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LETTER

Anthropogenic influences on 2022-like summer heatwaves over the Yangtze River valley and projected changes in the likelihood of the event

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Abstract

During summer 2022, a record-breaking heatwave occurred in China over the Sichuan Basin to the middle and lower reaches of the Yangtze River valley. Observational analysis shows that this heatwave event peaks around 17th August, with an anomaly of 10 day running mean Tmax anomalies (TXa10day) being equal to 4.15 °C, which is 4 times the interannual standard deviation. This event is too rare in both observations and model simulations during the historical period 1961–2022 to make robust attribution statements. Therefore, we focus on a 2022-like summer heatwave event, defined as a 1-in-100-year event with a TXa10day anomaly of 3.19 °C based on observations during 1961–2022. Based on the multi-model ensembles of the sixth Coupled Model Intercomparison Project (CMIP6), we find that anthropogenic forcings lead to an increased likelihood of a 2022-like summer heatwave event by about 3 times in the present climate (2018–2027), with greenhouse gas forcing enhancing the likelihood of this event and aerosol forcing reducing the likelihood of this event. This increase in likelihood corresponds to a change of return period from 1-in-53-year event under natural forcing to 1-in-17-year event under all forcing in the present climate. Climate model projections show that a 2022-like summer heatwave event will become more frequent in a warmer climate with the likelihood of such event increasing exponentially with increasing global warming level (GWL). Such an extreme event will become a 1-in-8.4-year, 1-in-5-year, 1-in-2-year and 1-in-1.3-year event under the SSP5-8.5 at the 1.5 °C, 2 °C, 3 °C and 4 °C GWLs compared with the present climate. These results suggest that China would face a challenge to take adaptation measures to cope with the projected frequency increase of the 2022-like summer heatwave.

1. Introduction

During summer 2022, China was affected by an unprecedentedly long and intense heatwave (Hua *et al* 2023, Ma and Yuan 2023, Tang *et al* 2023, Yin *et al* 2023). By the end of August, 23 provinces had experienced temperature over 40 °C and the daily maximum temperature (Tmax) equaled or exceeded their historical record at 366 national meteorological station, especially over the Yangtze River valley (Lu *et al* 2023). The intensity of this regional heatwave was the strongest since 1961. As reported by the Ministry of Emergency Management, the heatwave reached its peak in August 2022, affecting approximately 4.284 million hectares of crops and leaving 4.49 million people in need of subsistence assistance.

Previous studies have demonstrated that anthropogenic forcings, which include greenhouse gas, aerosols and land cover produced by human activities, have increased the frequency of the most extreme heatwaves around the world (e.g. Otto *et al* 2012, Horton *et al* 2015, Chen *et al* 2019, Ma *et al* 2020, Ren *et al* 2020, Feng *et al* 2025, Liang *et al* 2025). By using simulations from the Grid-point Atmospheric Model of the IAP LASG version 3 (GAMIL3), Zhang *et al* (2023a) found that the anthropogenic forcings increased the probability of Yangtze River heatwave in 2022 by ~11.1 times compared to natural forcing. Wang *et al* (2024) investigated a 2022-like heatwave using a reconstructed temperature time-series, and found that the occurrence probability increased by ~62.0 times due to human influences. Under present-day greenhouse gas forcing, heatwave events that were historically rare would occur more frequently (Cowan *et al* 2020). Considering the relative roles of greenhouse gas forcing and aerosol forcing on a 2022-like heatwave event, Liang *et al* (2024) found that the greenhouse gases increased the probability of the event by about 10 times under the past 30 years and that aerosols suppressed the occurrence of this event based on CMIP6. However, the simulations they used only included data up to 2020, which limits the ability to assess the 2022 heatwave event, and the results of human influence are based on the historical period. Thus, in this study, we extend time periods of the all forcing simulations and single anthropogenic forcing simulations with the SSP2-4.5 experiment, allowing for a more consistent and robust investigation of a 2022-like summer heatwave event under different anthropogenic forcings in the present climate.

Due to the continuing influence of global warming, warm extremes are also expected to become more frequent over China in the future (Sun *et al* 2014, Sun *et al* 2018, Hu and Sun 2020, Chen and Dong 2021, Wang and Yan 2021). Wang *et al* (2024) found that the 2022-like extreme heatwave event over the middle and lower reaches of the Yangtze River is projected to occur almost every 2 years by the 2050s under the SSP5-8.5 or by the 2070s under the SSP2-4.5. The 2022 summer heatwave in the middle reaches of the Yangtze River could occur every 8.5 years by 2070–2100 under the SSP3-7.0 (Hua *et al* 2023). In recent years, due to the goal set in the Paris Agreement (UNFCCC 2015), future projections based on target global warming levels (GWLs) have been more frequently used to communicate the impact of climate change. For example, Sun *et al* (2018) projected that heatwave events with Tmax above 35 °C in China (with return periods of 5, 10 and 50 years in the current climate (1995–2004)) will increase by 2.5, 3.5 and 5.5 times at the 1.5 °C GWL. However, an assessment of how the probabilities of a 2022-like summer heatwave change at different GWLs is still lacking. Moreover, as shown by Raftery *et al* (2017), the likely range of global mean surface temperature (GMST) increase is 2.0 °C–4.9 °C with a median of 3.2 °C by the end of the 21st century. Therefore, in order to provide comprehensive risk information to aid decision-making and strategic planning for the region, it is essential to quantify the changing risks associated with a 2022-like summer heatwave at 1.5 °C, 2 °C, 3 °C and 4 °C GWLs.

The CMIP6 models demonstrate overall improvements in simulating the statistical characteristics and spatial-temporal patterns of the observed temperature extremes in China compared with the previous phase (Chen *et al* 2020). Thus, this study uses observations and the multi-model ensemble from CMIP6, and is structured as follows: section 2 describes the data and methods used in this study. Section 3.1 shows the observed characteristics of the unprecedented 2022 summer heatwave in China and the associated physical processes. Section 3.2 illustrates the roles of anthropogenic forcings on the probability of the 2022-like summer heatwave event and discusses the role of individual anthropogenic forcings. The future changes of the 2022-like summer heat event at different GWLs are discussed in section 3.3 and the conclusions are summarized in section 4.

2. Data and methods

2.1. Data

The ERA5 reanalysis dataset is used for summers of 1961–2022 with a resolution of $0.5° \times 0.5°$ (Hersbach *et al* 2020). Xu *et al* (2022) demonstrated that the observed daily temperatures over China (mean temperature, maximum temperature and minimum temperature) is well reproduced by ERA5 reanalysis, especially during summer. Here we examine the performance of ERA5 by comparing it to the daily gridded CN05.2 temperature dataset during 1961–2020 which is derived from the National Meteorological Information Center of China through *in situ* observations at >2,400 stations over China, with a half degree horizontal resolution (Yu *et al* 2023). We find that ERA5 represents the spatial pattern of summer climatology and the extreme value (90th percentile) distribution of temperature during 1961–2020 with a high pattern correlation coefficient of 0.97 for both variables (Supplementary figure S1). The linear trend and interannual variability of Tmax anomalies during 1961–2020 are also captured by ERA5. Therefore, the Tmax and atmospheric circulation field data obtained from the ERA5 reanalysis dataset is suitable to analyze extreme events like 2022 heatwave.

The Climate Model Intercomparison Project (CMIP), the Detection and Attribution Model Intercomparison Project (DAMIP) and the Scenario Model Intercomparison Project (ScenarioMIP) from CMIP6 are used in this study (Eyring *et al* 2016, Gillett *et al* 2016). To analyze the influence of anthropogenic forcings on the likelihood of a 2022-like summer heatwave event, a 10 year window of 2018–2027 is selected to represent 2022. According to the time period simulated by each experiment (shown in Supplementary table S1), to discuss the 2022 all-forcing simulations (hist-ALL), we use the simulations over the period of 2018–2027 from the

SSP2-4.5 experiment in ScenarioMIP. For the 2022 natural-forcing simulations, we combine the simulations over the period of 2018–2020 from the hist-NAT experiment and the simulations over the period of 2021–2027 from the ssp245-NAT experiment in DAMIP. The all-forcing simulations are forced by both anthropogenic forcings (well-mixed greenhouse gases, anthropogenic aerosols, ozone, and land use change) and natural forcing (volcanic and solar activities), while the natural-forcing simulations are driven by natural external forcings alone (Gillett *et al* 2016). In order to analyze the relative roles of greenhouse gas forcing and aerosol forcing, the 10-year simulations are also selected from the hist-GHG and ssp245-GHG experiments and the hist-AER and ssp245-AER experiments in DAMIP. The greenhouse gas-forcing simulations are forced by only changes in well-mixed greenhouse gas changes and the aerosol-forcing results are forced by only changes in aerosol forcing (Gillett *et al* 2016).

To analyze the changes in future risk, we use future projections from ScenarioMIP over the period of 2015–2100. Specifically, we use scenario SSP3-7.0, which reaches a radiative forcing of 7.0 $W \cdot m^{-2}$ in 2100 with particularly high aerosol emissions, and SSP5-8.5, which represents the highest forcing pathway with a radiative forcing of 8.5 $W \cdot m^{-2}$ in 2100 (O'Neill *et al* 2016). Bilinear interpolation is used to regrid the model data to a common $1.5° \times 1.5°$ grid in order to facilitate model intercomparison. Considering the data availability, model performance and sufficient sample size, multi-ensemble simulations from 10 models are used (see Supplementary table S1). Before using the models to address the changes in likelihood of a 2022-like heatwave, we evaluated the performance of these models on simulating summer mean Tmax climatology over the study region during 1961–2022. Supplementary figure S2 shows that all models exhibit high pattern correlations with observation and are very close to the reference point which corresponds to the observational dataset, indicating that all models reproduce the observed spatial variations of summer mean Tmax over the study region.

Anthropogenic aerosol forcing plays a critical role in driving climate change over Asia. The simulation of aerosol-radiation and aerosol-cloud interactions in climate models is essential for understanding regional climate change and improving future climate projection (Wang *et al* 2021). To evaluate aerosol property in model simulations over the study region, Supplementary figure S3 shows the variations of aerosol optical depth at 550nm (AOD) in models and the MERRA-2 reanalysis (Randles *et al* 2017). To make the multi-model mean of simulations, the multi-ensemble mean is first calculated for each individual model and then the multi-model mean is computed as the mean of all models ensemble-means. Figure S3 shows that the time evolutions of AOD in CMIP6 model historical simulations are similar to those in the MERRA-2 reanalysis with a correlation coefficient of 0.87. The climatological spatial patterns over the study region between MERRA-2 and model also show high correlation with a value of 0.81. Therefore, despite biases in magnitude of AOD, the time evolution and spatial patterns of AOD exhibit good agreement between model simulations and MERRA-2, which indicates that the simulated aerosol impact is suitable for analyzing the local climate in this study.

2.2. Methods

2.2.1. Definition of the extreme index

This study focuses on regions from the Sichuan Basin to the middle and lower reaches of the Yangtze River valley (28~34°N, 102.5~121.5°E, black box in figure 1(a)). Considering the spatial extent and the magnitude of the temperature anomalies during summer 2022, an index showing the largest 10-day running mean Tmax anomalies in each summer (June-July-August) (TXa10day) is computed. Firstly, in order to remove the impact of the seasonal cycle on event selection, the daily Tmax anomalies relative to the daily 1961–1990 climatology are calculated for each calendar day and at each grid box (Peterson *et al* 2012). Then, the gridded Tmax anomalies are area-averaged over the study region. Finally, the 10-day running mean area-averaged Tmax anomalies are calculated and the hottest value in summer is chosen to be the TXa10day for each year. Furthermore, the TXa10day can be computed for each gridbox by using the above method (e.g., without making the area-average). If the TXa10day in 2022 in any given grid box is the largest since 1961, that grid box will be defined as a record-breaking grid box. To avoid systematic differences between the simulated and observed TXa10day index, the TXa10day values for observations model simulations are recomputed as the anomaly relative to the corresponding 1961–1990 climatologies.

The probability density functions (PDF) of TXa10day for each experiment is estimated using generalized extreme value (GEV) distribution (Ailliot *et al* 2011). The exceedance probability for the 2022-like summer heatwave event is estimated from GEV fitted PDFs for various experiments. All simulated years during the relevant time window are used to estimate the GEV distribution (e.g., for hist-ALL: 37 members x 10 years = 370 samples). The years used for each different experiment are shown in Supplementary table S1. The probability ratio (PR) in hist-ALL relative to hist-NAT is calculated to quantify the changing likelihood of a 2022-like summer heatwave event due to anthropogenic influences (Coles 2001, Allen 2003). The PR in future projections is calculated relative to hist-ALL to assess the likelihood changes relative to the present climate (2018–2027). The 95% confidence interval (95% CI) for both probability and PR are estimated by

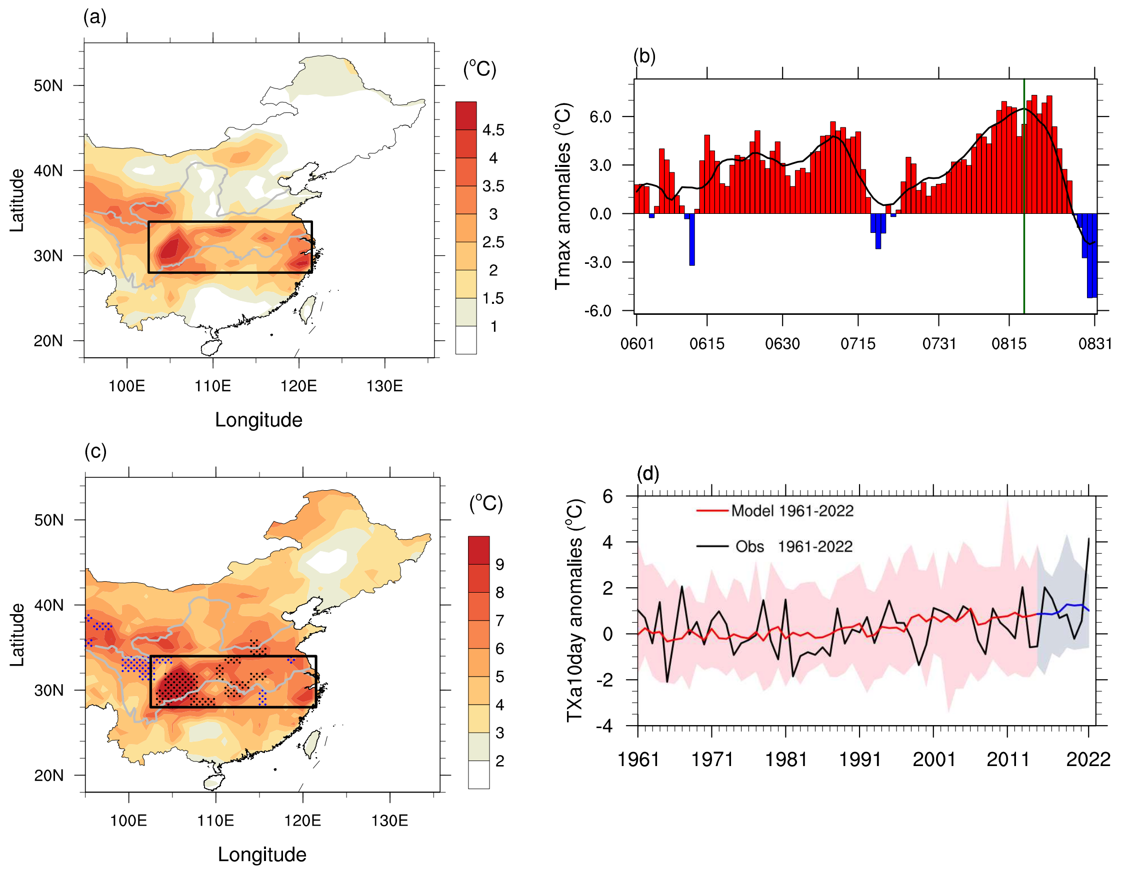

Figure 1. (a) Spatial distribution of summer mean Tmax anomalies (°C) in 2022 relative to 1961–1990 in observations. The black box represents the study region. (b) Time series of the observed daily Tmax anomalies and its 10-day running mean (black line, °C) area averaged over the study region during the 2022 summer. Red (blue) bars denote positive (negative) Tmax anomalies relative to the baseline period. The vertical green line represents the date when the TXa10day occurs in summer 2022. (c) Spatial distribution of the observed TXa10day (°C) in summer 2022. The black dotted regions are record-breaking areas and the blue dotted regions are the areas where the TXa10day of summer 2022 is the second largest since 1961. (d) Time series of regional averaged TXa10day anomalies (°C) relative to the climatology of TXa10day during 1961–1990 over the study region. The black line is observations during 1961–2022. The red line is multi-model ensemble mean based on historical simulation during 1961–2014 and the blue line is multi-model ensemble mean based on SSP2-4.5 during 2015–2022. The red and blue shaded is the maximum and minimum ranges of simulated TXa10day anomalies based on all model members.

bootstrapping 1000 resamples of model ensemble members to determine the empirical 2.5th and 97.5th percentiles (Peterson *et al* 2012); The detailed method is shown in Supplementary Method.

2.2.2. Time windows of the 1.5 °C, 2 °C, 3 °C and 4 °C global warming levels

In accordance with the IPCC AR6 report (Lee *et al* 2021), the GWLs are defined as the time periods when the GMST has warmed by 1.5 °C, 2 °C, 3 °C and 4 °C relative to the pre-industrial period (1850–1900). To avoid the threshold being crossed due to interannual variability, a 20-year running average is used to smooth the GMST time series (Liu *et al* 2020). When a specific GWL is reached, we define the associated period as the 20-year window which has 10 years before and 9 years after the year that exceeds these four global warming thresholds (Zhang *et al* 2023b). Thus, each model member has its own individual GWL time-period (Supplementary table S2 & S3). All members reach 3 °C GWL under the two scenarios (not shown), and all members reach 4 °C under the SSP5-8.5. However, only 19 members (7 models) reach this warming level under the SSP3-7.0.

3. Results

3.1. Observed characteristics of the 2022 summer heatwave event

Figures 1(a) and (c) show the spatial patterns of the summer mean Tmax anomalies and TXa10day during summer 2022, respectively. It can be seen that the TXa10day over the study region is much larger than the other regions with many record-breaking grid boxes. Large TXa10day values are also collocated with large seasonal mean Tmax anomalies (e.g., compare figures 1(a) and (c)). By taking the regional average, the TXa10day during

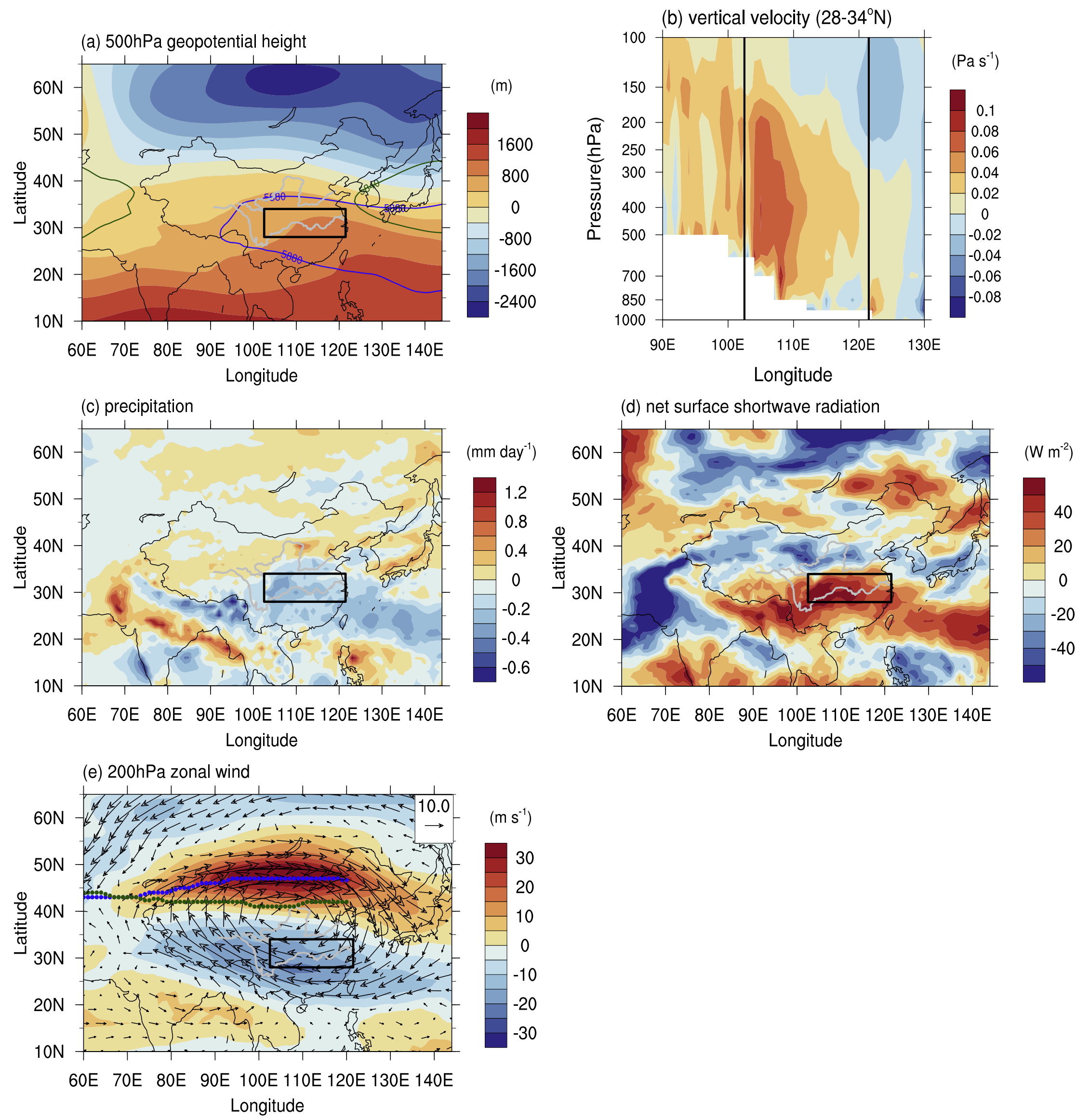

Figure 2. Spatial distributions of (a) 500-hPa geopotential height anomalies (m), (b) vertical velocity anomalies (Pa•s^{-1}) averaged over 28~34°N, (c) precipitation anomalies (mm•day^{-1}), (d) net surface shortwave radiation anomalies (W•m^{-2}) and (e) 200-hPa zonal wind anomalies and 200-hPa wind anomalies vector (m•s^{-1}) during 13th–22nd August relative to the climatology of 13th–22nd August during 1961–1990 based on ERA5. The blue line and green line in (a) represent the location of the western Pacific subtropical high during 13th–22nd August 2022 and 1961–1990 climatology, respectively. The blue line and green line in (e) represent the location of the 200-hPa westerly jet axis during 13th–22nd August 2022 and 1961–1990 climatology, respectively. The black box represents the study region.

summer 2022 over the study region occurred on 17th August with a value of 6.50 °C (figure 1(b)), corresponding to the 10-day running mean Tmax of 35.40 °C during the period 13th–22nd August in the region. The observed time series of the regional averaged TXa10day anomalies during 1961–2022 are also shown in figure 1(d). Over the study region, the summer 2022 TXa10day anomaly is 4.15 °C, which is the highest since 1961 and 4 times the interannual standard deviation.

Figure 2 illustrates the anomalous atmospheric circulations on 13th–22nd August associated with the 2022 heatwave event. The western Pacific subtropical high shows a westward shift and its western edge reaches the Tibetan Plateau (figure 2(a)). Under the control of this extremely westward subtropical high, the study region is dominated by anomalous descent (figure 2(b)), which will suppress convection and precipitation, and is consistent with the increases in the net surface shortwave radiation (figures 2(c) and (d), Wang *et al* 2016, Liu *et al* 2019a). The northward movement of the 200-hPa jet stream can also influence the vertical motion and water transport (Zhou *et al* 2022a, figure 2(e)), which is associated with positive temperature anomalies and reduced precipitation over the Yangtze River Valley (Liu *et al* 2019b, Zhou *et al* 2022b). Hence, the above anomalous atmospheric circulations contribute to this long-lasting and extreme heatwave event.

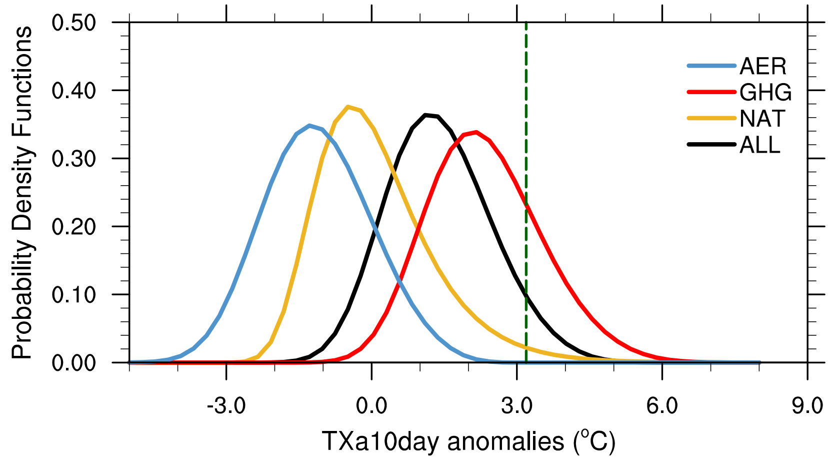

Figure 3. The GEV fitted probability density functions of regional averaged TXa10day anomalies for the present climate (2018–2027) under all forcing (black), natural forcing (yellow), greenhouse gas forcing (red) and aerosol forcing (blue). The green vertical dashed line represents the threshold of the observed 2022-like summer heatwave event. All simulated years during the relevant time window are used to estimate the GEV distribution.

3.2. Anthropogenic influences on the 2022-like summer heatwave event

Due to the influence of anthropogenic forcings, the occurrence of extreme heatwave events has become more frequent across China (Ma *et al* 2017, Ren *et al* 2020). Considering the high intensity and adverse impacts of the 2022 summer heatwave event, we now discuss the roles of anthropogenic forcings on the likelihood of this event.

The model performance of simulating TXa10day anomalies is evaluated by using the historical simulations and results are given in figure 1(d) and Supplementary figure S4. The multi-model ensemble mean of CMIP6 captures a slight increasing linear trend of TXa10day anomalies during 1961–2014 (figure 1(d)), especially a significant increasing linear trend (P=0.05) after 1982, which is also seen in observations. Note that the multi-model mean times series is not highly correlated with observed time series. However, this lack of correlation is expected since the simulated internal variability will not coincide with observations (Hawkins and Sutton, 2009). By using the K-S test, the distributions of the observed and simulated TXa10day anomalies for summers during 1961–2022 are found to be statistically indistinguishable (P=0.05, Supplementary figure S4). Since the TXa10day is calculated by taking the regional average over the study region, the difference in resolution between ERA5 and CMIP6 has little impact on the model evaluation (Supplementary figure S5). Therefore, CMIP6 model simulations are appropriate for further attribution analysis. However, the 2022 summer heatwave event is too rare in both observations and model simulations during the historical period 1961–2022 (Supplementary figure S4), which hinders robust conclusions on the influence of anthropogenic forcings on an event of the observed magnitude. Therefore, we define a 2022-like summer heatwave event by using the threshold of a 1-in-100-year heatwave event during 1961–2022 in observations with a value of TXa10day anomaly 3.19 °C, which is still larger than the observed TXa10day anomalies before 2022. The simulated probability of the 2022-like summer heatwave event is 1.2% during 1961–2022, which is also close to the 1% probability in observations.

Figure 3 shows the PDFs of TXa10day anomalies in the present climate under different forcings. In simulations with natural forcing, the probability of TXa10day which is larger than a 2022-like event is 1.9% (CI: 0.1%–3.4%) during the time window of 2018–2027. Under the influences of all-forcings, the PDF shifts rightward relative to the natural-forcing simulations and the probability of a 2022-like event is 6.0% (CI: 4.1%–7.7%) during the present climate. These results indicate that the 2022-like summer heatwave event is much more likely to occur under the influences of anthropogenic forcings and that, furthermore, the anthropogenic forcings have increased the occurrence of the 2022-like summer heatwave event by about 3 (CI: 1.5–72.6) times relative to the probability under natural forcing. Such a change corresponds to a change of return period from 1-in-53-year (CI: 29-1000 year) event under natural forcing to 1-in-17-year (CI: 13-24 year) event based on the time window of 2018-2027 under all forcing.

The PDFs of TXa10day anomalies in single forcing (hist-GHG and hist-AER) have also been analyzed to quantify relative roles of greenhouse gas forcing and aerosol forcing on the likelihood of a 2022-like summer heatwave event and the results are also shown in figure 3. The probability of a 2022-like event under only aerosol forcing is zero (CI: 0%–0.06%) during the present climate, due to the surface cooling caused by aerosols (Krishnan and Ramanathan 2002). In contrast, the likelihood of a 2022-like summer heatwave event is the

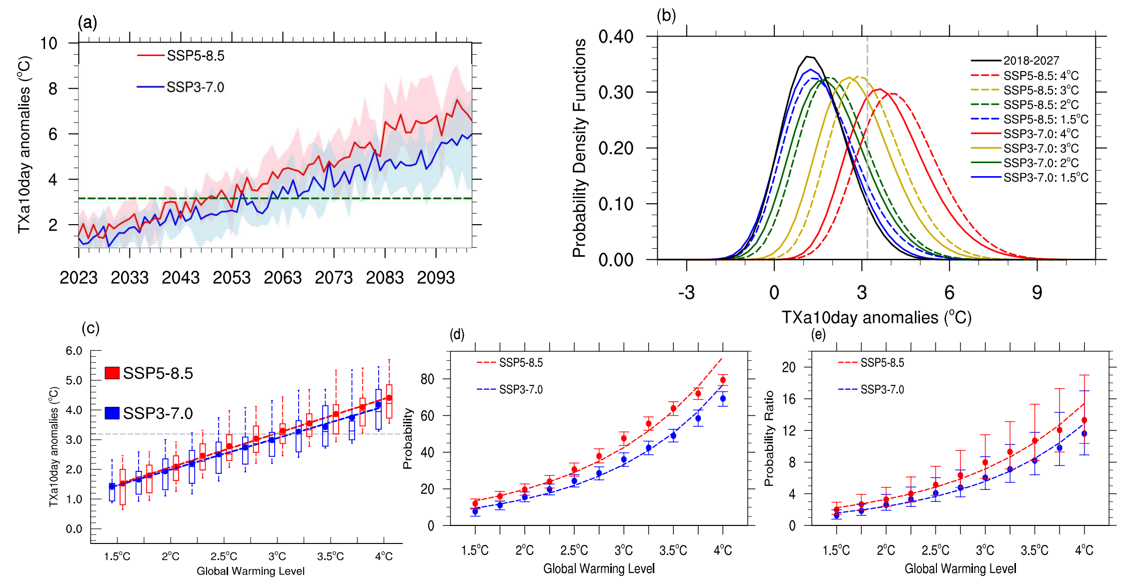

Figure 4. (a) Time series of simulated regional averaged TXa10day anomalies (°C) during the future climate under SSP5-8.5 (red) and SSP3-7.0 (blue) based on the multi-model ensemble mean. The anomalies are relative to 1961–1990. The shading is the interquartile ranges based on ensemble mean results. (b) The GEV fitted probability density functions of simulated regional averaged TXa10day anomalies in the present climate (2018–2027), at the 1.5 °C, 2 °C, 3 °C and 4 °C GWLs. All simulated years during the relevant time window are used to estimate the GEV distribution. Solid (Dashed) lines represent SSP 3-7.0 (SSP5-8.5). The grey dashed lines in (a) and (b) represent the threshold of a 2022-like summer heatwave event in observations. (c) Box plots of the TXa10day anomalies (°C) at different GWLs under the two scenarios. With each box, the horizontal lines from top to bottom denote the maximum value, the 75th percentile, the median value, the 25th percentile and the minimum value of the 10 models. The dot represents the multi-model ensemble mean. The dashed lines are the linear fit to multi-model ensemble mean. The grey line is the observed threshold of the 2022-like summer heatwave event. (d) The probabilities and the 95% confidence intervals (CIs) of a 2022-like summer heatwave event at the different GWLs and the fitted exponential curves under the two scenarios. (e) Same as (d), but for the probability ratios, which are defined as the ratios between the probability occurring at each GWL and the probability in the present climate.

much larger under the greenhouse gas forcing with a probability of 23.1% (CI: 18.9%–26.8%) during present climate. Compared with the probability under all forcings (6.0%), the 2022-like heatwave event is more likely to occur under greenhouse gas forcing and less likely to occur under aerosol forcing. This indicates that although anthropogenic forcings have overall increased the likelihood of a 2022-like heatwave event, specifically, greenhouse gases tend to amplify the occurrence of this event, whereas aerosols reduce the probability of this event. One uncertainty in figure 3 is that only three models have the ensemble ssp245-NAT, ssp245-GHG and ssp245-AER experiments. However, supplementary figure S6 shows that the PDFs of TXa10day anomalies are not sensitive to the inclusion of these three models, especially for the region of the PDF that is over the 3.19 °C threshold, indicating that these results are not sensitive to the number of members used.

3.3. Future projections of a 2022-like summer heatwave event at different global warming levels

As GMST increases under different future forcing scenarios, it is expected that there will be more warm extremes across China, which may lead to increases of heat-related mortality (Zhang *et al* 2023c). Therefore, we now assess how future climate change will increase the likelihood of a 2022-like summer heatwave event.

Figure 4(a) shows the time series of TXa10day anomalies over the study region during the period 2023–2100 from CMIP6 simulations, and shows that the TXa10day anomalies increases significantly in the future climate. The TXa10day anomalies under SSP5-8.5 are larger than the ones under SSP3-7.0 in most years, consistent with the larger anthropogenic forcing of SSP5-8.5. The TXa10day anomalies are projected to exceed the threshold of a 2022-like summer heatwave event after 2055 under SSP3-7.0 and after 2046 under SSP5-8.5.

Considering the different GWLs, figure 4(b) shows that the PDFs of the TXa10day anomalies shift to warmer values at the four GWLs compared with the present climate (2018–2027). For a 2022-like summer heatwave event, the probabilities that any given summer exceeds this threshold at the 1.5 °C, 2 °C, 3 °C and 4 °C GWLs are about 7.7%, 15.6%, 36.0% and 69.2% under SSP3-7.0, and 11.9%, 19.5%, 47.5% and 79.4% under SSP5-8.5, respectively (CIs are shown in figure 4(d)). These probabilities correspond to return periods of roughly once every 13.0 (CI: 10.6-20.0), 6.4 (CI: 7.5-11.8), 2.7 (CI: 2.5-3.0) and 1.4 (CI: 1.3-1.5) years under SSP3-7.0, and once every 8.4 (CI: 7.0-11.2), 5.0 (CI: 4.4-6.0), 2.0 (CI: 1.9-2.3) and 1.3 (CI: 1.2-1.3) years under SSP5-8.5 at the four GWLs. In other words, the probabilities of a 2022-like summer heatwave event are projected to increase by 1.3-fold, 2.6-fold, 6.0-fold and 11.5-fold at the 1.5 °C, 2 °C, 3 °C and 4 °C GWLs under

SSP3-7.0, and by 2.0-fold, 3.3-fold, 7.9-fold and 13.2-fold under SSP5-8.5, relative to the present climate with a probability of 6.0% (CIs are shown in figure 4(e)). Hence, the occurrence of a 2022-like summer heatwave event over the study region will be substantially more frequent in the future climate under the influence of global warming.

Figure 4(c) shows the relationships between magnitude of the TXa10day anomalies and the GWLs. The slope between TXa10day anomalies and GWLs is 1.06 (CI: 0.97-1.11) and 1.15 (CI: 1.12-1.18) under the SSP3-7.0 and SSP5-8.5, respectively. These results indicate that the magnitude of change in TXa10day anomalies is almost linear with GWLs and is slightly faster than global-mean warming. Figures 4(d) and (e) also shows how the probabilities and PRs for a 2022-like summer heatwave event evolve with increasing GWLs. With increasing GWLs, the probabilities and PRs of a 2022-like summer heatwave event exhibit exponential growth. In summary, a 2022-like heatwave event would be more frequent and intensified in a warmer world and the rate of risk increase far outpaces the rate of mean temperature rise.

In order to examine the sensitivity of the projected changes in the likelihood of the 2022-like summer heatwave event to the different number of ensemble members across models, we calculated PRs in five models which have multiple members simulations and one group model which includes those models with only one member. Supplementary figure S7 shows the probability ratios and their CIs at different GWLs in those individual models. Although there is a model uncertainty in the magnitudes of PRs among models, the PRs in these individual models still show exponential growth as they increase with the increasing GWLs. As the characteristics for individual models are consistent with the multi-model mean ones shown in figure 4(e), this indicates that the projected changes in likelihood for a 2022-like heatwave are consistent among different models.

4. Conclusions

Over the regions from the Sichuan Basin to the middle and lower reaches of the Yangtze River valley, a record-breaking heatwave event occurred during the 2022 summer. After removing the climatological daily mean of daily Tmax, the highest 10-day running mean of Tmax anomalies in each summer is used as an index (TXa10day) to represent this event. Observational analysis shows that the regional averaged TXa10day appears on 17th August with a value of 6.50 °C during the period 13th–22nd August. This corresponds to a TXa10day anomaly of 4.15 °C relative to the baseline period (1961–1990) climatology, which is 4 times the interannual standard deviation. This heatwave event is mainly controlled by the westward movement of the western Pacific subtropical high. The intense and stable subtropical high leads to a decrease of precipitation and increases of shortwave radiation over the study region, which promotes the formation of this long-lasting and extreme heatwave event.

In this study, considering the rare probability of the 2022 summer heatwave event, a 2022-like summer heatwave event is defined by using the threshold of a 1-in-100-year heatwave event with a TXa10day anomaly of 3.19 °C in observations during 1961–2022 in order to generate robust attribution conclusions. We used the multi-model ensemble simulations of CMIP6 models under all forcing, natural forcing, greenhouse gas forcing and aerosol forcing to explore the contributions of anthropogenic influences on the 2022-like summer heatwave event. In the present climate (2018–2027), our results show that the probability of a 2022-like summer heatwave event is 1.9% under natural forcing and 6.0% under all forcing. Thus, anthropogenic forcing has increased the likelihood of a 2022-like summer heatwave event by approximately 3 times relative to naturally forced changes in the present climate. Not surprisingly, greenhouse gas forcing dominates this increase in probability due to anthropogenic forcing; the probability of a 2022-like summer is 23.1% in the present climate under greenhouse gas forcing only, while this kind of extreme event is unlikely to occur only under aerosol forcing. Although the quantitative estimates of the magnitude of human influence differ among different studies due to the differences in datasets, methods and event definitions (e.g., Zhang *et al* 2023a, Liang *et al* 2024), the qualitative conclusion remains consistent that the human influence substantially increases the likelihood of a 2022-like heatwave event.

In the future, the magnitudes of the TXa10day anomalies in each summer are projected to be larger than the threshold of a 2022-like summer heatwave event after 2055 under SSP3-7.0 and after 2046 under SSP5-8.5. The probabilities and probability ratios defined as the probabilities at GWLs relative to the probability in the present climate of a 2022-like summer heatwave event both increase exponentially with the increasing of GWLs, and the probability under the SSP5-8.5 is larger than the one under the SSP3-7.0 at each GWL. At the 4 °C GWL, a 2022-like extreme event will become a 1-in-1.4-year and 1-in-1.3-year event under the SSP3-7.0 and SSP5-8.5, respectively, which is an increase of 11.5-fold and 13.2-fold compared with that simulated under the present climate.

Due to the extremity of the observed 2022 heatwave event, the definition of a 2022-like heatwave event is derived from the temperature index that characterizes the observed 2022 heatwave event. While this temperature definition provides a clear benchmark for quantifying extremes, it does not fully capture the associated atmospheric circulation anomalies which contribute to the extreme temperatures in 2022. Future work should include circulation-based indicators to provide events that are analogous to 2022 in order to evaluate them and provide a more comprehensive event definition and attribution.

Although there are uncertainties presented here, the increases of the likelihood of a 2022-like heatwave event suggests that ecosystem, society and human health over East China would face higher risks in the future. Local government and environment agencies would face a challenge to take adaptation measures to cope with the projected frequency increase of a 2022-like summer heatwave. Although the main characteristics of projected likelihood changes of a 2022-like summer heatwave event are consistent among different models, we have not analyzed whether the specific drivers of such simulated extreme events are similar to the observed. Moreover, understanding how the physical mechanisms may change in a warmer world is essential for improving future projections. Therefore, it is crucial that we continue to understand the mechanisms of such events, how they are represented in climate models, and what the impacts would be.

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Conflict of interest

The authors declared that they have no relevant financial or non-financial interests to disclose.

Data availability statement

The data that support the findings of this study are openly available at the following URL: https://help.ceda.ac.uk/article/4801-cmip6-data; https://cds.climate.copernicus.eu/datasets; https://data.cma.cn.

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Author contributions

Data collection and analysis were mainly performed by MZ. The first draft of this paper was written by MZ. BD, RS and JR helped to revise the manuscript. All authors read and approved the final manuscript.

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