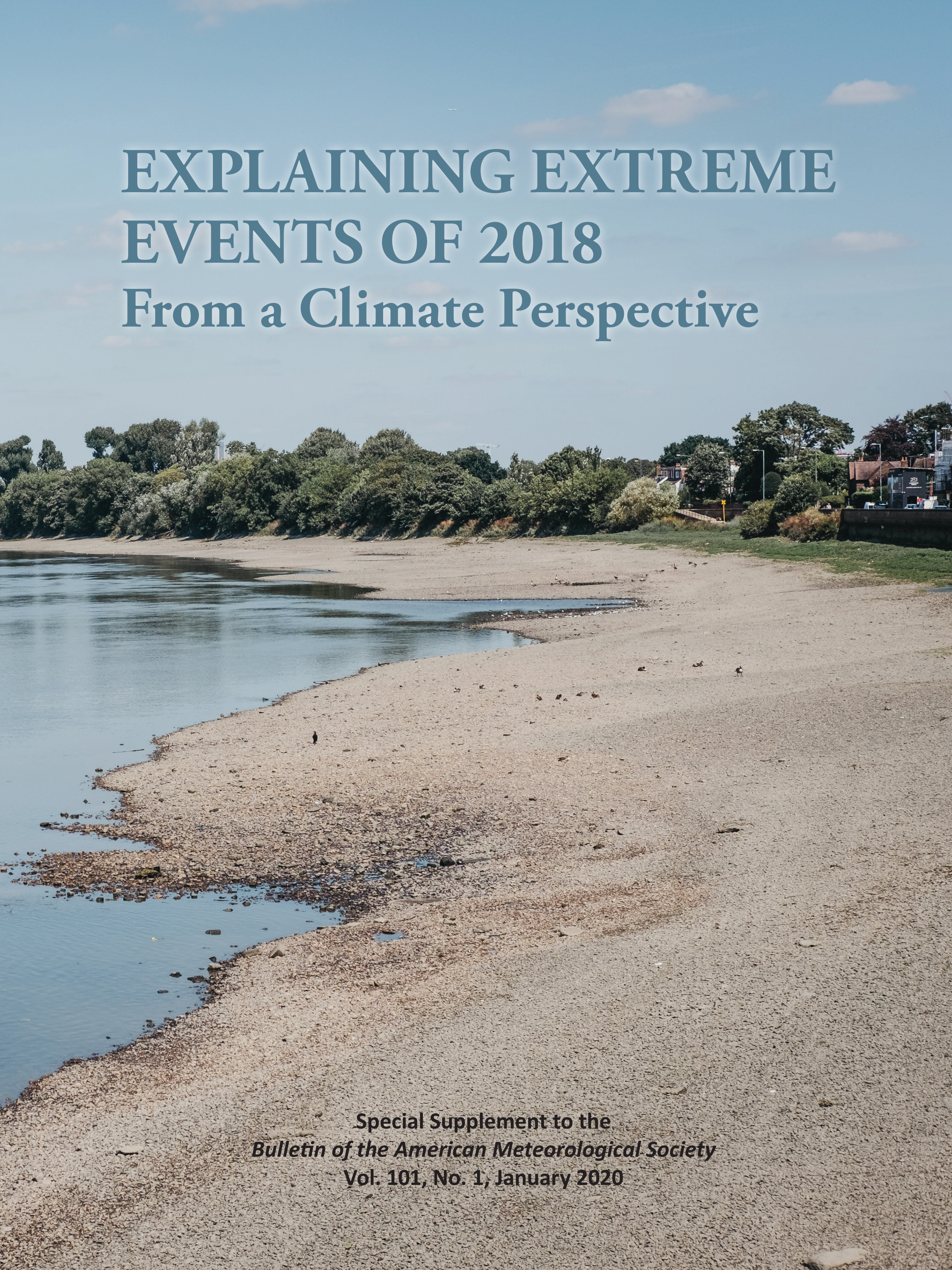
EXPLAINING EXTREME EVENTS OF 2018

From a Climate Perspective



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EXPLAINING EXTREME EVENTS OF 2018 FROM A CLIMATE PERSPECTIVE

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COVER CREDIT: iStock.com/Alena Kravchenko—River Thames receded during a heatwave in summer 2018 in London, United Kingdom.

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TABLE OF CONTENTS

ANTHROPOGENIC INFLUENCE ON 2018 SUMMER PERSISTENT HEAVY RAINFALL IN CENTRAL WESTERN CHINA

Wenxia Zhang, Wei Li, Lianhua Zhu, Yuanyuan Ma, Linyun Yang, Fraser C. Lott,
Chunxiang Li, Siyan Dong, Simon F. B. Tett, Buwen Dong, and Ying Sun

Anthropogenic forcing has reduced the probability of summer persistent heavy rainfall in central western China similar to 2018 by ~47%, but increased that of daily extremes by ~1.5 times, based on HadGEM3-GA6 ensembles.

During mid-June to mid-July 2018, parts of Sichuan, Gansu, and Shaanxi provinces in China were affected by a persistent heavy rainfall event. Accumulated rainfall during the four-week period 18 June to 15 July was 38% above the 1961–2010 climatology. This was very close to the record (44% set in 2016) for maximum summertime four-week rainfall since 1961 (Figs. 1a,b). During this persistent rainfall event, the maximum 1-day rainfall was the fifth most extreme in the wet season on record. This persistent intense rainfall event caused floods, landslides, and house collapses, affecting 2.9 million people and resulting in a reported direct economic loss of over 8.9 billion Yuan (1.3 billion U.S. dollars; National Disaster Reduction Commission; https://reliefweb.int/disaster/tc-2018-000110-chn).

Central western China is located to the east of the Tibetan Plateau and in the marginal East Asian monsoon region. Summer heavy rainfall here is mainly caused by large-scale circulation anomalies involving the western North Pacific subtropical high (WNPSH) and southwest monsoon trough, as well as mesoscale and synoptic-scale weather systems such as Tibetan plateau vortices (Zhou and Yu 2005; Dong et al. 2007; Ueno et al. 2011; Xiang et al. 2013; Chen and Xu 2016). Anthropogenic influences have been found on extreme rainfall events in parts of China, particularly to increase the intensity of short-term

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storms (Burke et al. 2016). Furthermore, understanding how anthropogenic forcings affect the duration and intensity of heavy rainfall events is important (e.g., Burke and Stott 2017). This study examines how human activities have affected persistent heavy and daily extreme rainfalls in 2018 summer over central western China.

DATA AND METHODS. The 2018 rainfall event was largely confined to 30°–38°N, 100°–110°E (black

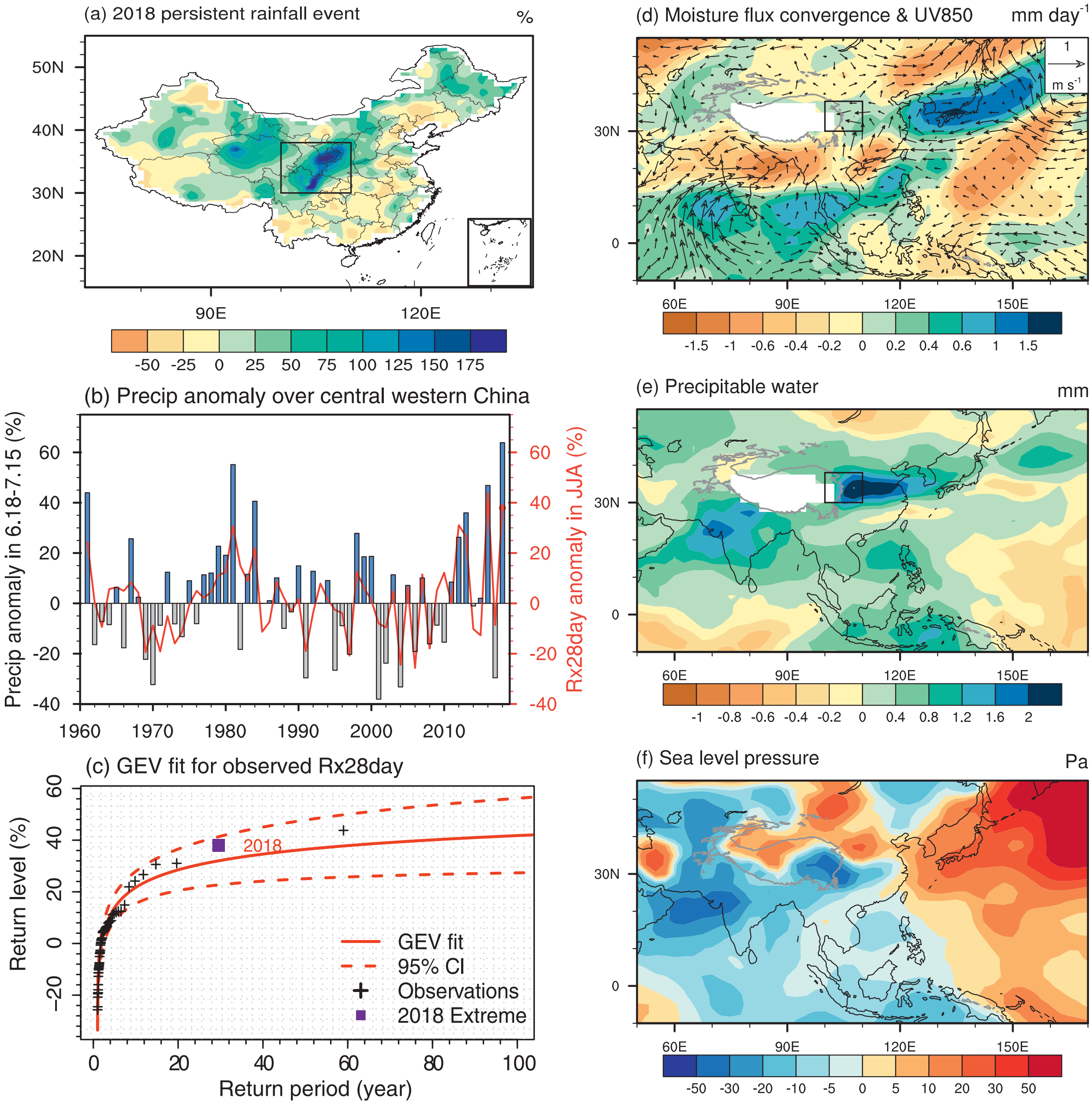

Fig. 1. (a) Observed rainfall anomalies accumulated during 18 Jun to 15 Jul 2018 relative to the 1961–2010 climatology over the same period (%). The black box denotes central western China (30°–38°N, 100°–110°E). (b) Time series of accumulated rainfall during 18 Jun to 15 Jul (bar) and Rx28day for June to August (red line) for the black box in (a), in percentage anomalies relative to 1961–2010. (c) GEV fit (red line) of observed Rx28day with 95% confidence intervals. The crosses are estimated from the empirical distributions of the observed Rx28day with the purple square denoting the 2018 event. Also shown are the regression of (d) column integrated moisture convergence (shading; mm day^{-1}) and 850-hPa horizontal winds (vector; m s-1), (e) total column water vapor (mm), and (f) sea level pressure (Pa) onto standardized rainfall anomalies over central western China during 18 Jun to 15 Jul for 1961–2018.

box in Fig. 1a). Gridded daily rainfall observations (0.5° × 0.5°) for 1961–2018 are from the China Meteorological Administration, using ~2400 stations over China with rigorous quality control (Shen et al. 2010). Daily circulation fields are from the NCEP–NCAR Reanalysis 1 (2.5° × 2.5°; Kalnay et al. 1996).

We use the latest Met Office HadGEM3-GA6-based attribution system at N216 resolution (hereafter simply HadGEM3-A; ~60 km at midlatitudes; Ciavarella et al. 2018). This attribution system comprises a pair of multidecadal ensembles, one with both natural and anthropogenic forcings (Historical) and the other with time-varying natural forcings and all anthropogenic forcings fixed at 1850 levels (HistoricalNat) and are described in the online supplemental material. The 2018 ensembles (termed HistoricalExt and HistoricalNatExt) are used in the attribution analysis.

We investigate the duration and intensity of heavy rainfall. The persistent heavy rainfall event is defined as the maximum accumulated rainfall over two to four weeks from June to August (hereafter Rx14day, Rx21day, and Rx28day), to avoid selection biases in the duration of events and test the robustness of the results. These three indices in 2018 summer were observed to be the second highest on record since 1961. The daily extremes are represented by the maximum 1-day and 3-day rainfalls (Rx1day, Rx3day), which, in summer 2018, were the fifth and third most extreme on record. Here Rx1day is defined as the summer maximum of regional average daily rainfall, considering that the occurrence of the Rx1day total in 2018 was associated with and occurred during the persistent rainfall. We mainly show results for Rx28day and Rx1day for conciseness.

As the model overestimates rainfall amount over this region compared to observations by 13% for the 1961–2010 climatology (see Figs. S1a,b in the online supplemental material), indices are normalized. We employ two methods of normalization. 1) RxNday (N = 1, 3, 14, 21, 28) is expressed as a percentage anomaly relative to the 1961–2010 climatology of RxNday. The Rx28day (Rx1day) in summer 2018 is 38% (27%) above the corresponding 1961–2010 climatology. 2) Daily rainfall is divided by the 1961–2010 June to August mean rainfall and then RxNday is computed (expressed in %). Thus, the intensity of Rx28day (Rx1day) in 2018 is 1.9 (5.5) times of the summer daily rainfall climatology. The two methods of normalization effectively correct the wet bias in the simulated rainfall indices (Figs. S2a–c). We show the results based on the first method of normalization in Figs. 2a–g. The two methods yield quantitatively consistent results (Figs. S2d–f), confirming the robustness of our results.

As the normalization only corrects the model climatologies of rainfall indices, we further evaluate the simulated heavy rainfall variability against observations using a Kolmogorov–Smirnoff (K-S) test. We fit the generalized extreme value (GEV) distribution to the rainfall indices and use it to estimate the occurrence probability and return periods for both observations and simulations. To estimate the changing likelihood due to anthropogenic forcing, the risk ratio (RR = P_{ALL}/P_{NAT}) is calculated using the GEV fit, which compares the occurrence probability between the HistoricalExt under all forcings (P_{ALL}) and HistoricalNatExt under natural forcings only (P_{NAT}). The risk ratio uncertainty is estimated via bootstrapping 1000 times, by resampling all ensemble members with replacement, and we show, as bracketed ranges after the value, the 5–95th percentiles of the empirical distribution throughout.

RESULTS. The observed Rx28day in summer 2018 (38% above climatology) corresponds to a 1-in-60-yr event in the observed records, based on the GEV fits (Fig. 1c). This type of anomalous rainfall, associated with enhanced moisture convergence, is primarily driven by enhanced low-level southerly winds carrying warm moist air from the western Pacific. This in turn is associated with the intensification and westward extension of WNPSH, and anomalous atmospheric moisture availability (Figs. 1d,f).

It is crucial for the model to realistically reproduce the large-scale circulations responsible for rainfall events. Here we evaluate the simulated summer mean rainfall and circulation interannual variability, which gives a background relevant to persistent heavy rainfalls. For interannual variations, HadGEM3-A captures the large-scale circulation anomalies responsible for the anomalous rainfall in the target region well. In both model and observations, heavy rainfall is associated with low-level anticyclonic anomalies from eastern China to the western Pacific, favoring southwesterly moisture transport to this region (Figs. S1c,d). Burke and Stott (2017) report that HadGEM3-A can reproduce the main features of the East Asian summer monsoon (EASM), although the simulated mean WNPSH and EASM circulation is weaker and shifted east compared with observations (Figs. S1a,b; Rodríguez et al. 2017). Thus, the model generally reproduces the physical processes related to seasonal rainfall anomalies, which are relevant to persistent heavy rainfalls examined in this study.

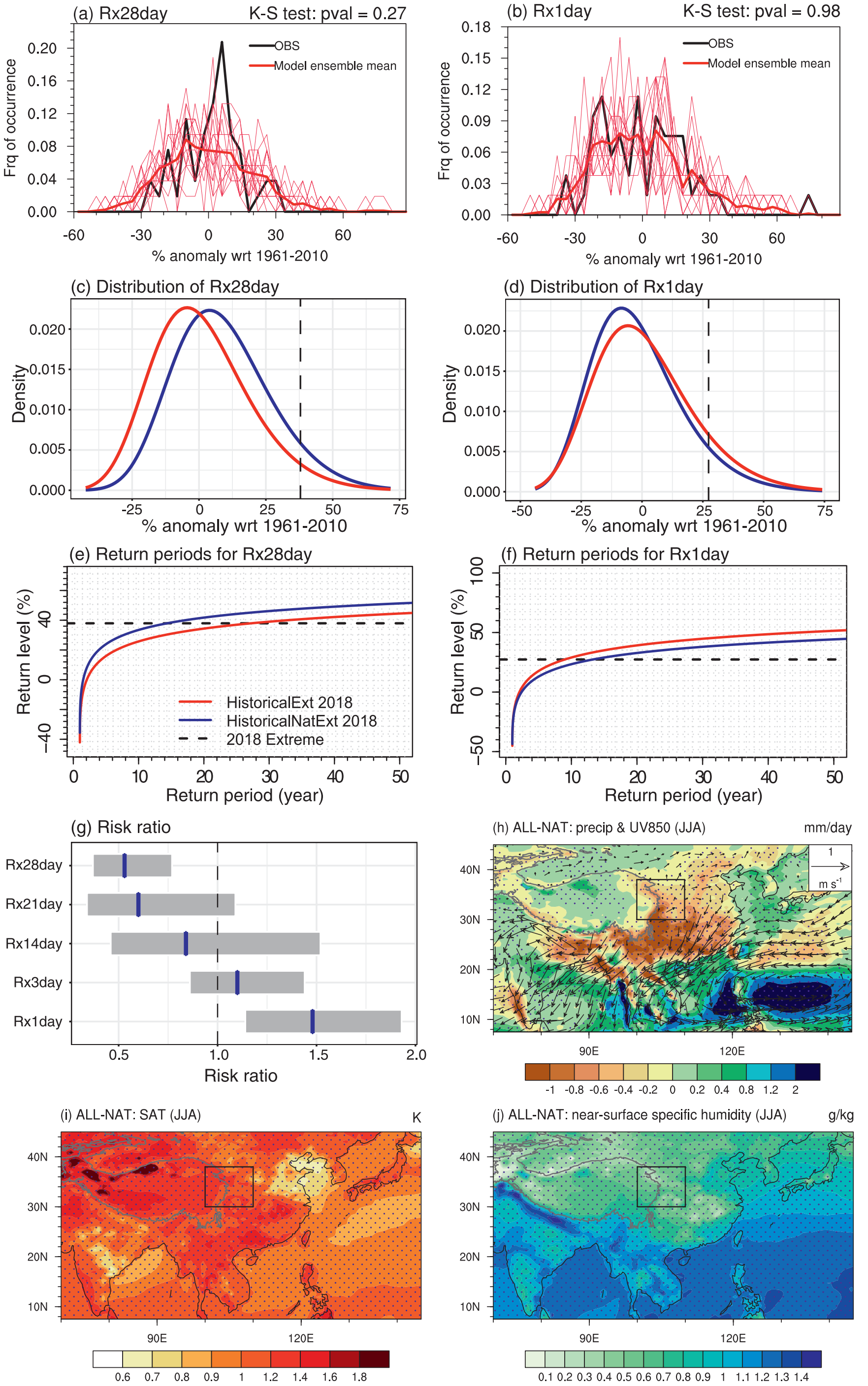

FIG. 2. (a),(b) Distributions of normalized Rx28day and Rx1day for observations (black) and Historical all-forcing simulations (red) for 1961–2013. The thin red lines denote individual members. The p values for the K-S test are shown at top right. (c),(d) GEV fits and (e),(f) return periods of normalized Rx28day and Rx1day for HistoricalExt (red) and HistoricalNatExt (blue) 2018 simulations. The dashed black lines denote the observed event in 2018. (g) The best estimates (blue lines) and 90% confidence intervals (gray shadings) of risk ratio for different rainfall indices. Also shown are multi-member mean differences of JJA mean rainfall and (h) 850-hPa winds, (i) near-surface air temperature, and (j) specific humidity between HistoricalExt and HistoricalNatExt ensembles. Dots indicate 10% significance level for the shaded fields.

The distributions of normalized heavy rainfall in the model and observations cannot be distinguished using the K-S test (p value > 0.05; Figs. 2a,b). We then compare the distributions of heavy rainfall in the HistoricalExt and HistoricalNatExt ensembles for 2018. For Rx28day, there is a shift toward weaker events if anthropogenic forcing is included, indicating a reduced probability of persistent heavy rainfalls (Figs. 2c,e). P_{NAT} for Rx28day > 38% above climatology is 0.070 (0.055–0.083), which reduces to 0.037 (0.028–0.046) for P_{ALL}. This gives a risk ratio of 0.53 (0.37–0.77; Fig. 2g), implying that the likelihood of the persistent heavy rainfall with a magnitude similar to 2018 summer in central western China is reduced by approximately 47% due to anthropogenic forcing by the best estimate.

For daily extremes, however, the distribution shifts toward intense events in HistoricalExt compared to HistoricalNatExt (Fig. 2d). Hence, anthropogenic forcing has increased the probability of Rx1day like that in summer 2018 from 0.075 (0.060–0.088) for P_{NAT} to 0.111 (0.091–0.128) for P_{ALL}, along with shortened return periods (Fig. 2f). This gives a risk ratio of 1.48 (1.14–1.93; Fig. 2g).

Thus, anthropogenic forcing has reduced the probability of persistent heavy rainfalls, but increased that of daily extremes. The risk ratio remains above one for Rx1day and decreases consistently as the duration of heavy rainfall increases (Fig. 2g).

Then why has anthropogenic forcing caused opposite changes in the probabilities of persistent heavy and daily extremes? Largely fueled by moisture convergence, the intensification of daily extreme rainfall is related to atmospheric moistening as temperature rises under anthropogenic forcing (Figs. 2i,j; Allen and Ingram 2002; Trenberth et al. 2003).

The weakened persistent heavy rainfalls under anthropogenic forcing are consistent with the significantly reduced EASM rainfall, due to the weakened EASM circulation (Fig. 2h). Thus, the weakened background mean circulations in response to anthropogenic forcing are unfavorable for summer persistent heavy rainfalls in central western China.

Further disentangling the contributions from greenhouse gases (GHG) and other anthropogenic forcings, specifically aerosols, would improve understanding of the attribution outcome (e.g., Rimi et al. 2019; Kumari et al. 2019). Despite the lack of separate forcing experiments from HadGEM3-A, we suspect that the weakening of the EASM and persistent heavy rainfalls due to anthropogenic forcings is largely induced by aerosols. These overwhelm the GHG-induced intensification of EASM and heavy rainfalls, based on physical understandings established in many previous studies using the CMIP5 ensemble (Song et al. 2014; Li et al. 2015; Zhang and Li 2016) and single models (Burke and Stott 2017; Tian et al. 2018).

However, with the future reductions in aerosols and continued increases in GHG, the probabilities of both daily and persistent heavy rainfalls in central western China would robustly increase, along with a wetter EASM, according to the CMIP5 ensemble (Table S1 and Figs. S2g–i; future projections directly comparable to the HadGEM3-A attribution runs are not available). This is consistent with previous studies indicating a general intensification in EASM circulation (Christensen et al. 2013; Wang et al. 2014) and persistent extreme rainfalls in East Asia (Chevuturi et al. 2018) under future warming. As such, the attribution outcome for the present day is not a simple analog for the future climate and the adverse impact of GHG-induced warming on flooding risks may exacerbate in the future.

We repeat our analysis with the northern boundary of the region modified from 38° to 40°N and find similar risk ratios. However, the model's ability to capture the persistent heavy rainfall variability decreases. This is possibly because the larger region additionally includes different climate regimes (cf. dashed and solid boxes in Fig. S1a), adding complexity to the rainfall variations. It implies the importance of selecting regions based on physical considerations (e.g., climate regimes) when testing the spatial scales.

CONCLUSIONS.

We show that anthropogenic forcing has opposing contributions to the probabilities of persistent and daily heavy rainfalls in the current climate. Anthropogenic forcing has reduced the probability of 2018 summer persistent heavy rainfall in central western China by ~47%, but increased that of daily extremes by ~1.5 times. This result is robust against different choices of events and methods of normalization. While it is a caveat of the study that the attribution results are based on a single-model ensemble, the model's ability to generally reproduce the large-scale circulation anomalies related to seasonal rainfall anomalies enhances the confidence in the results.

However, the attribution result for the present day is not analogous to what may be experienced in future with reduced aerosols, making decision-making for floods in this region more challenging. The current state-of-the-art climate models actually project increasing probabilities of both daily and persistent heavy rainfalls in this region. Further disentangling the contributions of GHG and anthropogenic aerosols on the risks of heavy rainfall, as well as quantification of future risks, needs to be explored more.

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