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Three consecutive tropical nights now likely in the UK

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Executive Summary

As an extreme weather event occurs, questions around the climate change context are asked with increasing frequency. This work presents the initial development and application of an attribution protocol, such that scientifically rigorous climate information can be compiled and communicated in a timely manner. Putting an extreme weather event into climate context allows the public and our customers to better understand the event and take avoidant action against adverse impacts as the weather occurs. Understanding how current or recent weather events could evolve in future climates engenders adaptive action. This adaptive action reduces the impact from future events as our climate changes.

The attribution protocol represents a step towards delivering attribution as a service. Climate attribution compares the likelihood of an event in the current climate to its likelihood in a counterfactual simulated world with only natural forcing (i.e. without human influence). This approach aims to answer questions such as, 'how often are we likely to see this type of event in the current climate?' or 'how has climate change altered the chances of this event occurring?'. To provide further context, climate projections consider how such events could evolve, exploring the question as to whether we could expect to see more similar events in future climate.

This study applies this protocol to the July 2022 event where, locally, temperatures did not drop below 20 degrees Celsius for three consecutive 24-hour periods. Hot nights during heatwaves are associated with increased mortality because of the function of sleep to regulate core body temperature. Our framing calculates the probability of this event with conditions similar to 2022 with and without anthropogenic influence. We find that this event was extremely rare in a pre-industrial climate (estimated percentage probability less than 1% per year) but in current climate something that would be expected to occur fairly frequently (up to 20% chance per year). In a future climate, the highest three-day minimum temperature seen per year is projected to increase. Given current impact from consecutive hot nights, this highlights the need to protect the population through the continued effective communication of weather warnings and the promotion of adaptive actions across timescales.

Introduction

This note documents a climate attribution study and future-climate hazard assessment for a spell of hot nights equivalent to that experienced during the summer of 2022. The study has been completed using a newly developed protocol for attribution studies, designed to deliver rapid attribution as a climate service. This is intended to ensure that scientifically rigorous and appropriately quality-assured attribution studies can be completed and communicated when there is a requirement to do so (for example ahead of, or shortly after, an extreme event). An important aspect of such communications usually includes an assessment and quantitative comparison of pre-industrial hazard likelihood to that in the present day, and can also include future hazard likelihood. This allows the Met Office to respond to commonly asked questions such as, 'how much has climate change altered the likelihood of an event of similar magnitude to the observed event?', 'how often are we likely to see this type of event in the current climate?' and 'will we expect to experience events of this magnitude more frequently in the future?'. This report describes the study completed during the first use of the attribution protocol.

We illustrate the protocol's first use with the heatwave that affected Europe, including the UK, during July 2022. This heatwave caused the issuance of the UK's first red warning for heat, with temperatures exceeding 40°C for the first time in the UK on 19 July. This attribution study builds upon existing analyses relevant to conditions during this period, such as studies of 40˚C in the UK by Christidis et al (2019) and by Zachariah et al (2022) and the study of the June 2022 Western Europe heatwave that followed by Christidis (2021) (Met Office, 2022). While these previous studies understandably focus on the peak of the heat, this current work considers the persistence of the heat over consecutive nights, due to the potential for adverse health impacts (e.g. Murage et al., 2017). We use the HadGEM3-A-N216 attribution system (Ciavarella et al. 2018) to compare estimates of the likelihood of occurrence of consecutive hot nights comparable to those experienced during summer 2022 with the likelihood of occurrence of such an event in a hypothetical pre-industrial summer. A future hazard assessment is conducted using the UKCP18 Local projections and compares estimates of the current likelihood of such an event to future likelihood under a high emissions scenario.

The effect of heat on a person depends on factors such as age and underlying health conditions (NHS, 2022). Over the population, the impacts of a heatwave depend on its duration and intensity, as well as factors such as acclimatisation and adaptability (Knowlton et al., 2009; World Health Organisation, 2018). For example, longer duration heatwaves significantly increase cardio-vascular mortality (Yin and Wang, 2017). Heat overnight is usually less intense than in the daytime, but high overnight temperatures are also linked to increased mortality (Royé et al, 2021; He et al, 2022) including in the UK (Murage et al., 2017), perhaps because cooler nights are important to facilitate sleep (Obradovich, 2017) and for physiological recovery from daytime heat. An earlier study indicated that hot nights could even have a greater adverse impact on human health than very hot days (Wang et al., 2019). Furthermore, high overnight temperatures mean buildings are less efficient at losing the heat they have accumulated during the day. Therefore, when indoors, people can be exposed to much higher temperatures than measured outside, and consecutive hot nights mean that these internal temperatures can rise over successive nights and continue to be elevated even after the heatwave ends. For these reasons, overnight temperatures are factored into the UK Health Security Agency's heat-health alert service (Met Office, 2023).

Given the importance of persistently high overnight temperatures, particularly for health outcomes, this study explores the heatwave that affected the UK in July 2022 through the minimum (overnight) temperatures over three days. Alongside the presentation of the attribution protocol, the specific aims of this study are to:

a) Define the index and identify a 'threshold' in the observations, for use in the model analysis;

b) Estimate the probability of the occurrence of this threshold in present-day and pre-industrial climate to assess the role of anthropogenic forcings; and

c) Quantify how this index for extreme heat is projected to change by the end of the 21st century under future climate change scenarios.

Data & Methods

The index we use represents the highest value of temperature anywhere in the UK, below which the temperature did not drop for a three-day period in July 2022 by identifying warm overnight (daily minimum)[1] temperatures. For each rolling three-day period within June, July and August, the lowest minimum temperature was calculated for each grid-point in the UK; i.e. selecting the value that temperatures did not drop below for each three-day period. A duration of three days was chosen for consistency with the definition of a heatwave[2]. The index for the study was taken to be the maximum of these values over each summer season and across the UK, to provide one value per year for the UK as a whole. The spatial maximum over the UK was chosen because during this event, we noted that it was these values that the media reported (e.g. 40˚C). This means the index is the highest (for the UK and over the year) value of the minimum (overnight) temperature over three days, giving this three consecutive warm nights (TCWN) index.

For the attribution study, we used simulations from the HadGEM3-A model (Ciavarella et al., 2018), which had been run at a resolution of N216 (giving grid boxes of around 60km over the UK) as part of a previous study; running the climate model is not part of the protocol. This is an atmosphere-only model constrained by observed sea-ice and sea surface temperatures that are historically observed (Rayner et al., 2003). To represent an ocean without human influence, anthropogenic temperature differences were separately simulated in CMIP5 and subtracted from the observed values (Christidis et al. 2013). CMIP5 is used for consistency with previous studies, and future work may consider inclusion of CMIP6. While 60km is coarser than the scales upon which extremes are observed, for attribution of temperature extremes this is a reasonable approach (Vautard et al., 2019). A mapping was performed to account for the different magnitudes of temperature at coarser resolution (described below). Four different experiments were performed:

Experiment Name	Years used	Ensemble size	Forcing	Purpose
historical	1960-2013	15	Observed	Model evaluation
historicalNat	1960-2013	15	Natural only	Model evaluation
ALL (historicalExt)	2022	525	Observed	Attribution
NAT (historicalNatExt)	2022	525	Natural only	Attribution

[1] Standard observing practice is that daily minimum temperature assigned to day D is the lowest temperature recorded through the 24-hour period from 0900 UTC on day D-1 to 0900 UTC on day D. The lowest temperatures will usually, but not always, occur in the hours shortly before dawn.
[2] Heatwaves in the UK are based on three or more days exceeding a threshold for daily maximum temperature, see https://www.metoffice.gov.uk/weather/learn-about/weather/types-of-weather/temperature/heatwave

For model evaluation, the TCWN index was first calculated on the historical experiment (with all climate forcings included, both natural and anthropogenic) and historicalNat experiment (with only natural forcings) and compared with observations, to assess the model's representation of this index. For the attribution to climate change, two further model experiments were used, historicalExt and historicalNatExt, hereafter called ALL and NAT respectively. These both consist of a large ensemble of simulations for 2022 conditions (525 members of each), so that the probability of events with equal or greater magnitude to the observed value in 2022 can be estimated reliably. The probabilities are calculated separately for ALL and NAT. When these probabilities are compared, we gain insight into the extent to which an event is attributable to anthropogenic climate change, conditioned on the observed sea surface temperature patterns that occurred during 2022.

Observed temperatures for the study come from HadUK-Grid[3] (Hollis et al., 2019), re-gridded to match the model data. Re-gridding is vital for model evaluation and interpretation since extreme indices such as the one calculated for this study are very sensitive to resolution. Working at lower resolution acts to smooth out extremes over the grid-boxes, as can be seen below in the calculations of how extreme temperatures vary at different resolution. This resolution dependence of extremes means that careful consideration must be given to how data and thresholds are compared. When the TCWN index was calculated over HadUK-Grid's original 1km resolution, the observed index value was 20.6˚C, meaning the event included at least three so-called 'tropical nights' (Kendon et al., 2022), when the temperature does not drop below 20˚C. Through aggregating the data to lower resolution, the equivalent thresholds are obtained for other resolutions. For N216 (HadGEM3-A's resolution), this gave an observed TCWN index value of 17.8˚C for the event in 2022. To allow comparison with climate projections for the UK (UKCP Local, details below), the TCWN index was also calculated on HadUK-Grid at 5km, giving 20.1 ˚C for this event. These calculations provide an approximate equivalence to the event at different resolutions, which is used throughout the rest of the study. That is, the event is labelled as a three-consecutive tropical night event, since the index is over 20 ˚C at the highest resolution available to us, of 1km. When comparing model data to observations, comparable resolutions are used; at N216 resolution, a value of 17.8˚C is used as the equivalent threshold; at 5km resolution, it is 20.1 ˚C.

Finally, the TCWN index was calculated in UKCP Local (Kendon et al., 2021; Kendon et al 2023), which is an ensemble of 12 climate models based on HadREM3-RA11M run at 2.2km, re-gridded to 5km for consistency with HadUK-Grid observations. These data cover the UK for the period 1980 to 2080 following a high emissions scenario (RCP8.5). Boundary

[3] HadUK-Grid website: https://www.metoffice.gov.uk/research/climate/maps-and-data/data/haduk-grid/haduk-grid [retrieved 2023-08-04]

conditions are provided by HadREM3-GA7.05 (UKCP Regional, 12km horizontal resolution) that in turn uses boundary conditions from HadGEM3-GC3.05 (UKCP Global, 60km). This allows evaluation of how the TCWN index may evolve in future climate on a spatial scale of 5km.

Protocol

Event attribution calculates how much climate change has altered the likelihood or intensity of an event occurring. There are several different approaches to event attribution (Stott et al., 2013; Otto, 2017; van Oldenborgh et al., 2021). The methodology we use in this study is based on an existing, peer-reviewed protocol described as the Risk-Based Approach in Otto (2017), which infers probabilities of extreme events with and without the effect of human influence. Our methodology is chosen with a view to developing attribution as a service and establishing a protocol that can be called upon readily as an extreme weather event occurs, while recognising the need for expert judgement. A similar methodology has been used in attribution studies as part of the UK-China Climate Science to Service Partnership, including application to metrics for high temperature (Chen et al, 2019; Ren et al., 2020). We have developed this protocol to include additional steps that improve the resilience and accountability of the process (Figure 1).

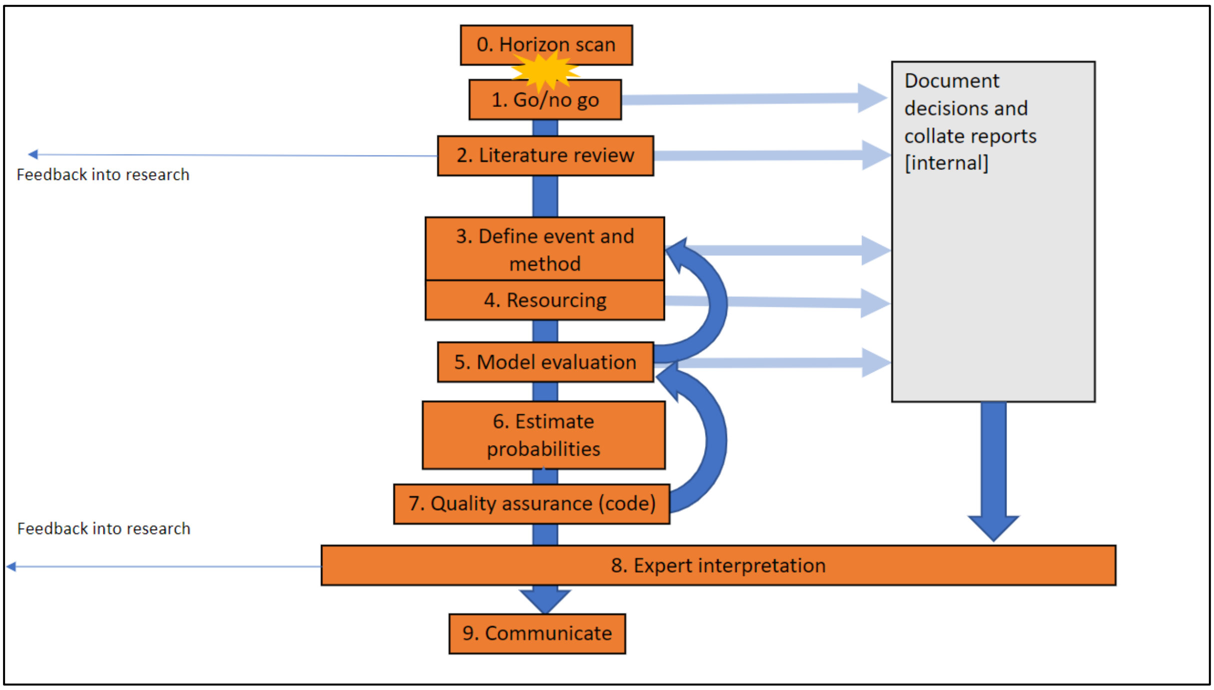

Figure 1: Illustration of the attribution protocol. An attribution study is triggered between steps 0 and 1.

The protocol begins with a ‘horizon scanning’ activity. In practice this is ongoing, and consists of several activities such as a regular meeting between attribution scientists, other climate scientists and communications professionals. These are used to identify any possible future events or stories that have or are likely to generate media interest (e.g. an expected record breaking month). Additionally, guidance from the Met Office Guidance Unit is regularly scanned for potential upcoming extreme events within medium-range forecasting systems. A Met Office-wide communications site also invites any member of staff to highlight the need for an attribution study. If a potential requirement for an attribution study is identified, a ‘go/no-go’ meeting is held. This meeting is attended by:

- a collection of technical experts to determine the scientific validity of a study, and to provide an initial view on whether an existing study from the literature may be suitable to use;
- a representative of the 'customer', who can describe what information is needed by the end-user; and
- a representative to determine who is available to run such a study (resourcing).

From step 1, all decisions are recorded within a decision log. This details the justification for decisions made within the protocol and is stored for reference.

If it is determined that the study is sufficiently useful, scientifically valid, and possible to resource, the process moves to step 2: to formally review the literature for suitable material. The literature review serves two purposes. Firstly, it may be decided that a sufficiently similar study has already taken place and no new study is needed. Alternatively, it can provide evidence to support further stages (e.g. to inform suitable framing, to demonstrate model suitability, or to provide lines of evidence that can support communication).

The third step is to identify the specific framing of the question being asked, ensuring the study is useful to the end-user, scientifically robust, and interpretable in relation to existing similar or related studies. In the current example, this included considering various heat-relevant metrics before deciding upon the TCWN index.

The fourth step reflects on the framing step, and assesses the available resources for delivering information within the time available. This includes available person time, depending on the available skills and the degree of technical and scientific development needed for each study.

The fifth step is to undertake model evaluation. This is performed by comparing the model's simulations of the climatology of the agreed index with observations. Here we use the model HadGEM3-A, for which evaluation has also been performed in other studies (Ciavarella et al., 2018; Vautard et al., 2019) that provide confidence that the model's representation of general circulation and of some types of extremes is realistic. We also analysed the synoptic circulation patterns associated with high values of the index and assessed whether they would reasonably generate a heatwave. This was done by comparing the surface pressure and 500hPa geopotential height to synoptic weather charts, and by using the operational forecasting experience available within the team.

Following the model evaluation, determining how values of the index differ between model and observations allows adjustments to be made for model bias. Climate models can show systematic biases compared to observations (e.g. Maraun 2016), for example consistently running warmer or colder than reality. Comparing the model and observations allowed calculation of an offset for the model data, which could then be applied to the attribution experiments to ameliorate any bias, as per Vautard et al. (2019) with HadGEM3-A. Note that the application of an offset is one method of bias correction; alternatives are discussed in

Maraun (2016). Testing the bias correction will be done by comparing the mean average and standard deviation of the model and observations, and testing the trends of the two datasets.

The sixth step quantifies the attribution of the event to climate change. A climatological distribution of the index is derived from an ensemble of bias-adjusted climate model simulations for one year (see Data section). To this, we fit a generalised extreme value (GEV) distribution and then calculate the probability of the index equalling or exceeding a particular value (in our example, the observed value of the TCWN index in summer 2022 at N216 resolution). We compare the probability of the index in two ensembles: one which includes all observed forcings (both natural and anthropogenic forcings) and sea surface temperatures and sea ice coverage as defined from observational data; and another which includes only natural forcings and an adjustment to the prescribed sea surface boundary conditions that removes the anthropogenic influence. This allows estimation of the effect of anthropogenic climate change on the likelihood of the event, usually through the risk ratio; that is, the event's probability with all forcings divided by the event's probability with only natural forcings. The risk ratio quantifies how much more (or less) likely the event is with all forcing compared to natural only forcing. For example, if with all forcings the event probability is calculated to be 0.01 (1 in 100) but with only natural forcings the probability is 0.005 (1 in 200), the risk ratio is 2 and the event is twice as likely due to anthropogenic forcing.

To quantify the uncertainty in the event probabilities, "bootstrapping" was performed; that is, assessing the accuracy by random resampling. Here, the resampling applies to the TCWN index values for the model ensemble, where the original values are sampled at random with replacement until there is a set of values the same size as the original, and the resulting set of values undergoes fitting the GEV and recalculating the probability, 1000 times. From the 1000 values of probability of the event with all forcing and 1000 with the natural-only forcing, we also calculate 1000 values of the risk ratio. In all three cases, we quote the 5th and 95th percentile of these ranges as a confidence interval on the statistic. If the interval were to encompass a risk ratio of 1 (which represents no change in probability), we would consider that anthropogenic climate change played no significant role in the event.

Following quality assurance of any code that was developed during the study in step 7, a range of experts is brought together to interpret the results in step 8. This aims to draw together the available lines of evidence including any new results, and assimilate them into clear messages that meet the identified need for attribution information. Finally, the results are communicated, which may include preparation of white papers (similar to the current study), discussion with operational meteorologists, or including the information in a media briefing.

This approach has been chosen to produce a timely and defensible estimate of event likelihood. It is acknowledged that this methodology uses only one climate model, and therefore does not account for uncertainties arising from model formulation. In this example of the July 2022 UK heatwave, the attribution results for other temperature metrics are consistent between HadGEM3-A and other models in Zachariah et al. (2022), so in this example including other models would likely have a small effect on the final results; however, this may differ in future studies. While improving the quality of evidence is possible (Otto et al., 2020), this choice is made with a view towards developing attribution into a service, when we must also consider the timeliness of information. Future work may include how to incorporate other sources of model information in a timely fashion.

Also, this methodology currently only represents one ‘framing’ of the attribution question, described by Otto (2017) as the risk-based approach. Within that approach, we are using climate model data from only 2022, meaning we are focussed on the effect of climate change on the likelihood of this this event happening in 2022; an alternative could be to use only observational data, which would explore how the likelihood of a similar event has changed over the duration of the observational record. Using a single model year also means the likelihood is predicated on a similar pattern of global sea-surface temperatures; an alternative approach could be to calculate the probabilities using model simulations for multiple years. Framing also includes the definition of the event (e.g. the region and season), which we expect will be different with subsequent triggers for the use of this protocol. The framing choices affect the final results, which can mean studies of the same event give different results; we expect that this would be discussed during our expert interpretation stage. Furthermore, we have selected a temperature-based metric where we expected anthropogenic climate change to have a significant effect; this is not always the case with other variables like rainfall or wind (Vautard et al., 2019). All these choices were made as we initially developed climate attribution as a service. When combined with model validation, literature review and expert interpretation, as is the case with this study, these choices are suitable for communicating the changing likelihood of a wide range of events. Future development of attribution as a service could include additional data sources, alternative framing approaches, differently defined extreme events, and other variables. We also have avenues for users to provide feedback as to how the information and service provision could be improved, which could guide how we develop attribution as a service.

Model Evaluation

Figure 2 shows the values of the TCWN index in the evaluation experiments (historical and historicalNat), alongside HadUK-Grid observations (all at N216 resolution). There are two points to discuss around this plot. Firstly, at the start of the period the historical and historicalNat have similar median index values, but towards the end the historical median values are higher than those in historicalNat, which is an indication that the TCWN index has been elevated by anthropogenic climate change.

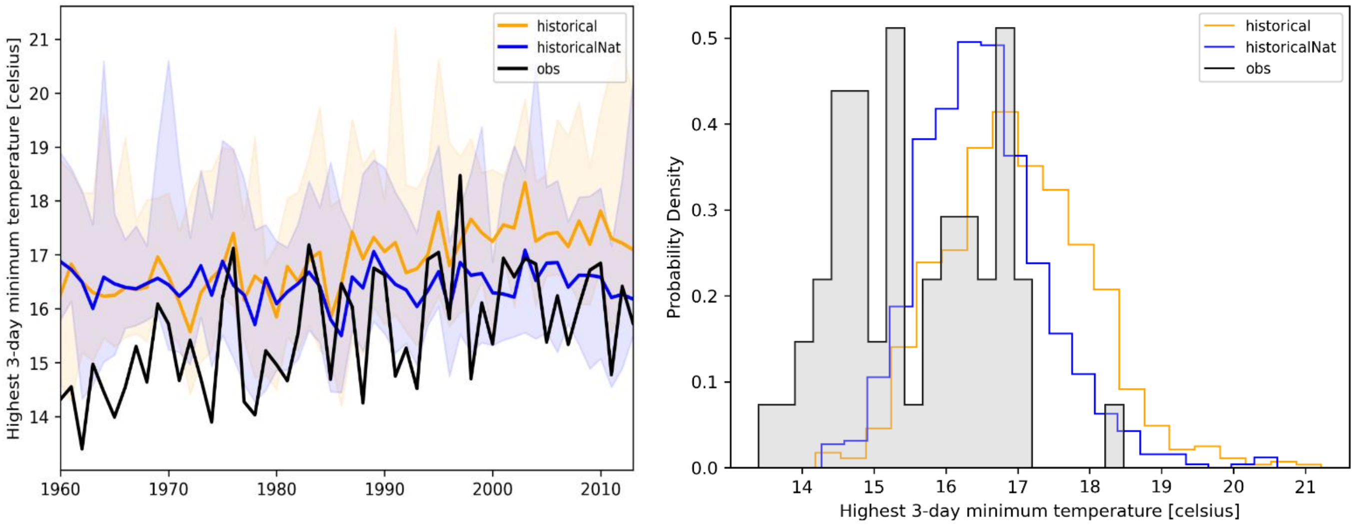

Figure 2: Time series (left) and histogram (right) of the three consecutive warm nights (TCWN) index in the evaluation model runs with all forcing (historical, in orange) and natural-only forcing (historicalNat, blue), with the thick lines showing the ensemble median and the shaded area the full (15 member) ensemble spread. Observations from HadUK-Grid (at N216) are overlaid (obs, black).

Secondly, there is clearly an offset between the observations and the historical model runs, implying there is model bias towards higher values. The offset bias correction method was chosen because Figure 2 illustrates that the historical frequency distribution of the TCWN index in HadGEM3-A-N216 matches the spread and shape of the observational frequency distribution well, but there is a displacement between the model and observations. To quantify this, the mean of the observations (15.570˚C) and historical simulations (16.992˚C) are notably different, but the standard deviations are similar (1.074 and 1.021, respectively). Also, analysing the linear trends on the observations and historical simulation data show that the slopes are similar, with the observations' trend line slope (7.57˚C year^{-1}) within the range of slopes across the 15 members of the historical ensemble (2.72 to 9.57˚C year^{-1}), meaning that we can apply the same offset through time. Therefore, we calculate the average value of this offset, and apply it to the model runs to assuage the bias.

Figure 3 shows how applying this offset to the historical model run brings the model's index values closer to the observed index values. With this offset removed (historicalOffset), the observations are judged to be well represented by the historical dataset in terms of trend and interannual variability of the observations compared to the individual ensemble members, with the observations now almost entirely within the ensemble spread for the historicalOffset data. The mean of the historicalOffset data (15.734˚C) is more similar to the observational mean (15.570˚C), but the standard deviation and trends remain consistent with the values before the offset was applied. This means that the model is deemed suitable for use in this study. The same offset is applied to the historicalExt and historicalExtNat model experiments used for the attribution step.

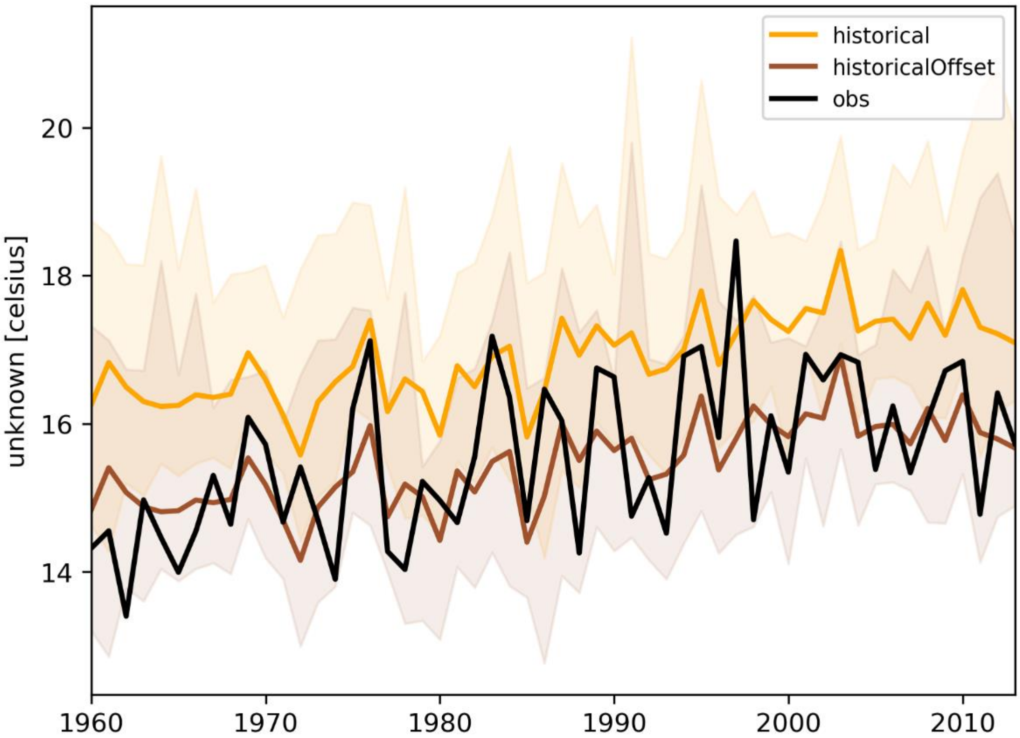

Figure 3: Time series of the three consecutive warm nights (TCWN) index in the evaluation model runs with all forcing (historical, in orange) and to the all forcing model runs with a correction applied (historicalOffset), with the thick lines showing the ensemble median and the shaded area the full ensemble spread. Observations from HadUK-Grid (at N216) are overlaid (obs, black).

As well as evaluating the chosen metric over the UK, we assess the synoptic conditions in which such extremes occur. Vautard et al. (2019) also assessed HadGEM3-A's ability to simulate the main processes that lead to extreme events, with a view towards their attribution. They find that weather patterns are well captured by the model, including those associated with temperature or rainfall extremes. We identify the three events with the highest TCWN index within the ALL experiment, where an event is a particular day in a particular ensemble member. Figure 4 shows the 500hPa geopotential height and pressure at mean sea level for these three events, to illustrate their synoptic setups:

- Event A has the jet stream passing to the northwest of the UK, meaning that the UK is on the warmer side of it. High surface pressure extending westwards from Scandinavia means that the southern half of the UK is sharing a warm airmass with the nearby European continent, consistent with high temperatures particularly in the southeast.

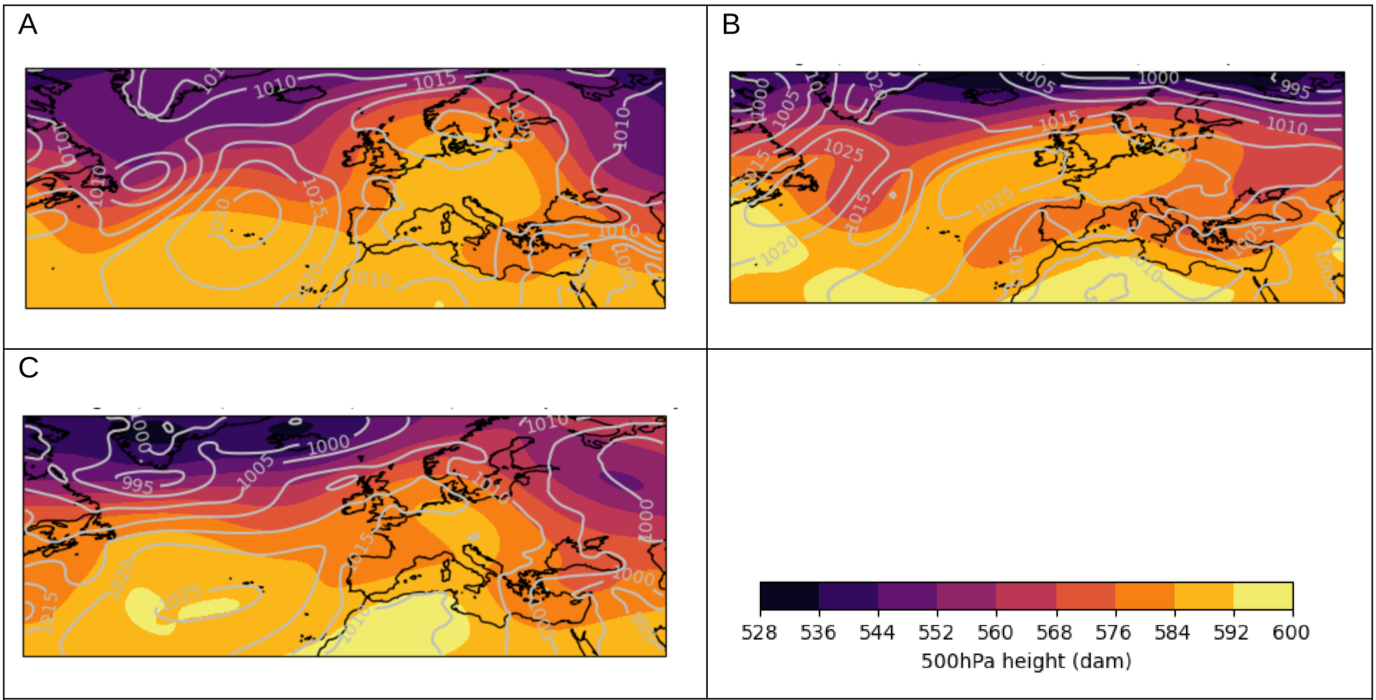

Figure 4: All 2022, geopotential height of 500hPa surface (colours) and pressure at mean sea level (grey contours). (A) 18th June in realisation 79, physics version 1; (B) 10th August in realisation 3, physics version 2; (C) 16th July in realisation 31, physics version 3.

- Event B has the jet stream to the north of the UK, with the Azores high extending over much of the UK. This would mean warm air originating from the tropics would likely be affecting much of England and Wales, consistent with high temperatures in that area.
- Event C again has the jet stream to the north of the UK, with the surface pressure showing some extension of the Azores high towards the UK (like event B) and some influence of the near European continent in the southeast of the UK (like event A). This setup would be consistent with high temperatures particularly in the southeast.

In summary, all three of these model events have synoptic situations that are consistent with high temperatures in the UK, with the jet stream to the north of the UK, high pressure over or near the UK, and warm air being drawn up from the near Continent or the tropical Atlantic. This indicates that the model is producing extremes in three-day minimum temperatures under synoptic conditions that would be expected to result in high temperatures across the UK.

Attribution

The data used for the attribution step considers model experiments only in the year of the event, 2022, but includes a greater number of ensemble members (525) than the evaluation period (15). In Figure 5, we compare the observed value of the TCWN 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 clearly much larger in ALL than NAT.

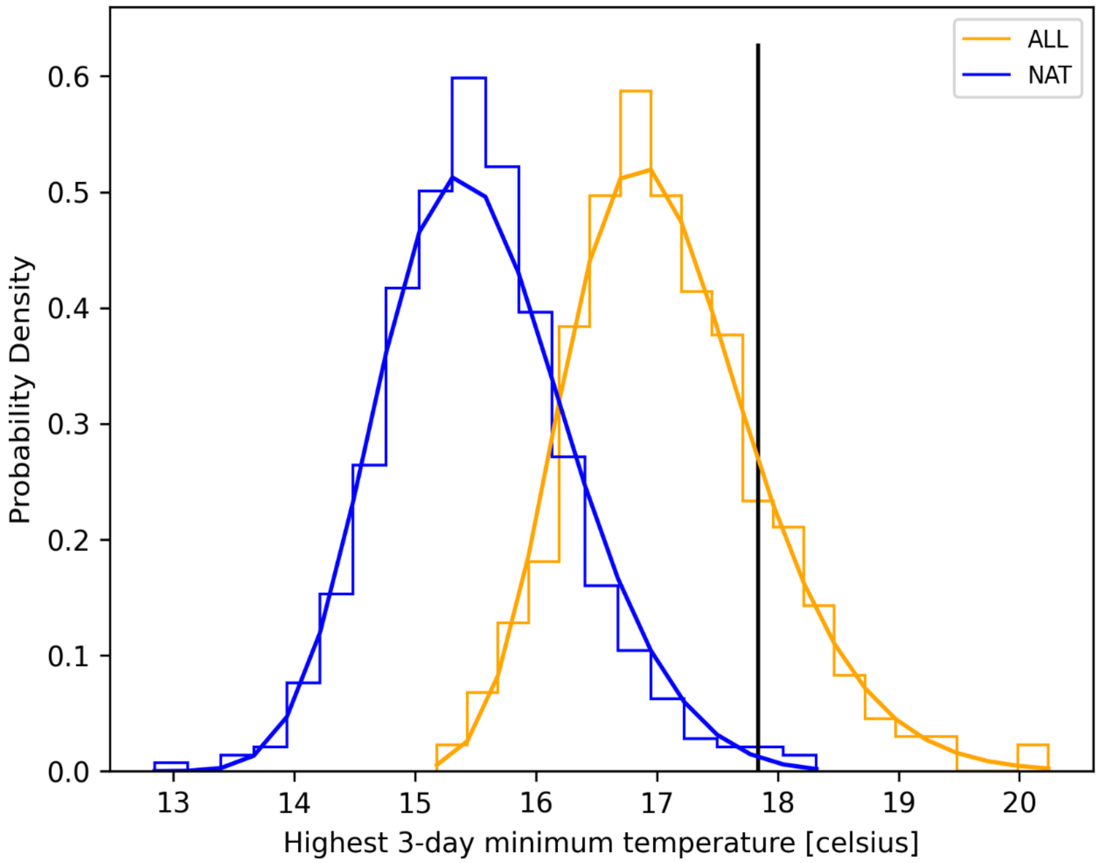

Figure 5: Histogram of the three consecutive warm nights (TCWN) index in the experiments with all forcing (historicalExt in orange) and with only natural forcing (historicalNatExt, blue), with the thin line showing the values from the model and the thick line the fit with a generalised extreme value distribution. The black vertical line shows the index value in HadUK-Grid observations re-gridded to the same resolution as the model experiments (N216; 17.8˚C).

To these histograms, we apply a generalised extreme value distribution, also plotted on Figure 5. 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.

Descriptor	**Probability**	**Confidence interval [5th percentile, 95th percentile]**
ALL (historicalExt)	0.173	[0.150, 0.193]
NAT (historicalNatExt)	0.0031	[0.0009, 0.0061]

These values imply that with only natural forcing, the chance of getting a TCWN index value of 17.8C or higher is 0.31% (equivalent to a 1 in 320 year return period), but with all forcing the chances are 17.3% (equivalent to approximately a 1 in 6 year return period). The values in the table also give a risk ratio of 56.1 [confidence interval: 26.8, 204.8]. These results show an increase in probability, compared to a similar condition in a pre-industrial climate, of the 2022 three-day tropical night event. They show that in a pre-industrial climate, it was extremely rare to experience such an event, whereas now the event is expected to occur fairly frequently.

Note that, due to the framing of our study, the calculations are based on only one year, so do not sample the full range of boundary conditions (e.g. sea-surface temperatures) and one model, so do not fully sample model uncertainty. However, the approximate change in likelihood for a hot event is in line with multi-model studies (e.g. Christidis et al., 2019, Zachariah et al (2022)).

Comparing the likelihood of three tropical nights in the 2022 simulations to the recent observed record one might note that the simulations contain more occurrences (91) compared to observations (1). This is for two reasons: firstly, the observed world represents a more limited sample (53 years of HadUK-Grid to a HadGEM3-A model ensemble of 525 members), so the model will have a greater number of these extreme events. Secondly, the current (2022) climate is warmer than any previous time in the observational world and that warming appreciably increases the probability of an event.

Projections

Here we focus on qualitative evaluation of the TCWN index in climate projections into the future. We use projections data from UKCP Local, run from 1980 to 2080 and regridded to 5km. For the 1980 to 2022 period, we compare it to observational data from HadUK-Grid (also regridded to 5km). Focussing on the climate of the recent past, Figure 6 shows the UKCP Local projections agree well with the HadUK-Grid observations, with the observations within the ensemble spread and the observations' year-to-year variability qualitatively similar to the variability in a single ensemble member. Therefore, we decide against performing bias correction with the UKCP Local for this evaluation.

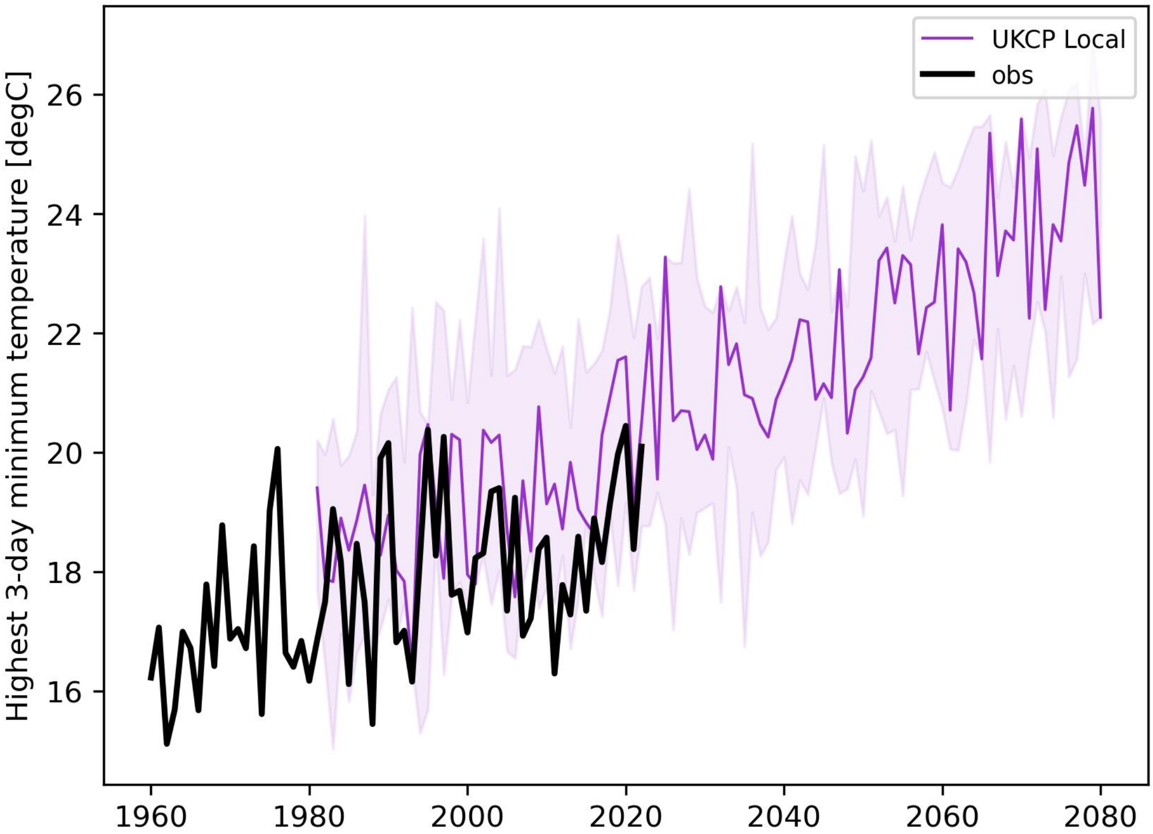

Figure 6: Time series of the three consecutive warm nights (TCWN) index in the experiments with the UKCP Local ensemble in purple, with the shaded area showing the full ensemble spread and the thicker line showing an individual ensemble member. The black line shows the index values in HadUK-Grid observations regridded to the same resolution as the model experiments (5km, giving a value of 20.1˚C in 2022).

In the future climate, the UKCP Local indicates that the TCWN index is projected to increase. Under this high emissions scenario (RCP8.5), the higher values observed in the late 1990s and early 2020s are, by the 2050s, towards the low end of the ensemble, and by the 2080s are exceeded by the full model ensemble. This is caveated that the underlying models are a sub-sample of the broader uncertainty; there are only 12 ensemble members from one climate model. While these 12 members are all plausible realisations of future climate, they are driven by a model with a relatively high climate sensitivity (Meehl et al.,

2020) meaning that other climate models are likely to give lower values for future temperatures. Furthermore, we only consider one emissions scenario (RCP8.5), which is a high emissions scenario that facilitates identification of how the index might change under climate change. The evolution of emissions is governed by policies, and how realistic RCP8.5 is remains the subject of debate (e.g. Hausfather and Peters, 2020; Schwalm et al., 2020). However, the increasing trend in the TCWN index is also seen (not shown) in UKCP Global, which includes other CMIP models and a lower emissions scenario (RCP2.6).

While our chosen TCWN index is only one heat-related metric, it was developed with consideration to the adverse impacts of heat, including the definition of heatwaves used for issuing weather warnings and the body's circadian rhythm whereby sleep is used to regulate core body temperature by increasing peripheral vascular flow to evacuate heat. This is impaired at high ambient temperature and humidity and for persons suffering from cardiovascular disease. The projected increase in the TCWN index is consistent with other studies (Hanlon et al., 2021; Kendon et al., 2021; Kendon et al., 2023; Kennedy-Asser et al., 2021). Given the adverse impacts of high overnight temperatures (e.g. Murage et al., 2017), the projections of an increasing trend in the highest three-day minimum temperature would be consistent with increasing heat-related mortality through the 21st century. This impact could be alleviated by mitigating carbon emissions or by facilitating adaptation to the projected changes. Overnight heat is most likely to affect people in their homes, so it is key that any adaptation strategy considers the factors that influence exposure and vulnerability of residents.

Conclusion

This work presents the development and application of an attribution protocol, intended for delivering attribution as a service such that scientifically rigorous attribution information can be communicated alongside, or shortly after, the weather event. Attribution studies compare the likelihood of an event in the current climate to its likelihood in a counterfactual simulated world with only natural forcing. This methodology includes properly defining the attribution question, evaluating the model, correcting model bias, calculating the probabilities with and without anthropogenic inputs in the current climate, and examining future climate projections. The simulation data come from HadGEM3-A-N216 for the attribution and the UKCP Local Projections for the future projections, which means we do not explore model uncertainty. This approach would be classed as medium quality by Otto et al. (2020) and does allow timely analysis and interpretation.

Future work from this study will focus on the development of attribution as a service. As different weather events give rise to different attribution questions, we expect the protocol to require refinement in order to answer them appropriately, particularly regarding the framing. We will also scope further scientific development of the protocol, for example including other climate models in the attribution study alongside HadGEM3-A-N216. Furthermore, for the future look we will explore projections aside from UKCP Local, which only represent a single, high emissions scenario and one underlying model that has high climate sensitivity relative to other models that contribute to CMIP.

This study considers the July 2022 event where locally (using observations from HadUK-Grid at 1km resolution) temperatures did not drop below 20 degrees for three consecutive 24-hour periods. Hot nights during heatwaves are associated with increased mortality with several possible physiological and behavioural explanations. One plausible explanation is that sleep is used to regulate core body temperature by increasing peripheral vascular flow to evacuate heat which can be impaired by high ambient temperature. Our framing calculates the probability of this event with conditions similar to 2022 (e.g. similar sea-surface temperatures), with and without anthropogenic influence. Consistent with other studies using other metrics of the same heatwave, we find that based on estimates from HadGEM3-A, this event was extremely rare in a pre-industrial climate (percentage probability 0.31% per year) but in current climate something that would be expected to occur fairly frequently (17.3% per year). In a future climate, the highest three-day minimum temperature seen per year is projected to increase. Given current impact from consecutive hot nights through increased mortality, these results emphasise the need to encourage both action to avoid the adverse impacts of consecutive tropical nights on short timescales and action to adapt to consecutive tropical nights on longer timescales.

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