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Emergence of heat extremes attributable to anthropogenic influences

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Key Points:
- We identify when the first attribution of heat extremes to anthropogenic climate change is possible
- Earliest attribution to anthropogenic influences in the 1930s globally and the 1980s in many regions
- Aerosol-induced cooling delayed emergence of the anthropogenic signal in Northern Hemisphere regions

Supporting Information:
- Text S1, Table S1, and Figures S1–S4

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Abstract Climate scientists have demonstrated that a substantial fraction of the probability of numerous recent extreme events may be attributed to human-induced climate change. However, it is likely that for temperature extremes occurring over previous decades a fraction of their probability was attributable to anthropogenic influences. We identify the first record-breaking warm summers and years for which a discernible contribution can be attributed to human influence. We find a significant human contribution to the probability of record-breaking global temperature events as early as the 1930s. Since then, all the last 16 record-breaking hot years globally had an anthropogenic contribution to their probability of occurrence. Aerosol-induced cooling delays the timing of a significant human contribution to record-breaking events in some regions. Without human-induced climate change recent hot summers and years would be very unlikely to have occurred.

1. Introduction

The field of event attribution has expanded greatly in recent years as scientists attempt to answer whether specific high-impact extreme weather events have become more likely due to anthropogenic climate change. These results are then used as a communication tool for journalists and the media to convey the effects climate change is having (or not having) on the likelihood of extremes such as heat waves and hot spells [*Stott et al.*, 2004; *Christidis et al.*, 2015; *Perkins and Gibson*, 2015; *Min et al.*, 2014], cold spells [*Christidis et al.*, 2014], droughts [*King et al.*, 2014; *Williams et al.*, 2015], and heavy rain events [*Pall et al.*, 2011; *King et al.*, 2013; *Singh et al.*, 2014]. Evidence for the great interest in event attribution from scientists and the wider public may be seen in the dedicated special issues of the *Bulletin of the American Meteorological Society* to this topic [*Peterson et al.*, 2012, 2013; *Herring et al.*, 2014, 2015].

Despite the great interest in this broad topic, there has been no previous analysis examining when attribution statements to human influences could first be made. Many attribution studies of recent hot extremes find a dominant contribution of anthropogenic climate change to their probability of occurrence. For example, human-induced climate change increased the likelihood of the record hot Australian summer of 2012/2013 by at least five times [*Lewis and Karoly*, 2013] and the record warm Central England temperature of 2014 by at least 13 times [*King et al.*, 2015a]. Previous work has also highlighted that around three quarters of daily-scale hot extremes may be attributed to warming associated with anthropogenic climate change [*Fischer and Knutti*, 2015]. The emergence of a statistically significant anthropogenic signal in climate extremes has been detected [*King et al.*, 2015b], and in some places, for temperature indices, the emergence occurred decades ago. It might, therefore, be expected that previous record warm events may also be attributable to human-induced climate change.

2. Data and Methods

In this study we use the well-established fractional attributable risk (FAR) [*Allen*, 2003] framework to investigate the changing influence of anthropogenic forcings on record-breaking hot seasons and years for different regions around the world. The probability of record hot events is compared between climate model simulations with both natural and anthropogenic forcings and simulations forced by natural climate influences only. The methods used in this study largely follow those of *King et al.* [2015a], however, with a modification to the temperature adjustment applied to the natural-forcings ensemble (historicalNat) and the use of moving windows and an evolving threshold in FAR calculations as described here. In this study, we take moving 21 year windows of the all- and natural-forcings ensembles of climate model simulations (centered on the year of interest) and calculate the FAR at each year back to 1900 or as far back as the observational data extend. Thus, an attribution of the record hot summer of 1976 in Central England, for example, involves calculating the probability of hot summers in the all-forcings ensemble for 1966–1986 and the natural-forcings ensemble for 1966–1986. Only matching pairs of natural- and all-forcings simulations are used to calculate the FAR statistics. The threshold used is the previous hottest summer, so that the likelihood of exceeding that threshold with a new record may be calculated.

Temperature data from observation-based data sets were retrieved for the different regions of study. The observational data sets used were the Australian Water Availability Project (AWAP) for Australia [*Jones et al.*, 2009], the Central England Temperature (CET) series [*Parker et al.*, 1992], E-OBS (for Europe) [*Haylock et al.*, 2008], the Global Historical Climatology Network- Climate Anomaly Monitoring System (GHCN_CAMS) for U.S. [*Fan and van den Dool*, 2008], the Asian Precipitation- Highly Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) dataset for East Asia [*Yatagai et al.*, 2012], and the Goddard Institute for Space Studies temperature series (for the globe) [*Hansen et al.*, 2010]. The regions analyzed here were chosen due to the availability of quality-controlled observational data, the recent record-breaking warm events in each region, and the associated event attribution studies that have been performed in some of these areas.

Monthly temperature data from the fifth phase of the Coupled Model Intercomparison Project [CMIP5; *Taylor et al.*, 2012] were extracted for 17 climate models (Table S1 in the supporting information). These models have at least three historical simulations, one historicalNat simulation, and one high greenhouse gas emission Representative Concentration Pathway (RCP8.5) simulation available for analysis. The model and gridded observational data (i.e., all except the CET and global series) were regridded onto a common $2° \times 2°$ grid and masked before area averaging for the regions shown in Figure 1, and anomalies were calculated (with respect to the 1961–1990 climatology). The models were evaluated based on their ability to simulate historical climate by performing a Kolmogorov-Smirnov test comparison with observational data. The models that adequately captured the observed temperature variability (defined as no more than one third of the historical simulations being significantly ($p < 0.05$) different than the observational series) for a given region were selected for further analysis (supporting information Table S1). An adjustment was applied to the historicalNat simulations to account for changes in temperature prior to the climatological reference period of 1961–1990 (similar to *King et al.* [2015a]). The adjustment was calculated as

$$\Delta T = \left\{\overline{T_{\mathrm{HIst}(1861-1890)}} - \overline{T_{\mathrm{HIst}(1961-1990)}}\right\} - \left\{\overline{T_{\mathrm{HIstNat}(1861-1890)}} - \overline{T_{\mathrm{HIstNat}(1961-1990)}}\right\}$$

where $\overline{T_{\mathrm{HIst}(1861-1890)}}$ and $\overline{T_{\mathrm{HIst}(1961-1990)}}$ are the averages of the variable in the historical simulations for 1861–1890 and 1961–1990, respectively, and $\overline{T_{\mathrm{HIstNat}(1861-1890)}}$ and $\overline{T_{\mathrm{HIstNat}(1961-1990)}}$ are the averages of the variable in the historicalNat simulations for 1861–1890 and 1961–1990, respectively.

The FAR statistics are then calculated for hot temperature events above the previous record anomaly in 21 year moving windows of the natural-forcings (historicalNat) and all-forcings (historical and RCP8.5) ensembles. As many historicalNat simulations end in 2005, for FAR statistics calculated from 1995 onward the window of the natural-forcings ensemble is fixed at 1985–2005. Windows of 21 years were chosen as the use of shorter periods would reduce sample sizes and the use of longer periods would lead to larger changes in the anthropogenic forcing between the start and end of the windowed period in the all-forcings ensemble.

To account for sampling uncertainty, the 21 year moving natural- and all-forcings ensembles associated with each year were bootstrapped (with replacement) 10,000 times on 50% subsamples of complete model simulations. These 10,000 bootstrapped estimates were used to calculate 10th and 90th percentile FAR estimates.

Definitions of when an anthropogenic influence could be detected were chosen adapted from those used in previous studies [*King et al.*, 2015a]. A *significant* anthropogenic influence is detected if the 10th percentile FAR value is greater than zero (i.e., human-induced climate change has *very likely* increased the likelihood of record-breaking hot events). A *significant and substantial* anthropogenic influence is detected if the 10th percentile FAR is greater than 0.5 (i.e., human-induced climate change has very likely at least doubled the likelihood of record-breaking hot events). Similarly, anthropogenic influences can be said to have significantly reduced the likelihood of hot events if the 90th percentile FAR is below zero. This happens in the middle twentieth century in Central Europe and East Asia due to the effect of anthropogenic aerosols.

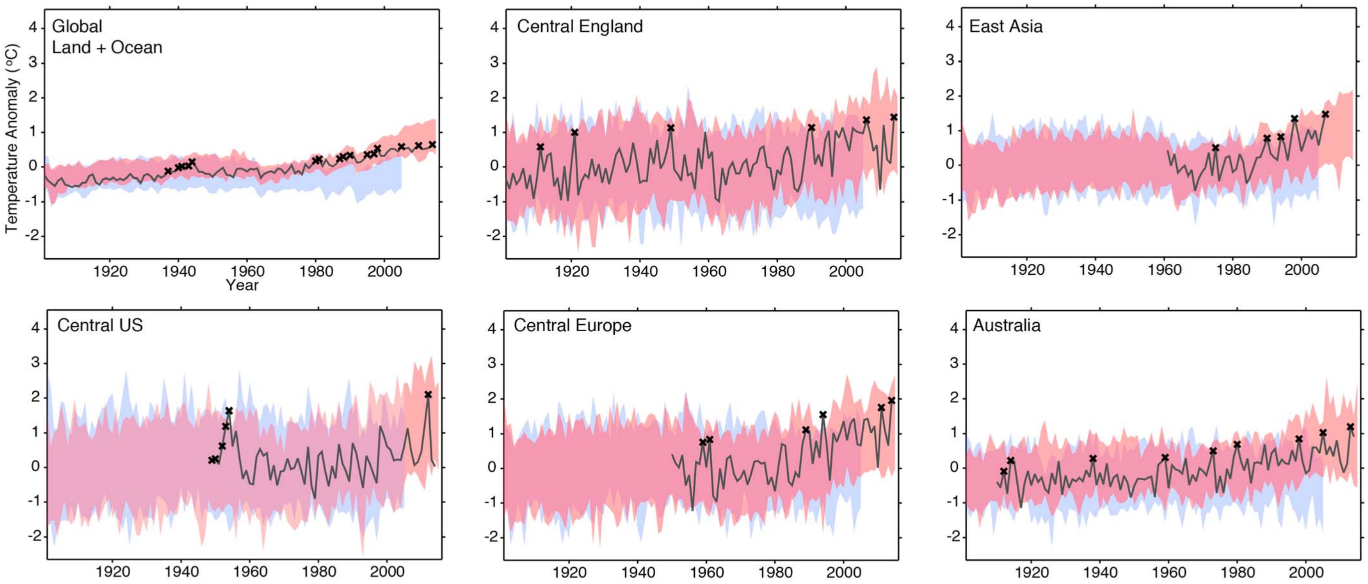

Figure 1. Modeled and observed annual temperature time series. Time series of observed (grey line), historicalNat ensemble (blue), and historical and RCP8.5 ensemble (orange) temperature anomalies for 1901–2015 (or shorter periods for some observational series) from the 1961–1990 climatology. Record-breaking years (excluding the first year in each time series) that are investigated here are marked with black crosses.

Sensitivity tests with regard to this choice of methodology were performed. The sensitivity of results to the use of fixed FAR thresholds and higher initial thresholds was tested. The results of these tests are discussed in the supporting information Text S1.

Using this adapted event attribution methodology, we answer the question of whether a discernible fraction of the probability of past extreme events can be attributed to anthropogenic influences. Of course, in many years and seasons that the FAR is calculated, no observed record-breaking extreme occurred. At those times the FAR represents the influence of human-induced climate change had an event exceeding the previous record occurred. We note that in this study, only statements on attribution to anthropogenic influences are made; in addition, each event is influenced by natural variability arising from climate modes such as the El Niño–Southern Oscillation.

3. Results

The six regions studied here show warming over the observational period with several hot records having occurred which are potentially attributable to anthropogenic climate change (Figure 1). The all-forcings simulations generally reproduce the observed warming trend, while the natural-forcings ensemble does not in recent years.

Time series of annual FAR values show large increases in the anthropogenic influence on record-breaking hot years for regions around the world (Figure 2). For time series representing larger regions of the world the imprint of an anthropogenic influence extends further back as interannual variability is reduced for larger spatial scales allowing the anthropogenic signal to appear earlier [*King et al*., 2015b]. All of the last 16 record hot years in the observed global series, starting as early as 1937, have a fraction of their probability of occurrence attributable to the anthropogenic influence on the climate. The globe experienced several record warm years in the late 1930s and early 1940s which might have been partially influenced by warm phases in both the Atlantic Multidecadal Oscillation and the Interdecadal Pacific oscillation.

Even at subcontinental scales, there is the emergence of an anthropogenic influence on hot years around the 1980s, although with large differences between regions. The evolving FAR threshold causes substantial shifts in the year-to-year FAR estimates in some cases. High uncertainties in some FAR series, such as the Central U.S., are related to there being few events above the FAR threshold in either the all- or natural-forcings ensembles. Thus, the selection of bootstrapped model simulations used to calculate the FAR estimate has a large influence in these cases. A notable feature in the Northern Hemisphere regions is the negative FAR

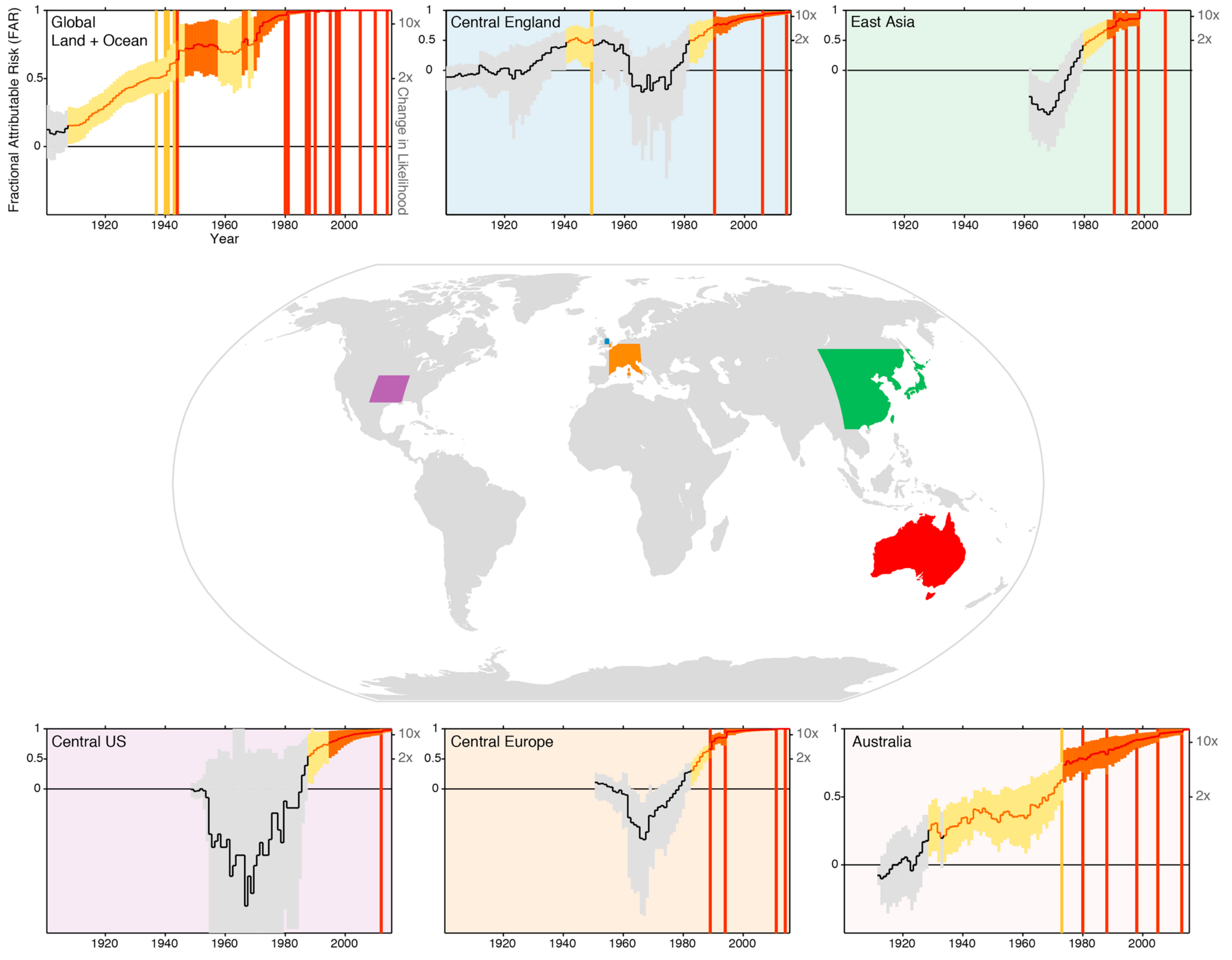

Figure 2. FAR time series of record-breaking hot years for the globe and five regions. The 10th to 90th percentile range of FAR estimates is shown with the best estimate FAR (bold line). The FAR estimates are shown in grey for years in which the 10th percentile FAR is below or equal to 0, in yellow for years in which the 10th percentile FAR is between 0 and 0.5, and in orange where the 10th percentile FAR is greater than 0.5. The orange and red vertical bars show years when the observed record could be attributed to anthropogenic influences. The corresponding changes in likelihood values are shown on the right axes. The background colors match the regions and their domains shown on the map. Note that in the Central U.S. series the full 10th–90th percentile range of FAR values is not shown in some years.

values seen in the middle twentieth century (and later in East Asia). This effect is related to anthropogenic aerosols [*Wild et al*., 2005] reducing the likelihood of hot years (supporting information Figure S1). The effect of anthropogenic greenhouse gases supersedes that of anthropogenic aerosols in later decades leading to an increase in the likelihood of hot years related to the total anthropogenic influence relative to natural-only forcings [*Min et al*., 2014]. In Australia, where the anthropogenic aerosol effect is weaker (supporting information Figures S1 and S2), the emergence of an anthropogenic influence, due to greenhouse gas emissions, is earlier. In every region studied here there are previous record hot years that can be attributed to human-induced climate change.

Time series of summertime FAR values (Figure 3; December-February for Australia and June-August for all other regions) show similar increases in the likelihood of record hot events due to anthropogenic influences. These time series bear broadly similar features to those seen in the annual FAR series. We find that many past record hot summers have a substantial fraction of their probability of occurrence attributable to anthropogenic climate change, including high profile events such as the 2003 hot European summer and the 2012/2013 record-breaking Australian summer. One exception is in Central England where the record hottest summer still dates

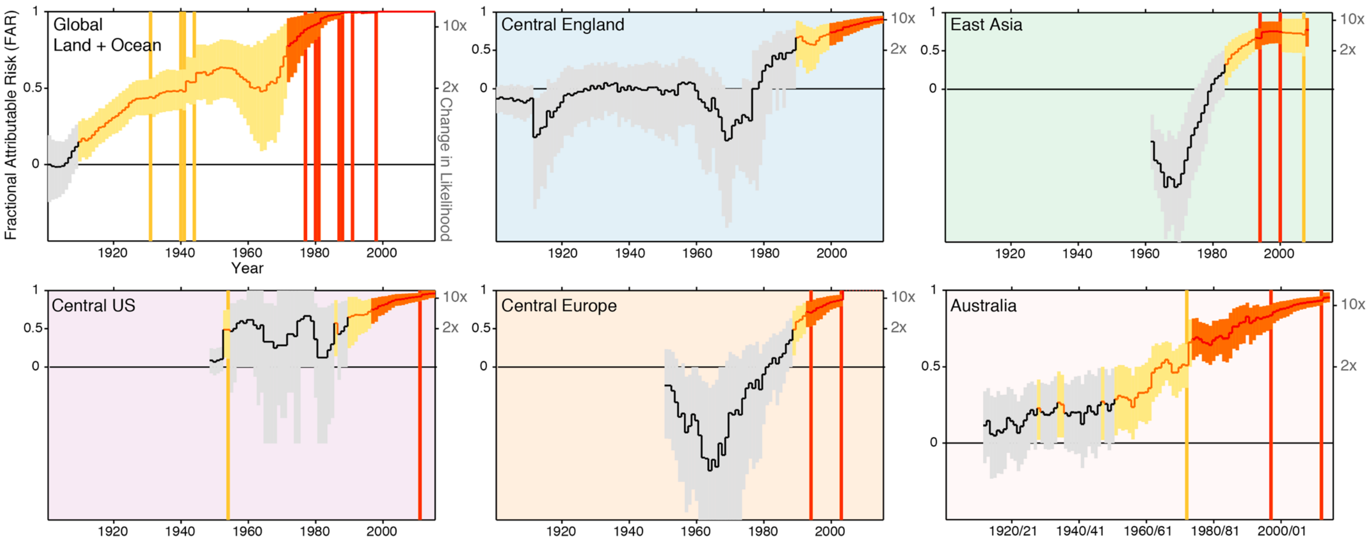

Figure 3. FAR time series of record-breaking hot summers for the globe and five regions. As Figure 2 but for June–August seasons for all regions, including the global series, except Australia where December–February values are shown.

back to 1976. Any hot summers that break this record in the future would have a significant and substantial fraction of occurrence attributable to anthropogenic climate change (assuming no significant decrease in the anthropogenic forcing on the climate). For many regions the FAR time series show a steady rise toward one in the recent period. However, in East Asian summers there is a plateauing in FAR values after the 2000 record. This is related to a higher threshold (i.e., the hot summer of 2000) causing slightly increased uncertainty in the FAR statistics after 2000. In contrast, Central Europe shows FAR values of one after the summer of 2003 which was such a strong record that the natural-forcings runs do not simulate summers as hot.

4. Discussion and Conclusions

Our findings are in agreement with those of previous event attribution studies. We find broadly similar FAR estimates for extreme events such as the record-breaking hot Australian summer of 2012/2013 [*Lewis and Karoly*, 2013] and the warm year in Central England in 2014 [*King et al.*, 2015a]. Differences between our results and those of other analyses are likely to be related to the choice of models, regridding techniques, region selection, and the period of analysis used. However, in addition to attributing recent extremes to climate change, this research highlights the role of climate change in previous extremes (e.g., the record-breaking hot summer of 1997/1998 in Australia) illustrating that the effect of climate change on extreme events extends back several decades. Our results also support recent findings of formal attribution studies which detected anthropogenic signals from the observed long-term increasing trends in the frequency and intensity of hot extremes on many land areas across the globe [*Morak et al.*, 2013; *Min et al.*, 2013; *Kim et al.*, 2015].

In this study we have shown that as well as recent climate extremes, many past record-breaking hot events are also attributable to anthropogenic climate change. This was done through adapting the commonly used FAR methodology in order to construct time series of FAR. This study was restricted to the globe as a whole and regions of the world with high-quality long observational time series of temperature. Also, we only considered hot temperature extremes on timescales of at least a month. This methodology may be extended to examine other climate indices and variables on differing timescales or to investigate high-impact extremes that were not record breaking.

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