LETTERS
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Rapid increase in the risk of extreme summer heat in Eastern China

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The summer of 2013 was the hottest on record in Eastern China. Severe extended heatwaves affected the most populous and economically developed part of China and caused substantial economic and societal impacts[1]. The estimated direct economic losses from the accompanying drought alone total 59 billion RMB (ref. 2). Summer (June–August) mean temperature in the region has increased by 0.82 °C since reliable observations were established in the 1950s, with the five hottest summers all occurring in the twenty-first century. It is challenging to attribute extreme events to causes[3-6]. Nevertheless, quantifying the causes of such extreme summer heat and projecting its future likelihood is necessary to develop climate adaptation strategies[7]. We estimate that anthropogenic influence has caused a more than 60-fold increase in the likelihood of the extreme warm 2013 summer since the early 1950s, and project that similarly hot summers will become even more frequent in the future, with fully 50% of summers being hotter than the 2013 summer in two decades even under the moderate RCP4.5 emissions scenario. Without adaptation to reduce vulnerability to the effects of extreme heat, this would imply a rapid increase in risks from extreme summer heat to Eastern China.

The 2013 summer was characterized by long-lasting and widespread heatwaves and severe drought in Eastern China, especially in the Yangtze River Valley (Supplementary Fig. 2); the average number of heatwave days (daily maximum temperature of 35 °C or more) was at a historical high of 31 days, more than twice the 1955–1984 long-term average, affecting over nine provinces with a population of more than half a billion[2]. Preliminary reports indicate impacts on human health, agriculture and energy demand for cooling[1], which is being used increasingly in China's rapidly growing urban areas. The five hottest summers in Eastern China's observed record over the past six decades have all occurred since 2000—in 2013, 2007, 2000, 2010 and 2011—with 2013 and 2007 summer temperatures being the hottest, at 1.1 °C and 1.0 °C above the 1955–1984 30-year average (Fig. 1). There is also a clear connection between summer heat and precipitation deficit; summer mean temperature and total precipitation are significantly negatively correlated at the local scale (Supplementary Fig. 3) and large negative precipitation anomalies are observed in the areas hit hardest by the 2013 summer heat (Supplementary Fig. 4). The recent frequent occurrence of hot summers and the unprecedented heat of the 2013 summer inevitably raises questions about whether and to what extent anthropogenic climate change has affected the intensity and frequency of occurrence of extremely hot summers in Eastern China and whether they will increase further in the future as anthropogenic climate influence continues to strengthen.

The observed warming of annual mean temperature and annual maximum and minimum daily temperatures in China has been attributed to anthropogenic influence at the national scale[8–10]. Past event attribution studies for the 2003 European heatwave[11] and the 2010 Russian heatwave[12,13] provide information on changes in the probability of similar events due to various causes. Here we specifically consider the most densely populated part of China, and we consider indicators of heatwave frequency as well as overall summer season heat. We attempt to put the extreme summer heat of 2013 into its historical perspective, and use it as a benchmark for projected future summer temperature changes to help local, regional and national policymakers understand the projections and thus increase their relevance to planning needs. Because higher summer temperatures are directly connected to a greater number of heatwave days (Fig. 1), and an earlier start and later end of heatwave seasons (Supplementary Fig. 5), we first investigate whether the long-term change in Eastern China summer temperature is attributable to anthropogenic and/or natural drivers of the climate system. We then estimate how the likelihood of a summer as warm as the 2013 summer has changed as a result of this anthropogenic interference on the climate system, and project how it will change in the future under the representative concentration pathways (RCP) emission scenarios[14].

We focus on Eastern China, which is defined as a rectangular box bounded by 105°–125° E and 20°–45° N (Supplementary Fig. 1). The region is often referred to as the East Asian summer monsoon region and has been widely considered in monsoon studies[15,16]; it also has the greatest population density and densest observational network in China. The regional average temperature evolution is well simulated by the multi-model ensemble mean from climate models participating in the Coupled Model Intercomparison Project Phase 5 (ref. 17; CMIP5, Supplementary Table 1) when they account for the combined effect of anthropogenic and natural forcing (ALL, Fig. 2), whereas warming in the region since the mid-1980s is not reproduced by the models when they account only for external natural forcing from volcanic activity and changes in solar output (NAT, Fig. 2).

We compare observed and simulated 5-year mean regional average summer temperatures by regressing the observed time series onto the signals for ALL and NAT for the period 1955–2012, first with separate regressions for each signal (one-signal analyses) and then jointly in a regression involving both signals (two-signal analysis). See Methods for details. In these analyses, we assume that the models produce the correct response patterns, but allow for the possibility that their amplitudes might differ between models and observations. The regression procedure thus

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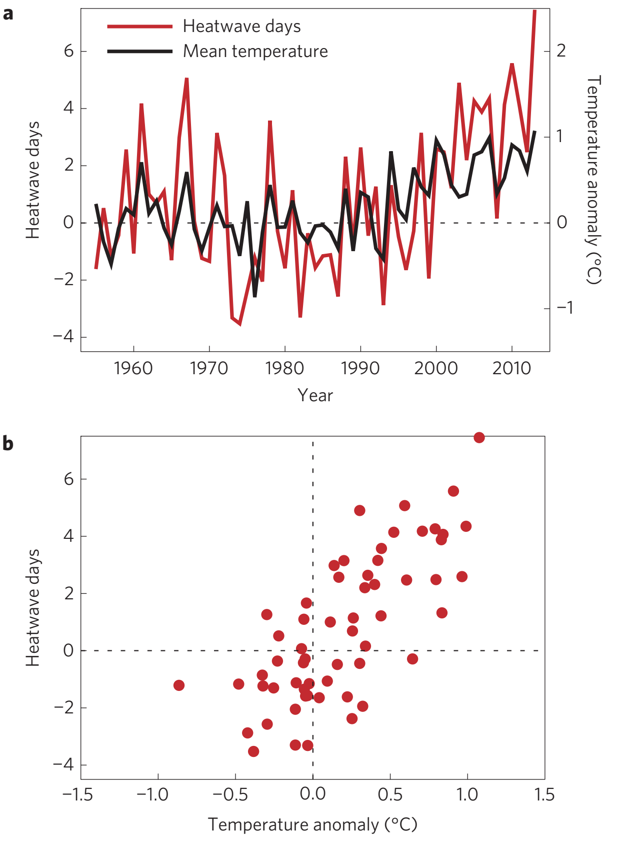

Figure 1 | Relationship between the number of heatwave days and summer mean temperature. a, Time series of the number of summer season (June–August) heatwave days and mean temperature anomalies relative to the 1955–1984 average. The correlation coefficient between the two series is 0.74. **b**, Scatter plot of heatwave days and summer temperature anomalies. A day is considered a heatwave day if the daily maximum temperature is 35 °C or above.

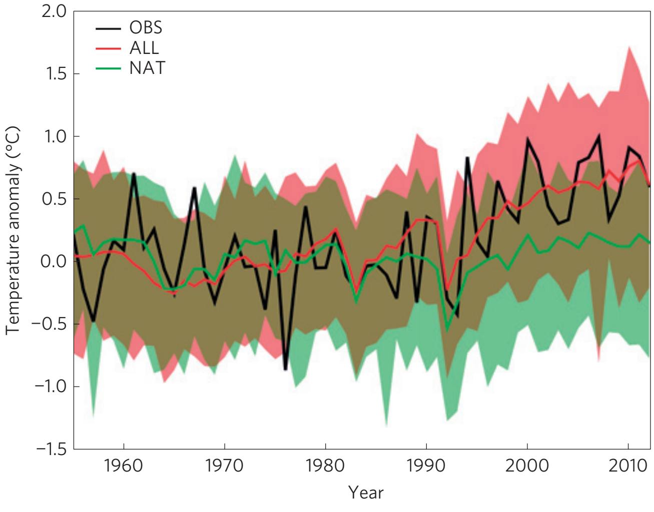

Figure 2 | Observed and simulated mean temperature in Eastern China. Eastern China annual June–August mean temperature anomalies for 1955–2012 relative to the 1955–1984 average. Black, red and green lines show the observed temperature, multi-model response to ALL and NAT forcing, respectively. The shading displays the 5–95% ranges of the ALL and NAT response in individual simulations. Data for the response to ALL forcing for 2006–2012 are extended using RCP4.5 simulations. Model simulations are listed in Supplementary Table 1.

estimates the amount (the scaling factor) by which the amplitude of the model-simulated responses to forcing must be altered to best match observed changes. By using two signals simultaneously in the regression it may be possible to separate the influences of individual combinations of forcings, such as anthropogenic and natural forcings, thereby improving confidence in the detection and attribution results. The residual consistency test[18] suggests no evidence of inconsistency between the regression residuals and the model-simulated variability in the 5-year mean series for the one- and two-signal analyses for ALL, but the one-signal analysis for NAT fails this test. The scaling factor for ALL is 0.93 (90% confidence interval 0.66–1.23, Fig. 3). The one-signal analyses confirm qualitative conclusions from Fig. 2 that the observed temperature change is consistent with the model-simulated response to ALL forcing, but it is not consistent with natural variability of the climate system or the response to NAT forcing alone. The two-signal analysis (Fig. 3) indicates that the effect of ANT (difference between ALL and NAT) is consistent with observed change and that the NAT signal is detectable with a *p*-value slightly smaller than 90%. As NAT forcing does not have a discernible long-term warming trend (Fig. 2), the observed summer temperature increase is mainly attributable to anthropogenic forcing.

We adjust observed summer regional mean temperatures to remove the best estimate of the attributed response to ALL forcing, the multi-model ensemble mean of ALL simulations multiplied by the scaling factor determined from the one-signal ALL forcing analysis, from the observations. We find that the 2013 summer is not amongst the hottest adjusted summer temperatures, which occur in 1994, 1967, 1961, 2000 and 2007, and are more evenly distributed in time (Supplementary Fig. 6). This, together with the attributable ALL-forced warming of 0.82 °C (90% confidence interval 0.57–1.07 °C, Fig. 3) clearly indicates that human activities have exacerbated summer heat in Eastern China in recent decades.

Now we estimate the frequency of extremely hot summers such as 2013 in the natural unperturbed climate system and in a world influenced by human-induced greenhouse gas increases. To this end, we require an estimate of the natural variability of summer temperature. The standard deviation of the adjusted (ALL-removed) series for 1955–2013 is 0.31 °C, whereas the mean value of standard deviations computed from 308 59-year series extracted from pre-industrial control simulations is 0.36 °C (5th and 95th percentiles 0.26 °C and 0.50 °C, respectively). Thus the multi-model consensus reproduces well the observed internal natural variability of the climate in the region. We therefore produce 308 plausible realizations of the 1955–2013 regional mean temperature evolution (referred to as reconstructed observations) by adding the best estimate of response to ALL forcing to the available control simulations. We find that the mean value of the standard deviations of the reconstructed observations is 0.50 °C (5th and 95th percentiles 0.39 °C and 0.63 °C, respectively), which is fully consistent with the standard deviation of 0.47 °C of the unadjusted observations.

The 1.1 °C 2013 summer temperature anomaly lies 3.5 standard deviations (of the adjusted temperature series) above the 1955–1984 mean. The best estimate of response to ALL forcing is 0.82 °C above the 1955–1984 climatology by 2013, which means that anthropogenic forcing may have increased the mean state of summer temperature by 2.6 standard deviations. Thus the record high 2013 summer temperature is only about 0.9 standard deviations above the climatology that is estimated to be appropriate for 2013 based on the influence of external forcing. This increase in the mean state combined with relatively small summer temperature variability in Eastern China has a strong impact on the likelihood of extreme summer heat occurrence. The percentages of years with

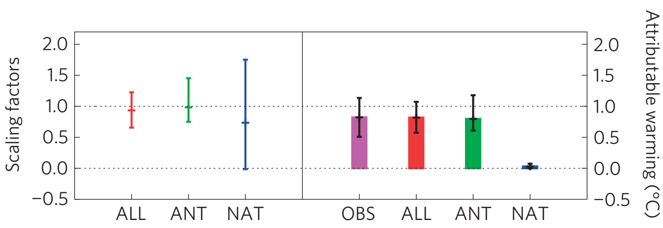

Figure 3 | Scaling factors and attributable warming. Best estimates of the scaling factors and their 5–95% uncertainty ranges (left) and corresponding attributable warming and their 5–95% uncertainty ranges (right) from one-signal (ALL) and two-signal analyses (ANT and NAT) of Eastern China 5-year mean summer (June–August) temperatures for 1955–2012. In the one-signal analysis, the observed temperature is regressed onto the multi-model mean responses to ALL forcing. In the two-signal analyses, the observed temperature is regressed onto the multi-model mean temperature response to NAT and ANT (difference between responses to ALL and NAT from available simulations) simultaneously. Attributable warming is estimated as the linear least-square trends of the relevant time series multiplied by corresponding scaling factors. OBS represents the linear least-square estimate of the trend from the observation for 1955–2012.

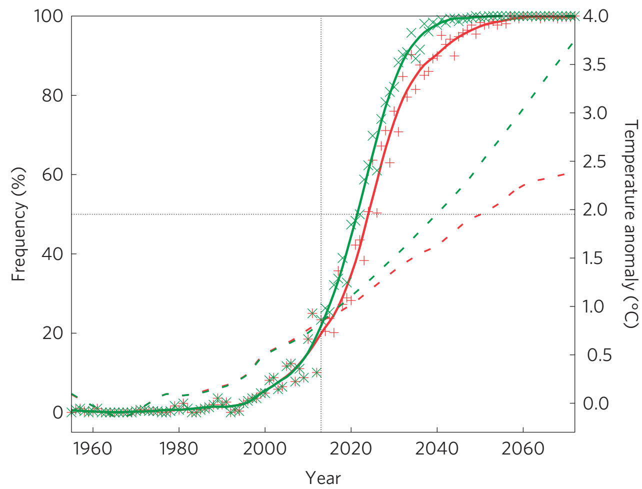

Figure 4 | Frequency of extreme hot summer recurrence. Time evolution of the frequency of summer temperature anomalies above 1.1 °C, relative to the 1955–1984 mean, in the reconstructed observations (1955–2013) and in the observationally constrained projections (2014–2072) under RCP4.5 (plus) and RCP8.5 (cross) emission scenarios (left-hand scale). The solid smooth curves are LOESS (local regression) fitting. The dashed curves represent projected ensemble mean temperature changes under the relevant emission scenarios (right-hand scale) and are shown here for reference. Results for RCP4.5 and RCP8.5 are represented by red and green, respectively.

temperature anomalies at or above 1.1 °C in the control simulations and in the reconstructed observations averaged over the 59-year period are 0.37% and 3.48%, respectively. The corresponding 90% confidence intervals are estimated to be 0.29%–0.44% and 1.51%–6.90%, respectively (Supplementary Information). We estimate therefore that the observed record high 2013 summer temperature would be roughly a once-in-270-year event (90% confidence interval 227–344 years) in the unperturbed world and that it was a once-in-29-year event (90% confidence interval 15–66 years) averaged over the 59-year observed record for 1955–2013. However, the background climate appropriate to 2013 is very likely warmer than the average for 1955–2013; thus, as we discuss next, the current expected waiting time between extreme heat events such as that of summer 2013 is much less than 29 years. We extend the reconstructed observations to the future by adding observationally constrained future projections[19] to pre-industrial control simulations where the constraint is imposed by multiplying the multi-model mean responses under the RCP4.5 and RCP8.5 emission scenarios with the anthropogenic forcings response scaling factor obtained from our two-signal analyses. In doing so, we assume no changes in future interannual variability, and that the scaling factor based on historical observations and the historical combination of anthropogenic forcings remains appropriate for future combinations of anthropogenic forcings, in which aerosols are a less important factor. The result shows a very grim future for the region in terms of the frequency of hot summers such as that of 2013. We count the number of times temperature anomalies exceed 1.1 °C within the 308 reconstructed observations or future projections in individual years from 1955 to 2072 and find rapid increases in event frequency (Fig. 4). Event frequency is about 23% (90% confidence interval 8%–49%) for year 2013, corresponding to an expected event recurrence time in 2013 of 4.3 years (90% confidence interval 2.0–12.5 years), a more than 60-fold increase from the natural state of the climate. This frequency increases to 50% by 2022 under RCP8.5 and by 2024 under RCP4.5. We also examined the frequency for the five hottest summers occurring in any given period of 13 or fewer consecutive years over a 59-year period in the control simulations and in the reconstructed observations. We find that the probability of a clustering of the five hottest years within a 13-year period or less is only 2.0% in the control simulation, whereas it reaches 32% in the reconstructed observations, with most of the occurrences near the end of series due to the strong human-induced warming trend. This is a 16-fold increase.

Urbanization associated with rapid economic development is known to have enhanced the Chinese temperature trend[20–22]. This effect may have contributed approximately 0.2 °C to the summer temperature warming in Eastern China (Supplementary Figs 7 and 8). Removing this effect from the observations and repeating the above analyses reduces the best estimate of attributable warming to anthropogenic forcing to 0.62 °C (Supplementary Fig. 9). The combined effect of urbanization and anthropogenic influence to the climate system is estimated to have a similar impact on the recurrence of 2013-like summer heat in the past and the projected future (Supplementary Fig. 10).

Our results indicate that the increasing frequency of extreme summer heat in Eastern China is primarily attributable to the anthropogenic emission of greenhouse gases, with rapid urbanization leading to the expansion of urban heat islands contributing as a secondary factor. Human influence has produced a very large increase in the probability of clustering of extremely hot summers in the twenty-first century and of long-lasting severe heatwaves such as that of 2013. Extreme summer heat at the magnitude experienced in 2013 is not a rare event when considered relative to the climate appropriate to 2013; heat of this magnitude is estimated to be a once-in-29-year event averaged over the 1955–2013 climates, with a much lower frequency of occurrence at the beginning of the period, rising to a once-in-4.3-year event in 2013. In contrast, such an event is estimated to have been a once-in-270-year event under pre-industrial conditions. Given the warming to which we are already committed[23], such summer heat is projected to become much more frequent in the near future, regardless of future emission scenarios even assuming, as we have done, that further urban development will not contribute additionally to projected temperature changes from external forcing on the climate system. It is projected that, by 2024, at least 50% of summers will be as hot as the 2013 summer. The increase in summer heat would inevitably lead to more widespread, long-lasting and severe heatwaves in the region. The increase in summer heat, combined with the region's rising population and wealth, would produce higher risks for human health, agricultural systems and energy production and distribution systems if sufficient adaptation measures are not in place.

Methods

We quantify the consistency between observed and model-simulated temperature changes using an optimal fingerprint method[24,25]. This method expresses the observations ($\mathbf{y}$) as a sum of scaled responses or 'fingerprints' ($\mathbf{X}$) estimated from forced GCM simulations plus internal variability ($\boldsymbol{\varepsilon}$): $\mathbf{y}=\mathbf{Xb}+\boldsymbol{\varepsilon}$. We regress the observations onto the multi-model mean ALL and NAT responses separately to identify observed responses to individual forcing factors ('one-signal analysis'). To examine the relative contribution of natural and anthropogenic forcings to the observed changes, we also conducted 'two-signal analysis' by regressing observations onto the ALL–NAT and NAT responses simultaneously. These regressions scale the model-simulated fingerprints to best fit the observations. The scaling factors $\mathbf{b}$ were estimated using the total least-squares method[18]. Detection is claimed if the 90% confidence interval of the scaling factor lies above zero, and attribution is supported by the analysis if this confidence interval also includes one. The observations and model-simulated responses are centred to the 1955–1984 climatology appropriate to the data source before the regression analyses.

The regression was conducted over 1955–2012 for one-signal ALL or NAT analysis and for two-signal ALL–NAT and NAT analysis on non-overlapping 5-year averages, with the last 5-year average represented by the mean values from 2010–2012. Model simulations under ALL forcing end in 2005 for many models. Model simulations under the RCP 4.5 emission scenario are used to extend the historical period ALL simulations for 2006–2012. We use NAT simulations by eight GCMs for the period 1955–2012. Temperature responses to external forcing over Eastern China are spatially homogeneous; thus we use the regional average to increase signal to noise ratio. Averaging over 5-year periods reduces variability in the observations and noise in the signal data. We use the period 1955–2013 to estimate the frequency of recurrence for 2013-like summer temperatures in the observed record.

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Author contributions

X.Z. and Y.S. designed the analysis. H.W., Y.S., T.H. and H.Y. conducted the analysis. Y.S. and X.Z. wrote the initial draft. F.W.Z. and L.S. helped with the analysis and edited the manuscript. G.R. identified the rural stations for the estimation of urbanization effects in temperature and helped in the analysis and interpretation of urbanization effects.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to X.Z.

Competing financial interests

The authors declare no competing financial interests.