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Quantifying the extremity of 2022 Chinese Yangtze River Valley daily hot extreme: fixed or moving baseline matters

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Abstract

In 2022, an extreme heatwave struck the Yangtze River Valley (YRV) of China. Existing studies have highlighted its record-breaking magnitude by comparison with historical records using a fixed baseline. However, the quantification of extremity relies on the choice of baseline. While using fixed baseline allows us to understand the changes in extremes with the background warming, the use of moving baseline quantifies the extremity relative to recent climatology, and thus, takes into account the societal adaptation capability to global warming. Here, we revisit the 2022 heatwave in China and examine the extremity of daily hot extreme by comparing the two methods. Using a fixed baseline, daily hot extremes occurred in 2022 in the upper and middle reaches of YRV broke records since 1971. Nevertheless, using a moving baseline, daily hot extremes broke records only in the upper reaches (Sichuan Basin). In addition, it is not the most extreme event (measured by standard deviation (SD) anomalies), as China has experienced ∼13 more extreme events since 1971. The future projections show that, when using fixed baseline, 2022 Sichuan basin like extreme will occur every 2–12 years in 2081–2100 period under high-emissions scenarios, and will sweep China. Approximately 2%–25% of continental China will experience daily hot extreme with magnitude exceeding 5 SDs. Nevertheless, the projected changes based on moving climatology are weak, indicating that if we take measures to enhance our adaptability to background warming, the risks associated with hot extremes would be reduced in China.

1. Introduction

In summer 2022, the Yangtze River Valley (YRV) in central eastern China has featured a high-profile heat wave. The Sichuan–Chongqing region, which is located in the upper bound of the YRV, showed the highest number of days with daily maximum temperature above 40.0 °C (Lin *et al* 2022b). The continuous high temperature seriously affected local life and economic activities, led to hydrologic power shortages in Sichuan and wildfires in western Chongqing (Lu *et al* 2023, Wang *et al* 2023). Whether this event is record-breaking and how such kinds of extreme event will evolve in the future are a matter of significant concern for the scientific community.

The quantification of the intensity and extremity of extremes, such as using temperature anomalies and percentile thresholds (e.g. Griffiths *et al* 2005, Liu *et al* 2013), depends on the choice of baseline (Yosef *et al* 2021, Dunn and Morice 2022, Thomas *et al* 2023). For assessing the magnitude of the 2022 YRV heatwave, existing studies have used temperature anomalies (He *et al* 2023, Lu *et al* 2023) and extreme indices (Tang *et al* 2023), and the results indicated that record-breaking heatwaves have occurred in the YRV, particularly in the Sichuan–Chongqing region and downstream areas. Most of these existing assessments are based on fixed historical climatology spanning 1979–2022 period, which have retained the warming trend and exhibit a rise in the magnitude of extremes as the warming trend continues. However, the impact of hot extremes is related to the development status (Romanello *et al* 2021). The overall resilience of humanity to extreme heat events has increased over time, due to the developments at the individual, technological and health system level (Gosling *et al* 2017, Bi *et al* 2023). Therefore, the assessment of heatwave extremity also needs to consider the period when the heatwave occurs, namely comparing extremes to the continuously evolving period.

Previous studies using traditional fixed baseline have indicated that hot extremes are becoming more frequent and severe across China with global warming (e.g. Li *et al* 2018, Sun *et al* 2018, Wang and Yan 2021, Ma and Yuan 2023, Wei *et al* 2023). These results illustrate how the future will change if no measures are taken. However, as humans and natural systems are gradually adapting to long-term climate change (Thompson *et al* 2022), it is also essential to examine the magnitudes of extremes with the growing adaptation capacity taken into account. Such information is expected to aid decision-making. In addition, previous research indicates that internal variability exerts a primary influence in climate change over the next decades (Hawkins and Sutton 2009, Deser *et al* 2012, Fischer *et al* 2013). However, the number of model samples used in previous studies is limited, which may not be able to capture the more extreme and rare events in the future. In recent years, the emergence of single-model initial-condition large ensembles provides more ensemble members, more reasonably captures internal variability, and thus can better quantify the influence of internal variability, and facilitate the projection of rare extreme events (e.g. Kay *et al* 2015, Maher *et al* 2021, Zhou 2021, Liao *et al* 2024a).

Here, we place the magnitude of 2022 YRV daily hot extreme in the context of whole China, and aim to address the following questions by comparing the results obtained using both fixed and moving baselines: (1) Was the 2022 YRV daily hot extreme the most extreme event on record? (2) How does the extremity of this event compare to events in other regions of China spanning 1971–2022 period? (3) How often will such rare daily hot extremes occur with warming trend in the YRV? (4) How many regions in China are projected to experience daily hot extremes like or even more extreme than the magnitude of 2022 YRV extreme?

2. Data and methods

2.1. Datasets

The following observational datasets of the daily maximum temperature (Tmax) spanning 1961–2022 are used: (1) the observational gridded Tmax data derived from the National Meteorology Information Center of China (CN05.1), having a $0.25° \times 0.25°$ resolution, which is interpolated from over 2400 stations across China using 'anomaly approach' (Wu and Gao 2013); (2) the gridded reanalysis data obtained from the European Centre for Medium-Range Weather Forecasts (ERA5) (Hersbach *et al* 2018), having a spatial resolution of $0.25° \times 0.25°$.

Three sets of single-model initial-condition large ensembles are used and bilinearly interpolated into $1° \times 1°$:

(1) The Canadian Earth System Model vertion5 Large Ensemble (CanESM5-LE), consists of 50 ensemble members, and exhibits an equilibrium climate sensitivity (ECS) of 5.6 K (Swart *et al* 2019). The historical simulations span the period 1850–2014, while the projections cover the 2015–2100 period under three shared socioeconomic pathways (SSPs) (SSP1-2.6, SSP2-4.5 and SSP5-8.5) scenarios following the CMIP6 design. The Tmax data of CanESM5-LE spanning 1961–2100 in historical simulations and projections under SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios are assessed.
(2) The Flexible Global Ocean–Atmosphere–Land System Model, grid-point version 3 Large Ensemble (FGOALS-g3 LE), which includes 110 ensemble members, with an ECS of 2.8 K (Lin *et al* 2022a). The FGOALS-g3 LE includes historical simulations spanning 1850–2014, along with projections from 2015 to 2099 under the SSP5-8.5 scenario, adhering to the CMIP6 design. The Tmax data of FGOALS-g3 LE spanning 1961–2099 in historical simulations and projections under SSP5-8.5 scenario are analyzed.
(3) The Community Earth System Model version 1 Large Ensemble (CESM1-LE), which comprises 40 ensemble members covering the period 1850–2100, with an ECS of 4.1 K (Meehl *et al* 2013). The CESM1-LE includes historical simulations (1850–2005) and projections (2006–2100) under Representative Concentration Pathway (RCP) 8.5 scenario following the CMIP5 design. The Tmax data of CESM1-LE spanning 1961–2100 in historical simulations and projections under RCP 8.5 scenario are analyzed.

2.2. Bias correction and model assessment

If we compare the model simulations to the observations directly, the three large ensemble models can capture the spatial pattern of Tmax over China well, with spatial correlation coefficients greater than 0.85 (figure S1), but the simulated regional average Tmax series deviates from the observations overall (figure S2). Hence bias correction is needed.

We use a statistical bias correction method to correct the climatology of model-simulated Tmax data. This method can preserve both the variability across all time scales and the long-term trend of the model data (Hempel *et al* 2013, Nangombe *et al*

2019). We calculate the bias using the model ensemble median and further correct each member individually (figure S2). We first calculate the average difference C between observations and simulations for each month during the period 1961–2005 (45 years) based on the following formula:

$$C = \frac{\sum_{i=1}^{m=45} T_i^{\text{obs}} - \sum_{i=1}^{m=45} T_i^{\text{model}}}{45} \quad (1)$$

where T_i^{obs} represents the monthly average Tmax of CN05.1 at each grid point of year i, while T_i^{model} is model simulation. In bias correction and model evaluation, CN05.1 is interpolated to 1° × 1°. Then the corrected Tmax for historical simulations and projections can be estimated from

$$TT_{i,j}^{\text{model}} = C + T_{i,j}^{\text{model}} \quad (2)$$

where $TT_{i,j}^{\text{model}}$ is the corrected Tmax for year i and day j in the corresponding month at each grid point, while $T_{i,j}^{\text{model}}$is before corrected.

After bias correction, the temporal characteristics of heatwaves in the Sichuan Basin are well reproduced in the simulations (figure S2).

2.3. Regions

The definition of extreme events depends on the selection of spatial scale. In this study, we calculate daily extreme index based on regional averages rather than grid points. The calculation of regional average is done using a grid area weighted averaging method (Jones and Hulme 1996).

Stone (2019) has defined five sets of regions over global land areas, based on political and economic divisions. The regions are consistent with decision-making and disaster response, and have been widely used for analyzing extreme events. The regional divisions we used here have a subregion area size of ~0.1 Mm^2 (1 Mm^2 = 1 million km^2), approximately equivalent to a diameter of about 350 km. Specifically, adjacent county-level administrative regions within a province, which have political/economic connections and are geographically contiguous, are merged into regions with an area of approximately 0.1 Mm^2 each (Stone 2019). This results in dividing each province into several regions of approximately equal area, ultimately, dividing the mainland of China into 116 sub-regions (figure S3).

2.4. Definition of daily extreme index

Following Thompson *et al* (2022), we measure the magnitude of hot extremes by the number of standard deviations (SDs) from the mean. Since the index is calculated on a daily basis, it is called daily extreme index:

$$\text{daily extreme index} = \frac{\text{regional average Tmax} - \text{mean regional average Tmax}}{\text{SDs}}. \quad (3)$$

It serves as an objective indicator of the magnitude of hot extremes that can be compared across regions. Note that this index based on temperature SD anomalies does not necessarily allow a direct comparison of impacts across a broad swath of region, due to different temperature variance in different regions (Guirguis *et al* 2018).

Firstly, the regional average Tmax for each day from 1961 to 2022 (taking historical analysis as an example) is calculated in each region.

Secondly, we calculate the mean regional average Tmax and SDs in two different ways: (1) Fixed climatology: for each region, we choose 1981–2010 as baseline, select 3 months each year with the greatest regional average Tmax, calculate their mean and SD, and then compute the index for each day from 1971 to 2022. (2) Moving climatology: we select the preceding 10 years as the baseline for each year.

Finally, we select the maximum daily extreme index for each region from 1971 to 2022, representing the most extreme event in the historical analysis.

3. Results

3.1. Observed YRV daily hot extreme of 2022

We first compare the differences in Tmax during summer between two reference periods: the entire time period from 1971 to 2022 and the current decade from 2012 to 2021. The results indicate that in almost entire YRV, the average Tmax of current decade is higher than that of the entire period commonly used, with the maximum difference exceeding 4.5 °C (figure 1(a)). This results in that positive anomalies are observed only in the upper reaches of the YRV and Yangtze River Delta relative to the baseline of current decade, with the largest positive anomaly about 2 °C centered in the Sichuan basin (27 °N–32 °N, 103 °E–107 °E) (figure 1(b)). This is different from existing studies based on fixed baseline, where the entire YRV shows positive anomalies (e.g. He *et al* 2023, Lu *et al* 2023). This suggests that the selection of the reference period also affects the assessment of heatwave extremity in China as in other parts of the world (Yosef *et al* 2021, Dunn and Morice 2022, Thomas *et al* 2023). Assessing the recent extremity of heatwaves based on current decade is equivalent to assessing it based on the current climate (Thompson *et al* 2022).

To further reveal the baseline-dependence of the extremity, we compare the summer 1971–2022 Tmax anomalies averaged over the Sichuan basin

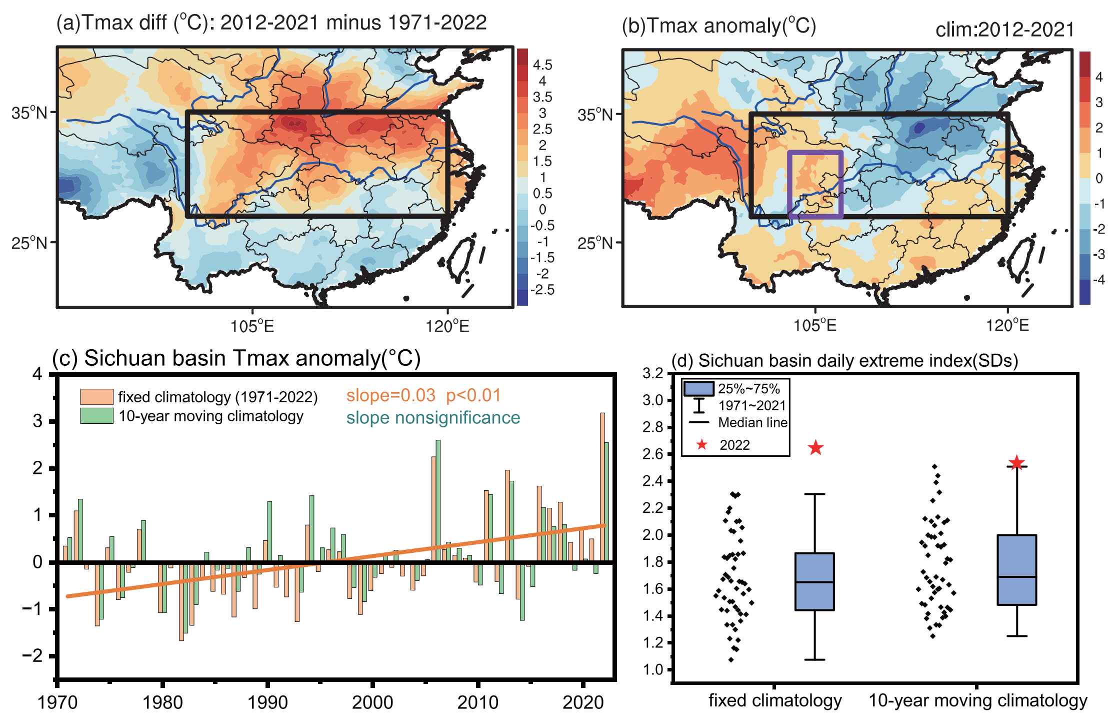

Figure 1. Characteristics of the 2022 YRV daily hot extreme in observations. (a) Average Tmax difference in JJA between the periods of 2012–2022 and 1971–2022 (unit: °C), black boxes indicate the YRV (27°–35 °N, 100°–120 °E), black boxes indicate the YRV (27°–35 °N, 100°–120 °E). (b) Tmax anomaly in the JJA of 2022, relative to 2012–2021 (unit: day), purple boxes indicate the Sichuan basin (27°–32 °N, 103°–107 °E). (c) Time series of regional average Tmax anomaly in JJA for Sichuan basin spanning 1971–2022 (unit: °C). Green bars use the fixed climatology (1971–2022), green line represent the trend of green bars, while orange bars and line use the 10-year moving climatology. (d) The daily extreme index of Sichuan basin from 1971 to 2022 using two baselines: fixed climatology (left) and 10-year moving climatology (right). Boxplot covers the range from 1971 to 2021, with a red star symbolizing the year 2022. The Tmax data is derived from CN05.1.

based on two climatology: fixed climatology spanning 1961–2022 period and 10 year moving climatology (figures 1(c) and (d)). The Tmax anomaly series using the moving climatology does not show a significant trend, unlike using the fixed climatology (slope $= 0.03$, $p < 0.01$) (figure 1(c)). This indicates that the use of 10 year moving baseline excludes the effect of long-term climate changes in the measure of hot extremes. It is reasonable to assume that the risks related to long-term climate changes can be effectively managed by humans and natural ecosystems through adaptation activities, as suggested previously (Thompson *et al* 2022, Pisor *et al* 2023). Therefore, it can serve as a rough or optimistic approximation of the long-term climate adaptation impact (Stevenson *et al* 2022). In comparison, fixed baseline with the warming trend being preserved exhibits assessments without adaptation.

We further compare the number of SDs from the mean using two baselines. The magnitude of hot extremes calculated using a moving baseline, ranges from 1.25 to 2.51 SDs, with the 22nd August 2022 event reaching an unprecedented 2.52 SDs (figure 1(d)).While the results obtained from the fixed climatology are larger, reaching 2.67 SDs (figure 1(d)). This indicates that this unprecedented daily hot extreme in Sichuan basin was attributed to both internal variability and anthropogenic warming (He *et al* 2023, Liang *et al* 2024). In August 2022, the anomalous eastward extension of South Asian High (SAH) (figure S4(a)) and the anomalous westward extension of Western North Pacific Subtropical High (WNPSH) (figure S4(c)) controlled the Sichuan Basin, resulting in suppressed convection (figure S4(b); Zhou *et al* 2023, Zhang *et al* 2023a, 2023b, Qian *et al* 2024, Wang *et al* 2024). Anomalously straight 500 hPa Eurasian teleconnection pattern at high latitudes (figure S4(c); Hao *et al* 2022), anomalous 200 hPa Silk Road pattern at mid-high latitudes (figure S4(a); Zhang *et al* 2023a), and enhanced convection in northern South China Sea (figure S4(b)), all contribute to the maintenance and strengthening of SAH and WNPSH. The abnormality of the WNPSH is also related to the La Niña sea surface temperature pattern (Tang *et al* 2023, Liao *et al* 2024b, Gong *et al* 2024). Additionally, there is a strong coupling between soil moisture and temperature in the southeastern part of the Sichuan Basin (figure S4d). Previous study also finds that the soil moisture-temperature feedback enhanced the heatwave in eastern Tibetan Plateau (Gong *et al* 2024).

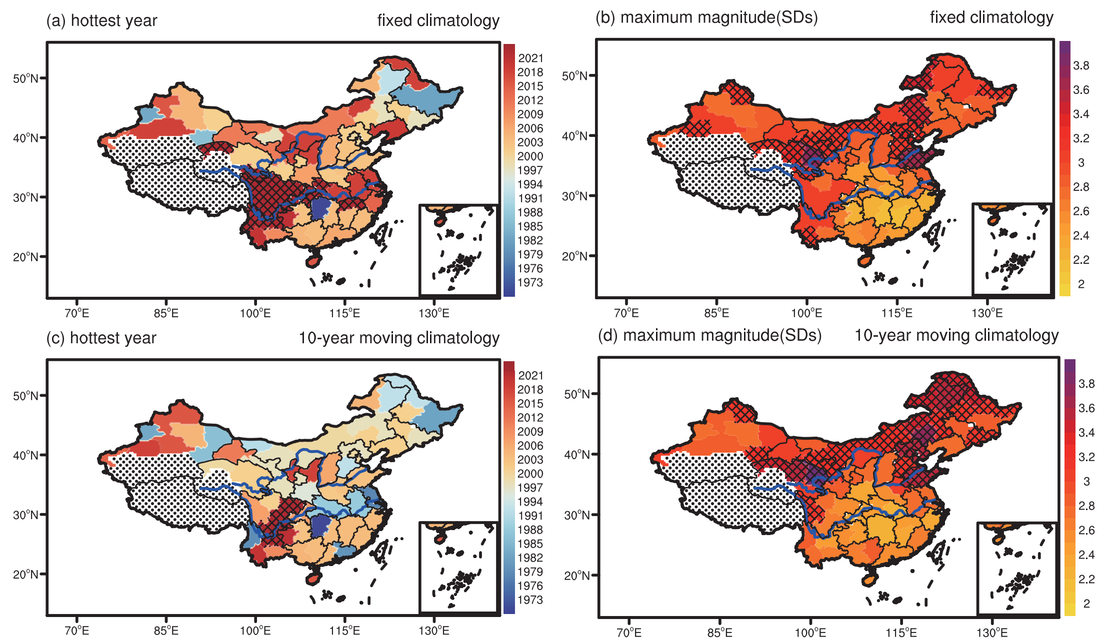

Figure 2. The most extreme hot events in various regions of China from 1971 to 2022. (a) The year when the most extreme hot events took place based on fixed climatology (1981–2010) (unit: year). Cross labels indicate regions where the events occurred in 2022. (b) The magnitude of the most extreme hot events based on fixed climatology (unit: SD). Cross labels indicate regions where the magnitude exceeds 3 SDs. (c) Same as (a), but using 10 year moving climatology. (d) Same as (b), but using 10 year moving climatology. Dotted regions are masked due to data limitation. The Tmax data is obtained from CN05.1.

3.2. Daily hot extremes over China in the history

To investigate the extremity of 2022 YRV heatwave in the context of China, we calculate the year and value of the maximum daily extreme index in various regions of China from 1971 to 2022 based on two climatology: fixed climatology spanning 1981–2010 period and 10 year moving climatology. To facilitate the study of hot extremes in different regions of China, we use a regional partitioning method specifically designed for analyzing extreme events, which divides mainland over China into 116 sub-regions (See Data and Methods, and also figure S3). We mask some regions where there are few observational stations and are poor in agreement between ERA5 and CN05.1 (figure S5), and finally 94 regions are left.

Over the past 50 years, inspection of the year with the most extreme daily temperature in each region (figures 2(a) and (c)) reveals that, when using fixed climatology (figure 2(a)), over 90% of the regions experienced their most extreme daily events in the recent 20 years, and the 2022 daily hot extremes occurred in most of the upper and middle reaches of the Yangtze River were record-breaking events. While using 10 year moving climatology (figure 2(c)), only 50% of the regions experienced most extreme daily events within the recent 20 years, notably the 2022 record-breaking hot extreme were concentrated solely in the Sichuan Basin. This suggests that using fixed baseline preserves the warming trend, making current events more likely to break historical records, while employing moving baseline avoids the overestimation of current events and the underestimation of historical events, thus makes extremes across different time periods comparable.

Furthermore, compared to all the daily hot extremes in other regions of the mainland of China over the past 50 years, how does the extremity of the record-breaking 2022 hot extreme in the Sichuan basin fare? Has China experienced some events of greater magnitude in history? We examined the magnitude distribution of most extreme historical daily events (figures 2(b) and (d)) and the results from the two baselines display a high level of consistency, indicating the magnitude of 2022 Sichuan Basin hot extreme (2.52SDs using moving baseline; 2.86 SDs using fixed baseline) is not the greatest when compared to the historical events occurred in other regions of China. The magnitude exceeding 3 SDs is mainly distributed in the north of 30°N, located in the region 30 °N–55 °N, 80 °E–130 °E (figures 2(b) and (d)). We further compare the results of ERA5 and CN05.1 (figure S5) and tabulate 13 hot extreme events exceeding 3 SDs based on the 10 year moving climatology (table S1). All the events listed have occurred in the North China. Some famous and well known extreme events have been identified, for example, in 1999 and 2000, China experienced hot and dry summers, leading to severe drought with an affected area of 20 700 million m^2, resulting in 20%–30% agricultural yield reduction in the North China (Wei *et al* 2004).

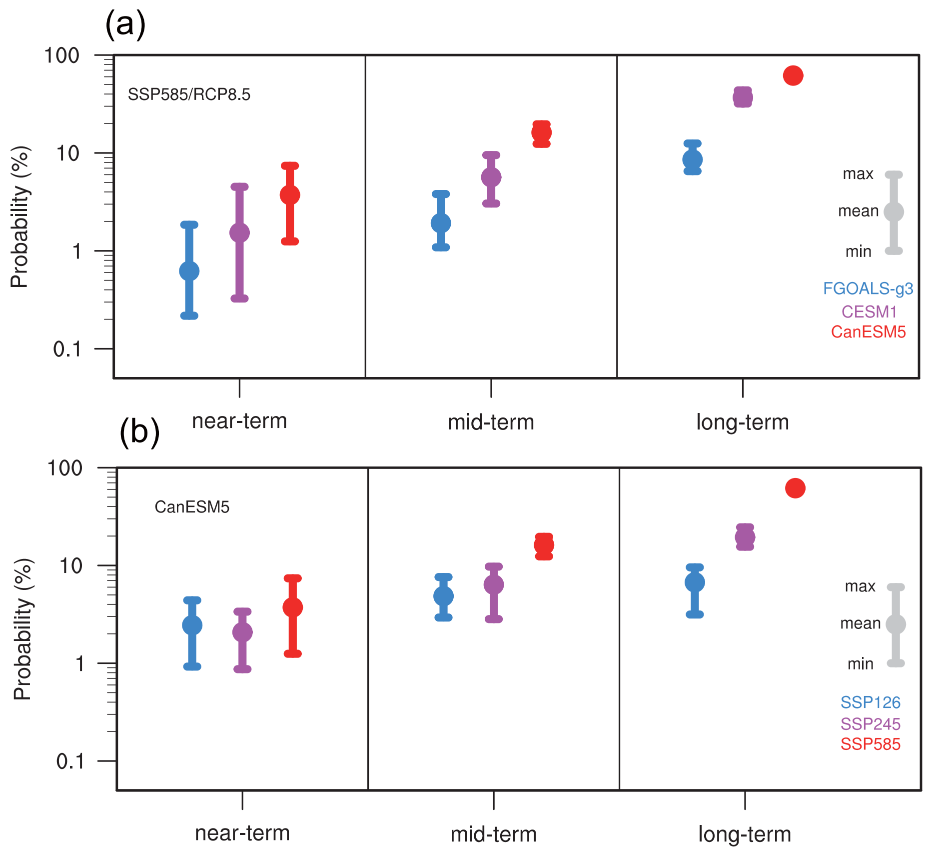

Figure 3. The projection of the recurrence of the 2022 Sichuan basin daily hot extreme. (a) Under the high-emissions scenarios (SSP5-8.5/RCP8.5), the projections are shown using three models: CanESM5 (50 members), CESM1 (40 members) and FGOALS-g3 (110 members). (b) Using CanESM5, the results are displayed under three scenarios: SSP1-2.6, SSP2-4.5, SSP5-8.5. The projections are divided into three time periods: near-term (2021–2040), mid-term (2041–2060) and long-term (2081–2100). Circular markers represent the recurrence of the event on any given day during the time period, based on the ensemble mean, vertical lines indicate the range of uncertainty derived from the ensemble members.

3.3. Sichuan basin daily hot extremes in the future

Above analysis shows that the 2022 hot extreme in the Sichuan basin was an unprecedented event (figure 2(a)). We further calculate the return period of this rare events in future climate change projection (see supplementary methods SM2), by using the projections of three large ensembles with different climate sensitivity under the high-emission scenarios (SSP5-8.5/RCP8.5) (figure 3(a)). We also examine the results of high sensitivity climate ensemble under three different emission scenarios (figure 3(b)), since there is still a chance of climate sensitivity exceeding the best estimate of IPCC AR6 (Sherwood *et al* 2020, Forster *et al* 2021).

Under the current climate condition (2015–2024), the probability of a 2.52 SDs event occurring on any given summer day is about 0.4%–1.4% (figure S6). The probability of recurrence increases over time and is influenced by future scenarios and model sensitivity (figures 3 and S6). The higher the model sensitivity is, the greater the probability is (figures 3(a) and S6(a)). For the long-term projection under high-emission scenarios, the probability of the 2022 Sichuan basin heatwave is ∼8% in FGOALS-g3, ∼37% in CESM1, and ∼61% in CanESM5, respectively (figure 3(a)). The probability increases with the intensity of emission in the scenarios (figure 3(b) and figure S6(b)). The long-term projection of a high climate sensitivity model (CanESM5) shows that a heatwave event of 2.52 SDs in Sichuan basin will occur approximately every 2 years under the SSP5-8.5 scenario, 5 years under the SSP2-4.5 scenario, 16 years under the SSP1-2.6 scenario (figure 3(b)). This suggests that by the end of the 21st century, heatwaves like the one experienced in the Sichuan basin in 2022 will become more frequent and even occur as a regular phenomenon unless a large-scale reduction in greenhouse gas emissions is achieved.

3.4. Future changes of daily hot extremes in China

We further project the future changes in the occurrence extent of daily hot extremes in China by calculating the percentages of regions that will experience events with magnitudes exceeding 1, 2, or 3+ SDs under high-emissions scenarios (figure 4). We use two baselines: fixed climatology spanning 1981–2010 period and 10 year moving climatology. The observational data and model simulations show great consistency during the historical period (figure 4).

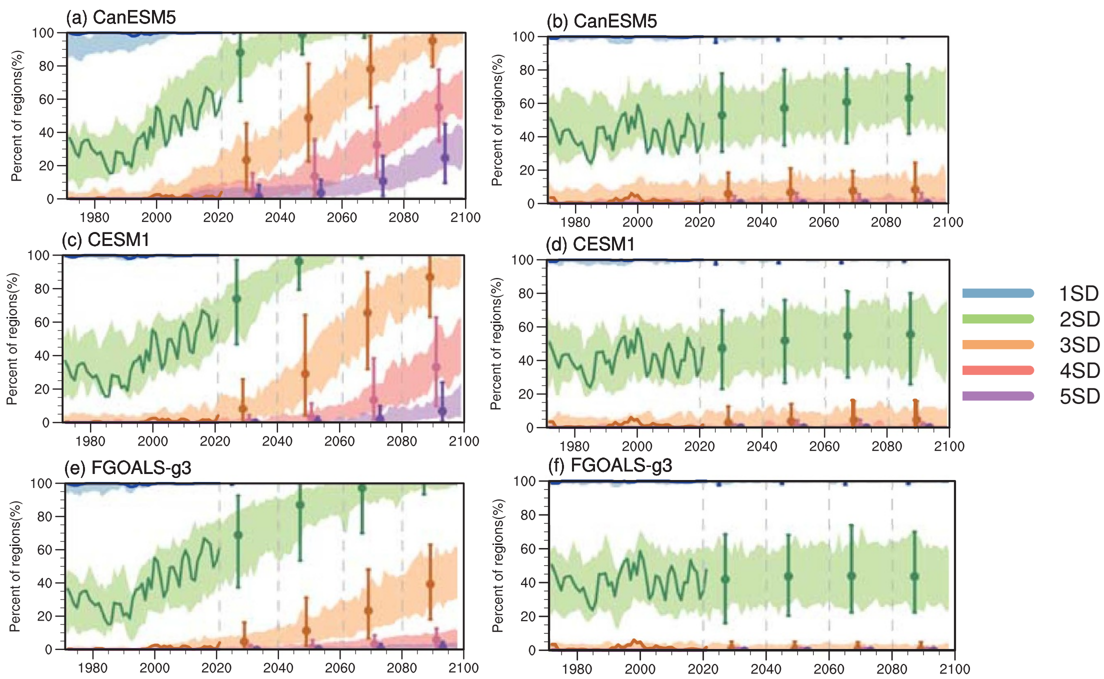

Figure 4. The percentage of regions across China experiencing events annually with magnitudes ranging from 1 to 5 SDs, calculated using 1985–2010 fixed climatology in historical simulations and projections under high-emissions scenarios (SSP5-8.5/RCP8.5), with different ensembles: (a) CanESM5 (50 members), (c) CESM1 (40 members), (e) FGOALS-g3 (110 members). (b), (d), (f) Same as (a), (c), (e), but calculated using moving climatology. Bold lines represent CN05.1 data, shading indicates the range among ensemble members, and bar plots represent projections every 20 years, spanning from 2021 to 2100. Circular markers denote the ensemble mean, while vertical lines are derived from the range of ensemble members.

The results show that when using a fixed baseline (figures 4(a), (c) and (e)), the percentage of regions surpassing each threshold will continue to increase with the warming trend. By the end of the 21st century, the magnitude of events in all regions of China may exceed 2 SDs from the mean. This suggests that by the year 2100, daily hot extremes of similar intensity to the 2022 YRV daily hot extreme will likely affect the entire China if we do not take mitigation measures. Additionally, by 2100, nearly 7% (2%) of the regions will experience extreme events surpassing 5 SDs from the mean, as indicated in the results of CESM1 (FGOALS-g3), this percentage rises to approximately 25% in CanESM5. While using moving climatology, we further find that the percentages of regions experiencing hot extremes exceeding different thresholds remain relatively stable (figures 4(b), (d) and (f)). This suggests that changes in daily extreme temperatures are primarily attributed to shifts in the warming trend of mean state. Thus, if we continually adapt to background changes by taking measures, the risks associated with hot extremes may decrease in China.

4. Conclusions and discussions

We compare the extremity of 2022 YRV daily hot extremes in the context of China spanning the period 1971–2022 based on the fixed climatology (1981–2010 period) and the 10 year moving climatology. We also project future changes of such rare events.

The comparison in the record-breaking events of 2022 indicate that, when using fixed climatology, the daily hot extremes in upper and middle reaches of the Yangtze River broke the records over the past 50 years. While using moving climatology, only the extreme in the Sichuan basin in August 2022 broke the record, with a magnitude of 2.52 SDs. But compared to other regions in China, this magnitude is not the strongest. We have identified a list of 13 extreme hot events since 1971 with magnitudes exceeding 3 SDs, and most of the events are less-well-known.

For the long-term projection (2081–2100) under the SSP5-8.5/RCP8.5 scenario, if we do not take measures to address global warming (fixed climatology), the 2022 Sichuan Basin like daily hot extreme with a magnitude of 2.52 SDs will occur approximately every 13 years in FGOALS-g3, 3 years in CESM1, and 2 years in CanESM5. Hot extremes with a similar magnitude as the 2022 extremes in the YRV will influence all parts of China, and nearly 2%–25% of the land area over China will experience extreme events with magnitudes more than 5 SDs which is approximately 2–3 times higher than the 2022 YRV hot extremes. Based on 10 year moving climatology, the projected magnitude of daily hot extremes does not change significantly in the future. This implies that if we consistently adapt to background warming by implementing adaptation measures, the impacts of daily hot extremes may be reduced (Stevenson *et al* 2022).

In addition, we should acknowledge that changing the baseline period may potentially hinder the appropriate management to climate-related health risks (Thomas *et al* 2023). This is particularly important for vulnerable groups like the elderly and outdoor workers, who may lack the ability to cope with high temperatures effectively (Ebi *et al* 2021, Romanello *et al* 2021). To avoid possible misleading the public and decision-makers, we highlight that relying solely on adaptation measures is insufficient to minimize risks, reducing greenhouse gas emissions is crucial to slow the rate of global temperature rise, thereby reducing the frequency and intensity of heatwave events and mitigating their impact on vulnerable populations. Both climate change adaptation and climate change mitigation measures are crucial in coping with global warming.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Open Research

ERA5 reanalysis data are sourced from the European Center for Medium Range Weather Forecasts [https://cds.climate.copernicus.eu/#!/search?text=ERA5&type=dataset]. CN05.1 is provided by Climate Change Research Center, Chinese Academy of Sciences [https://ccrc.iap.ac.cn/resource/detail?id=228]. CanESM5 model outputs are publicly accessible via the Earth System Grid Federation [https://esgf-node.llnl.gov/search/cmip6/]. FGOALS-g3 data can be obtained from [www.scidb.cn/en/detail?dataSetId=f75af1c5d2cf484faa354437dc85acfc]. CESM1 model data sourced are from the National Center for Atmospheric Research [www.earthsystemgrid.org/dataset/ucar.cgd.ccsm4.output.html]. The data in this study is analyzed with NCAR Command Language (NCL). The core codes of the 'daily extreme index' are obtained by Thompson *et al* (2022) in [https://zenodo.org/record/6325508].

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