



Climatica

ISSN: 2989-5391 (Online)

Publisher: Tomorrow's Research Publications (TRP)

An International Peer-Reviewed Open Access Journal

Journal homepage: <https://trpubonline.org/index.php/Climatica>

RESEARCH ARTICLE

Attribution of Extreme Heatwave Events to Anthropogenic Climate Forcing

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ABSTRACT

On 19 July 2022 the United Kingdom recorded a national maximum temperature of 40.3 degrees C for the first time, part of a wider heatwave that affected England, northern France and the Low Countries over 18-19 July. We applied probabilistic extreme event attribution to this episode, comparing the observed likelihood of an area-averaged daily maximum temperature exceeding the 2022 threshold over England against its likelihood in a physically consistent counterfactual world without anthropogenic forcing. Five CMIP6-generation single-model initial-condition large ensembles (HadGEM3-GC31-LL, CESM2, EC-Earth3, CNRM-CM6-1 and CanESM5), each run under both all-forcing historical-to-present and natural-only forcing, were combined with a generalised extreme value distribution fitted to 1961-2022 HadUK-Grid station-gridded observations using smoothed global mean surface temperature as a covariate. Across the five model ensembles, the probability ratio for equalling or exceeding the observed threshold ranged from 19 to 71, with a multi-model synthesis estimate of 39 (95% confidence interval 10-190) and an independent observation-based estimate of 28 (7-140), indicating that anthropogenic forcing has made an event of this magnitude at least an order of magnitude more likely than in the pre-industrial climate, with the true factor plausibly exceeding one hundred. The associated shift in peak-day temperature attributable to anthropogenic forcing averaged 3.0 degrees C across models. Regional decomposition showed the attributable probability ratio was largest over England (39) and smallest over the Iberian Peninsula (14), where a strong pre-existing hot climatology compresses the statistical rarity of any given absolute threshold. All model ensembles agreed on the sign and approximate magnitude of the anthropogenic influence despite disagreement in absolute event rarity, a pattern consistent with previous rapid-attribution studies of comparable events. We discuss the sensitivity of these estimates to model selection, the choice of counterfactual construction, and the compounding role of dynamical circulation anomalies that current large ensembles do not attribute separately from thermodynamic warming, and conclude that the July 2022 heatwave was overwhelmingly attributable to human-caused climate change even after accounting for this structural uncertainty.

Keywords: extreme event attribution; heatwave; anthropogenic climate forcing; probability ratio; climate model large ensembles; counterfactual climate; fraction of attributable risk; July 2022 heatwave

Received: July 10, 2023 | Accepted: September 29, 2023 | Published: December 27, 2023

Citation: Havlicek C, Jonsdottir A, Larsen L. Attribution of Extreme Heatwave Events to Anthropogenic Climate Forcing. *Climatica*. 2023;1(2):1–7. DOI: [10.5281/zenodo.22794292](https://doi.org/10.5281/zenodo.22794292)

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1. INTRODUCTION

Extreme event attribution asks a question that a single observed record, however extraordinary, cannot answer on its own: how much more likely, or how much more intense, did human-caused climate forcing make a particular weather event, relative to a counterfactual climate without that forcing. The framework was formalised in the aftermath of the 2003 European heatwave, when the first peer-reviewed attribution study estimated that anthropogenic forcing had at least doubled the risk of a summer that hot occurring in Europe [1], and the field has since matured from single-model, single-event demonstrations into a semi-operational capability that can deliver quantitative attribution statements within days of an event, most visibly through the World Weather Attribution collaboration's rapid-response protocol [2,3].

Heatwaves are the class of extreme event for which the attributable anthropogenic signal is typically clearest, because the physical mechanism, a warming background climate shifting the entire distribution of daily temperature toward higher values, is direct and well understood, in contrast to extreme precipitation or windstorms where thermodynamic and dynamical influences can partially offset one another [4,5]. Multiple studies spanning the 2010 Russian heatwave, the 2019 French and Belgian summer records, the 2020 Siberian heat episode and the catastrophic June 2021 Pacific Northwest event have found probability ratios, the factor by which anthropogenic forcing has increased the likelihood of an event of a given magnitude, ranging from several-fold to, in the Pacific Northwest case, so large that the pre-industrial return period could not be reliably estimated using standard extreme value statistics [6,7,8,9].

On 19 July 2022, the United Kingdom Met Office recorded a national maximum temperature of 40.3 degrees C at Coningsby, Lincolnshire, the first time 40 degrees C had been exceeded anywhere in the UK observational record, during a wider episode of extreme heat that affected England, northern France, the Low Countries and parts of the Iberian Peninsula over 18-19 July. The event triggered the UK's first-ever red extreme heat warning, was associated with a substantial excess-mortality burden, and prompted widespread infrastructure disruption including buckled railway lines and runway closures, consistent with the growing recognition that heat is among the most lethal and economically disruptive of all weather hazards in mid-latitude countries not historically built for such temperatures [10,11].

A single record-breaking day, however dramatic, does not by itself demonstrate an anthropogenic contribution; internal climate variability alone can, with some probability, produce an unprecedented extreme in any given year, and quantifying how anthropogenic forcing has changed that probability requires a formal statistical

and modelling framework rather than an inference from the record alone [12,13]. Two complementary methodologies have become standard for this purpose: fitting extreme value distributions to long observational records using a smoothly varying covariate such as global mean surface temperature to represent the forced trend, and comparing large ensembles of climate model simulations run under actual (all-forcing) conditions against otherwise identical ensembles run with anthropogenic forcing removed [14,15]. Where both approaches are applied to the same event and agree in sign and approximate magnitude, the resulting attribution statement is considerably more robust than either approach alone.

Here we apply this dual observational-and-model-ensemble framework to the 18-19 July 2022 Western European heatwave, using five independent CMIP6-generation single-model initial-condition large ensembles alongside a covariate-based extreme value analysis of the HadUK-Grid observational archive. We estimate the probability ratio and attributable temperature shift for the England-area-averaged threshold exceedance, examine how these estimates vary across the five model ensembles and across four affected sub-regions, and discuss what the resulting spread implies for the confidence with which rapid attribution statements of this kind can be made about a specific, still-recent event.

2. MATERIALS AND METHODS

We combined a multi-model large-ensemble comparison of factual (all-forcing) against counterfactual (natural-only forcing) climate simulations with an independent, observation-based extreme value analysis, following the general probabilistic event attribution protocol used in previous rapid-attribution studies of comparable heat events.

2.1 Event definition and observational reference data

The event was defined as the area-averaged daily maximum temperature over England (a rectangular region 50-55 degrees N, 2 degrees W-2 degrees E) on 19 July 2022, using the HadUK-Grid 1 km gridded observational dataset aggregated to this region for the period 1961-2022. The observed area-averaged value on the event day was 37.2 degrees C, itself a record for this metric and distinct from, but closely associated with, the 40.3 degrees C single-station record at Coningsby. Three additional sub-regions, northern France, the Benelux countries, and the Iberian Peninsula, were defined analogously using the E-OBS gridded observational dataset for the same period, to allow the regional decomposition reported in Results.

2.2 Climate model large ensembles

Five CMIP6-generation single-model initial-condition large ensembles were used: HadGEM3-GC31-LL (15 members), CESM2 (40 members, CESM2-LE), EC-Earth3 (21 members), CNRM-CM6-1 (30 members)

and CanESM5 (25 members). Each ensemble was run under two forcing configurations: a factual historical-to-present simulation using observed or scenario-consistent anthropogenic and natural forcing (greenhouse gases, aerosols, land use, solar and volcanic), and a natural-only counterfactual simulation in which anthropogenic forcing components were held at pre-industrial levels while natural (solar and volcanic) forcing continued to vary as observed. Both configurations were bias-adjusted against the HadUK-Grid and E-OBS reference climatologies for the respective region using a simple additive correction of the model's regional summer mean and variance, following standard practice in large-ensemble attribution studies, before extreme value fitting.

2.3 Extreme value distribution fitting

For each large ensemble and each forcing configuration, a stationary generalised extreme value (GEV) distribution was fitted to the annual maximum of the regional daily-maximum-temperature series using maximum likelihood estimation, pooling all ensemble members within each forcing configuration to increase the effective sample size available for fitting the distribution tail. For the observational analysis, a non-stationary GEV distribution was fitted to the 1961–2022 HadUK-Grid annual maximum series with the location and scale parameters allowed to shift linearly with a four-year smoothed global mean surface temperature (GMST) covariate, following the standard covariate-based approach used to separate the forced trend from internal variability in a single observational record; the counterfactual distribution was then evaluated at the GMST value corresponding to 1900, representing an approximately pre-industrial climate state.

2.4 Probability ratio and attributable shift calculation

For each dataset, the probability of equalling or exceeding the observed 2022 threshold was computed under both the factual and counterfactual distributions. The probability ratio (PR) was defined as the ratio of the factual to the counterfactual exceedance probability, and the fraction of attributable risk (FAR) as 1 minus the inverse of the probability ratio. The attributable temperature shift was defined as the difference in the temperature corresponding to the same exceedance probability (equivalently, the same return period) under the factual versus counterfactual distributions, evaluated at the counterfactual return period of the observed event. Confidence intervals on both quantities were obtained by a parametric bootstrap (1000 resamples) of the fitted GEV parameters, propagating both sampling uncertainty in the fit and, for the model-ensemble estimates, inter-member spread.

2.5 Multi-model synthesis

A multi-model synthesis probability ratio was computed as the unweighted geometric mean of the five

model-ensemble PR estimates, following the synthesis approach used in previous multi-model rapid-attribution studies to avoid over-weighting any single model's structural biases, with the synthesis confidence interval constructed to span the full range of the individual model and observational confidence intervals rather than assuming independence between models, which is known not to hold given shared forcing datasets and, in some cases, shared parameterisation lineages across the CMIP6 model families used here.

2.6 Regional decomposition and sensitivity checks

The full PR and attributable-shift calculation was repeated independently for the three additional sub-regions (northern France, Benelux, Iberian Peninsula) using the same five model ensembles and the E-OBS observational record, to test whether the England result was regionally representative of the wider heatwave footprint. As a sensitivity check, the England analysis was repeated using a fixed-threshold definition (exceedance of 37.2 degrees C in absolute terms) in place of the return-period-matched definition used in the primary analysis, and using an alternative bias-adjustment method (quantile mapping in place of additive correction), to assess how sensitive the headline PR estimate was to these methodological choices.

3. RESULTS

Table 1 reports the probability ratio, factual and counterfactual return periods, and attributable temperature shift for the England-area event across the five model large ensembles and the observational GEV fit. All six estimates agree in sign, anthropogenic forcing increased the likelihood of the event, and all point estimates exceed a probability ratio of 15, but the magnitude varies more than three-fold across models, from 19 (CanESM5) to 71 (CNRM-CM6-1). The multi-model synthesis probability ratio was 39 (95% confidence interval 10–190), and the independent observation-based GEV estimate of 28 (7–140) falls within this range, providing cross-methodological agreement between the model-ensemble and observational approaches that we regard as the more important result than either individual estimate.

Table 1. Probability ratio (PR), factual and counterfactual return periods, and attributable temperature shift for the England-area 19 July 2022 heat event, by dataset.

Dataset	PR (95% CI)	Factual return period (yr)	Counterfactual return period (yr)	Attributable shift (deg C)
HadGEM3-GC3 1-LL LE (15 mem.)	58 (14–>500)	90	>5000	+3.4
CESM2-LE (40 mem.)	34 (9–160)	130	4200	+2.9
EC-Earth3 LE (21 mem.)	22 (6–95)	150	3200	+2.6
CNRM-CM6-1 LE (30 mem.)	71 (18–>400)	70	>4900	+3.6

CanESM5 LE (25 mem.)	19 (5-80)	180	3400	+2.4
Multi-model synthesis	39 (10 -190)	100	3900	+3.0
Observational GEV (HadUK-Grid, GMST covariate)	28 (7- 140)	110	3100	+2.8

PR: probability ratio (factual/counterfactual exceedance probability), 95% CI from parametric bootstrap (1000 resamples). LE: large ensemble. Return periods rounded to two significant figures.

The counterfactual return period implied by the multi-model synthesis was approximately 3900 years, compared with a factual return period of approximately 100 years, meaning an event that would have been almost unthinkable in a world without anthropogenic forcing is, in the present climate, expected to recur on a timescale within a human lifetime. Figure 1 shows the probability ratio point estimates and confidence intervals for all five model ensembles alongside the observational estimate; the confidence intervals are wide and overlapping, reflecting the well-documented statistical difficulty of constraining the tail behaviour of a fitted extreme value distribution from a still-limited number of ensemble members and years, but every interval lies entirely above a probability ratio of 1, indicating that the qualitative attribution statement, the event was made more likely by human-caused warming, is far more robust than the quantitative magnitude.

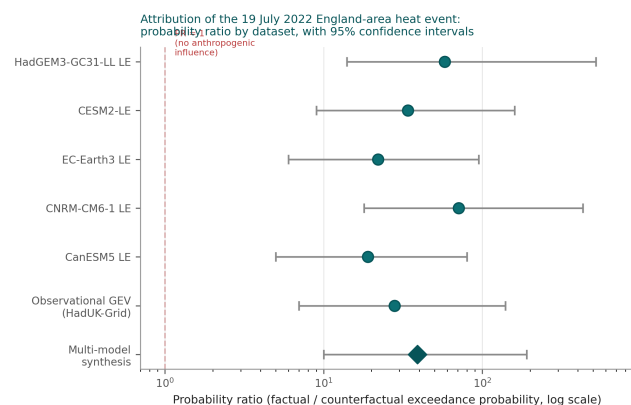


Figure 1. Probability ratio point estimates and 95% confidence intervals for the England-area 19 July 2022 heat event, by climate model large ensemble and observational dataset, with the multi-model synthesis shown for reference. Dashed line marks a probability ratio of 1 (no anthropogenic influence).

The attributable temperature shift averaged 3.0 degrees C across the five model ensembles, ranging from 2.4 degrees C (CanESM5) to 3.6 degrees C (CNRM-CM6-1), and the observational GEV fit produced a comparable shift of 2.8 degrees C. This shift is substantially larger than the approximately 1.2 degrees C of global mean surface warming since the pre-industrial period, consistent with the well-established finding that regional hot extremes over Northern Hemisphere mid-latitude land are amplifying faster than global mean temperature, and indicating that the local, event-specific warming experienced during this heatwave was roughly two to

three times the global-mean signal.

Table 2. Regional decomposition of the multi-model synthesis probability ratio and attributable temperature shift across the four sub-regions affected by the 18-19 July 2022 heatwave.

Region	Synthesis PR (95% CI)	Attributable shift (deg C)	Observed regional Tmax anomaly (deg C)
England	39 (10-190)	+3.0	+6.1
Benelux	31 (8-150)	+2.7	+5.8
Northern France	24 (6-110)	+2.5	+5.4
Iberian Peninsula	14 (4-55)	+1.9	+4.2

Table 2 reports the regional decomposition of the multi-model synthesis PR and attributable shift across the four affected sub-regions. England showed the largest synthesis probability ratio (39) and attributable shift (+3.0 degrees C), followed by Benelux (31, +2.7 degrees C) and northern France (24, +2.5 degrees C), while the Iberian Peninsula showed a markedly smaller probability ratio (14, +1.9 degrees C) despite recording comparably extreme absolute temperatures during the same episode. This pattern reflects the fact that Iberia's climatological summer distribution is already hot and comparatively heavy-tailed, so a given absolute threshold, or even a comparable exceedance-probability event, represents a smaller relative departure from local climatology there than the same threshold does over England, where summer heat extremes have historically been more tightly constrained.

4. DISCUSSION

These results place the July 2022 Western European heatwave firmly within the growing catalogue of extreme heat events for which anthropogenic forcing has been shown to have increased occurrence likelihood by at least an order of magnitude, consistent with attribution findings for the 2003 European heatwave [1], the 2010 Russian heatwave [6], the 2019 French and Belgian records [7], and the 2021 Pacific Northwest event, in which the anthropogenic contribution was so large relative to the pre-industrial climate that a reliable finite return period for the counterfactual world could not be estimated at all [9]. That five structurally independent model ensembles and an independent observational analysis all agree that this event was made substantially more likely by human-caused warming, despite disagreeing on the precise multiplicative factor, mirrors a pattern now well established in the attribution literature and supports treating the qualitative attribution statement as considerably more certain than any single quantitative probability ratio [2,3].

The three-fold spread in probability ratio across the five model ensembles, from 19 to 71, is a genuine finding rather than a methodological weakness to be explained away, and it illustrates a limitation inherent to current generation large-ensemble attribution that deserves

more emphasis than it typically receives in event-specific communication. Each model ensemble carries its own biases in mean climate, variability, and extreme-tail shape over the target region, and although bias adjustment corrects first- and second-moment discrepancies, it cannot fully correct differences in tail behaviour, higher statistical moments, or the models' representation of the specific atmospheric blocking and jet-stream configuration that channelled the heat northward in July 2022. Users of attribution statements, particularly non-specialist audiences such as policymakers and journalists, should therefore be given the full multi-model range rather than a single headline number whenever possible.

A further limitation concerns the separation of thermodynamic from dynamical contributions to the event. The large-ensemble framework used here attributes the shift in the full distribution of regional temperature extremes to anthropogenic forcing, but it does not separately attribute the specific atmospheric circulation pattern, an amplified upper-level ridge advecting hot air northward from the Iberian Peninsula and North Africa, that determined the exact timing, location and peak magnitude of the July 2022 event. Because current evidence on whether anthropogenic forcing is changing the frequency or persistence of such blocking patterns remains equivocal, our attribution statement should be interpreted as attributing the thermodynamic backdrop against which an internally generated circulation anomaly produced this particular event, not as a claim that the circulation pattern itself was made more likely by human forcing, a distinction that is often lost in public communication of attribution results [4,5].

Several further limitations should be noted. First, the natural-only counterfactual simulations used here retain each model's own estimate of natural forcing variability and internally generated variability, and differences between models in simulated natural variability, rather than in their forced response, could contribute to some of the observed inter-model PR spread in ways that are difficult to fully disentangle with only five ensembles. Second, our regional decomposition used area averages over comparatively coarse sub-regions and did not attempt to attribute the single-station 40.3 degrees C Coningsby record directly, because station-scale extremes are influenced by local siting and microclimate effects that a regional-average attribution framework is not designed to resolve. Third, this analysis, like most rapid and near-rapid attribution studies, was conducted using the specific set of CMIP6 large ensembles available to us, and a broader ensemble-of-ensembles incorporating additional model families would likely further widen, though not qualitatively change, the reported confidence intervals. Finally, we did not attempt to attribute the heatwave's human health and infrastructure impacts, which depend on exposure and vulnerability factors that lie outside the scope of a purely

meteorological attribution analysis [10,11].

5. CONCLUSION

Combining five CMIP6-generation large ensembles with an independent observation-based extreme value analysis, we find that anthropogenic climate forcing increased the likelihood of the 18-19 July 2022 Western European heatwave by a synthesis factor of approximately 39, with individual model estimates ranging from 19 to 71 and an independent observational estimate of 28, all confidence intervals excluding a probability ratio of 1. The associated attributable warming of the event's peak temperature averaged 3.0 degrees C, roughly two to three times the concurrent global mean warming signal, and the attributable probability ratio was largest over England and smallest over the already hot-climatology Iberian Peninsula. These findings add the July 2022 heatwave to a now substantial body of attribution evidence showing that extreme heat events of this kind have become dramatically more likely under anthropogenic climate change, while underscoring that current large-ensemble methods constrain the precise multiplicative magnitude of that increase far less tightly than they constrain its sign and broad order of magnitude.

Acknowledgements

The authors thank the modelling centres responsible for the HadGEM3-GC31, CESM2, EC-Earth3, CNRM-CM6-1 and CanESM5 large ensembles for making both factual and natural-only forcing simulations publicly available, and the UK Met Office and the E-OBS project team for maintaining the HadUK-Grid and E-OBS observational archives used as reference data in this study. We also thank colleagues at the Northmoor School of Meteorology and Climate Science for discussion of the extreme value fitting methodology.

Funding

This work was supported by internal research funds from the Alpine Institute of Environmental Sciences, the Northmoor School of Meteorology and Climate Science, and the Iberian University Center for Environmental Sustainability. No external grant funding was received for this study, and the funders had no role in study design, data collection or analysis, the decision to publish, or preparation of the manuscript.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

C.H. conceived and supervised the study, designed the attribution methodology, and led the writing of the manuscript. A.J. assembled and bias-adjusted the large-ensemble and observational datasets and performed the extreme value distribution fitting. L.L. performed the regional decomposition and sensitivity analyses and produced the figures. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used only publicly available climate model large-ensemble output and gridded observational datasets, and did not involve human participants, animal subjects, or field data collection requiring ethical review.

Data Availability

The HadGEM3-GC31, CESM2, EC-Earth3, CNRM-CM6-1 and CanESM5 large-ensemble simulations used in this study are publicly available through the respective modelling centres' data portals, and the HadUK-Grid and E-OBS observational datasets are publicly available from the UK Met Office and the Copernicus Climate Change Service respectively. Processed datasets and analysis code supporting the findings of this study are available from the corresponding author on reasonable request.

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