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Anthropogenic Influences on 2019 July Precipitation Extremes Over the Mid–Lower Reaches of the Yangtze River

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Understanding the driving factors for precipitation extremes matters for adaptation and mitigation measures against the changing hydrometeorological hazards in Yangtze River basin, a habitable area that provides water resources for domestic, farming, and industrial needs. However, the region is naturally subject to major floods linked to monsoonal heavy precipitation during May–September. This study aims to quantify anthropogenic influences on the changing risk of 2-week-long precipitation extremes such as the July 2019 extreme cases, as well as events of shorter durations, over the middle and lower reaches of Yangtze River basin (MLYRB). Precipitation extremes with different durations ranging from 1-day to 14-days maximum precipitation accumulations are investigated. Gridded daily precipitations based on nearly 2,400 meteorological stations across China are used to define maximum accumulated precipitation extremes over the MLYRB in July during 1961–2019. Attribution analysis is conducted by using the Met Office HadGEM3-GA6 modeling system, which comprises two sets of 525-member ensembles for 2019. One is forced with observed sea-surface temperatures (SSTs), sea-ice and all forcings, and the other is forced with preindustrialized SSTs and natural forcings only. The risk ratio between the exceedance probabilities estimated from all-forcing and natural-forcing simulations is calculated to quantify the anthropogenic contribution to the changing risks of the July 2019–like precipitation extremes. The results reveal that anthropogenic warming has reduced the likelihood of 2019-like 14-days heavy precipitation over the mid–lower reaches of the Yangtze River by 20%, but increased that of 2-days extremes by 30%.

Keywords: precipitation extreme events, climate change, Yangtze (Changjiang) catchment, attribution studies, anthropogenic influence

INTRODUCTION

During July 3–16, 2019, the mid–lower reaches of the Yangtze River basin (MLYRB) suffered from prolonged heavy precipitation, with regional-mean record-breaking precipitation total of 232 mm (90% higher) against the 1961–2010 July climatology of maximum 14-days accumulated rainfall of 122 mm. This event endangered the main stream of the Yangtze River, including Poyang Lake (China's largest freshwater lake) and Dongting Lake, by producing severe floods. Heavy rain and floods killed 37 people, affected 10.3 millions of residents, and damaged 776,900 hectares of farmland across four provinces (China Ministry of Emergency Management, 2020). The direct economic loss is estimated to be at least 32 billion RMB (equivalent to US $4.6 billion).

Tens of millions of people live in the floodplain of the MLYRB, a habitable area that provides water resources for domestic, farming, and industrial needs. However, the MLYRB is naturally subject to major floods linked to monsoonal heavy precipitation during May–September (Jiang et al., 2008). In this region, water level rises and soils get saturated gradually because of the accumulation of earlier-stage (April–June) monsoon rainfall. When compounded with subsequent heavy precipitation in the following months, persistent events, in particular, catastrophic floods and landslides, can occur.

Understanding the driving factors for precipitation extremes matters for adaptation and mitigation measures against the changing hydrometeorological hazards in this vulnerable region. This study aims to address this scientific question by quantifying anthropogenic influences on the changing risk of 2-week-long precipitation extremes such as the July 2019 case, as well as events of shorter durations, over the MLYRB.

DATA AND METHODS

Precipitation extremes during July 3–16, 2019, in the Yangtze River basin (YRB), severely hit widespread regions (566,357 sq km) within the study basin (**Figure 1A**). Gridded daily rainfall observations (0.56° × 0.83°) for 1961–2019 from ~2,400 quality-controlled meteorological stations (Shen et al., 2010) are used. This data set is provided by the China National Meteorological Information Center.

The Met Office HadGEM3-GA6 attribution model at a spatial resolution of 0.56° × 0.83° was applied in this study. The model outputs include 525 members of all forced simulations (Historical2019) conditioned on the observed 2019 sea surface temperature (SST) and sea ice from the HadISST data set (Rayner et al., 2003), and simulations of the natural climate (Natural2019) with anthropogenic signals removed from 2019 SST patterns and with preindustrial levels. Additional 15-member ensembles (Historical) spanning from 1960 to 2013 were ran using SST boundary conditions and historical forcing conditions to provide a baseline climatology. More details for the design of HadGEM3-GA6 attribution model are provided in Christidis et al. (2013) and Ciavarella et al. (2018).

The multimodel ensembles from the Coupled Model Intercomparison Project Phase 5 (CMIP5) were also employed to further corroborate the attribution results. Climate simulation experiments of historical, historicalNat, and the Representative Concentration Pathway projection scenario 8.5 (RCP8.5) are used in this study. Specifically, historical runs reflect observed atmospheric composition changes due to both anthropogenic and natural forcings, whereas historicalNat only considers the forcings of natural factors including solar irradiance and volcanic aerosols (Van Vuuren et al., 2011). Only model runs that provide daily-scale simulations in historical, historicalNat, and RCP8.5 experiments (the latter are needed for extending historical simulations) were used. This criterion leaves us 36 members from 16 models (**Table 1**). Then, two 36-member ensemble simulations were constructed for the attribution analysis. CMIP5 historicalNat runs for 1996–2005 were used as natural-forcing runs (NAT), and RCP8.5 runs for 2016–2025 were used to represent the 2019 state driven by all forcings (ALL). The selection of time periods for both CMIP5 ALL and NAT simulations is to avoid impacts from major volcano activates such as the 1991 eruption of Mount Pinatubo. Since the historical runs terminate at the end of 2005, CMIP5 historical (1961–2005) and RCP8.5 simulations (2006–2010) were combined to provide a baseline climatology. This is because the projected greenhouse gas forcings of RCP8.5 are more consistent with the present realization than other scenarios (Peters et al., 2013). Note that, unlike HadGEM3-GA6 simulations based on 2019 SSTs, CMIP5 simulations encompass a wide range of ocean states. Consequently, the event probabilities estimated hereafter are differently conditioned, such that the results from the two model sets will not be directly comparable.

Extreme precipitation events of varying durations (RxNday, N = 2, 3, 7, 14) are defined based on the regional-mean maximum accumulated rainfall during July. These RxNday extreme events were expressed as the precipitation anomaly (mm/day) with respect to the 1961–2010 climatology, serving to remove the mean bias in model climatology. The exceedance probability values of the 2019-like RxNday extreme events were estimated from the generalized extreme value (GEV) (Jenkinson, 1955; Ailliot et al., 2011) fitted probability distribution function (PDF) of precipitation anomalies. The risk ratios ($RR = P_{ALL}/P_{NAT}$) between the exceedance probabilities of the RxNday precipitation anomalies estimated from all forcings (P_{ALL}) and natural-only forcing simulations (P_{NAT}) were calculated to quantify the changing risk of the 2019-like precipitation extremes due to anthropogenic influences. RR uncertainty with 90% confidence interval (90% CI) was estimated by identifying the empirical 5th and 95th percentiles among 1,000-times resampling of model ensemble members by using Monte Carlo bootstrapping procedure (Christidis et al., 2013). Doing each bootstrap, model ensemble simulations are randomly resampled with replacement to get a set of new data with the same length as the original. A two-sample Kolmogorov–Smirnoff (K-S) test (Hodges, 1958) with a significance level of 0.05 was applied to test whether the distributions of observed and simulated precipitation anomalies during 1961–2010 are from the same population. Note that precipitation

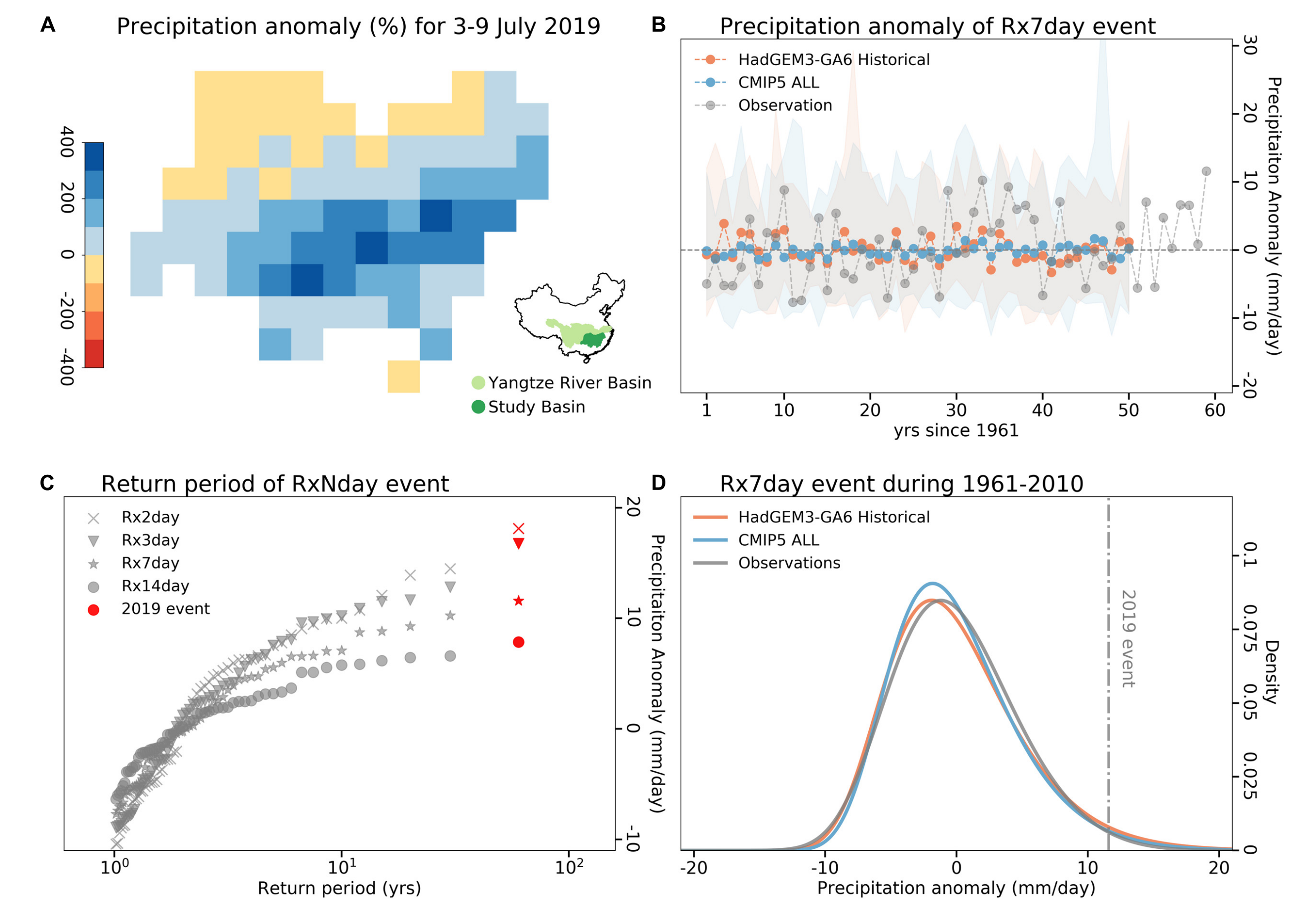

FIGURE 1 | (A) Normalized observed anomalies (%) in precipitation accumulations for 3–9 July 2019 with respect to the Rx7day July precipitation anomalies during 1961–2010 climatology. The study basin (dark green) was located at the mid-lower reaches of the Yangtze River Basin; **(B)** Time series of observed and simulated Rx7day July precipitation anomalies with respect to the 1961–2010 climatology. The shaded areas indicate the spread of 15 and 36 members of HadGEM3-GA6 Historical and CMIP5 ALL simulations, respectively, whereas the dotted lines show their ensemble means; **(C)** The empirical return periods of RxNday July events estimated from the observations during 1961–2019; **(D)** PDFs of Rx7day July precipitation anomalies for the observations, HadGEM3-GA6 Historical and CMIP5 ALL ensemble simulations during 1961–2010 climatology.

anomalies estimated from each model were calculated with their own 1961–2010 climatology, serving to remove the model climatological mean bias.

RESULTS AND DISCUSSION

During July 3–16, 2019, the mid–lower reaches of the Yangtze River were continuously hit by heavy rainfall, of which from July 3–9, precipitation totals more than doubled in 70% of the grids and even tripled in 40% of the grids with respect to the 1961–2010 climatological counterparts during July (**Figure 1A**). From the perspective of regional mean, the observed 2-, 3-, 7-, and 14-days events are all the wettest case on record since 1961 (**Figure 1C**).

Model performances are evaluated against the 1961–2010 climatology. It is clear that the observations were enveloped in their 90% CI uncertainty range for Rx7day event. The probability distributions of simulations and observations are not distinguishable based on visual inspection (**Figure 1D**) and K-S test (Pval=0.97 for HadGEM3-GA6 and Pval=0.63 for CMIP5, **Table 2**). Note that while precipitation anomalies are reasonably simulated by HadGEM3-GA6 and CMIP5, residual errors (systematic and random) remain in both models in terms of actual precipitation values.

To quantify the anthropogenic influences on the changing risk of precipitation extremes, the distributions of all forcings and natural-only forcing simulations are compared. For Rx2day event, the PDFs of all forcing simulations for both HadGEM3-GA6 and CMIP5 models shift toward the larger precipitation anomalies (**Figure 2A**), which indicates the increased probability of daily extreme event when anthropogenic influences are included. Specifically, the exceedance probability of HadGEM3-GA6 Natural2019 increases from 0.008 (90% CI, 0.004–0.013) to HadGEM3-GA6 Historical2019 of 0.011 (90% CI, 0.006–0.016), giving an RR of 1.36 (90% CI, 0.63–3.08) for the 2019-like Rx2day event. While P_{NAT} of CMIP5 NAT increases from 0.016 (90% CI, 0.007–0.024) to P_{ALL} of 0.020 (90% CI, 0.011–0.029) for CMIP5 ALL, which gives the empirical RR of 1.27

TABLE 1 | List of 36 ensemble members from 16 CMIP5 models used in this study.

Models	Resolution (lat × lon)	No. of members
ACCESS1.3	1.25 × 1.875	1
BNU-ESM	2.7906 × 2.8125	1
CCSM4	0.94 × 1.25	3
CESM1-CAM5	0.94 × 1.25	1
CSIRO-Mk3.6.0	1.865 × 1.875	10
CanESM2	2.7906 × 2.8	5
GFDL-CM3	2.0 × 2.5	1
GFDL-ESM2M	2.0225 × 2.5	1
HadGEM2-ES	1.25 × 1.875	4
IPSL-CM5A-LR	1.8947 × 3.75	3
IPSL-CM5A-MR	1.2676 × 2.5	1
MIROC-ESM-CHEM	2.7906 × 2.8125	1
MIROC-ESM	2.7906 × 2.8125	1
MRI-CGCM3	1.1215 × 1.125	1
NorESM1-M	1.8947 × 2.5	1
BCC-CSM1	2.7906 × 2.8125	1

(90% CI, 0.60–2.94). That is, the likelihood of 2019-like Rx2day precipitation extreme has increased by about 30% over the study basin because of the anthropogenic influences. Return periods of simulations also confirm that 2019-like daily precipitation extreme happens more frequently because of anthropogenic influences (**Figure 2B**).

For the Rx14day event, however, the PDFs shift toward the smaller anomalies in all forcing simulations compared to those in natural-only forcing simulations, particularly for HadGEM3-GA6 simulations (**Figure 2C**). Specifically, anthropogenic influences reduce the exceedance probability of the 2019-like Rx14day event from 0.006 (90% CI, 0.002–0.010) of P_{NAT} to 0.003 (90% CI, 0.001–0.006) of P_{ALL} for HadGEM3-GA6 simulations, which gives an empirical RR of 0.50 (90% CI, 0.14–1.42). The CMIP5 multimodel attribution system provides similar results, i.e., RR of 0.82 (90% CI, 0.49–2.12). Thus, the likelihood of 2019-like Rx14day persistent heavy precipitation is reduced by about 20% at least over the study basin because of anthropogenic forcings. Return periods of simulations also confirm that the persistent heavy precipitation became less frequent in July because of anthropogenic influences (**Figure 2D**).

The intensification of daily precipitation extremes could be largely related to atmospheric moistening as temperature rises due to anthropogenic forcings (Allen and Ingram, 2002), while the reduced probability of 14-days extreme rainfall due to anthropogenic forcings might be largely induced by aerosols. By scattering and absorbing solar radiation, increased aerosols over East Asia lead to the weakening of the East Asian summer monsoon (EASM) and reduced summer seasonal mean precipitation over monsoon regions (Song et al., 2014; Tian et al., 2018; Dong et al., 2019; Zhou et al., 2020). These changes induced by aerosols can overwhelm the greenhouse gasses–induced intensification of EASM and precipitation (Song et al., 2014; Tian et al., 2018; Zhou et al., 2020), leading to weakening of EASM, reduced summer mean, and summer persistent (e.g., 14-days) heavy rainfall. Further disentangling the contributions from greenhouse gasses and aerosols on extreme precipitation on different time scales would improve understanding of the attribution outcome.

These findings are consistent with the attribution outcomes in Li et al. (2018, 2021) and Zhang et al. (2020), which all reported anthropogenic influences reduced the likelihood of warm-season persistent precipitation extremes but focused on subregion at the lower reaches of YRB, central-western China, and southern China, respectively. As the other side of the coin, Lu et al. (2021) found that the anthropogenic influences increased the 2019 May–June like droughts over southern China [Figure 2D in Lu et al. (2021)].

Similar attribution analysis was also conducted with respect to the RxNday (N = 2, 3, 7, 14) precipitation extremes during summertime from June to August. These supplementary analyses serve to test the sensitivity of attribution conclusions on timing (entire summer vs. July) of cases considered. It was found that anthropogenic influences have reduced the likelihood of similar summertime Rx14day precipitation extremes by about 20% in HadGEM3-GA6 and 10% in CMIP5, whereas the likelihood of 2019 July-like Rx2day precipitation extremes has increased about 35% and 50% in HadGEM3-GA6 and CMIP5, respectively (**Supplementary Figure S2**). The attribution analysis was also repeated based on percentage anomaly thresholds (precipitation anomaly divided by summer/July climatology) for events of various durations (figures omitted). The qualitative statement that anthropogenic forcings have made short-duration precipitation

TABLE 2 | Attribution results for July RxNday events with risk ratio, exceedance probability from all forcings, and natural-only forcing simulations.

Model	Event	RR (90% CI)	P_{ALL} (90% CI)	P_{NAT} (90% CI)	K-S test (Pval)
HadGEM3-GA6	Rx2day	1.36 (0.63–3.08)	0.011 (0.006–0.016)	0.008 (0.004–0.013)	0.46
	Rx3day	1.45 (0.60–3.77)	0.008 (0.004–0.013)	0.006 (0.003–0.010)	0.53
	Rx7day	1.19 (0.52–2.98)	0.007 (0.004–0.012)	0.006 (0.003–1.010)	0.97
	Rx14day	0.50 (0.14–1.42)	0.003 (0.001–0.006)	0.006 (0.002–0.010)	0.86
CMIP5	Rx2day	1.27 (0.60–2.94)	0.020 (0.011–0.029)	0.016 (0.007–0.024)	0.32
	Rx3day	1.21 (0.50–3.47)	0.012 (0.006–0.019)	0.010 (0.004–0.016)	0.43
	Rx7day	1.60 (0.67–3.96)	0.012 (0.006–0.019)	0.007 (0.003–0.012)	0.63
	Rx14day	0.82 (0.49–2.12)	0.025 (0.016–0.035)	0.031 (0.012–0.042)	0.66

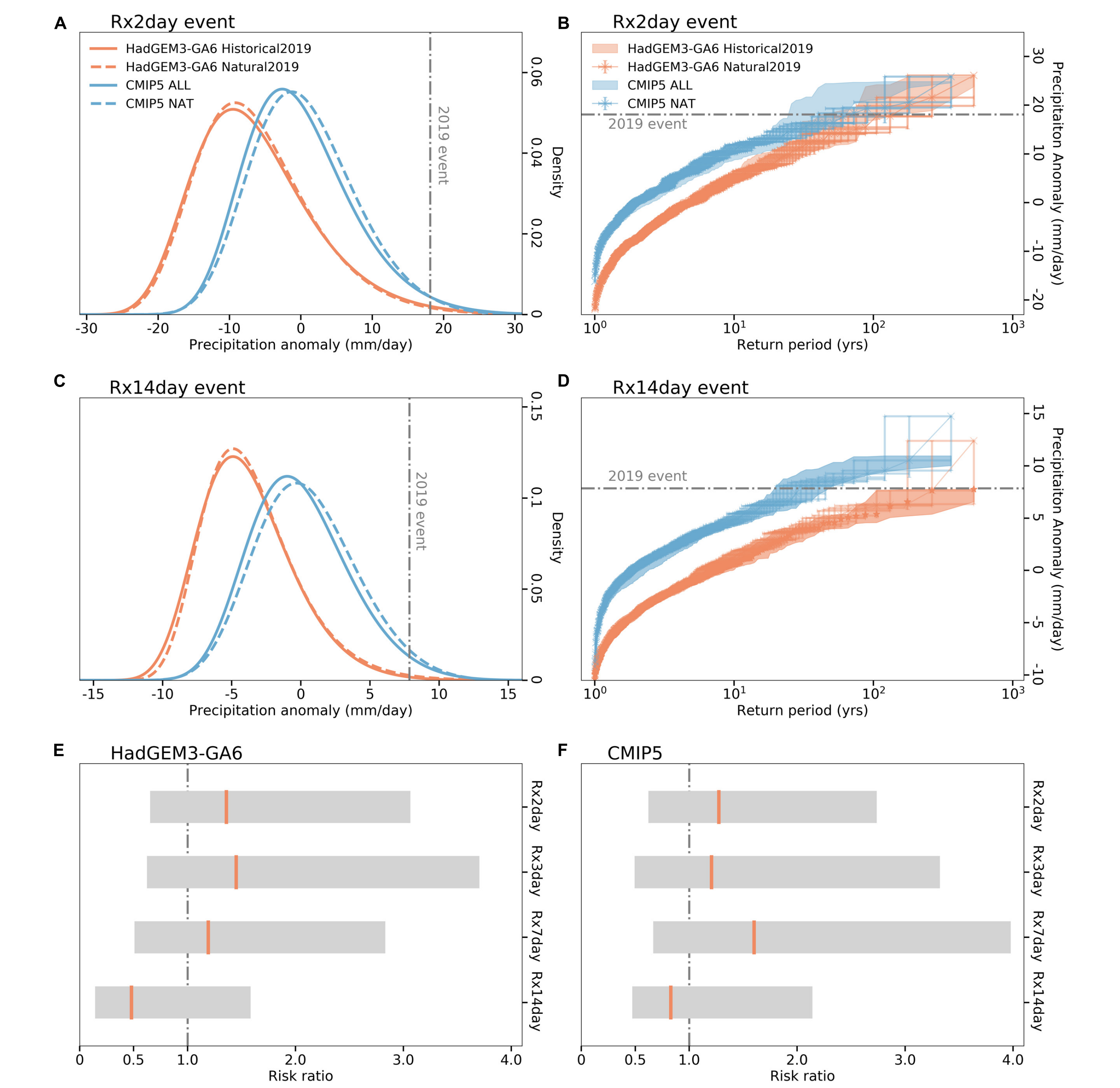

FIGURE 2 | PDFs of precipitation anomalies for the HadGEM3-GA6 and CMIP5 model ensembles with all-forcings (orange) and natural-only forcings (blue) simulations for **(A)** Rx2day and **(C)** Rx14day extreme events; Return periods of **(B)** Rx2day and **(D)** Rx14day extreme events estimated from the HadGEM3-GA6 and CMIP5 model ensembles; Empirical risk ratios (vertical line) with 90% confidence interval (shaded) for RxNday extreme events estimated from the **(E)** HadGEM3-GA6 and **(F)** CMIP5 multimodel ensembles.

extremes more frequent but long-lived events less frequent robustly holds.

CONCLUSION

This attribution analysis reveals that anthropogenic forcings reduce the likelihood of 2019 July-like persistent heavy precipitation event (Rx14day) by about 20% at least, but increase those of daily precipitation extremes (Rx2day) by about 30% over mid–lower reaches of the YRB. The findings are robust against attribution models, timing, and the form of thresholds (absolute anomalies or percentage anomalies) considered. This study highlights that despite reduced risks from long-lasting precipitation extremes, anthropogenic forcings pose the populous and highly urbanized YRB at higher risks of flash floods and resultant hydrometeorological hazards due to the increase of shorter-duration precipitation extremes.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

BD, ST, FL, HW, YC, and NN conceived and planned the experiments. NN, YC, and HW carried out the experiments. YHC, DL, RL, XF, XW, ZH, and YY contributed to data preparation. NN took the lead in writing the manuscript. All authors provided critical feedback and helped to shape the research, analysis, and manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2020.603061/full#supplementary-material

REFERENCES

Ailliot, P., Thompson, C., and Thomson, P. (2011). Mixed methods for fitting the GEV distribution. *Water Resour. Res.* 47, 1–14.

Allen, M. R., and Ingram, W. J. (2002). Constraints on future changes in climate and the hydrologic cycle. *Nature* 419, 228–232. doi: 10.1038/nature01092

China Ministry of Emergency Management (2020). *2019 Top 10 Natural Disasters in China*. Available online at: https://www.mem.gov.cn/xw/bndt/202001/t20200116_343570.shtml (accessed April 13, 2020).

Christidis, N., Stott, P. A., Scaife, A. A., Arribas, A., Jones, G. S., Copsey, D., et al. (2013). A new HadGEM3-A-based system for attribution of weather-and climate-related extreme events. *J. Clim.* 26, 2756–2783. doi: 10.1175/jcli-d-12-00169.1

Ciavarella, A., Christidis, N., Andrews, M., Groenendijk, M., Rostron, J., Elkington, M., et al. (2018). Upgrade of the HadGEM3-A based attribution system to high resolution and a new validation framework for probabilistic event attribution. *Weather Clim. Extremes* 20, 9–32. doi: 10.1016/j.wace.2018.03.003

Dong, B., Wilcox, L. J., Highwood, E. J., and Sutton, R. T. (2019). Impacts of recent decadal changes in Asian aerosols on the East Asian summer monsoon: roles of aerosol–radiation and aerosol–cloud interactions. *Clim. Dyn.* 53, 3235–3256. doi: 10.1007/s00382-019-04698-0

Hodges, J. (1958). The significance probability of the Smirnov two-sample test. *Arkiv för Matematik* 3, 469–486. doi: 10.1007/bf02589501

Jenkinson, A. F. (1955). The frequency distribution of the annual maximum (or minimum) values of meteorological elements. *Q. J. R. Meteorol. Soc.* 81, 158–171. doi: 10.1002/qj.49708134804

Jiang, T., Kundzewicz, Z. W., and Su, B. (2008). Changes in monthly precipitation and flood hazard in the Yangtze River Basin, China. *Int. J. Climatol.* 28, 1471–1481. doi: 10.1002/joc.1635

Li, C., Tian, Q., Yu, R., Zhou, B., Xia, J., Burke, C., et al. (2018). Attribution of extreme precipitation in the lower reaches of the Yangtze River during May 2016. *Environ. Res. Lett.* 13:014015. doi: 10.1088/1748-9326/aa9691

Li, R., Li, D., Nanding, N., Wang, X., Fan, X., Chen, Y., et al. (2021). Anthropogenic influences on heavy precipitation during the 2019 extremely-long rainy season in Southern China. *Bull. Am. Meteorol. Soc.* 102, S71–S76.

Lu, C., Chen, R., Jiang, J., Ullah, S., Yu, R., Lott, F. C., et al. (2021). Anthropogenic influence on 2019 May-June persistent drought in southwestern China. *Bull. Am. Meteorol. Soc.* 102, S65–S70.

Peters, G. P., Andrew, R. M., Boden, T., Canadell, J. G., Ciais, P., Le Quéré, C., et al. (2013). The challenge to keep global warming below 2 °C. *Nat. Clim. Change* 3, 4–6. doi: 10.1038/nclimate1783

Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., et al. (2003). Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res. Atmos.* 108, 4407–4437. doi: 10.1029/2002jd002670

Shen, Y., Xiong, A., Wang, Y., and Xie, P. (2010). Performance of high-resolution satellite precipitation products over China. *J. Geophys. Res. Atmos.* 115:JD012097. doi: 10.1029/2009jd012097

Song, F., Zhou, T., and Qian, Y. (2014). Responses of East Asian summer monsoon to natural and anthropogenic forcings in the 17 latest CMIP5 models. *Geophys. Res. Lett.* 41, 596–603. doi: 10.1002/2013gl058705

Tian, F., Dong, B., Robson, J., and Sutton, R. (2018). Forced decadal changes in the East Asian summer monsoon: the roles of greenhouse gases and anthropogenic aerosols. *Clim. Dyn.* 51, 3699–3715. doi: 10.1007/s00382-018-4105-7

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., et al. (2011). The representative concentration pathways: an overview. *Clim. Change* 109:5. doi: 10.1007/s10584-011-0148-z

Zhang, W., Li, W., Zhu, L., Ma, Y., Yang, L., Lott, F. C., et al. (2020). Anthropogenic influence on 2018 summer persistent heavy rainfall in Central Western China. *Bull. Am. Meteorol. Soc.* 101, S65–S70.

Zhou, T., Zhang, W., Zhang, L., Zhang, X., Qian, Y., Peng, D., et al. (2020). The dynamic and thermodynamic processes dominating the reduction of global land monsoon precipitation driven by anthropogenic aerosols emission. *Sci. China Earth Sci.* 63, 919–933. doi: 10.1007/s11430-019-9613-9

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.