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LETTER

Attributing human mortality during extreme heat waves to anthropogenic climate change

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Abstract

It has been argued that climate change is the biggest global health threat of the 21st century. The extreme high temperatures of the summer of 2003 were associated with up to seventy thousand excess deaths across Europe. Previous studies have attributed the meteorological event to the human influence on climate, or examined the role of heat waves on human health. Here, for the first time, we explicitly quantify the role of human activity on climate and heat-related mortality in an event attribution framework, analysing both the Europe-wide temperature response in 2003, and localised responses over London and Paris. Using publicly-donated computing, we perform many thousands of climate simulations of a high-resolution regional climate model. This allows generation of a comprehensive statistical description of the 2003 event and the role of human influence within it, using the results as input to a health impact assessment model of human mortality. We find large-scale dynamical modes of atmospheric variability remain largely unchanged under anthropogenic climate change, and hence the direct thermodynamical response is mainly responsible for the increased mortality. In summer 2003, anthropogenic climate change increased the risk of heat-related mortality in Central Paris by ~70% and by ~20% in London, which experienced lower extreme heat. Out of the estimated ~315 and ~735 summer deaths attributed to the heatwave event in Greater London and Central Paris, respectively, 64 (±3) deaths were attributable to anthropogenic climate change in London, and 506 (±51) in Paris. Such an ability to robustly attribute specific damages to anthropogenic drivers of increased extreme heat can inform societal responses to, and responsibilities for, climate change.

1. Introduction

Over Europe, both the long-term climate response, and changes in extreme temperatures have been shown to be unequivocally related to anthropogenic climate change [1, 2]. During 2003 the synoptic and land-surface conditions were such that much of Europe experienced an unprecedented heatwave during summer [3]. While heatwaves have occurred subsequently [4], none have reached the level of impact on human health observed in 2003, in part because of the improved emergency response plans from national governments [5, 6], but also due to extremely high temperatures during the 2003 heatwave (figure 1). A clear example is the 2012 European heatwave, which is the only event to exceed 2003 in magnitude using the diagnostic in figure 1. Given the link between temperature and human well-being [7, 8], there is a need to understand how heat wave characteristics have changed due to human induced climate change.

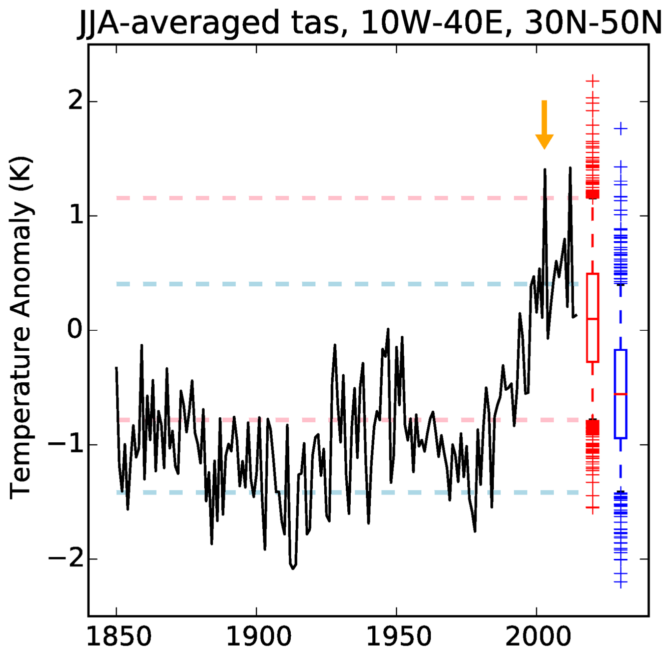

Figure 1. Mean summer temperature anomaly (relative to 1985–2010) in observations (CRUTEM4; black line) averaged over a region covering the Mediterranean [21]. The box and whisker plots show the median, interquartile range, 5%–95% range and more extreme data as + symbols over the same region for the (red) Actual scenario and (blue) Natural scenario. Horizontal dashed lines show the 5%–95% range of the modelled data. Year 2003 is marked with an orange arrow.

Health effects from exposure to heat range from minor illness, to increased risk of hospitalisation and death. Heat can often exacerbate existing medical conditions and contribute to the increased risk of mortality. There are a number of factors which may modify or contribute to the mortality risk from heat [9, 10], including social status, individual behaviour, the extent of urbanisation, and the influence of increased air pollution which may occur during hot periods [11]. Given the complex interaction of these factors, the mortality count of each heatwave is very dependent on the event location, timing and past experiences of the local populations.

Here, we perform a combined data analysis and modelling study, utilising end-to-end attribution assessment techniques [12]. Given that heat related mortality is likely to increase under a warmer climate [13–16], our framework allows us to trace anthropogenic influence on the likelihood of summer heatwaves through to altered levels of human mortality. Specifically we assess any attribution of localised mortality to climate change that may be identified from the immediate thermodynamical warming, and through secondary warming mechanisms such as changing weather patterns.

2. Methods

2.1. Observation and reanalysis data

Observational sub-daily temperatures and dew-point temperatures over London and Paris are taken from the Met Office Integrated Data Archive System (MIDAS). Following Baccini *et al* [17] we use the nearest airport weather station to the city; Heathrow and Orly for London and Paris, respectively. When considering the Mediterranean region, we use the gridded near surface air-temperature data set CRUTEM4 [18], available from 1850–present on a 5 × 5 degree grid. For atmospheric field analyses, we use daily averaged geopotential height at 500 hPa from the European Centre for Medium Range Weather Forecasting ERA-Interim reanalysis, which has a ~80 km horizontal resolution [19]. All data are available to download via the British Atmospheric Data Centre (BADC; http://badc.nerc.ac.uk). Daily recorded all-cause mortality was obtained from the Office for National Statistics (ONS; http://www.ons.gov.uk) for Greater London (population of 7 154 000), and from the Institut National de la Santé et de la Recherche Médicale (Inserm, http://www.inserm.fr/) for Central Paris (for a standard population of 2 126 000).

2.2. Climate simulations

We use the data generated by simulations run as part of the citizen science Weather@home project, that allows for huge numbers of ensemble members to be run on volunteered computers from around the world [20]. To adequately understand the extremes, a ~25 km resolution regional model over Europe (HadRM3P) is embedded in a global atmosphere-only model (HadAM3P). The UK Met Office's land-surface scheme, MOSES2, is also used to better represent conditions specific to the 2003 heat wave in the regional model (figure S4). Specifically, MOSES2 allows for nine different land surfaces (tiles) within a grid box. For validation of the global model see Massey *et al* [20] and supplementary information (SI).

For London and Paris, we output data on the urban tile at the latitudes and longitudes of each respective city. We consider the grid boxes within a diameter of 50 km for London, and 35 km for Paris, in line with the sizes of each city. All grid boxes used to represent the cities have a high urban-tile fraction compared with other land-surface types. Repeating the analysis for a single grid box at the location of the airport station data gives similar temperature projections. Mean biases in the model data are low (typically less than 0.5 K; and probably due to the strong land–atmosphere coupling in our model (see SI)), and are adjusted for by bias correcting the mean model climatology (over 1985–2010) with the station data climatology over the same period (see, for instance, [20]). This is the recommended method of bias correction for temperature data from the Inter-Sectoral Impact Model Inter-comparison Project (ISI-MIP) [22] that specifically considers use of general circulation model (GCM) output with impact models (including health impact models).

Two experiments have been performed using this model set up; (1) simulations of the year 2003 whereby all known climate forcings are included in the model, (2) simulations of 2003 whereby only natural internal and external forcings are included (i.e. no anthropogenic climate change). We simulated 2000 model years (ensemble members) for each of the experiments, and under this experimental design the climate is stationary for each individual experiment. Each experiment is spun up from an initial control state for 1 year to account for long-memory processes (such as soil moisture) to equilibrate. The model forcing files and boundary conditions are those as detailed in [20] for the Actual conditions scenario, and preindustrial versions for the Natural conditions scenario. The prescribed sea surface temperatures (SSTs) are taken from the operational sea surface temperature and sea ice analysis (OSTIA) data set [23] in the first instance, and from a naturalised OSTIA data set in the second instance. For the naturalised OSTIA data, we make use of the individually forced simulations taken from the Coupled Model Inter-comparison Project, phase 5 (CMIP-5). The change in SST patterns required to transform the OSTIA data set into a naturalised SST data set is calculated from the difference between the SST patterns in the CMIP-5 historical and so-called historicalNat simulations (as in, for instance, [24]). Because there is no way of knowing *a priori* whether these transformed SST patterns are correct or not, we choose ten different CMIP-5 models to estimate the change in SSTs thereby sampling across a whole range of possible warming patterns removed from the observed SSTs, the same as those used in [24].

2.3. Health impact assessment (HIA) methodology

All-cause mortality is recorded daily, along with the specific cause of death (for example cardiovascular disease or cancer) but there is no way to make a direct connection between deaths recorded during a heat wave and exposure to heat specifically, since the deaths could be related to a range of factors. To estimate the number of deaths which were attributable to heat, therefore, we use a relationship which relates a change in apparent temperature (AT) with a change in the baseline mortality rate, taking account of confounding factors [17].

The number of heat-related deaths (M) in each city, for a season (June–August) was estimated using the following relationship

$$M = \sum_{i=1}^{N} DM_i (1 - e^{-b\Delta AT_i}). \tag{1}$$

Heat related mortality was calculated daily, on each day (i) over N total days in the season. DM_i represents the recorded daily mortality in the city of London or Paris for summer 2003, b is the exposure–response relationship which relates AT and mortality for London or Paris and represents the % increase in mortality per 1 °C increase in maximum AT above a threshold (1.54 (±0.53)% for London and 2.44 (±0.36)% for Paris), published by Baccini *et al* [17]. AT is a heat and humidity based measure of relative discomfort [25], defined as in [26] as: AT $= -2.653 + 0.993\ t_{\max} + 0.0153\ t_{\mathrm{d,max}}^2$, where $t_{\max}$ is the daily maximum temperature, and $t_{\mathrm{d,max}}$ is the daily maximum dew-point temperature, and used to derive the temperature–mortality relationships in Baccini *et al* [17]. ΔAT_i is the daily maximum AT on day i above the threshold (23.9 °C (±0.13) for London and 24.1 °C (±0.7) for Paris).

We have carried out the HIA based on all-cause mortality for both cities, whereas the coefficient in Baccini *et al* [17] is derived using all-cause mortality excluding external causes. The choice of a slightly different dataset was due to data access. This may have led to a small overestimation in heat-related mortality; for example figures from the ONS suggest that deaths from external causes for London from 1996–2013 accounted for 3.3% of the total number of deaths.

Maximum AT on each day were calculated as an average of the present day and the previous 3 days, in accordance with Baccini *et al* [17] to allow for possible lag effects. For calculations of mortality in 2003 based on observed AT, we used the observations from MIDAS stations for London and Paris. For calculations of mortality based on the two forcing scenarios, we used the simulated AT from the Natural and Actual model ensembles.

2.4. Uncertainty analysis

Internal model variability is assessed by simulating ~2000 initial condition perturbation ensemble members for each of the Actual and Natural scenarios.

Uncertainty in the Naturalised scenario is assessed using multiple different SST estimates from ten models that participated in CMIP-5 (see sections 2 and 2.2). The use of multiple model-derived SSTs also allows for some measure of model uncertainty. However, we did not explicitly repeat our full analysis with additional models, as there is no framework to build such large ensembles using them. Sampling uncertainty is estimated using a Monte Carlo resampling technique, with replacement, of all ensemble members from the individual scenarios, performed ten thousand times. The 5–95 percentile range of the resultant distribution is then plotted. Finally, the 5%–95% uncertainty range given for heat–mortality response coefficients and AT thresholds in Baccini *et al* [17] is used to calculate the uncertainty in heat related mortality.

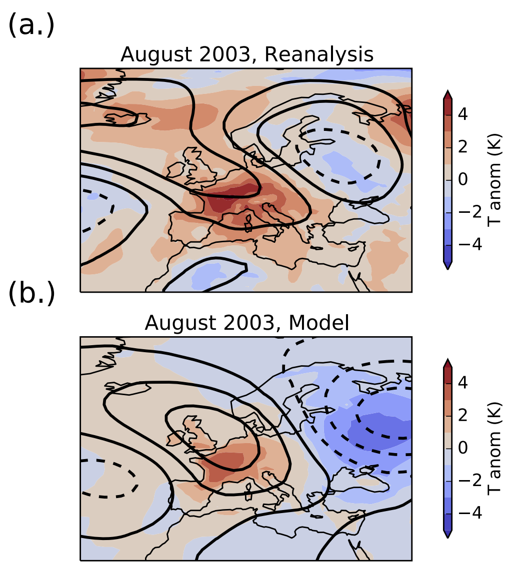

Figure 2. Synoptic conditions for August 2003. In (a) ERA-Interim reanalysis and (b) the top 5% of model simulations with a similar synoptic circulation pattern to that observed in 2003. The similarity of the modelled synoptic circulation pattern to the observed pattern is diagnosed by matching the differences between the Z500 'centres of action' from the high and low in (a). Filled contours show the near surface temperature anomaly. Line contours show the geopotential height at 500 hPa anomaly. Contours intervals are every 30 m and negative anomalies are dashed. Anomalies are relative to the 1979–2012 period.

3. Analysis

As the entire summer of 2003 was known to be persistently hot, we define the heatwave 'event' as the inclusive June–August period. To analyse the event we use a global atmosphere-only climate model to internally drive a 'nested' 25 km regional model covering Europe [18]. Individual model simulations capture the observed spread in recent summer temperatures well (figure 1, red bar) and are notably warmer than estimates of 2003 in the absences of anthropogenic warming (see section 2) (figure 1, blue bar). We also test the capability of the model for capturing the synoptic conditions of the 2003-like heatwave. The highest observed temperatures in 2003 were during August, with the largest temperature anomalies located over France (figure 2(a), filled contours). The synoptic circulation was in an Atlantic/European ridge regime [27] (line contours), which allowed warm air to be advected poleward from nearer the equator. A composite average based on the top 5% of ensemble members with most similar synoptic situations (see figure caption) to the reanalysis shows very similar temperature anomalies over France (figure 2(b)). This large-scale wave pattern is considered to be a key forcing mechanism for the extreme summer temperatures, whereby a resonant growth of wavenumber 6–8 Rossby quasi-stationary waves (near-static planetary waves) is thought to be linked with the high temperature anomalies over France in 2003 [28]. Ultimately, these waves may form Atlantic and/or European ridges (as was the cause in 2003) or blocks.

We find clear examples of simulations with similar synoptic wave characteristics to that occurring in 2003 (figure S1). When we formally identify the dynamical modes using the latest relevant 2003 wave diagnostics [28], we find that the model represents the temporal and spatial structure of them well (figures 3, S2). Critically, we see an increase in the frequency of heat waves over France when we explicitly detect 2003-like ridging events in our ensemble members (figure 3(b)). These factors indicate our ensemble is capable of capturing synoptic and climate conditions of the event. The large ensemble, by placing analysis in a probabilistic framework, allows attention to then be moved to an attribution assessment. We focus on two major European cities; Paris, which recorded unprecedented levels of mortality during the 2003 heat wave, and London, which experienced increased mortality but to a lesser extent than that of Paris. By comparing these cities we avoid a natural selection bias in focussing on the most extreme cases.

For the HIA for heat related mortality, we use AT [25], a measure of human discomfort based on temperature and relative humidity. This metric was used in a directly relevant epidemiological analysis [17], to calculate heat–mortality response relationships for the 2003 heat wave, for Paris and London, as well as other cities.

The daily AT is well modelled in simulations, with numerous examples of heat waves as extreme as that observed in early August 2003 (figure S3). Mortality estimated from observed AT (figure 4) show that during 2003 (thick line) there is a clear peak in early August, in agreement with published estimates indicating that 2003 was an unprecedented event. Over the 3-month period June–August 2003, the seasonal heat-related mortality rate was around 4.5 per 100 000 for London and 34 per 100 000 for Paris, although the

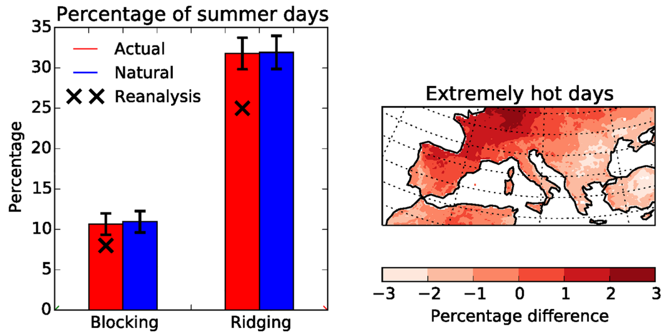

Figure 3. Blocking, ridging and warm days. (left) Percentage of summer days in blocking and ridging regimes for the (red) Actual scenario and (blue) Natural scenario. Black crosses show the percentage in reanalysis. (right) Percentage geographical differences in extremely (above the 95 percentile) hot days between summers defined as in a ridging regime, and summers not defined as in a ridging regime.

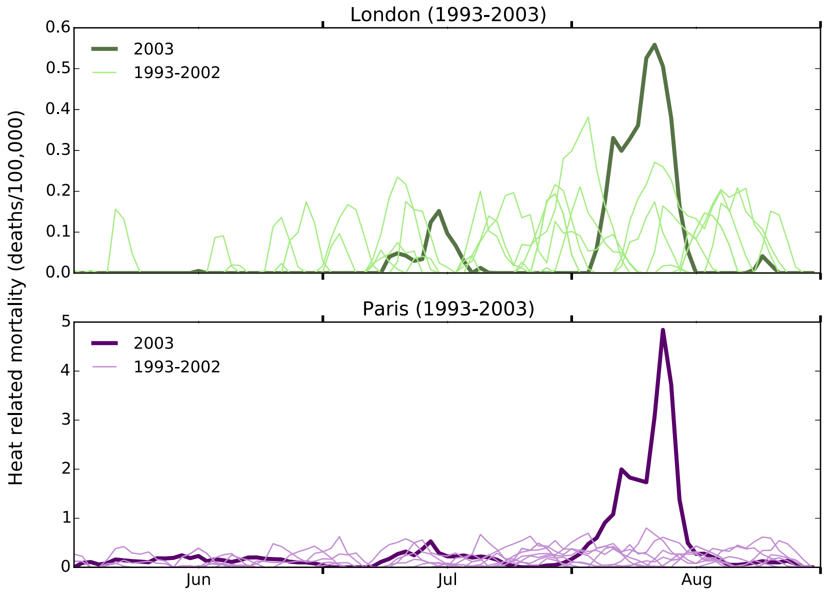

Figure 4. Daily time series of heat-related mortality. Estimated mortality throughout the summer period calculated from observed AT in London (top) and Paris (bottom). The thin lines are heat-related mortality calculated from AT observations covering 1993–2002. The thick line is the same but for 2003. Mortality counts are expressed per 100 000 population of each city. Note how the event, although extreme in London, was much less out of the ordinary than in Paris.

daily mortality rate in Paris peaked at 5 per 100 000 population at the height of the heat wave.

To understand any attributable role human influence on climate played in the 2003 event, we perform two experiments, and use the modelled AT as input to the HIA. The initial set of simulations employs known forcing conditions of ocean surface temperature, sea-ice extent and atmospheric gas compositions for the year 2003 (hereafter, 'Actual' conditions). The second set employ naturalised year 2003 estimates of the same forcing conditions (hereafter, 'Natural' conditions), which are representative of pre-industrial times. A meteorological analysis of these simulations shows ~1 K warming over Southern Europe in the Actual conditions compared to the Natural conditions scenario simulations, and with the variability of the event well captured by the model (figure S4). As natural SST patterns are not directly observable, we estimate them from ten independent climate models thereby creating ten estimates of the 'possible' natural SSTs (see section 2). For each of these ten estimates of pre-industrial forcing conditions, we present the mean change in temperature from the Actual conditions scenario for Paris and London, and from this calculate using our HIA, the change in overall cumulative summer (June–August) mortality (figure 5). Temperature increases have a higher impact on mortality in Paris over London, with the rate of increase for each city given by the slope of the best-fit line. The deviations of each point from the best fit lines indicates that the range in predicted AT is at least partially dependent on the naturalised SST pattern used, hence it is important to include the full spread in our analysis.

Many attribution studies to date have been hampered by only having available a small number of simulations. Our experiment, generating ~2000

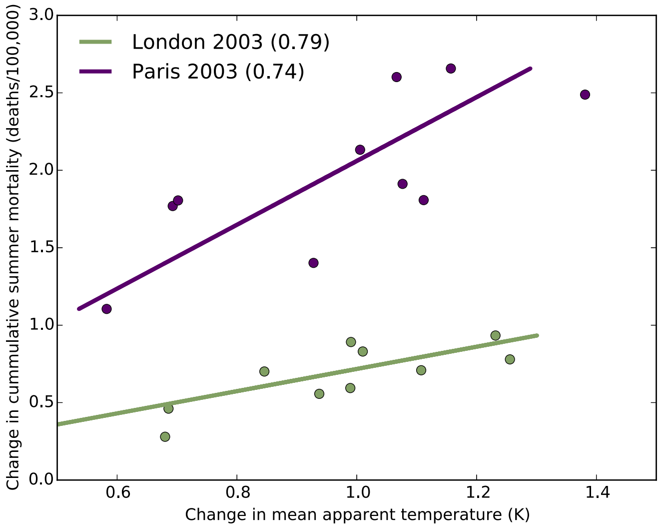

Figure 5. Apparent temperature to mortality relationship. Correlation between the mean summer apparent temperature and mean cumulative mortality in Paris (purple) and London (green) during 2003. Each point shows the Actual conditions minus one of the Natural conditions scenarios. There are ten different 'possible' Natural scenarios, based on ten estimated naturalised SST patterns. Mortality units are expressed in deaths per 100 000 population of the city. The correlation coefficient is given in parenthesis.

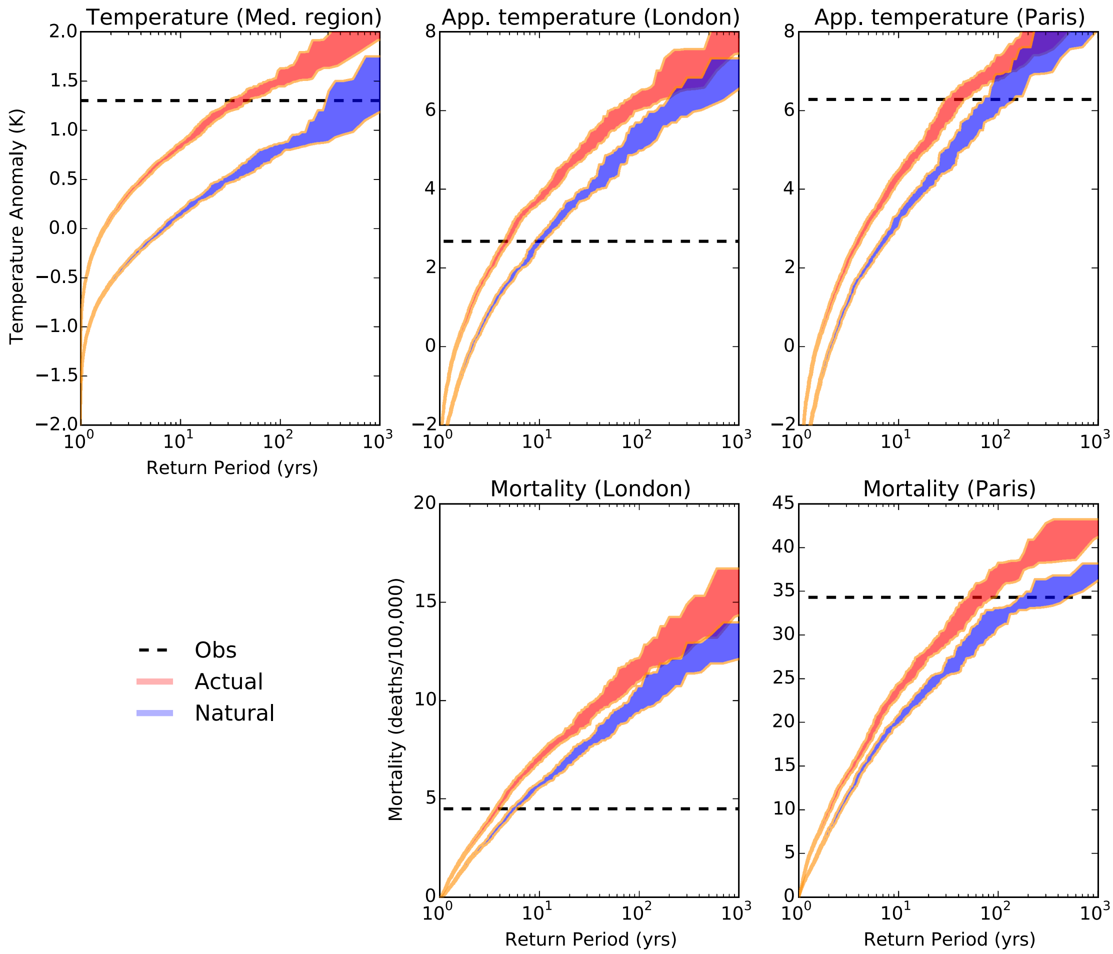

Figure 6. Temperature and mortality return period curves. (top, left) Summer-averaged temperature over the Mediterranean region and (top, middle and right) summer averaged apparent temperature over London and Paris. The bottom panels show the same but for cumulative summer heat-related mortality. Mortality counts are expressed per 100 000 population of the city. 5%–95% confidence intervals are plotted on the return level curves. The dashed line on each panel shows the value of the observed event.

simulations all with slightly different initial conditions, allows sampling of inherent chaotic nonlinear aspects of the atmospheric system. We use our super-ensemble framework to ask how rare was the observed 2003 event, and has human influence on climate changed this? Although the largest mortality signal in 2003 was over the first two weeks of August, here we choose to concentrate on the full seasonal analysis, again to avoid any selection bias arising from the most extreme signal. When summer (June–August) averaged temperatures are considered over a region covering the Mediterranean (figure 6) [21], we see an event of magnitude identical to the 2003 observed event (dashed line) has changed from a 1-in-500-year event (±200) in the Natural scenario, to a 1-in-40-year event (±10) in the Actual scenario, around an order of magnitude increase, consistent with [4, 21].

Observed summer AT over both cities is extreme, particularly in Paris (figure 6, top, dashed lines). In both model scenarios there are ample simulations that capture this (red and blue regions), in conjunction with the dynamical analysis and an analysis of the soil moisture (see SI), it adds confidence that 2003-like events are well represented in our simulations. Our results show that over both cities, the frequency of 2003-like heatwaves has increased due to anthropogenic climate change, but that this arises from the direct thermodynamical response of radiative forcing rather than a secondary dynamical response. The comparison between the Actual and Natural scenarios indicate that in London, summers as hot as that observed in 2003 previously occurred as a 1-in-10-year event (±0.5), but increased to a 1-in-3-year event (±0.5) under anthropogenic emissions. Likewise in Paris, the event went from a 1-in-92-year event (±12), to a 1-in-30-year event (±10).

To determine whether any human influences contributed to the mortality associated with the 2003 heat wave, we compare mortality estimated in the Actual scenario, with that of the Natural scenario. To quantify the human impact on the occurrence of the extreme 2003 heat wave, we use the fraction of attributable risk (FAR) [29], defined as $\mathrm{FAR} = 1 - (P_{\mathrm{NAT}}/P_{\mathrm{ACT}})$, where P_{NAT} is the probability of exceeding a pre-defined threshold in the Natural scenarios, and P_{ACT} is the probability of exceeding the same threshold but for the Actual scenarios. Here, our threshold is the heat related mortality count calculated from observations (figure 4). Using this analysis framework, the FAR is 0.70 (±0.07) for Paris, and 0.20 (±0.01) for London, indicating a strong anthropogenic influence on the mortality for Paris, which was made ~70% more likely. The cumulative 2003 summer heat related mortality calculated from observed AT was 34 in Paris and 4.5 in London (per 100 000 population). Hence these FAR statistics indicate that human influence was responsible for ~24 heat related deaths in Paris, and ~1 in London (per 100 000 population). Accounting for the population of the cities where mortality data is considered (7 154 000 for Greater London, and 2 126 000 for Central Paris; see section 2), the total number of heat-related deaths attributable to human influences is 506 (±51) in Central Paris, and 64 (±3) in Greater London during the summer of 2003. Return level statistics show that the 2003-like mortality event in Paris went from a 1-in-300-year event (±200), to a 1-in-70-year event (±30), whereas the less extreme event in London increased from a 1-in-7-year event (±0.5) to a 1-in-2.5-year event (±0.2) (figure 6, bottom). The mortality count attributable to anthropogenic influences in these cities is notably high. However, London and Paris are just two of a large number of cities that were impacted by the 2003 heatwave, therefore the total European-wide mortality count attributable to anthropogenic climate change is likely to be orders of magnitude larger than this.

The analysis above has used the mid-range heat–mortality relationship from the HIA in Baccini *et al* [17], and where the uncertainty presented is from the atmospheric modelling. Uncertainty from the HIA can also be included using the 5%–95% ranges from Baccini *et al* [17]. This then gives for the lower estimate of the HIA, 410 (±40) deaths that are attributable to anthropogenic climate change in Paris, and 50 (±3) in London during the summer of 2003. If the upper limit is used, then 602 (±64) deaths are attributable to anthropogenic climate change in Paris, and 80 (±4) in London.

4. Discussion

Our large climate-modelling ensemble within an 'end-to-end' attribution framework enables a robust attribution of heat-related deaths at local scales to anthropogenic climate change. Several researchers have recently argued that such an ability to robustly attribute specific damages to anthropogenic drivers of increased extreme heat can inform societal responsibilities for the costs of both 'loss and damage' and adaptation in developed as well as developing countries [30–32]. Further work can be done to extend the approach taken in this analysis to similarly quantify the climate change-exacerbated damages from other extreme events, and to incorporate into climate model assessments projections of changes in future regional scale damages under differing scenarios of further warming and investments in climate adaptation. The climate projections community have a challenging task ahead, as climate projection studies need to make plausible estimates of changes to societal and physical factors (e.g. demographics and the extent of urbanisation) in order to estimate future heat related mortality.

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