Conditional attribution of climate change and atmospheric circulation contributing to the record-breaking precipitation and temperature event of summer 2020 in southern China

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Abstract
Quantification of the contribution of atmospheric circulation to damaging extreme weather and climate events and the attribution of extreme events in the context of climate change has been gaining worldwide interest. Attribution analysis helps us to better understand the risks associated with the effects of climate change on extreme events. However, the contribution of atmospheric circulation, as well as the influence of climate change, to the record-breaking precipitation event in the middle and lower reaches of the Yangtze River and the concurrent record-breaking hot event in South China during the Meiyu period (June–July) in 2020 are still unclear. In this study, we use flow analogues to estimate how much the atmospheric circulation can explain these two extreme events and the influence of climate change. The results show that the atmospheric circulation explains 70.73% and 43.61% of the extreme precipitation event and the concurrent hot event, respectively. Compared with past climate, the occurrence risk of an event reaching or exceeding the 2020 Meiyu amount under similar atmospheric circulation conditions increased by 5.1 times under the present climate, 80% of which can be attributed to climate change. In addition, hot events similar to the 2020 event cannot occur under past climate, while those reaching or exceeding a one standard deviation threshold increased from 0.58% under past climate conditions to 68.83% under the present climate, 99% of which can be attributed to climate change. These results are beneficial for the understanding and prediction of extreme events in the context of climate change in this region.

1. Introduction

During the Meiyu period (June and July) in 2020, the largest precipitation event since 1960 occurred over the middle and lower reaches of the Yangtze River (figure S1 (available online at stacks.iop.org/ERL/16/044058/mmedia)) in China, with rainstorm alerts for 41 consecutive days issued by the National Meteorological Center (www.cma.gov.cn/2011wmhd/2011wzbft/202007/t20200717_558692.html). According to the National Climate Center of China, the Meiyu period lasted 62 d in 2020, with the precipitation amount reaching 759.2 mm, which was 1.2 times more than the average amount during the period 1981–2010 (http://news.weather.com.cn/2020/12/3427356.shtml) [1]. The record-breaking precipitation event resulted in severe flooding due to the heavy rainfall and its long duration. Across China, 634 rivers were flooded and exceeded the water level required to issue warnings, causing direct economic losses of 178.96 billion Chinese Yuan (CNY) and leaving 219 people dead or missing (www.chinanews.com/sh/2020/08-14/9264482.shtml). At the same time, South China (figure S1) experienced a persistent and intense extreme hot event. Haikou in Hainan Province (figure S1(a)) experienced 44 hot days during the Meiyu period, which was far more than in previous years (www.cma.gov.cn/2011wmhd/2011wzbft/2011wftzb/202007/t20200731_559715.html). The extreme heat contributed to a widespread drought in South China, with 758 000 km² of land above the
severe drought level in mid-July (https://mp.weixin.qq.com/s/fjDvB-En0vd1PbR6CMKzhaQ). Both the middle-lower reaches of the Yangtze River and South China are regions in that are home to important urban agglomerations for the country, where numerous people live and important economic centers are located. Therefore, the understanding of these two concurrent extreme events is important for disaster prevention and mitigation for these regions in the future.

Previous studies have suggested that the atmospheric circulation contributes to the occurrence of Meiyu [2–4]. In particular, the expansion and contraction of the western side of the western Pacific subtropical high (WPSH) affects the location and direction of the Meiyu rainbelt [5]. During the Meiyu period in 2020, the periodic oscillations of the WPSH and the southwesterly low-level jet, along with the associated repeated development of water vapor convergence and upward movement, led to a super-Meiyu and corresponding extreme precipitation [1], while the interaction between the WPSH and South Asian high in June, as well as that between the South Asian high and midlatitude Mongolian cyclone in July, also played a role [6]. Previous research has indicated that extreme hot events are related to persistent anticyclonic circulation [7], in which a westward-stretching WPSH often causes the occurrence of heatwaves in South China [8, 9]. To what extent, therefore, did the atmospheric circulation contribute to these two concurrent extreme events in 2020? Can it fully explain their occurrence and magnitudes? If not, what else played a role? Addressing these questions is important for future prediction.

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change stated that it is an indisputable fact that the global climate has been warming in recent decades [10]. Global warming has affected the climate around the world to varying extents, such as the increase in daily minimum and maximum temperatures and the higher frequency of warm days and warm nights [11]. The main impact of climate change that people are perceiving is the increasing frequency and intensity of some types of extreme weather and climate events, which have a substantial influence on societies, economies and ecosystems [12–14]. Therefore, attribution of extreme events is a field of study that has been attracting a lot of attention amongst researchers in recent years. Specifically, it aims to analyze whether extreme events have changed and can be attributed to the influence of anthropogenic climate change, which is key to understanding the risks associated with climate change [13, 14]. Attribution analysis can provide a scientific basis for decision-makers to formulate policies to deal with climate change [15]. Thus, for the two record-breaking extreme events that occurred during the Meiyu period in 2020, it is important to determine to what extent they were affected by climate change. Previous studies have tended to focus on a single variable of a single event (for example, attribution of the European heatwave in 2003 [12], the high summer temperature in eastern China in 2013 [16], the record-breaking cold event in eastern China in January 2016 [17], and the extreme precipitation event in the Yangtze River valley in warm season 2016 [18–20], or different variables of a single event in the same region (for example, attribution of fires in Northeast Australia in 2018 [21], drought in the southeast periphery of the Tibetan Plateau in 2009 [22], and hot and dry extreme events in Northeast China in the spring and summer of 2017 [23]). To the best of our knowledge, no study has yet focused on the attribution of different variables of different but concurrent events in two different regions, which is what we aimed to do in the present reported work.

In this paper, we analyze the characteristics of the two extreme events using station observation data and reanalysis data, and address the following two questions by carrying out a conditional attribution exercise [24] with circulation that was fixed to the observations using flow analogues: (a) how much did the atmospheric circulation contribute to the record-breaking precipitation event in the middle and lower reaches of the Yangtze River and the concurrent exceptional hot event in South China during the Meiyu period in 2020? (b) Under similar atmospheric circulation conditions, how much did climate change affect the occurrence probability of these two extreme events? This study provides an important reference for the understanding and prediction of extreme weather and climate events in the context of climate change in this region.

2. Data and methods

2.1. Data

The observational data of daily maximum temperature (tmax) and 24 h precipitation used in this study came from the Daily Dataset of Surface Climatic Data of China (V3.0) (SURF_CLI_CHN_MUL_DAY_V3.0), from which 640 stations covering the period from 1960 to 2020 were selected. After repeated quality testing and control, the quality and integrity of all elements in this dataset were found to be higher than other previous ground data products, and the accuracy rate is close to 100% (http://data.cma.cn/data/cddetail/dataCode/SURF_CLI_CHN_MUL_DAY_V3.0.html). The tmax data used have been homogenized [25] and updated. As for precipitation data, these tend not to be homogenized owing to their greater variability, which increases the uncertainty in the homogenized results [26].

Daily mean sea level pressure (SLP) and geopotential height at 500 hPa (Z500) data were obtained from the NCEP/NCAR Reanalysis 1 dataset [27], with a resolution of 2.5° × 2.5° and a time period...
from 1960 to 2020. Compared with other reanalysis products, this dataset covers a wider time range and is updated in a timely manner, allowing us to quickly carry out analysis after the occurrence of the events.

2.2. Event definitions
We focus on the record-breaking precipitation event in the middle and lower reaches of the Yangtze River and the concurrent exceptional hot event in South China during the Meiyu period (June–July) in 2020 (figures 1(a), (c) and S1). During this period, the middle and lower reaches of the Yangtze River were controlled by an anomalous cyclonic circulation, and the intensified WPSH extended westward to South China (figures 1(e) and S1). To consider the effect of this atmospheric circulation on the two extreme events, we divided the regions into the middle and lower reaches of the Yangtze River (120.0°E|35.0°N, 123.0°E|30.0°N, 108.0°E|25.0°N, 105.0°E|30.0°N) and South China (120.0°E|29.0°N, 123.0°E|22.7°N, 109.0°E|18.0°N, 106.0°E|24.3°N). These two regions cover most of the record-breaking stations (figures S1(b) and (c)), and both the observed total precipitation and tmax anomaly (with respect to a 1981–2010 climatology) averaged over the corresponding regions break the historical record during the Meiyu period in 2020 (figures 1(b) and (d)), proving that the selected regions can reflect the intensity of extreme precipitation and temperature. The regional-averaged anomaly was calculated following the standard calculation in the service system of the China Meteorological Administration, such as in Meiyu monitoring indices [28], by using the average anomaly of all stations in the region. Because the region is small and the stations are dense in eastern China, this calculation is close to an area-weighted average. We adopted the Wang and Swail (2001) iterative method [29] (WS2001) and further considered repeat values in significance testing [30] to calculate the linear trend and the corresponding statistical significance of the observed total precipitation and tmax anomaly, allowing outliers in the data, a non-normal distribution and autocorrelation [29, 30].

2.3. Flow-analogues method
To estimate the contribution of the atmospheric circulation to the two concurrent events, we selected historical atmospheric circulation patterns that were similar to the one in 2020 to simulate the
total precipitation and tmax anomaly using the flow-analogues method [31, 32]. The sampling window was set to 61 d in consideration of the seasonal cycle of circulation, precipitation and tmax, as in Jézéquel et al [32]. We carried out parameter sensitivity tests (figures S2 and S3), including the number of analogues, the size of the domain, variables representing the circulation, and a measure of similarity. After sensitivity tests, the 10 best analogues were chosen because the differences between 5 and 25 were small and 10 was the best for tmax (figures S2(a) and S3(a)); the calculation region was defined as (123.0° E|35.0° N, 123.0° E|16.0° N, 102.0° E|16.0° N, 102.0° E|35.0° N) (figures 1(e), S2(b) and S3(b)), which includes the intensified WPSH and the anomalous cyclonic circulation to the northwest side of the WPSH; SLP was selected as the flow variable after comparing with Z500 (figures S2(c) and S3(c)), both of which are the most commonly used variables to study the atmospheric circulation in the flow-analogues method [32]; and the similarity between atmospheric circulation patterns was measured by the spatial correlation coefficient (figures S2(d) and S3(d)). According to Jézéquel et al [32], we first removed the nonlinear trend in the circulation, total precipitation and tmax anomaly, respectively, before calculating the analogues, the aim being to remove the influence of external forcings and consider the role of atmospheric circulation alone. Different from Jézéquel et al [32], the nonlinear trend we used here was based on quadratic polynomial fitting. The results were close to those from the adaptive trend based on the ensemble empirical mode decomposition method [33]. The detailed steps we used to carry out the flow-analogues method are as follows: (a) We calculated the spatial correlation coefficient of the detrended SLP anomaly between each day during the Meiyu period (June and July, 61 d in total) in 2020 and the same date ±30 d from 1960 to 2019, and then selected the ten best analogues. (b) For each day, one of these ten best analogues was randomly picked, so that the corresponding variables could be reproduced into a new sequence with a length of 61 d, and then this new sequence was averaged. (c) To obtain robust results, the simulation process was repeated 100 000 times.

Taking into account the possible systematic bias at sampling and the influence of the persistence of atmospheric circulation, we calculated Control-1 and Control-M according to Jézéquel et al [32]. Control-1 was obtained by picking randomly within the sampling interval in the above step (b) and then simulating the corresponding variables. Considering the persistence of atmospheric circulation, Control-M was similar to Control-1, but analogues in the adjacent M days were not repeatedly picked, where M is the number of days that atmospheric circulation persists. To determine the value of M, we developed the following method. For each year from 1960 to 2020, we constructed an autoregressive moving average model for each grid during the Meiyu period, and determined the order according to Akaike’s information criterion. Then, the median of the auto-correlation order of all grids was taken as the auto-correlation order of the year. Finally, the median was calculated again for the 61 year sequence as the days that atmospheric circulation persists. By doing so, we obtained M = 6 here (note that M depends on the target region and the length of both the study period and sampling window). Before estimating the contribution of atmospheric circulation, the sampling bias from Control-6 was removed, so that the obtained atmospheric circulation in adjacent days was purely random, rather than the possibility of being picked from adjacent days with similar atmospheric circulation patterns as in Control-1.

2.4. Influence of climate change

We also applied the flow-analogues method to different periods: the past (1960–1984) and present (1985–2019) climate [34], to estimate the influence of climate change on precipitation and tmax. To retain the influence of climate change, we did not detrend the total precipitation and tmax anomaly prior to running the simulation. As the number of simulations approached 100 000, the results tended to conform to a normal distribution according to the central limit theorem. After fitting the flow-conditioned total precipitation and tmax anomaly based on the normal distribution, we estimated the occurrence probability of extreme events exceeding a certain threshold in the past (P_b) and present (P_f) climate; then, the fraction attributable risk (FAR, 1 − P_b/P_f) was calculated to evaluate the influence of climate change on the occurrence probability of extreme events [12, 13, 35].

To the best of our knowledge, no published study has used the flow-analogues method for attributing extreme events to climate change in China, although it has been used to estimate the contribution of atmospheric circulation to the record-breaking heat event over Northeast Asia in 2018 [36], as frequently used in Europe for the estimation of the contribution of atmospheric circulation to extreme events, such as in Jézéquel et al [32]. The estimation of the contributions of atmospheric circulation and climate change to extreme events is now put in the same framework in the present study.

3. Results

3.1. Extreme events in the Meiyu period 2020

On the basis of the data we used, during the Meiyu period in 2020, record-breaking extreme precipitation and an exceptional hot event occurred over the middle and lower reaches of the Yangtze River (figures 1(a) and (b)) and South China (figures 1(c) and (d)), respectively; many stations approached or even exceeded historical records (figure S1).
A record-breaking precipitation event was centered in the south of Anhui Province (figures S1(a) and (b)) and concentrated in the middle and lower reaches of the Yangtze River. On 18 July, the precipitation anomaly at Liu’an station in Anhui reached 282.40 mm. The concurrent exceptional hot event was centered around the coast of Fujian Province (figures S1(a) and (c)). The tmax anomaly in most regions of South China reached or exceeded $+1.0^\circ C$, and even reached $+11.17^\circ C$ at Ningde station in Fujian on 16 June.

From the regional average, the total precipitation anomaly in the middle and lower reaches of the Yangtze River during the Meiyu period showed a slight linear increasing trend from 1960 to 2020 (figure 1(b)), with a rate reaching $+7.40$ mm/decade ($-4.25$ to 20.48 mm/decade), which failed to pass the statistical significance test ($P < 0.05$). The nonlinear trend changed from an initial upward trend to a downward one after 2004 (figure 1(b)), possibly due to the weakening of southwesterly water vapor transport caused by the eastward retreat of the WPSH [37]. Since the beginning of the 21st century, the total precipitation averaged over this region has been lower than the climatology for 14 years, but the observed anomaly reached a record high of 246.71 mm (2.8σ) in 2020. The tmax anomaly in South China also shows a linear increasing trend (figure 1(d)), with the magnitude reaching $+0.128^\circ C$/decade (0.040 $^\circ C$/decade–0.225 $^\circ C$/decade), which is statistically significant at the 0.05 level. Meanwhile, the nonlinear trend also increased after 1986 at an increasing rate (figure 1(d)). Since the beginning of the 21st century, tmax averaged over South China has been above the climatology for 17 years, with the observed anomaly exceeding 1σ ($+0.62^\circ C$) for 6 years and even reaching $+1.35^\circ C$ (2.2σ) in 2020. The difference between the trends indicates that, during the Meiyu period, compared with the total precipitation anomaly in the middle and lower reaches of the Yangtze River, the tmax anomaly in South China had a stronger response to external forcing.

The record-breaking precipitation and concurrent exceptional hot event persisted strongly. During the Meiyu period in 2020, the middle and lower reaches of the Yangtze River experienced continuous overcast rain, with precipitation higher than the climatology for 42 d and the precipitation anomaly exceeding $+10$ mm for 11 d (figure 2(a)). The positive precipitation anomaly was mainly concentrated in three time periods (12–23 June, 2–12 July and 15–20 July) and peaked (+23.91 mm) on 19 July; tmax in South China was higher than the climatology for 52 d, and the tmax anomaly exceeded $+2^\circ C$ for 21 d (figure 2(b)). Furthermore, tmax was more persistent, concentrated in two periods (from 10 June to 7 July and from 11 to 31 July), and reached $+4.26^\circ C$ on 12 June.

### 3.2. Contribution of atmospheric circulation

Figure 2 shows the simulated results using the flow-analogues method. For the detrended total precipitation anomaly, the flow-conditioned anomaly averaged by the ten best analogues could not reach the observed daily anomaly for 40 d, and 4 d were outside the range of the flow-conditioned anomaly (indicating that atmospheric circulation alone cannot explain the observed precipitation anomaly; figure 2(a)). For the detrended tmax anomaly, the averaged flow-conditioned anomaly failed to reach...
the observed daily anomaly for 49 d and 12 d were outside the range (figure 2(b)). The flow-conditioned anomalies failed to simulate the observed anomalies for most of the days concerned, suggesting that the two extreme events cannot be explained from the perspective of atmospheric circulation only.

Next, we quantified the contribution of atmospheric circulation to the record-breaking precipitation and concurrent exceptional hot event. According to the results from the 100 000 simulations, partial flow-conditioned detrended total precipitation anomalies were able to reach the observed anomaly, with a median of 164.90 mm (figure 3(a)). The observed precipitation anomaly was almost the 95% quantile in the 100 000 detrended samples. In contrast, all the flow-conditioned detrended tmax anomalies were unable to reach the observed anomaly, with a median of 0.58 °C (figure 3(b)). The medians of both Control-1 and Control-6 were close to 0 (Control-6, −9.59 mm and −0.01 °C, respectively), indicating that the sampling bias was small. We divided the difference between the median of the flow-conditioned anomaly and the median of Control-6 by the observed anomaly to estimate the contribution of atmospheric circulation, as done in Jézéquel et al [32], and found that atmospheric circulation explained 70.73% and 43.61% of the total precipitation and tmax anomalies, respectively. This result indicates that the contribution of atmospheric circulation to this record-breaking precipitation event was higher than the contribution of atmospheric circulation to the concurrent exceptional hot event. The region to which we applied the flow-analogues method included the intensified WPSH and the anomalous cyclonic circulation, which was associated with water vapor convergence, to the northwest side of the WPSH during the Meiyu period in 2020 (figures 1(e) and S1(a)). In the sensitivity tests, with expansion of the region, the contribution of atmospheric circulation decreased, which indicates a strong dependence of precipitation on such an atmospheric circulation pattern (figure S2(b)). Therefore, the atmospheric circulation can explain most of this record-breaking precipitation event. Reasons why the flow-conditioned anomaly was unable to reach the observed anomaly for tmax may be: (a) based on the analysis above, the tmax anomaly in South China increased significantly after 1986 (figure 1(d)), possibly caused by external forcing, while historically similar atmospheric circulation was unable to reflect such an increasing trend; (b) the flow-analogues method fails to take into account the role of thermodynamic processes such as soil moisture feedback [32], which may also have played a role in the occurrence and development of this exceptional hot event.

3.3. Contribution of climate change

As atmospheric circulation does not explain both events completely, what role did climate change play? Flow-conditioned anomalies simulated from the present climate (1985–2019) were closer to the observed anomaly than those from the past climate (1960–1984) (figures 3(c) and (d)), suggesting that under atmospheric circulation patterns similar to the 2020 pattern, the positive anomalies corresponding to the present climate are stronger, and climate change increases the occurrence probability of this record-breaking precipitation and concurrent exceptional hot event. After fitting the flow-conditioned
anomalies simulated from different periods, we found that the occurrence probability of precipitation events with intensity reaching or exceeding the 2020 record-breaking precipitation event increases from 1.23% ($P_0$) in the past to 6.25% ($P_1$) at present. Climate change increases the occurrence risk of events similar to this record-breaking precipitation event by 5.1 times ($P_1/P_0$), and the corresponding FAR reaches 0.80, suggesting that 80% of the current occurrence probability can be attributed to the influence of climate change (figures 4(a) and (b)). For the tmax anomaly, climate change significantly shifts the distribution to the right (µ: 0.19 °C versus 0.71 °C; figure 4(c)). We selected $1\sigma$ (+0.62 °C) as the threshold because the flow-analogues method fails to simulate the observed tmax anomaly in past climate (FAR is equal to 1 if the observation of 2020 is used as a threshold). The occurrence probability of temperature events reaching or exceeding this threshold increases from 0.58% ($P_0$) in the past to 68.73% ($P_1$) at present, with the corresponding FAR reaching 0.99 (figure 4(d)). This result suggests that climate change has changed the occurrence of temperature events reaching or exceeding $1\sigma$ from rare in the past to common today. The discrepancy between the flow-conditioned anomalies of total precipitation and those of tmax simulated from different periods indicates that tmax is affected more strongly by climate change. In addition, as the threshold increases, the FAR of both the simulated precipitation and tmax anomalies increases (figures 4(b) and (d)), indicating that under similar atmospheric circulation, the stronger the event is, the larger the occurrence probability of extreme precipitation and hot events in these two areas is increased by climate change. The uncertainty ranges of the fitted distribution and those of FAR obtained from 10 000 bootstrap simulations were trivial (figure 4), suggesting that our results are robust.

4. Discussion

We also carried out a sensitivity test for different choices of reanalysis datasets. We used 6 h SLP data from the Japanese 55 year Reanalysis (JRA-55) [38] and the fifth-generation reanalysis data product of the European Centre for Medium Range Weather Forecasts (ERA5) [39] from 1960 to 2020. For each day, we averaged the 6 h SLP data to obtain the daily mean SLP. The results (figure S4) showed that overall the results from the three reanalysis datasets were similar, and that the NCEP/NCAR reanalysis was the best in terms of both cases in our study. Its flow-conditioned anomaly was slightly closer to the observed anomaly than that of JRA-55, for both precipitation and tmax (figures S4(a) and (b)). The ERA5 dataset was the worst in terms of tmax (figure S4(b)), possibly due to the fact that the period between 1950 to 1978 in ERA5 (a preliminary version released) suffered from tropical cyclones that were sometimes unrealistically intense (https://confluence.ecmwf.int/display/CKB/ERA5+back+extension+1950-1978+%28Preliminary+version%29%3A+tropical+cyclones+are+too+intense), which is important in our study.
region and study period where and when tropical cyclones are active. Therefore, we only present the results from the NCEP/NCAR reanalysis in the main text of this paper.

One possible explanation for our attribution results for the precipitation event may be due to the increase in water vapor under climate change. Previous studies have suggested that the water-holding capacity of the atmosphere increases by about 7% for every 1 °C rise in temperature according to the Clausius–Clapeyron relation [40]. As for the hot event, climate change provided warmer background conditions for its occurrence, with the increase in regional-averaged tmax over South China during the Meiyu period between the past and present climate reaching 0.38 °C. Further study is needed to quantify the contribution of human-induced climate change. In addition, in a broad sense, the events in our study belonged to the category of ‘spatially compounding events’ as classified by Zscheischler et al [41], although we treated them as two concurrent events and carried out the attributions separately. Future work could estimate the probability that these two events occur at the same time.

Although we cannot rule out the possibility that natural variability alone could have caused this precipitation extreme (figure 3(a)), climate change increased its occurrence probability (figure 4(a)). Under this circumstance, active adaption and mitigation measures are important to reduce the impact and losses caused by disasters under climate change [42].

5. Conclusions

In this study, we investigated the record-breaking precipitation event that occurred over the middle and lower reaches of the Yangtze River and the concurrent record-breaking hot event in South China in June and July covering the Meiyu period in 2020. These two events were characterized by high intensity and strong persistence. According to the trend from 1960 to 2020, the total precipitation anomaly increased slightly at a rate of +7.40 mm/decade, while the tmax anomaly showed a statistically significant increasing trend at a rate of +0.128 °C/decade.

We then simulated the two events using a refined flow-analogues method. The simulation results showed that, compared with no-flow-conditioned simulations, the atmospheric circulation contributed 70.73% and 43.61% to the record-breaking precipitation and concurrent exceptional hot event, respectively, indicating that these two events cannot be explained by atmospheric circulation alone. The reason why atmospheric circulation can explain most of the intensity of this record-breaking precipitation event may be because the occurrence of this event was closely related to the anomalous cyclone and the intensified WPSH. However, the atmospheric circulation can only explain less than half of the intensity of the exceptional hot event, possibly due to the fact that historically similar atmospheric circulations fail to reflect the increasing trend of the tmax anomaly under external forcings and fail to consider the role of thermodynamic processes [32].

We also simulated the total precipitation and tmax anomaly from the past (1960–1984) and present (1985–2019) climate, respectively. The results indicated that, under similar atmospheric circulation patterns, climate change makes the occurrence probability of events similar to the record-breaking precipitation event increase from 1.23% in the past to 6.25% at present, and the occurrence risk increases by 5.1 times, with the corresponding FAR reaching 0.80. The occurrence probability of a temperature event reaching or exceeding $1\sigma$ increases from 0.58% to 68.83%, with the corresponding FAR reaching 0.99. Therefore, under similar atmospheric circulation conditions, these two exceptional events have been exacerbated by climate change, with the temperature event being the more strongly affected.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html.

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