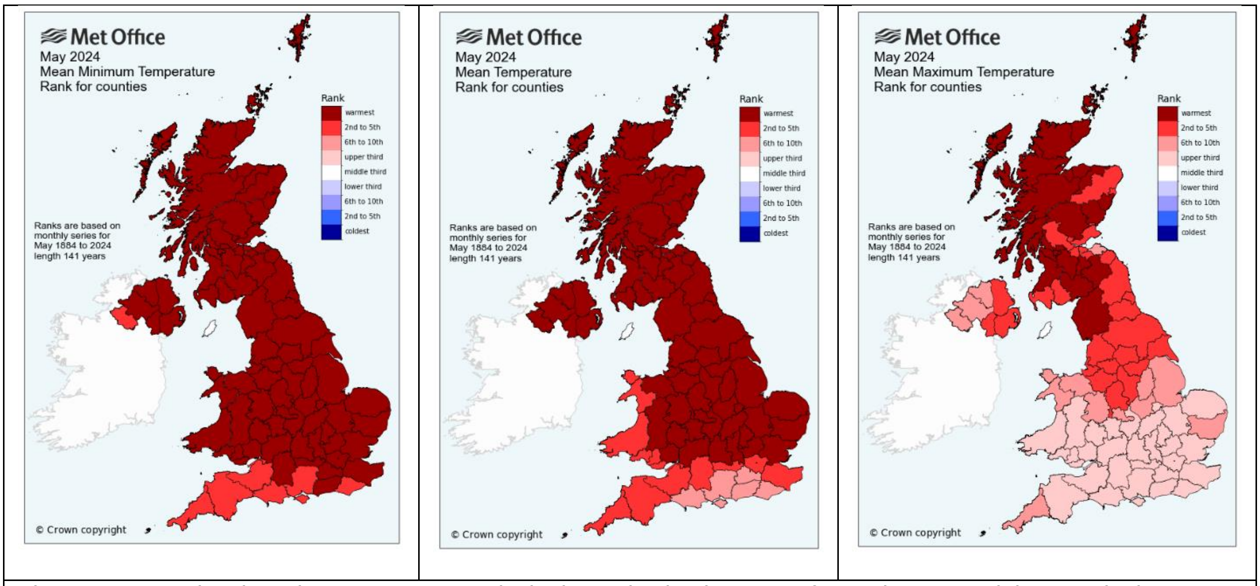

Figure 1: Maps showing where May 2024 ranks in the series back to 1884 for each ceremonial county in the UK, for (left) minimum temperature, (middle) mean temperature, and (right) maximum temperature.

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[3] May 2024 Monthly Weather Report : https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/summaries/mwr_2024_05_for_print_v1.pdf [accessed 2023-06-11]

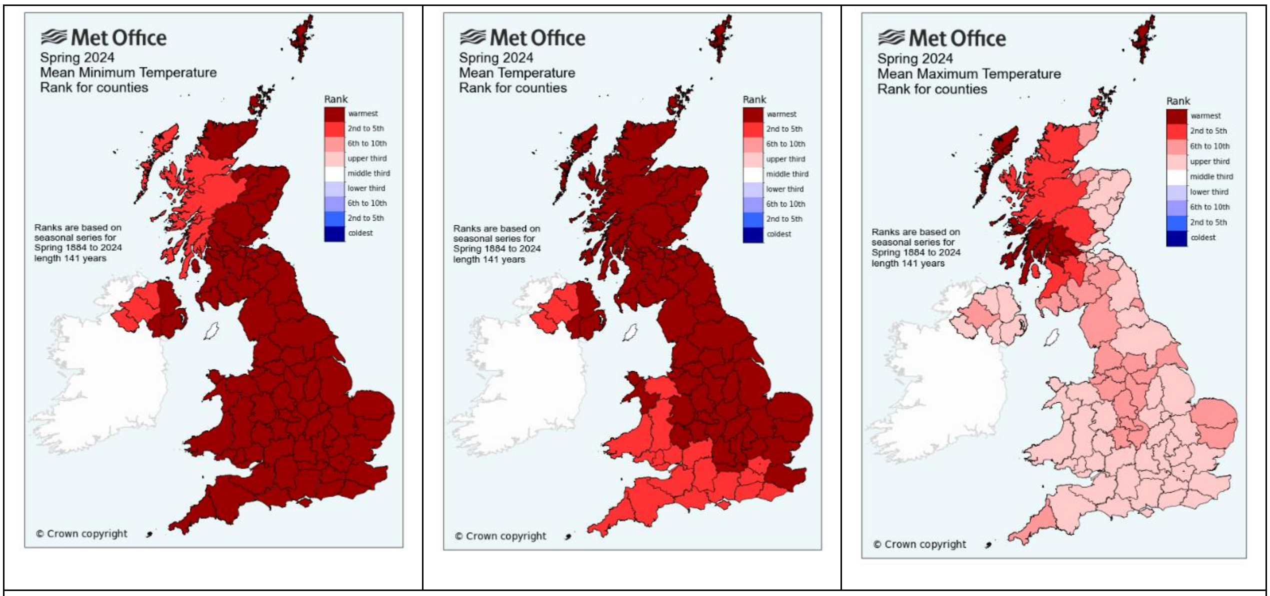


Figure 2: Maps showing where Spring 2024 ranks in the series back to 1884 for each county in the UK, for (left) maximum temperature, (middle) mean temperature, and (right) minimum temperature.

The role of the May marine heatwave in the record-breaking heat in May

The UK is surrounded by shallow seas (0-250m deep), called the Northwest European shelf (NWS). Sea surface temperatures over the NWS have been increasing by 0.3°C/decade over the last 40 years, with the top 9 warmest years occurring after 2002 (as noted by the Marine Climate Change Impacts Partnership, MCCIP). This is leading to more frequent marine heatwaves (MHW) around the British Isles. An additional factor in early 2024 was the decaying El Niño conditions which had peaked in 2023, and had previously led to record-breaking northern hemisphere marine temperatures (Esper et al, 2024). Marine heatwaves are defined as periods of at least 5-days exceeding the 90th centile of sea surface temperature (SST), calculated from the first 30-years of the satellite observation period (1982-2012). These sea surface-based temperature anomalies usually last for 5-30 days around the UK and are associated with weather anomalies (Berthou et al. 2024). MHWs are categorised on a scale of I (moderate) to IV (extreme) based on deviation from local climatology.

In response to the record-breaking UK air temperature and marine temperatures in June 2023, a new technique was tested to determine the influence of the marine temperatures on UK weather. In the UK June 2023 broke its monthly-mean (air) temperature record by 0.9°C. Berthou et al. (2024) showed that the unprecedented widespread 2-3°C SST anomaly which lasted for 16 days in June, was responsible for approximately 0.6°C of the land anomaly. They demonstrated that the marine heatwave amplified the land heatwave in June 2023 through the advection of warm oceanic air anomalies onto land under weak wind regimes and sea breezes. The methodology developed by Berthou et al. (2024) is as follows: they use a replica of our regional operational system (UKV) and run it forced at its boundaries with global operational analysis to reproduce the weather of a given month as closely as possible. It is run twice: once with observed satellite SSTs (ATMostia) and once with 1982-2012 mean climatological SSTs (ATMclim). The difference between the two runs shows how local SST anomalies influence land anomalies. These SST anomalies result from a mix of climate change, decadal variability and weather variability, as shown in Berthou et al. (2024).

The SSTs in 2024 started warm, with an anomaly close to a category I marine heatwave (Figure 3). This warm anomaly persisted until the start of May, when it amplified and reached marine heatwave status. This marine heatwave lasted for the whole month of May and the first week of June. It peaked to category II on the week of 18th-24th May (Figure 3). Figure 4 shows its spatial extent for that week, showing it was affecting the whole of the Northwest European shelf and reached category II in the Northern North Sea and the Celtic Sea, with +2.5-3.5°C locally. Figure 5a shows the evolution of sea surface temperature averaged over the NWS (thick black contour in Figure 4 for the month of May), showing the anomaly peaked on 21st May at +2.3°C. The May average SST anomaly was 1.6°C. The marine heatwave was associated with a two-week period of either weakly cyclonic or anticyclonic weather regimes (1, 5 & 6 in the Neal et al. (2016) classification), which means generally weak wind and waves over the North Sea. Satellite imagery (not shown) and model data (Figure 6a) confirm that whilst the UK as a whole was relatively cloudy for the month of May, the North Sea and Celtic Sea experienced fairly clear skies during this period. The monthly-mean SST anomaly pattern (Figure 7a) and the monthly-mean short wave radiation patterns (Figure 6b) are very similar, with areas of clear skies corresponding with areas of heightened SSTs. This indicates the May 2024 marine heatwave was likely driven by solar radiation, like in June 2023 (Berthou et al. 2024).

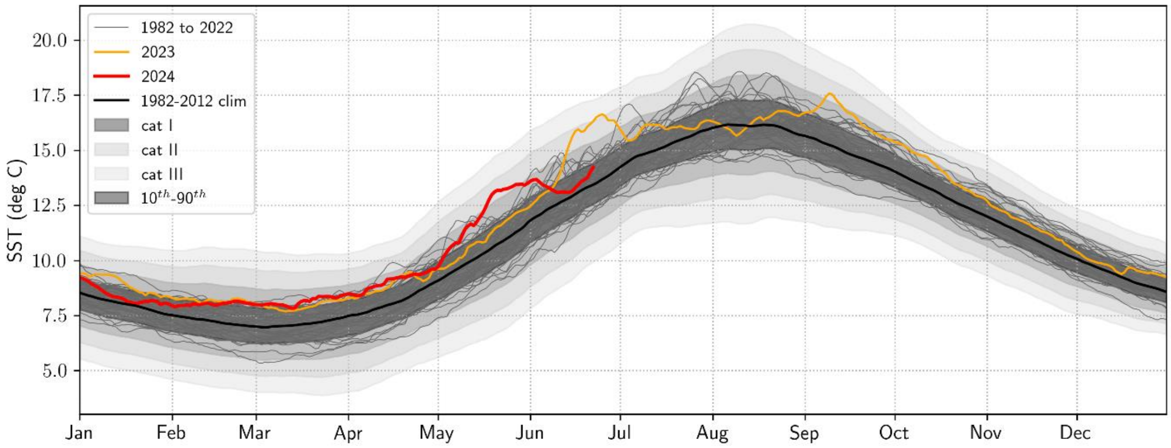


Figure 3: Sea surface temperature averaged over the Northwest European shelf for 1980-2024 (seas shallower than 250m surrounding UK) from the Operational Sea Surface Temperature and Ice Analysis (OSTIA), mean climatology (1982–2012 in full line), Shading: Category I, Category II, Category III marine heatwaves using Hobday et al. (2018). 2024 is shown in bold red.

Applying the Berthou et al. (2024) method shows that the May marine heatwave over the Northwest European shelf warmed the UK by +0.5°C (relative to the 1983-2012 baseline) on average over the month of May (Figure 5).

Like in June 2023, the May 2024 marine heatwave contributed significantly to the land record anomaly. To put it into context, the UK mean temperatures in May broke the previous record by around +1°C. The east coasts of Scotland and England were the most impacted by the marine heatwave (0.8-1.0°C, Figure 7b). This is likely because of their location close to the North Sea where the largest SST anomaly is located, and because of the weak north and easterly airflow that dominated in May (weather regimes 1&5, Neal et al. (2016)). Note Norway was not impacted by this marine heatwave despite the largest SST anomalies being located near its coasts (Fig. 7a) because of these northerly and easterly regimes. Minimum and maximum daily temperatures were impacted in a similar way.

As described earlier, it is not possible in this analysis to attribute how much of the marine heatwave anomaly, or the UK land temperature response, are driven by climate change. At least a portion of the 0.5°C marine-heatwave-induced anomaly is likely to have a climate change component. The seas are on average warmer now than they were during the period 1983-2012, and this will have ‘pepped up’ the weather-driven warm sea temperatures. For context, the May mean air temperature anomaly was +2.7°C relative to the 1983-2012 baseline but just +2.4°C relative to 1991-2020, indicating a warming of air temperatures of around 0.3 °C between the periods 1983-2012 and 1991-2020. To better understand the role of climate change in the chance of hitting the record-breaking temperatures of May/Spring 2024 a rapid attribution study has been conducted and is described in the following sections.

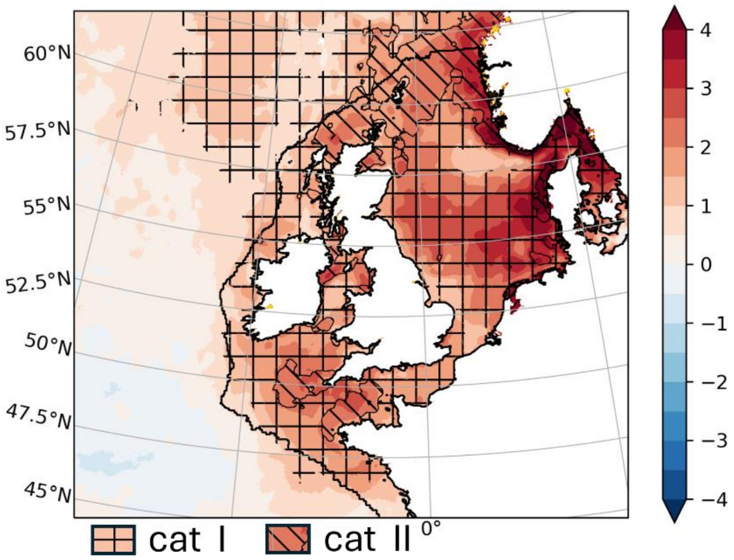


Figure 4: Sea surface temperature anomaly for 18 - 25 May from 1982-2012 climatology. Squared hatches: marine heatwave category I, backslashes: marine heatwaves category II. 18-25 May is peak week of MHW (highlighted in red in Figure 15). The boundary of the Northwest European shelf is also marked with a black line.

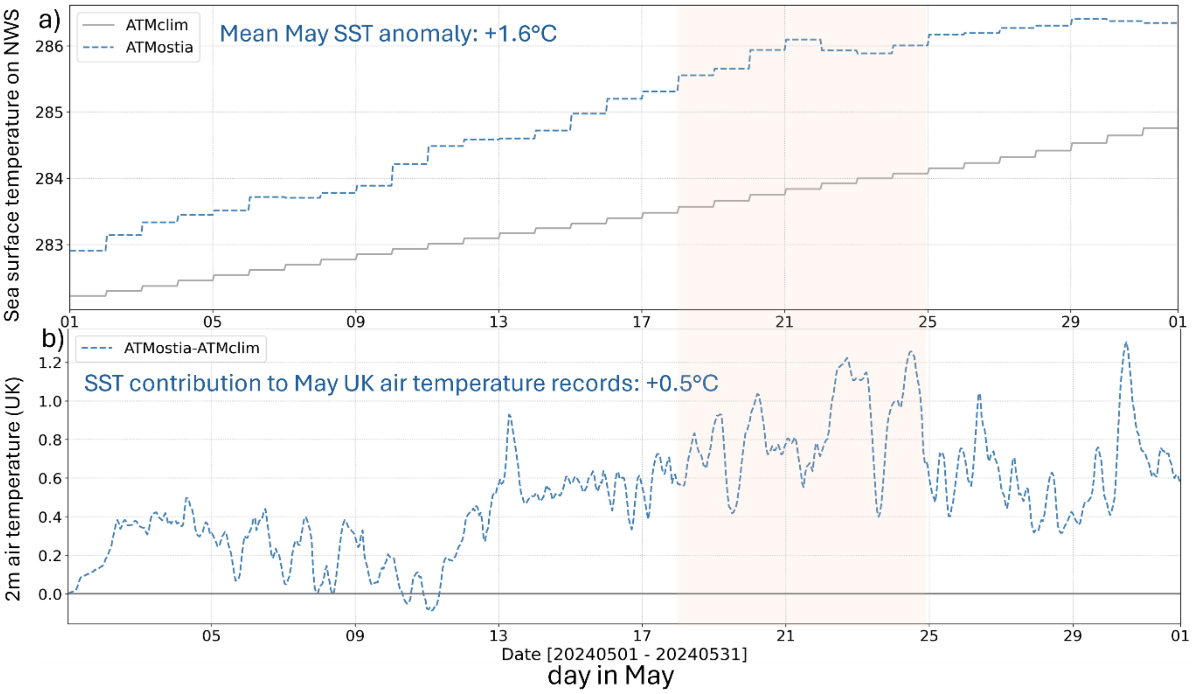


Figure 5: Time series of a): averaged SST over the Northwest European shelf (region enclosed by black line on Figure 4). Dashed blue: actual SST (ATMostia), grey: climatology (ATMclim). b) averaged air temperature difference over the UK of the simulation with marine heatwave (ATMostia) and the one with climatological SSTs (ATMclim). Shaded area shows the time window on which Figure 4 was averaged.

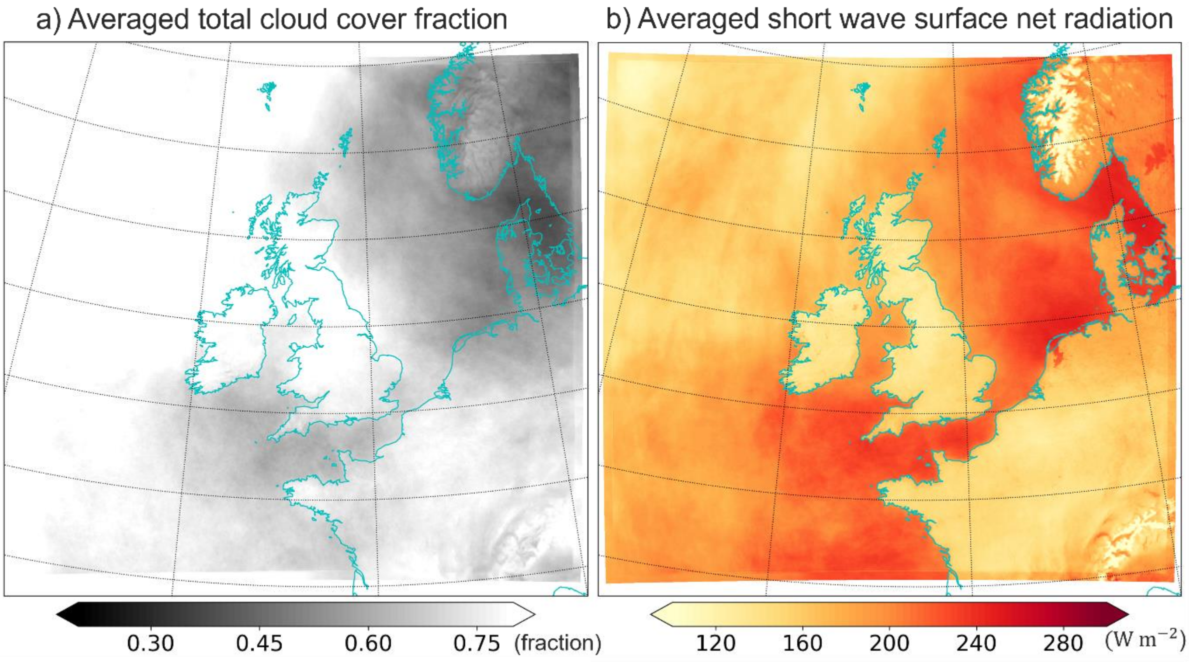


Figure 6: Model data from the 1-month simulations using a similar set-up to the regional operational forecasting model. a) Averaged cloud cover fraction over the month of May 2024 b) Averaged net short wave solar radiation reaching the surface over the month of May 2024.

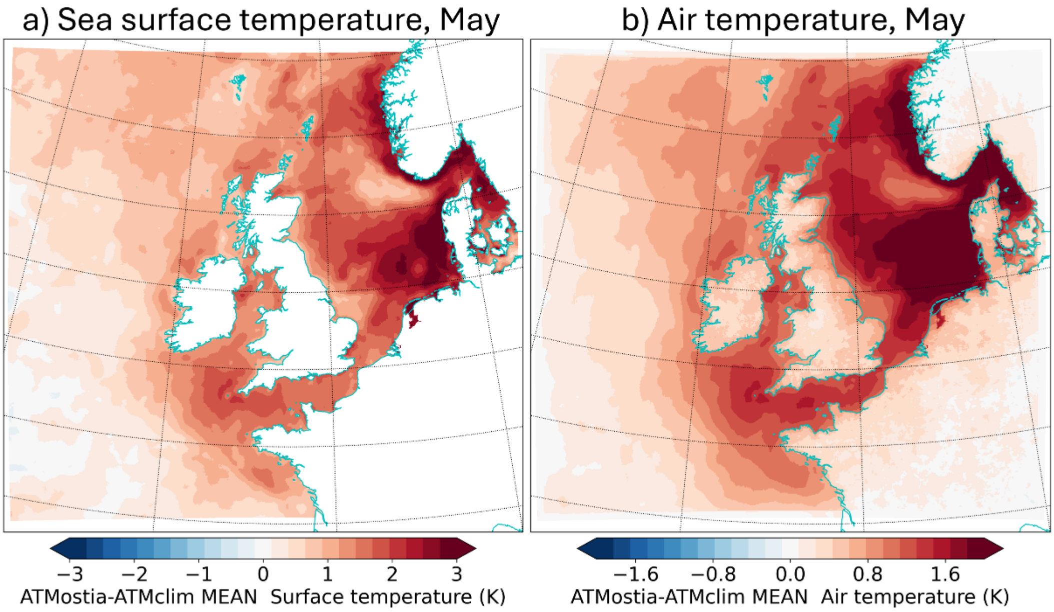


Figure 7: a) Averaged sea surface temperature anomaly over the whole month of May. b) averaged air temperature impact of the marine heatwave (ATMostia-ATMclim). Note colour scale difference between a and b.

Attribution Study Data

For the attribution study, we used simulations from the HadGEM3-A model (Ciavarella et al., 2018), which has been run at a resolution giving grid boxes of around 60km over the UK. While 60km is coarser than the scales upon which some extremes are observed, for attribution of temperature extremes averaged over the UK and an entire month and season this is a reasonable approach (Vautard et al., 2019). The 60km resolution was chosen as it is the finest resolution that can be used with HadGEM3-A; hence observations were also regridded to 60km. HadGEM3-A is an atmosphere-only model, and Table 3 summarises the experiments used. There are two configurations of the model for two different ensembles resulting in four experiments described in Table 3. The first configuration uses observed sea-ice and sea surface temperatures (Rayner et al., 2003) and are referred to as ‘historical’ and ALL in Table 3. A second configuration that represents a climate without human influence by removing estimates of warming in global sea surface temperatures based on results from the fifth phase of the coupled model intercomparison project (CMIP5), and prescribing pre-industrial greenhouse gas and aerosol concentrations (Christidis *et al*., 2015) referred to as historicalNat and NAT in Table 3. The bulk of the historical period 1960-2013 is run as an ensemble of 15 members and used for model evaluation, while for the ALL and NAT over the period 2017-2023 a much larger ensemble of 525 members is used in order to be able to adequately capture the distribution of extremes in the model.

Table 3. HadGEM3-A data summary

Experiment Name	**Years used**	**Ensemble size (per year)**	**Forcing**	**Purpose**
historical	1960-2013	15	Observed	Model evaluation
historicalNat	1960-2013	15	Natural only	Model evaluation
ALL (historicalExt)	2017-2023	525	Observed	Attribution
NAT (historicalNatExt)	2017-2023	525	Natural only	Attribution

Observed temperatures for the study come from the monthly average of the daily mean temperatures from HadUK-Grid (Hollis et al., 2019), regridded to the same (60km) resolution as the HadGEM3-A data and averaged over the UK. The HadUK-Grid temperature data covers the period from 1884, up to the present day but the most recent year’s data are provisional while the underlying observations are received, checked, and finalised. The values for May 2024 and Spring 2024 as of 2nd June 2024 are shown in Tables 1 and 2, respectively.

Furthermore, we qualitatively assess projected May and Spring temperatures over the UK using the UK Climate Projections (UKCP; Murphy et al., 2018), as per the attribution study for September (Pirret and Wallace, 2023). The Probabilistic Projections provide sample realisations for average temperature for four future emissions scenarios to 2100. They provide a comprehensive sampling of uncertainty and are expected to well represent the climate of UK temperatures for May and Spring.

Attribution Study Method

To complete the study, we begin by calculating indices to represent the quantities we wish to investigate and identify the thresholds in each. The indices are the UK averages for May or Spring of either daily mean, maximum or minimum temperatures (i.e. six separate indices). These indices are calculated for every year within each of the time series in Table 3, as well the observed dataset. The threshold value is the UK average daily mean, maximum, and minimum temperatures for May and Spring 2024 taken from the HadUK-Grid re-gridded to around 60km.

For each of the indices, we first use the HadGEM3-A ‘historical’ simulations for the period 1960 to 2013 compared to HadUK-Grid observations for model evaluation and bias identification (see Model Evaluation section). To ameliorate model bias, we find the difference between the mean of the historical model data and the mean of the observations, and then apply the offset to all four model experiments. We also calculate where the observations lie within the model spread for five statistical measures: standard deviation, gradient of the trendline, skew and kurtosis. This step checks whether the model captures the observations (i.e. that the observations lie close to the middle of the range of values given by the model) or not.

Once the bias correction has been applied to them and where the statistical checks are passed, the ‘extension’ runs of HadGEM3-A (Table 3) were used to calculate the two probability estimates for a) and b) described in the introduction (i.e. the approximate present-day, and hypothetical ‘natural-climate’ chance, of observing the May/Spring 2024 UK temperatures). The data available for these runs covers the period 2017-2023, which we assume is suitably representative of an approximately stationary period of present-day climate. This ensemble of 525 members giving a sample of 3675 events for each experiment, which is judged sufficiently large to sample both natural variability and extreme events, which is important to the estimation of the chance of UK record temperatures. This approach of taking a several-year sample of attribution simulations is sometimes referred to as the unconditional approach (Christidis, 2021; Otto, 2017) in that we do not constrain the estimation of probability to only reflect conditions (e.g. sea surface temperatures) from the year in question. Although the results will still be partially conditioned on any multi-decadal scale variability in SST patterns for the period 2017-2023.

The probabilities are calculated by fitting a Gaussian distribution to each sample (Pirret and Wallace, 2023), then bootstrapping the samples to calculate uncertainty estimates on the probabilities (Pirret et al, 2023). We then output the probability densities from the ALL (historicalExt) and NAT (historicalNatExt) experiments. From this, we can calculate the likelihood of our threshold values being reached or exceeded; see the section entitled ‘Climate Attribution’.

Attribution Simulation Evaluation

The HadGEM3-A system has been subject to extensive evaluation and has previously been deemed suitable for use for statistics such as UK and monthly means values (Pirret and Wallace, 2023). However it is still an important step to evaluate the specific metric being studied. For HadGEM3-A, we validate this assumption using simple statistical tests, performed after an offset has been applied for bias correction. Where these tests confirm that the simulations are fit for purpose, we proceed to climate attribution. Where the model does not pass these statistical tests, the attribution results are not considered robust.

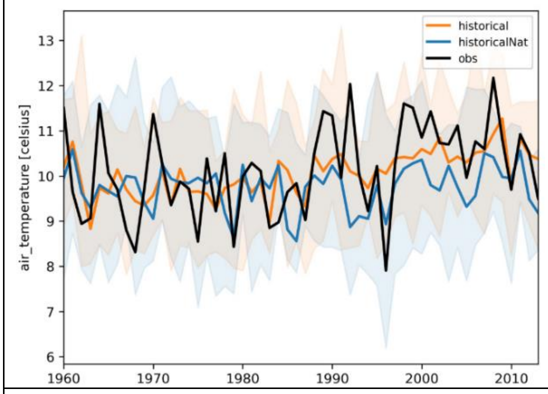
Evaluation considers the extent to which the HadGEM3-A historical ensemble reproduces the observations in terms of key summary statistics: mean, standard deviation, trend, skew, and kurtosis over the historical period (1960-2013). These statistics are calculated using the python scipy.stats functions (Virtanen et al., 2020).

May

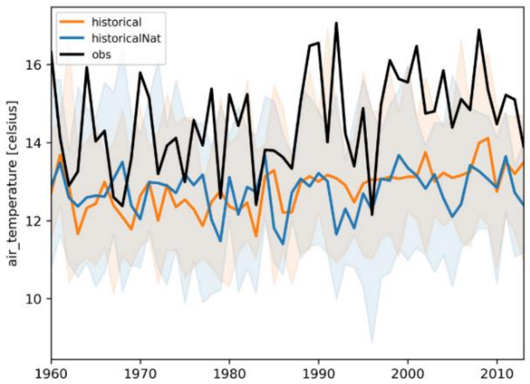
First, we explore the UK and May averages of daily mean, maximum and minimum temperatures. The timeseries in Figure 8 provide a qualitative assessment that the ‘historical’ models (i.e. when all forcings are included) capture the observed variability and trend relatively well. Observations for daily mean temperatures are well captured by the models; for daily maximum temperatures models run cooler than observations; and for daily minimum temperatures, models run slightly warmer than the observations, though observations remain within the ensemble spread for majority of the timeseries. A bias correction is applied as a simple shift in the mean to all the simulations before further evaluation.

Investigation of the summary statistics also indicates that the ‘historical’ simulations capture the relevant features of the observations. To explore how well the observations sit within the ensemble for a few key statistics, we calculate the gradient of the trendline, standard deviation, skew, and kurtosis for the 15 members of the historical HadGEM3-A ensemble and the observations and then rank them from lowest to highest. Where the statistics for the observations sit within the range of the same statistics calculated on the ensemble, this indicates that the simulations reasonably well reproduce the key features of the observations and supports existing validation.

a. May mean of daily mean temperature



b. May mean of daily maximum temperature



c. May mean of daily minimum temperature

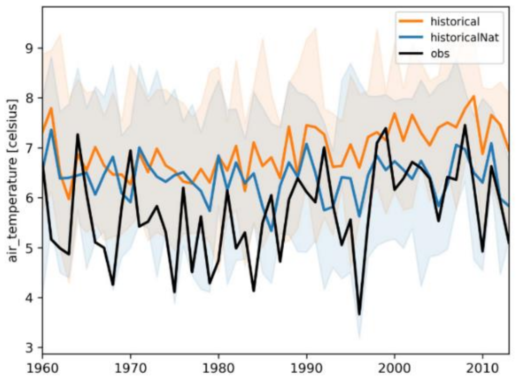


Figure 8: The UK May temperatures a) mean, b) maximum, and c) minimum, from HadGEM3-A (historical, orange, and historicalNat, blue; see Table 3), with the thick lines showing the ensemble median and the shaded area the full (15 member) ensemble spread. Observations from HadUK-Grid (at N216) are overlaid (obs, black).

The statistical results are presented graphically in Figure 9 and Figure 10, which illustrate where the value for each statistic calculated from observations lies within the range of values from the historical model simulations. Figure 9 shows that following bias correction, the observed mean value lies centrally in the model spread.

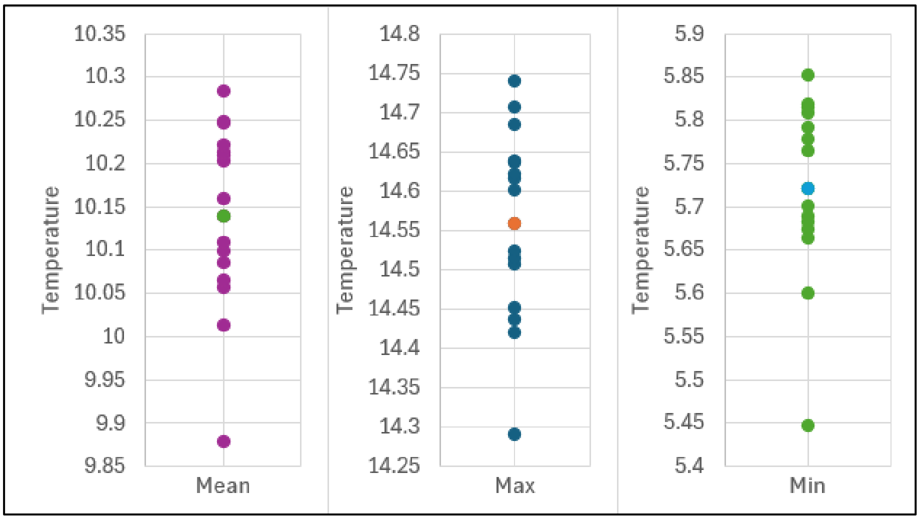


Figure 9: Values of the mean over the historical period (1960-2013), for the May and UK average of (left) daily mean temperature, with the observations in green and the HadGEM3-A model simulations in purple; (middle) daily maximum temperature, with observations in orange and models in blue; (right) daily minimum temperature, with observations in blue and models in green.

Figure 10 illustrates the relative ranks of the observations and model members, for each of standard deviation, gradient of trendline, skew and kurtosis. For daily minimum temperatures, for each standard deviation and trend gradient, the observations sit between the 6th and 8th (of 16) ensemble members of the historical simulations, indicating that the simulations well capture these aspects of the observations. However, skew and kurtosis for observations are slightly on the lower end of the ensemble (with observations sitting between the 4th and 5th and 5th and 6th ensemble members, respectively). This may result from natural variability, but the observations are still fairly central in the model ensemble spread so we determine that the ensemble captures the observations.

Again for daily mean temperature, standard deviation, and trend statistics are central to the range of ensemble members, whereas skew and kurtosis for observations sit at the lower end of the ensemble range, indicating that the simulations well capture mean, standard deviation, and trend, but may under-estimate skew and kurtosis aspects of the observations. Again, for all statistics, the observations are fairly central to the range of values from the models, meaning that the model captures the observations.

For daily maximum temperatures, the observed trend gradient sits centrally within the model spread, being between the 6th and 7th (mean) and 7th and 8th (trend gradient) ensemble members, indicating that the simulations well capture these aspects of the observations. Meanwhile, for skew and kurtosis, the observations are on the lower end of the ensemble (with observations sitting between the 3rd and 4th and 4th and 5th ensemble members, respectively), while for standard deviation the observations are at the upper end of the ensemble (between the 12th and 13th ensemble members). While this could indicate a systematic bias in the ability of the model to pick up the real-world response to climate forcings, the observations lie well within the spread of each statistic from all of the ensemble members, and so we proceed to climate attribution for May for all three temperature metrics.

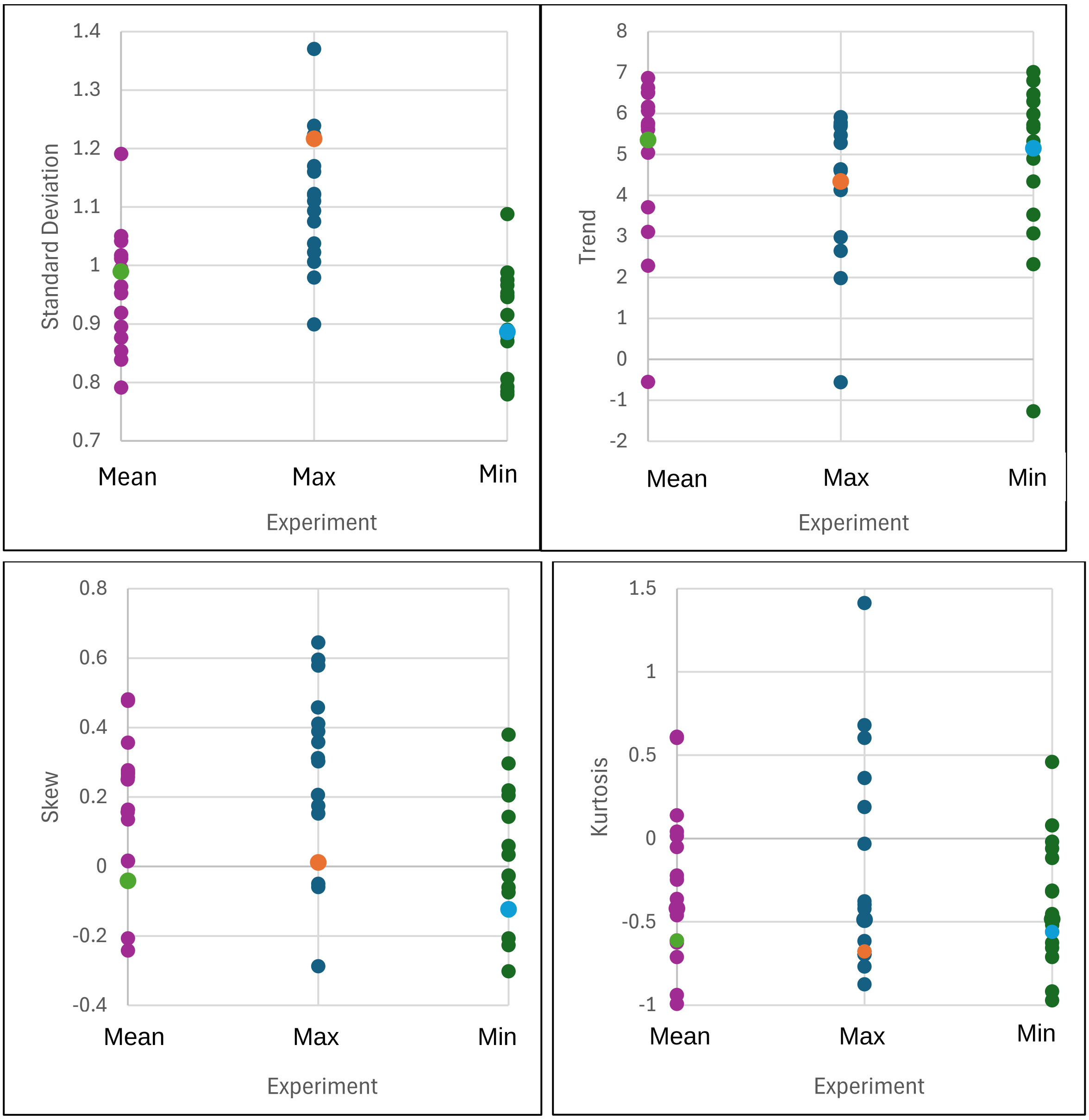
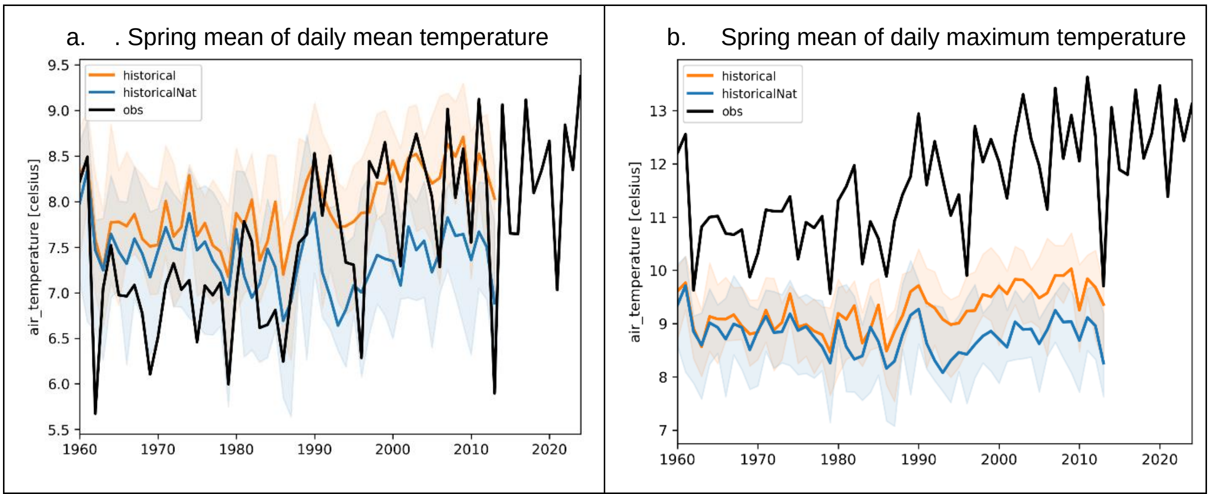


Figure 10: As per Figure 9, but for a) standard deviation, b) gradient of trendline, c) skew, and d) kurtosis.

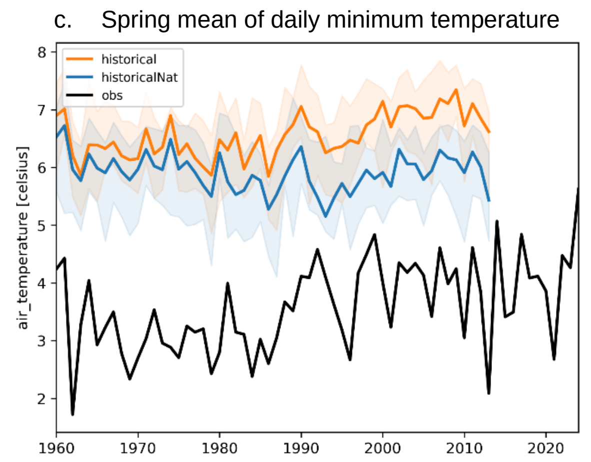
Spring

Over the Spring period, the season-mean of the daily mean temperature shows good agreement between model and observations (Figure 11a). However, the daily maximum (Figure 11b) and daily minimum (Figure 11c) show substantial cold and warm biases respectively, and also appear less dispersive in the model than in the observations. First, we correct the mean by applying an offset to the model members, before proceeding to explore how other statistics are represented in the models.



a. . Spring mean of daily mean temperature

b. Spring mean of daily maximum temperature



c. Spring mean of daily minimum temperature

Figure 11: the UK and Spring averages for daily a) mean, b) maximum, and c) minimum temperatures, from HadGEM3-A (historical, orange, and historicalNat, blue; see Table 3), with the thick lines showing the ensemble median and the shaded area the full (15 member) ensemble spread. Observations from HadUK-Grid (at N216) are overlaid (obs, black).

In all three temperature measures, the observations have standard deviations higher than any ensemble member (Figure 12a). This implies that the model does not capture the year-to-year variability in the observations. Furthermore, the gradient of the trendline in observations is towards the low end of such gradients in the model ensemble, and for daily minimum temperature has the lowest value (Figure 12b). While this could be related to the sampling of the natural variability and could be ameliorated by exploring a longer time-period of data, this is not possible given the available data. It is also possible that the trend being higher is the result of a bias in the model. Further assessment of the cause of the discrepancy and potential correction are beyond the scope of the current study. Also, while Figure 12 shows that the observed skew and kurtosis lie fairly centrally within the model spread for most metrics, this is not the case for kurtosis in the daily minimum temperature metric (1st i.e. lowest) or for skew in the daily maximum temperature metric (13th). This might indicate that more complex bias adjustment would be appropriate, but this requires further exploration and is beyond the scope of the current study. For the two reasons above, we do not proceed to attribute Spring as an entire season, instead focussing on the record-breaking month of May.

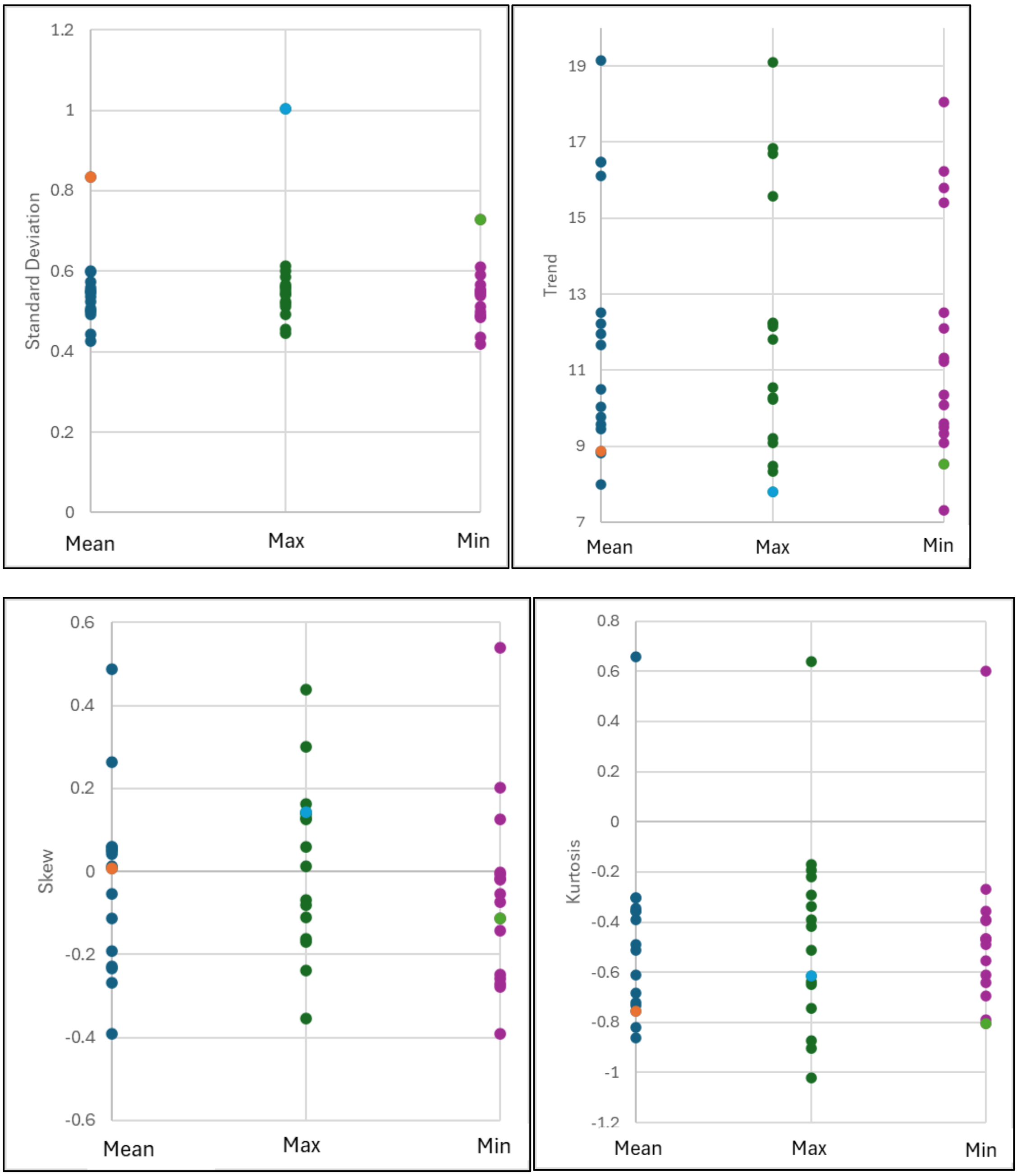
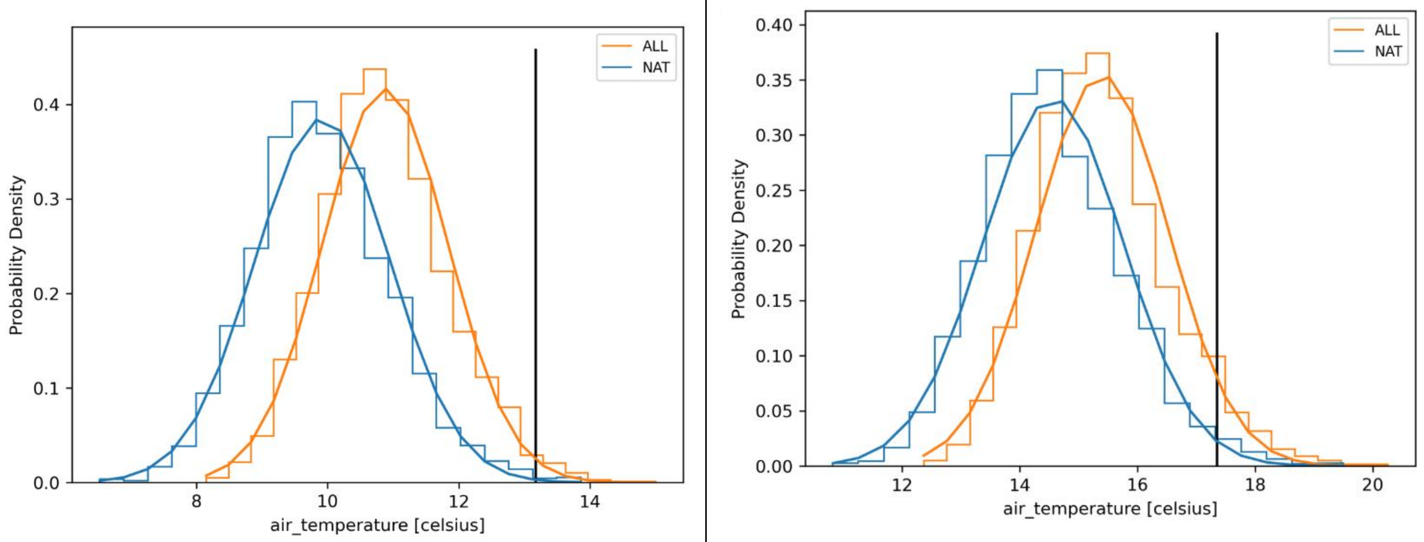


Figure 12. As per Figure 10, but for temperatures averaged over the UK and Spring (March-April-May).

Climate Attribution

The data used for the attribution step considers model experiments for the years 2017-2023 and includes a greater number of ensemble members per year (525) than the evaluation period (15). In Figure 13, we compare the observed value of the index to histograms of the values in the bias-adjusted ALL and NAT ensembles. The area to the right of the black vertical line is proportional to the probability of the observed value being equalled or exceeded. This area is greater in ALL than NAT for all three investigations.



a. May mean of daily mean temperature

b. May mean of daily maximum temperature

c. May mean of daily minimum temperature

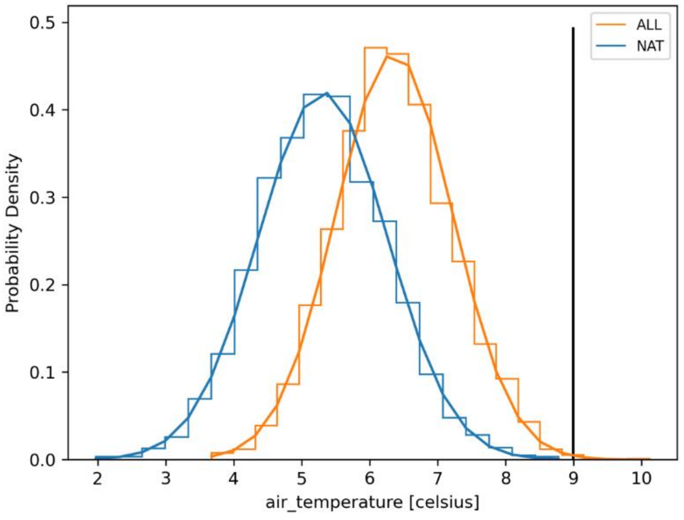


Figure 13: Histogram of the average over the UK and May for daily a) mean, b) maximum, and c) minimum temperature, in the experiments with all forcing (ALL in orange) and with only natural forcing (NAT, blue), with the stepped line showing the values from the model and the smooth line the fit with a Gaussian distribution. The black vertical line shows the index value in HadUK-Grid observations in 2024 at N216 (13.17˚C, 17.35˚C, 8.99˚C respectively).

To these histograms, we apply a Gaussian distribution, calculated using the python scipy.stats functions (Virtanen et al., 2020) and plotted on Figure 13. From that we calculate the probability of equalling or exceeding the observed value, with the probabilities in the two experiments displayed in the middle column below. To estimate the sampling uncertainty of this result, a bootstrapping methodology is applied to the ensemble members within each of ALL and NAT, shown in the right-hand column.

Table 4. Probabilities (calculated from Gaussian fit) of reaching or exceeding the May average of daily mean/min/max temperature thresholds in present-day ('all') and natural ('nat') climate, presented with bootstrapped confidence intervals (at the 5th and 95th percentiles). Temperatures given to 2 decimal places for consistency with Table 1, other values to 3 significant figures.

	Mean	Maximum	Minimum
threshold:	**13.17**	**17.35**	**8.99**
all_prob:	0.00827	0.0413	0.00109
all_boot_5:	0.00684	0.0367	0.000877
all_boot_95:	0.00979	0.0457	0.00136
nat_prob:	0.000845	0.00996	5.31E-05
nat_boot_5:	0.000645	0.00835	3.80E-05
nat_boot_95:	0.00111	0.0116	7.41E-05
risk ratio:	9.78	4.15	20.58
risk_boot_5:	6.92	3.43	13.9
risk_boot_95:	13.43	5.04	31.4

For May daily mean temperature: the previous May average mean temperature record of 12.1°C in 2008 and 2017 has been broken by one degree Celsius in 2024. Table 4 shows that the central estimate of the probability of this average temperature being reached or exceeded in May in the present climate is low at just 0.8% probability (giving a return period of around 120 years). Moreover, this event would have been between 6 and 14 times less likely in the counterfactual climate without the influence of anthropogenic activities on the climate system. Furthermore, bootstrapping illustrates the range of confidence at the 5th to 95th percentiles, examining the range of these confidence intervals reveals there is no crossover between the two experiments, reinforcing that there is a significant difference between the present-day and the natural climates.

For May daily maximum temperature: the analysis shown in Table 4 implies that with only natural forcing, the chance of seeing the provisional 2024 record temperature or higher is very small (1.8%, return period 1 in 54 years). In the present climate, whilst still rare, it has a probability of around 4% annually (giving a return period of around 1 in 24 years). Similar to the results for May mean daily temperature, the confidence intervals for the probabilities do not overlap between the two experiments, and changes in probabilities are similar. The record temperatures are between 3 and 5 times more likely in the present climate, compared to climate with only natural forcing.

For May daily minimum temperature: the May 2024 minimum temperature value is extremely rare, with probability in the current climate of approximately 0.1% (return period around 1 in 914 years), but in the natural climate this would have been practically impossible at probability of approximately 0.005%. Because of the rarity of these events estimates of the probabilities have greater uncertainty. This means that we cannot be confident that the change in likelihood is reliable, we can however be confident that the event would have been highly unlikely in a natural climate.

Note that, due to the framing of our study, the calculations are based on a small number of years (2017-2023), so do not sample the full range of boundary conditions (e.g. sea-surface temperatures) and use one model, so do not fully sample model uncertainty. However, the changes in likelihood are in line with the direction of trends in UK climate projections found in previous studies of UK temperature extremes (Kendon *et al.,* 2023a), their attribution to anthropogenic factors (Lowe and Wallace, 2023; Pirret and Wallace, 2023), and that the chance of hot temperatures has increased significantly over the 20th century in the UK and Europe (e.g. Christidis et al., 2020; McCarthy et al., 2019; Christidis et al., 2015).

Despite limitations, our results show that climate change has significantly increased the probability of warm Mays. The effect of anthropogenic climate change on the record high temperatures of May 2024 is to increase their probability, compared to a climate with only natural forcing. This is shown especially by risk ratios being much greater than one, including at both the 5th and 95th percentile confidence bounds.

Climate Projections

Projections using the UKCP Probabilistic strand of data show that the chances of temperatures like those observed in 2024 increases through the 21st century. The extent to which these chances increase depends on the emissions scenario; in the relatively low emissions scenario of RCP2.6, the chances increase to the mid-century and then level off; in the higher emissions RCP8.5, the chances continue to increase until the end of the century. This occurs across the two different time averaging periods (May and Spring) and the three metrics (daily mean, maximum and minimum temperature). This is illustrated in the figures below; a representative subset of the plots. For example, Figure 14 shows how the May and UK mean of daily mean temperature is projected to increase in all four emissions scenarios.

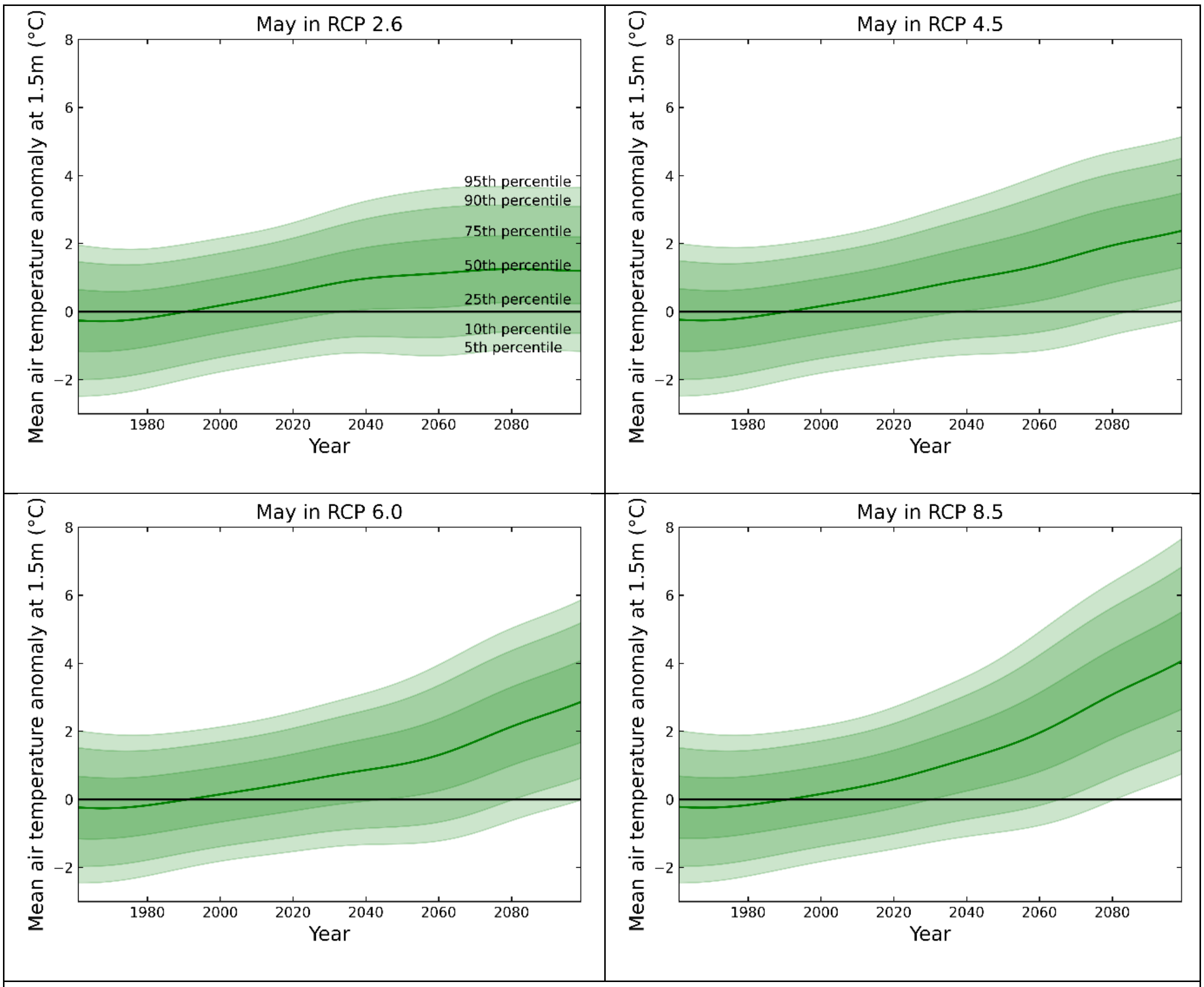


Figure 14: UKCP Probabilistic Projections for the May and UK mean of daily mean temperatures, compared to a baseline of 1981-2000, for four RCPs. The anomaly for 2024 was 2.96ºC.

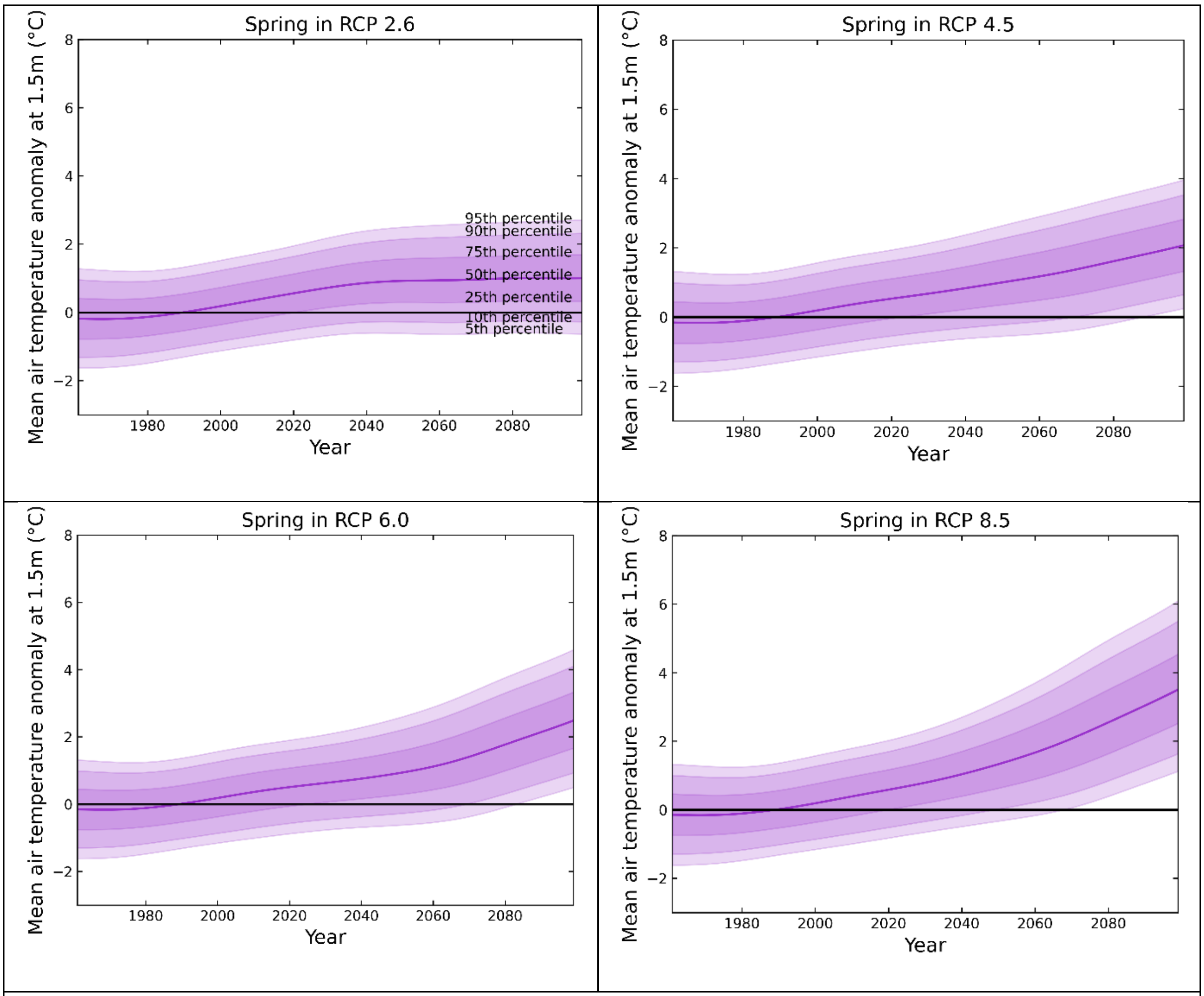


Figure 15: UKCP Probabilistic Projections for the Spring and UK mean of daily mean temperatures, compared to a baseline of 1981-2000, for four RCPs.

The temperature increases are less marked in the Spring average of daily mean temperatures (Figure 15), compared to the May average (Figure 14).

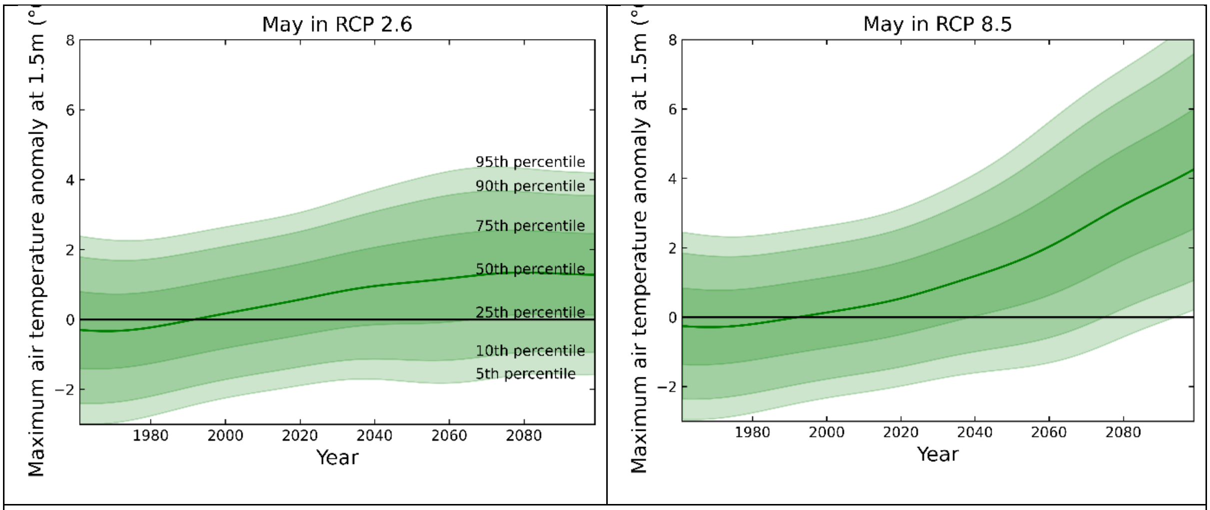


Figure 16: UKCP Probabilistic Projections for the May and UK mean of daily maximum temperatures, compared to a baseline of 1981-2000, for two RCPs. The observed anomaly for 2024 was 2.63ºC.

The projected increase over the 21st century can also be observed in the May averages of daily maximum temperature (Figure 16) and daily minimum temperature (Figure 17), though the spread of results is slightly larger in maximum temperatures.

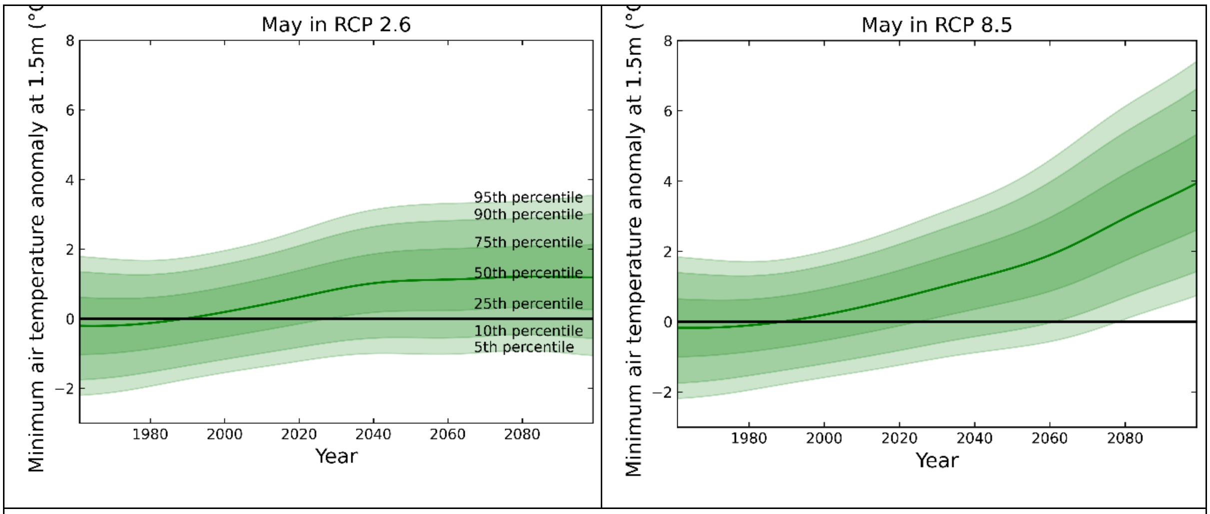


Figure 17: UKCP Probabilistic Projections for the May and UK mean of daily minimum temperatures, compared to a baseline of 1981-2000, for two RCPs. The observed anomaly for 2024 was 3.19ºC.

These results are in line with existing studies showing an upward trend in UK average spring temperatures (Kendon *et al.*, 2023a, Figure 11), which continue in future projections (Kendon *et al.*, 2023b, Figure 8).

Summary

Despite public perception, May 2024 saw record breaking temperatures over the UK, with minimum temperatures breaking the previous record by over 1°C, average temperatures by around 1°C. Maximum temperatures were less than 0.1°C from the current record. These are from a series from 1884.

To investigate the causes of this extreme heat, two complementary approaches were taken. The first was to understand the role of the coincident marine heatwave around UK waters. Marine heatwaves are driven by a number of factors, including recent weather, decadal variability and climate change.

To isolate the role of climate change a climate attribution study was also undertaken.

Applying the Berthou et al. (2024) the marine heatwave study found the May marine heatwave over the Northwest European shelf warmed the UK by +0.55°C (relative to the 1983-2012 baseline) on average over the month of May.

Despite somewhat cloudy conditions over UK land during May, the marine heatwave was found to coincide with generally clear skies and weak wind and wave conditions over the North Sea, which are known to drive marine heatwaves. This, combined with frequently north or easterly airflow, allowed the marine temperatures to influence UK land. Interestingly, due to the predominant wand direction, Norway’s temperatures were not similarly influenced, despite the proximity of Norway to the high marine temperatures.

As well as the weather conditions described above, some of this marine-heatwave-induced anomaly is likely to be a result of climate change. Note for example, that the difference in UK average air temperature between 1983-2012 and 1991-2020 is around 0.3°C.

The attribution study considers the change in likelihood of the May heat, relative to a natural climate. The conclusion from this study was that the risk of extreme heat such as seen in May 2024 has been significantly increased by climate change. The study indicates that the minimum temperature observed is at least 14 times more likely than in a pre-industrial climate, for maximum temperatures the change in likelihood is estimated at least 3 times more likely. For mean temperatures the change is 7 times.

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