Earth's Future

RESEARCH ARTICLE
10.1029/2023EF003613

Attribution of the Record-Breaking Extreme Precipitation Events in July 2021 Over Central and Eastern China to Anthropogenic Climate Change

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Key Points:

- Global warming might have no (a detectable) contribution to the occurrence probability of a precipitation extreme like the 2021 extreme precipitation event (EPE) in central (eastern) China
- Anthropogenic climate change contributed to +47%/+55% of the decrease/increase in the occurrence probability of the 2021 EPE in central/eastern China
- By the end of the 21st century, the likelihood of such event in central/eastern China would be increased by 14/15 times under SSP585

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Citation:

Wang, L., Gu, X., Slater, L. J., Lai, Y., Zheng, Y., Gong, J., et al. (2023). Attribution of the record-breaking extreme precipitation events in July 2021 over central and eastern China to anthropogenic climate change. *Earth's Future*, *11*, e2023EF003613. https://doi.org/10.1029/2023EF003613

Received 23 FEB 2023
Accepted 6 SEP 2023

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Abstract

In July 2021, Typhoon In-Fa produced record-breaking extreme precipitation events (hereafter referred to as the 2021 EPEs) in central and eastern China, and caused serious socioeconomic losses and casualties. However, it is still unknown whether the 2021 EPEs can be attributed to anthropogenic climate change (ACC) and how the occurrence probabilities of precipitation events of a similar magnitude might evolve in the future. The 2021 EPEs in central (eastern) China occurred in the context of no linear trend (a significantly increasing trend at a rate of 4.44%/decade) in the region-averaged Rx5day (summer maximum 5-day accumulated precipitation) percentage precipitation anomaly (PPA), indicating that global warming might have no impact on the 2021 EPE in central China but might have impacted the 2021 EPE in eastern China by increasing the long-term trend of EPEs. Using the scaled generalized extreme value distribution, we detected a slightly negative (significantly positive) association of the Rx5day PPA time series in central (eastern) China with the global mean temperature anomaly, suggesting that global warming might have no (a detectable) contribution to the changes in occurrence probability of precipitation extremes like the 2021 EPEs in central (eastern) China. Historical attributions (1961–2020) showed that the likelihood of the 2021 EPE in central/eastern China decreased/increased by approximately +47% (−23% to +89%)/+55% (−45% to +201%) due to ACC. By the end of the 21st century, the likelihood of precipitation extremes similar to the 2021 EPE in central/eastern China under SSP585 is 14 (9–19)/15 (9–20) times higher than under historical climate conditions.

Plain Language Summary

Central and eastern China experienced record-breaking extreme precipitation events (EPEs) in July 2021. The summer maximum 5-day accumulated precipitation (Rx5day) of the 2021 EPE in central (eastern) China exceeded the climatology during 1981–2010 by 116.8% (96.1%). Under climate conditions of 1961 and 2021 and based on observations, the 2021 EPE was estimated to be a 1-in-76-year event and 1-in-212-year event in central China, respectively, and a 1-in->10,000-year and a 1-in-256-year event in eastern China, respectively. Here, we estimate the contribution of anthropogenic climate change (ACC) to precipitation extremes of a similar magnitude to the 2021 EPEs and project how their probability might change in the future, based on climate projections from Coupled Model Intercomparison Project Phase 6. We estimate that ACC is responsible for +47%/+55% of the decrease/increase in the occurrence probability of the 2021 EPE in central/eastern China. By the end of the 21st century under a high emission scenario, the probability of occurrence of precipitation extremes similar to the 2021 EPE in central/eastern China is projected to be 14/15 times larger than under historical climate conditions. Our results highlight that EPEs in central

Writing – review & editing: Xihui Gu, Louise J. Slater, Yangchen Lai, Yanhui Zheng, Jie Gong, Moctar Dembélé, Fatih Tosunoğlu, Jianyu Liu, Xiang Zhang, Dongdong Kong, Jianfeng Li

and eastern China are becoming more frequent and more extreme in response to increasing greenhouse gas emissions.

1. Introduction

From 17–31 July 2021, 14.79 million residents, located mainly in the Henan province of central China, and 4.82 million residents mainly in the Jiangsu and Zhejiang provinces of eastern China, experienced record-breaking and persistent extreme precipitation events (EPEs) related to Typhoon In-Fa (TIF) (hereafter, 2021 EPEs). The 2021 EPEs resulted in disastrous stormwater and flooding that killed 302 people and caused a direct economic loss of at least 123.3 billion Chinese Yuan (about 19.1 billion US dollars). Given the record-breaking magnitudes and the catastrophic losses of these events, it is of great importance to estimate how their occurrence probabilities are evolving from the past to the future.

There have been many studies on the causes of the 2021 EPEs from viewpoints of synoptic analysis, moisture source, and precipitation efficiency (Nie & Sun, 2022; Wu et al., 2022; Yang et al., 2022; J. Yin et al., 2022; L. Yin et al., 2022). Synoptic analysis indicates that the strong southeasterly flow between the Western Pacific Subtropical High (WPSH) and TIF conveyed abundant water vapor to central China and caused strong convergence and lifting motion due to the orographic barrier, which enhanced the 2021 EPE in central China (Nie & Sun, 2022; J. Yin et al., 2022; J. H. Zhao et al., 2022). Yang et al. (2022) found that the synoptic environment and weak steering flow caused TIF's long duration over eastern China and adjacent regions, triggering the extremely persistent EPE in eastern China. An analysis of moisture sources by Nie and Sun (2022) found that abundant moisture was conveyed to central China by three main routes triggered by the WPSH, the contribution of WPSH and TIF, as well as the contribution of WPSH and Typhoon Cempaka. Overall, Southern China and the western North Pacific (WNP) contributed 38.1% and 30.0% of moisture sources to the 2021 EPE in central China, respectively. In addition, the convergence of water vapor flux was the key physical factor that impacted large-scale precipitation efficiency, and the net water vapor consumption in microphysical processes obviously affected cloud-microphysical precipitation efficiency (L. Yin et al., 2022). Recently, the contribution of anthropogenic climate change (ACC) to global EPE occurrences (beyond the 2021 event) has been demonstrated in different parts of the world (Fischer & Knutti, 2015; Liu, Qiao, et al., 2021; Patricola & Wehner, 2018). However, it is unclear how ACC has impacted the occurrence probabilities of the 2021-like EPEs in central/eastern China. Moreover, a projection of future occurrence probabilities of precipitation extremes of a similar magnitude to the 2021 EPEs in central/eastern China is of scientific and practical importance to improve flood prevention under future climate change.

The occurrence probabilities of EPEs may be altered by ACC (Fowler et al., 2021; IPCC, 2012; Mann et al., 2017; Mitchell et al., 2016; van Oldenborgh et al., 2018, 2021; Vogel et al., 2019; Willems et al., 2012; T. J. Zhou et al., 2019), as ACC has affected the stationarity of climate (Cheng et al., 2014; McMichael et al., 2006; Slater et al., 2021; Trenberth, 2011; Van Aalst, 2006). From the perspective of long-term trends, the ACC signal has been detected in the intensification of EPEs in some regions. For instance, it is estimated that ACC has intensified EPEs during 1951–2003 over two-thirds of land areas in the Northern Hemisphere (Min et al., 2011). Paik et al. (2020) found that the increased global land extreme precipitation during 1951–2015 can be mostly attributed to increases in anthropogenic greenhouse gas emissions. The ACC may also have substantially influenced the probability of the occurrence of regional individual EPEs. For example, W. Zhang et al. (2020) detected that anthropogenic forcing contributed to 47% of the decrease in the occurrence probability of the persistent summer EPE (maximum accumulated 28-day precipitation) over central western China in 2018. T. Zhou et al. (2021) estimated that greenhouse gas forcing led to 44% of the increase in the occurrence probability of the record-breaking persistent EPE (maximum 28-day accumulated precipitation) over eastern China in 2020. Based on these studies, we guess that ACC may also be changing the occurrence probabilities of precipitation extremes such as the 2021 EPEs in central and eastern China.

This study aims to answer the following questions: to what extent does ACC contribute to the occurrence probabilities of precipitation extremes like the 2021 EPEs, and how will the occurrence probabilities of such precipitation extremes change in a warming climate?

2. Data and Methods

2.1. Observations and Simulations

We used daily gridded precipitation observations at a 0.5° × 0.5° resolution during 1961–2021 from the China Meteorological Data Service Center (Guan et al., 2022; W. Zhao et al., 2019). The global mean temperature

Table 1
Basic Information of the 10 CMIP6 Models Used in This Study

Models	Short name	All	GHG	AER	NAT	SSP126	SSP245	SSP370	SSP585
ACCESS-CM2	M1	1	1	1	1	1	1	1	1
ACCESS-ESM1-5	M2	1	1	1	1	1	1	1	1
BCC-CSM2-MR	M3	1	1	1	1	1	1	1	1
CESM2	M4	1	1	1	1	1	1	1	1
CanESM5	M5	1	1	1	1	1	1	1	1
FGOALS-g3	M6	1	1	1	1	1	1	1	1
GFDL-CM4	M7	1	0	0	1	0	1	0	1
GFDL-ESM4	M8	1	1	1	1	1	1	1	1
IPSL-CM6A-LR	M9	1	1	1	1	1	1	1	1
MRI-ESM2-0	M10	1	1	1	1	1	1	1	1

Note. "1" ("0") represents the simulations that are (not) available for the corresponding model and scenario.

anomaly (GMTA) was retrieved from the National Aeronautics and Space Administration Goddard Institute for Space Studies (NASA GISS) surface temperature analysis (GISTEMP Team, 2022; Lenssen et al., 2019).

We employed historical simulations under all (ALL) forcing, natural-only (NAT) forcing, greenhouse gas-only (GHG) forcing, and aerosol-only (AER) forcing, as well as future projections under four emission scenarios from 10 models taking part in the Detection and Attribution Model Intercomparison Project (DAMIP) in the Coupled Model Intercomparison Project Phase 6 (CMIP6; Eyring et al., 2016; Gillett et al., 2016; see Table 1). In this study, the four future emission scenarios are the Shared Socioeconomic Pathways (SSP) 126, 245, 370, and 585 (O'Neil et al., 2016), which cover the period from 2015 to 2100. The ALL forcing was extended from 2015 to 2020 with SSP585 (C. Zhou et al., 2018), so that all historical simulations have the same study period of 1961–2020. All simulations were interpolated to the resolution of 1.5° × 1.5° using the bilinear interpolation method (Gu et al., 2019; Liu, You, et al., 2021).

2.2. Generalized Extreme Value Statistical Model

We analyzed the summer (June–August) maximum 5-day accumulated precipitation (Rx5day) due to the persistence of the 2021 EPEs in central and eastern China. In 2021, the EPE is defined as the Rx5day during 17–31 July. To facilitate comparison between observations and simulations, the Rx5day was expressed as the percentage precipitation anomaly (PPA):

$$\mathrm{PPA} = \frac{x_i - x_{\mathrm{climatology}}}{x_{\mathrm{climatology}}} \times 100\% \quad (1)$$

where x_i and $x_{\mathrm{climatology}}$ represent the summer Rx5day time series during 1961–2021 and the 1981–2010 climatology of Rx5day, respectively.

The generalized extreme value (GEV) distribution (Schaller et al., 2016; W. Zhang et al., 2020; C. Zhou et al., 2018; T. Zhou et al., 2021) was used to fit the time series of Rx5day PPA:

$$F(x|\mu,\sigma,\xi) = \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-\frac{1}{\xi}}\right\} \quad (2)$$

where μ, σ, and ξ represent the location, scale, and shape parameters of the GEV distribution, respectively. μ and σ are related to the magnitude and variability of extreme events, respectively; and ξ dominates the upper tail characteristic of the extreme event frequency curve.

To explore the possible connection between global warming (mainly induced by GHG emissions) and changes in the occurrence probability of EPEs, the scaled GEV function was applied, in which the location and scale parameter depends on GMTA, and the shape parameter is constant (Philip et al., 2022; Van Der Wiel et al., 2017; C. Zhou et al., 2018):

$$\mu(T) = \alpha + \mu_1 T \tag{3}$$

$$\ln\sigma(T) = \beta + \sigma_1 T \tag{4}$$

where $\mu(T)$ and $\sigma(T)$ denote the location and scale parameters of the scaled GEV distribution, respectively; α, μ_1, β, and σ_1 are the corresponding regression coefficients; and T represents GMTA.

2.3. Occurrence Probability Attributed to ACC

The fraction of attributable risk (FAR; C. Zhou et al., 2018; T. Zhou et al., 2021) was used to estimate the influence of ACC on the occurrence probabilities of precipitation extreme like the 2021 EPEs:

$$\text{FAR} = (P_1 - P_2)/P_2 \tag{5}$$

where P_1 and P_2 denote the occurrence probabilities (i.e., reciprocals of the return periods estimated by the GEV distribution) of the 2021 EPEs under different historical forcings and future scenarios, respectively. Specifically, when we quantify the influence of ACC on this event, P_1 and P_2 represent the occurrence probabilities of the event under the ALL forcing and NAT forcing, respectively; and when we quantify the influence of the GHG (AER) forcing on this event, P_1 and P_2 represent the occurrence probabilities of the event under the ALL forcing (including GHG and AER forcings) and AER (GHG) forcing only, respectively. It should be noted that ACC mainly reflects the net result of these two counter-acting effects of GHG and AER.

In addition, the risk ratio (RR) was used to assess the changes in the occurrence probability of precipitation extreme like the 2021 EPEs under future climate conditions (W. Zhang et al., 2020; T. Zhou et al., 2021):

$$\text{RR} = \frac{P_{\text{future}}}{P_{\text{historical}}} \tag{6}$$

where P_{future} and $P_{\text{historical}}$ represent the occurrence probabilities under future and historical climate conditions, respectively. RR can be converted to FAR, that is, FAR = RR − 1. Both the 5%–95% confidence interval (90% CI) of FAR and RR were estimated via 1000-member bootstrap (Lu et al., 2021; W. Zhang et al., 2020; C. Zhou et al., 2018).

2.4. Identification of the Emergence Time of ACC

Internal variability (natural-only forced variability) indicates that climate components move within the climate system (IPCC, 2013). However, its effect on EPEs might be weakened due to the continually increasing influence of ACC. Here, we identify the emergence time (ET) of the ACC to explore when the change of summer Rx5day exceeds the ranges of internal variability (L. Zhang et al., 2021):

$$\text{ET} = \left(x_t - \overline{x}_{1861-1910}\right) - \sigma_{1861-1910} \tag{7}$$

where x_t represents the 20-year running mean of the summer Rx5day during 1911–2100. $\overline{x}_{1861-1910}$ and $\sigma_{1861-1910}$ denote the mean and standard deviation of the summer Rx5day during 1861–1910. The 50-year baseline period from 1861 to 1910 when anthropogenic forcing was closer to a preindustrial state, was widely used to gauge quasi-natural variability (Abatzoglou et al., 2019; King et al., 2015). The first year when the ET is greater than 0 represents the emergence time of ACC.

3. Results

3.1. Extremity of the 2021 EPEs

The observed summer Rx5day during the climatological period of 1981–2010 gradually decreases from coastal areas to inland areas (Figure 1a). The 2021 EPEs (Figure 1b) were largely confined to central China (32°–37°N, 111°–116°E) and eastern China (28°–34°N, 118°–123°E), and the magnitude of their Rx5day PPA was positive

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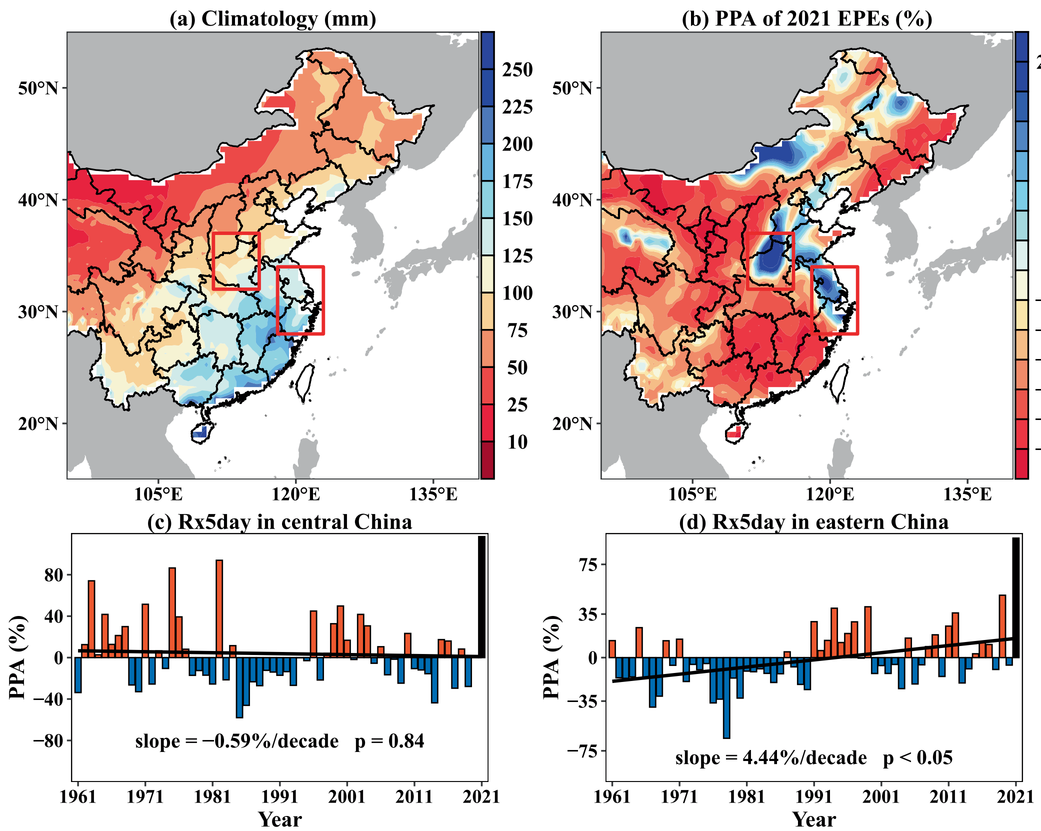

Figure 1. Spatial and temporal patterns of the observed summer (June–August) maximum 5-day accumulated precipitation (Rx5day) over central and eastern China, respectively. In panel a, climatology represents the annual mean Rx5day during the climatological period of 1981–2010. In panel b, percentage precipitation anomaly (PPA) denotes the spatial distribution of percentage precipitation anomaly value during the 2021 extreme precipitation events (EPEs) (unit: %; see Equation 1). In panels c and d, PPA denotes the region-averaged percentage precipitation anomaly (unit: %; see Equation 1). PPA of 2021 EPEs (17–31 July 2021) is computed relative to the climatological Rx5day for JJA. "slope" and "p" values denote estimated long-term changes and corresponding p-value using the modified Mann-Kendall method (Hamed & Rao, 1998). The black bars in panels c and d denote the PPA of Rx5day during Typhoon In-Fa (TIF) in 2021.

(>200% and >20% at most of grids in the corresponding red box, respectively), relative to the summer Rx5day climatology. Compared with the area-averaged summer Rx5day PPA time series over land during 1961–2021 (Figures 1c and 1d), the 2021 EPEs broke historical records, reaching 116.8% and 96.1% higher than the climatology in central and eastern China, respectively.

In central China, the Rx5day PPA of the 2021 EPE occurred in the context of no linear trend of EPEs during 1961–2021 ($p = 0.84$; Figure 1c). Conversely, eastern China experienced the Rx5day PPA of the 2021 EPE in the context of a significantly linear increasing trend of EPEs at a rate of 4.44%/decade (90% CI: 3.11%–5.79%/decade; $p < 0.05$; Figure 1d). Thus, the occurrence of the 2021 EPE in central China in the context of no change in the summer Rx5day PPA time series suggests no apparent direct linkage between the 2021 EPE in central China and global warming. However, in eastern China, the Rx5day PPA time series shows a significant increasing trend, indicating that global warming may have impacted the occurrence of the 2021 EPE in eastern China through the long-term increase of EPEs.

To explore the linkage between global warming and the occurrence probabilities of EPEs in central and eastern China, respectively, we employed the observed Rx5day PPA time series and GMTA during 1961–2021 to build the scaled GEV distribution (Figure 2). The Rx5day PPA time series in central China showed a slightly negative correlation ($r = -0.02$, $p = 0.86$) or no association with GMTA, and the location parameter of the scaled GEV distribution showed no change with the increased GMTA (Figure 2a). This implies that global warming may not be the key reason in impacting the occurrence probability of precipitation extremes like the 2021 EPE in central China. Or there may be a signal of global warming in the likelihood of the 2021 EPE in central China, but this

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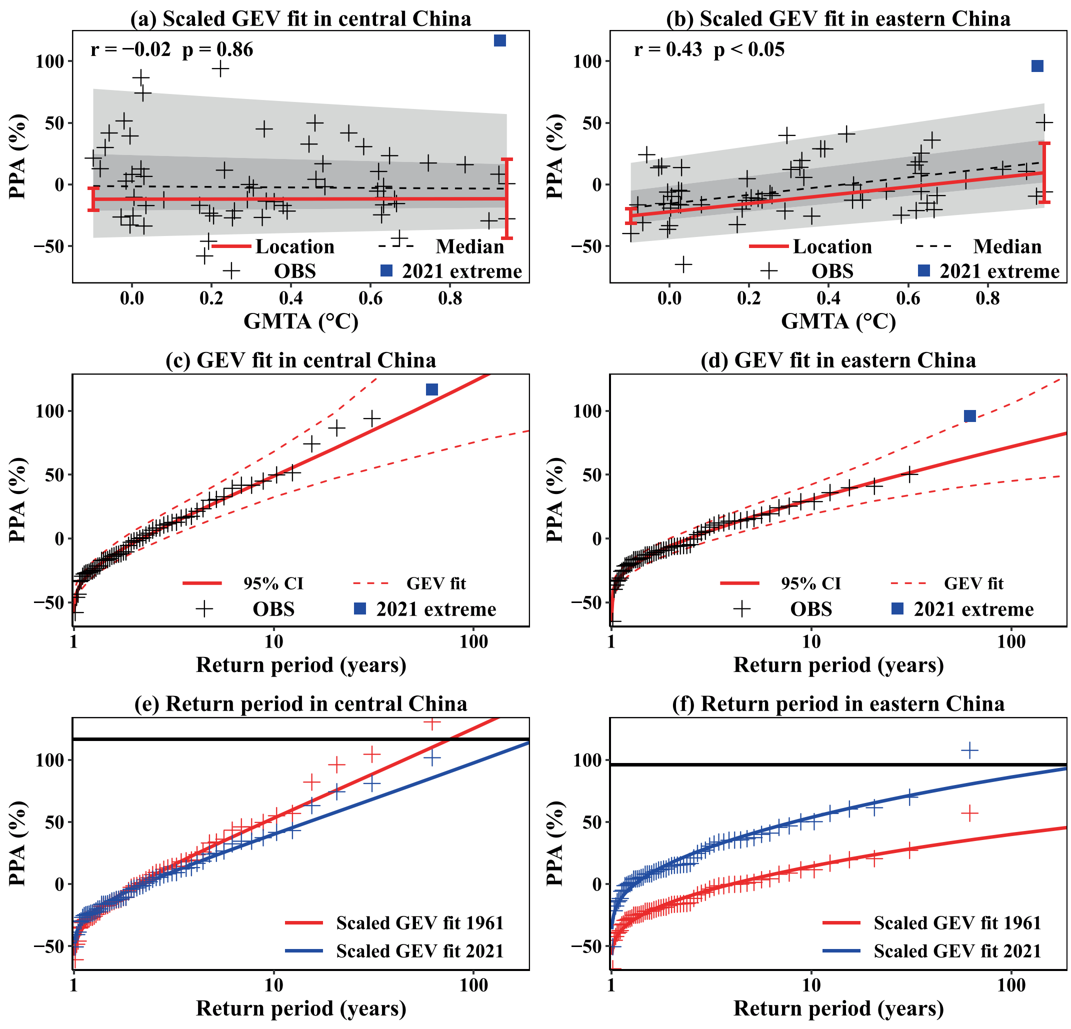

Figure 2. The generalized extreme value (GEV) distribution and return period (unit: years) estimations of the observed summer Rx5day percentage precipitation anomaly (PPA) (%) during 1961–2021 in central and eastern China, respectively. In panels a and b, location (red line) and scale parameters depend on global mean temperature anomaly (GMTA; units: °C), and the shape parameter is constant (see Equations 2–4). In panels c and d, return periods (red lines) for the observed summer Rx5day PPA are estimated when all three parameters of the GEV distribution are constant. In panels e and f, return period plots (red and blue lines) for the observed Rx5day PPA are shown under the GMTA of 1961 and 2021 using the scaled GEV distribution (see panels a and b). Observations for 1961–2021 are shown twice: one shifted up with the GMTA trend to 2021 (blue crosses), and the other shifted down to 1961 (red crosses). The black horizontal lines present the PPA locations of the 2021 extreme precipitation events (EPEs). The dashed lines in panels c–f represent the 90% confidence interval (CI) estimated via bootstrapping 1,000 times (W. Zhang et al., 2020; C. Zhou et al., 2018).

signal was masked by variability. In contrast, this correlation was significantly positive ($r = 0.43$, $p < 0.05$) in eastern China, and the location parameter of the scaled GEV distribution significantly increased with the increased GMTA (Figure 2b), indicating that global warming may have increased the occurrence probability of precipitation extremes like the 2021 EPE in eastern China.

From the GEV distribution of the observed Rx5day PPA time series during 1961–2021, we estimated that the 2021 EPE in central China was a 1-in-84-year event, while that in eastern China was close to a 1-in-444-year event (Figures 2c and 2d). Under the GMTA of 1961 and 2021, a precipitation extreme like the 2021 EPE in central China is estimated as a 1-in-76-year (1-in-26-year to 1-in->1,000-year) event and 1-in-212-year (1-in-29-year to infinite) event, respectively (Figure 2e). In contrast, a precipitation extreme like the 2021 EPE in eastern China represents a 1-in->10,000-year (1-in-122-year to infinite) event under the GMTA of 1961 (Figure 2f). However, it markedly decreased to a 1-in-256-year (1-in-24-year to infinite) event when the observations were

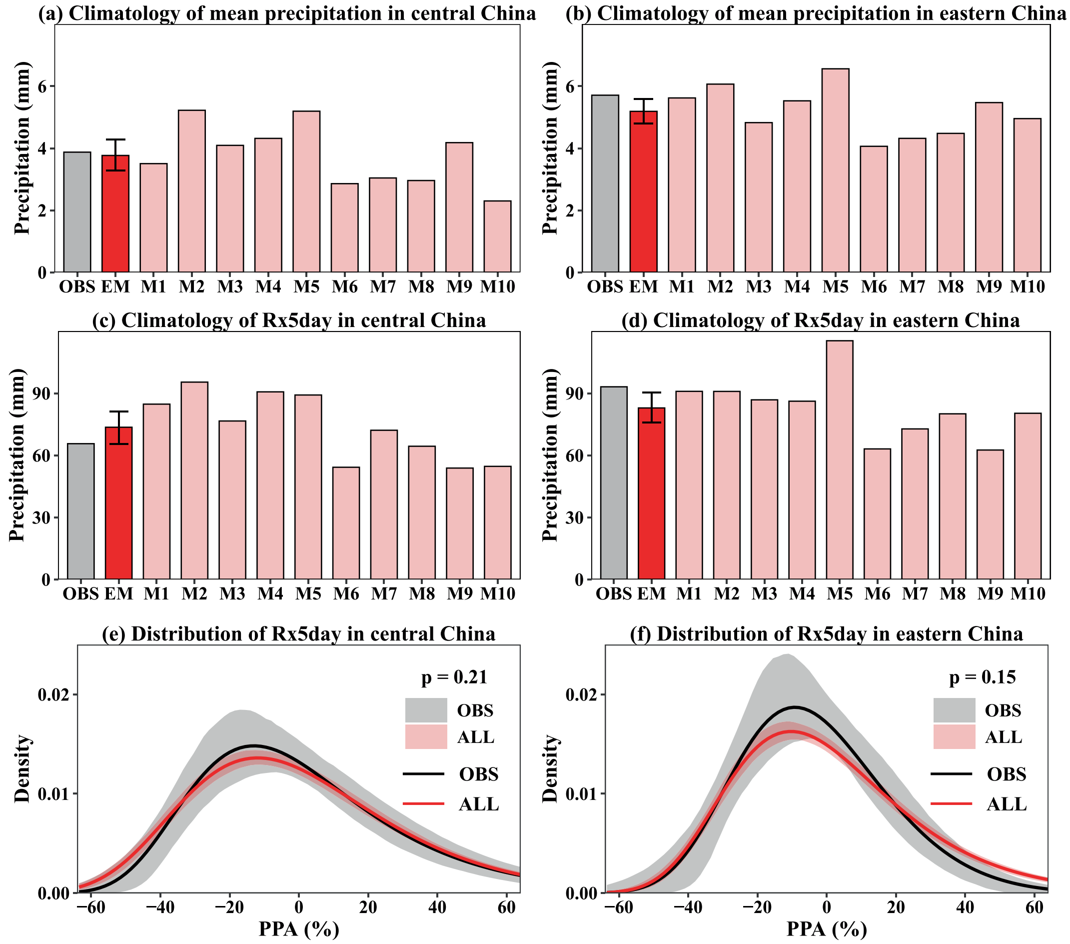

Figure 3. Distributions of summer mean precipitation (unit: mm; a and b), mean Rx5day (c and d) during the climatological period, and the generalized extreme value (GEV) distributions of the Rx5day percentage precipitation anomaly (PPA) (e and f) during 1961–2020 for observations (OBS) and historical all-forcing (ALL) simulations in central and eastern China, respectively. In panels a–d, the red and pink bars denote precipitation from the multi-model ensemble mean (EM) and individual models (M1–M10, see Table 1), respectively. The black error bars denote the 90% confidence interval (CI) based on the ensemble mean of all models (i.e., M1–M10). In panels e and f, the area-weighted Rx5day PPA time series from observations and simulations are fitted using the GEV distribution with all three parameters held constant. The black line and gray area (red line and pink area) indicate the best estimates and the 90% CI based on observations (simulations), respectively. The 90% CI was estimated via bootstrapping 1,000 times (W. Zhang et al., 2020; C. Zhou et al., 2018). The *p* values in panels e and f were estimated via the Kolmogorov-Smirnov test (C. Zhou et al., 2018).

shifted upwards with the GMTA of 2021. This indicates that global warming has increased the occurrence probability of a precipitation extreme like the 2021 EPE in eastern China.

3.2. Attribution of the Likelihood of Precipitation Extremes Like the 2021 EPEs

The observed summer mean precipitation during the climatological period is 3.88 mm (5.71 mm) in central (eastern) China, and is underestimated by 0.3% (0.9%) based on the ensemble mean of multiple CMIP6 models (Figures 3a and 3b). Similarly, the mean observed summer Rx5day in central (eastern) China was 65.64 mm (93.13 mm) during the climatological period, but this value was overestimated (underestimated) by 12% (10%) by the ensemble mean of the CMIP6 models (Figures 3c and 3d). Although there are slight deviations between the observations and simulations, the observations fluctuated within the 90% CI (estimated by bootstrapping 1,000 times) of the simulations during the climatology period in central and eastern China (Figures 3a–3d), indicating that CMIP6 can reasonably reproduce summer precipitation in central and eastern China.

In addition, the attribution of occurrence probabilities of precipitation extremes like the 2021 EPEs to ACC depends on whether model simulations can capture the probability distribution of observed EPEs. The GEV

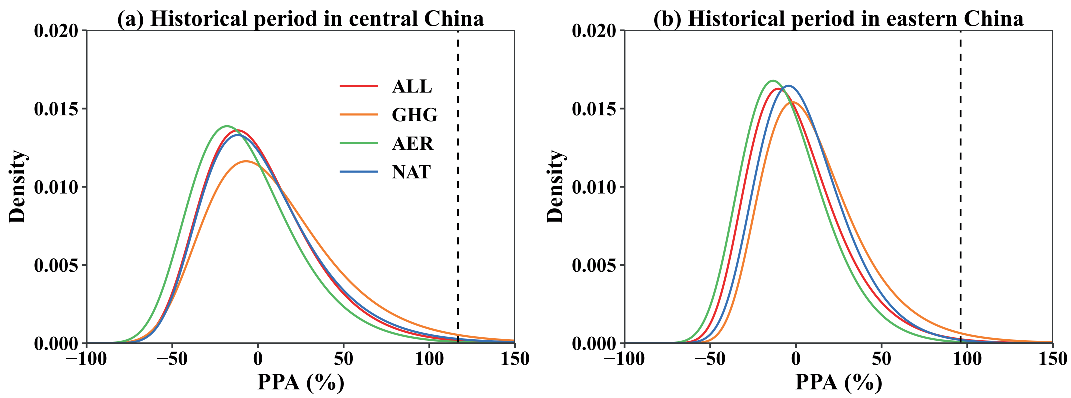

Figure 4. The generalized extreme value (GEV) probability density curves for summer Rx5day percentage precipitation anomaly (PPA) (unit: %) under different forcings with 540–600 samples during 1961–2020 in central and eastern China. Each model under a given forcing has 60 summer Rx5day PPA values (i.e., 60 samples) during 1961–2020. Hence, both ALL and NAT (GHG and AER) forcings provide 540 (600) samples from 9 (10) models (see Table 1) during 1961–2020. "ALL," "GHG," "AER," and "NAT" represent historical all, greenhouse gases only, aerosol only, and natural only forcings, respectively. The dashed vertical lines show the PPA locations of the 2021 extreme precipitation events (EPEs).

distribution was used to fit the probability distribution of observed and simulated EPEs (i.e., the Rx5day PPA time series in this study, Figures 3e and 3f), respectively. As Figures 3e and 3f shows, most of the CMIP6 model distribution (under the ALL forcing) of Rx5day PPA time series during 1961–2020 are within observational uncertainty; this is the case in both central and eastern China. To be specific, the simulated and observed probability density curves passed the Kolmogorov-Smirnoff test ($p = 0.21$ and 0.15 in central and eastern China, respectively).

Different external forcings may have various impacts on the occurrence probabilities of precipitation extremes like the 2021 EPEs in central and eastern China. Here, we quantified the contributions of different forcings (i.e., ALL, NAT, GHG, and AER forcings) to the likelihood of 2021 EPEs (Figure 4). In central China, the upper tail of probability density curve is slightly shifted to the left when we compare the probability density curves under ALL (the red one) and NAT (the blue one) forcings (Figure 4a). The occurrence probability of the 2021 EPE in central China is of 0.66% (0.36%–0.97%) under the NAT forcing, compared with 0.35% (0.13%–0.57%) under the ALL forcing. This suggests that the likelihood of the 2021 EPE in central China was decreased by approximately +47% (−23% to +89%) due to ACC (see Table 2).

In central China, we compared ALL forcing (mainly GHG and AER forcings) with the AER forcing to quantify the GHG forcing's influence on the likelihood of precipitation extremes like the 2021 EPE (Figure 4a). The result shows that the probability density function distribution is shifted toward more intense events in the ALL forcing compared to the AER forcing. Specifically, GHG/AER forcing increased (decreased) the occurrence probability of the 2021 EPE from 0.14% (0.04%–0.24%)/1.49% (1.14%–1.86%) in AER (GHG) forcing to 0.35% (0.13%–0.57%) in ALL forcing, suggesting that GHG/AER forcing resulted in the occurrence probability of precipitation extreme like the 2021 EPE increased/decreased by approximately +152% (−47% to +483%)/+76% (+45%–95%) (Table 2). It should be noted that the impacts of GHG and AER forcings on the occurrence probabilities of the 2021 EPEs were not linearly counterbalanced (Sun et al., 2016; W. Zhang et al., 2018). In eastern China, ACC led to the occurrence probability of precipitation extreme like the 2021 EPE increased by +55% (−45% to +201%), while GHG/AER forcing caused this probability to increase/decrease by approximately +437% (+92%–943%)/71% (+43%–90%) (Figure 4b and Table 2).

Table 2
Contributions of External Forcings to Likelihood of Precipitation Extremes Like the 2021 EPEs

	Central China		Eastern China	
Contribution	Estimate	90% CI	Estimate	90% CI
FAR_{ANT}	−47%	−89% to 23%	55%	−45% to 201%
FAR_{GHG}	152%	−47% to 483%	437%	92% to 943%
FAR_{AER}	−76%	−95% to −45%	−71%	−90% to −43%

Note. FAR_{ANT}, FAR_{GHG}, and FAR_{AER} represent the fraction of attributable risk in ANT (ALL-NAT; i.e., ACC), GHG, and AER, respectively.

The next question is why ACC caused opposite changes (i.e., −47% vs. +55%) in the occurrence probabilities of the 2021 EPEs between central and eastern China. Under GHG forcing, global warming continually increases, which further enhances water vapor content in the atmosphere and is thus

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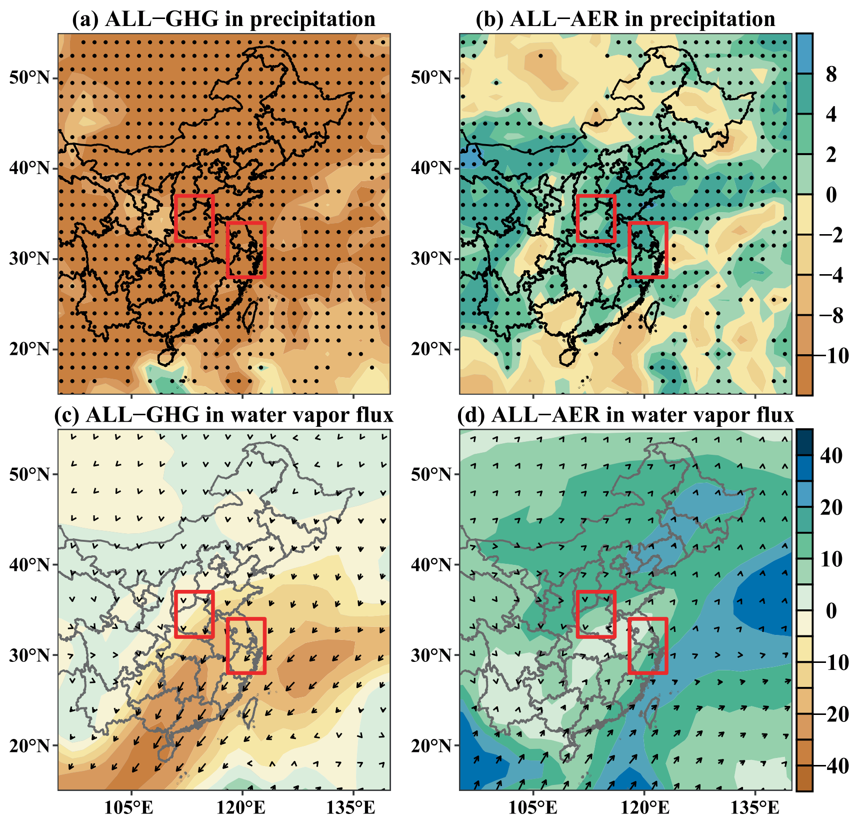

Figure 5. Spatial patterns of the influence of aerosol (AER) (i.e., ALL-GHG) and greenhouse gas (GHG) (i.e., ALL-AER) forcings on summer mean Rx5day (a and b) and water vapor flux (c and d) over the historical period (1961–2020). In panels a and b (c and d), the color shadings represent the percentage difference in summer mean Rx5day (water vapor flux) between the ALL forcing and other forcings (i.e., GHG and AER forcings) during 1961–2020. The dots in panels a and b indicate that the signs of >60% Coupled Model Intercomparison Project Phase 6 (CMIP6) models are consistent with the sign of the ensemble mean of the 9 (10) CMIP6 models. The units of arrow vectors and shaded areas in panels c and d are 40 kg m^{-1} s^{-1} and kg m^{-1} s^{-1}, respectively.

conducive to the occurrence of EPEs (Burke & Stott, 2017; Trenberth et al., 2003; T. Zhou et al., 2021). Both central and eastern China witnessed the increased summer mean Rx5day and water vapor flux during 1961–2020 under GHG forcing (Figures 5b and 5d), which increased the occurrence probabilities of the 2021 EPEs in central and eastern China.

From the thermodynamic effect, AER forcing had a cooling effect on global warming, which may have reduced water vapor content in the atmosphere and thereby suppressed the occurrence of EPEs (Figures 5a and 5c; Jiang et al., 2015; Lau, 2016; Lu et al., 2021; Ma et al., 2017; Wu et al., 2016). From the dynamic effect, the decreased atmospheric temperature due to AER forcing may have reduced the land-sea thermal contrast and weakened the East Asian Summer Monsoon (Mu & Wang, 2021; Song et al., 2014), which may have been detrimental to conveying water vapor from the South China Sea and WNP to the further north and inland areas (such as central China; Figure 5c). The suppression effect of AER forcing on EPEs may be more obvious in central China close to the north than in eastern China close to the south. As a result, our findings suggest that the GHG-induced increase in the probabilities of precipitation extremes like the 2021 EPEs may have been counterbalanced by the AER-induced decrease, which showed a net decrease (increase) in central (eastern) China.

3.3. Likelihood Projections of Precipitation Extremes Like the 2021 EPEs Under Future Warming

Since GHG forcing can enhance the likelihood of precipitation extremes like the 2021 EPEs in both central and eastern China, the next question is how the likelihood of such extremes may change under different GHG emission scenarios in the future. Figure 6 shows that summer Rx5day PPA time series in central (eastern) China are projected to significantly increase at rates of 1.64%/decade, 1.67%/decade, 1.66%/decade, and 2.18%/decade

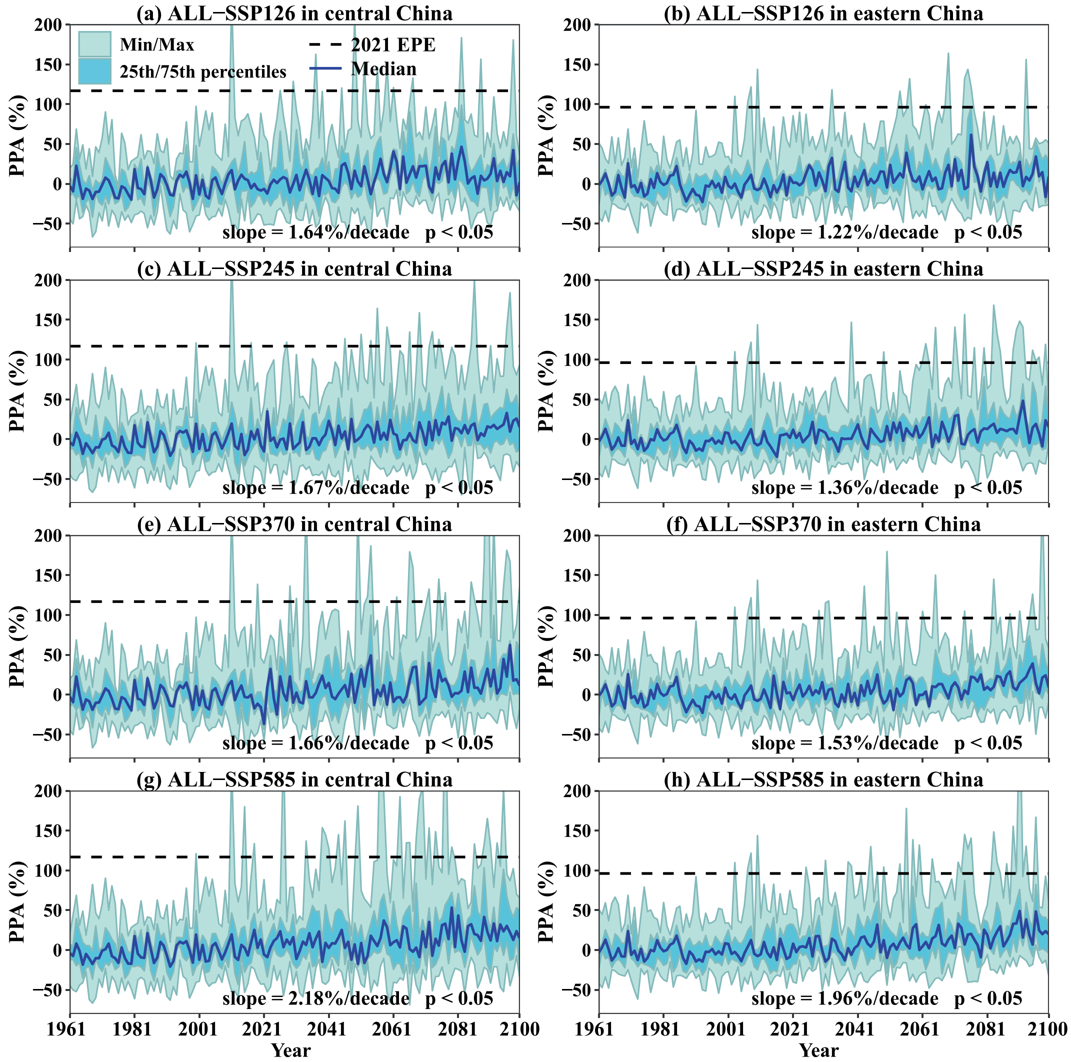

Figure 6. Trends in summer Rx5day percentage precipitation anomaly (PPA) (unit: %) under the ALL forcing simulations and different future scenarios (SSP126, SSP245, SSP370, and SSP585) during 1961–2100 in central (left column) and eastern China (right column). The dashed horizontal lines present the observed Rx5day PPA of the 2021 extreme precipitation events (EPEs). The dark blue line indicates the median Rx5day PPA of ensemble members, the inner blue shading indicates the 25th and 75th percentiles, and the outer blue shading indicates the minima and maxima. "slope" and "*p*" values denote estimated long-term changes and corresponding *p*-value using the modified Mann-Kendall method.

(1.22%/decade, 1.36%decade, 1.53%/decade, and 1.96%/decade) under SSP126, SSP245, SSP370, and SSP585 during 1961–2100, respectively. By the end of the 21st century, Li et al. (2022) also found that summer precipitation in East China (25°–34°N, 110°–123°E) under the future scenarios is expected to increase at rates of 9.3% (SSP126), 11.1% (SSP245), 9.3% (SSP370), and 14.8% (SSP585), respectively. Both central and eastern China witnessed an increasing magnitude of EPEs with continued climate warming, implying that the occurrence probabilities of precipitation extremes like the 2021 EPEs are likely to increase in the future.

As Figure 6 shows, neither central nor eastern China experienced a Rx5day PPA that exceeded the 2021 EPEs (represented by the dashed line) before the year 2000. In the 21st century, precipitation extremes like the 2021 EPEs are likely to become more frequent (from 0% to 6%; Figures 6 and 7). In particular, the probabilities of the Rx5day PPA surpassing the 2021 EPEs in central (eastern) China during 2081–2100 are 1.5% (0.5%), 2.5% (5.5%), 5% (3%), and 4.5% (5.5%) under SSP126, SSP245, SSP370, and SSP585 during 1961–2100, respectively.

We also investigated the emergence time of the ACC signal based on projected summer Rx5day anomalies under different scenarios (i.e., SSP126, SSP245, SSP370, and SSP585; Figure 8). Before the 1970s, summer

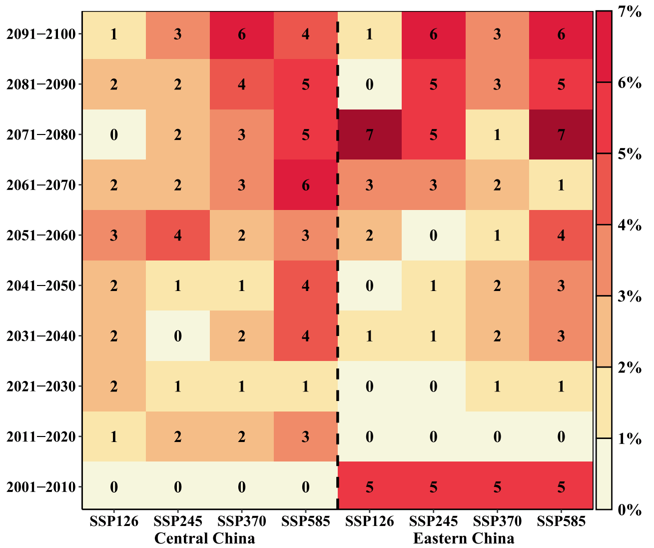

Figure 7. Probabilities (unit: %) of surpassing the observed Rx5day percentage precipitation anomaly (PPA) of the 2021 extreme precipitation events (EPEs) under different future scenarios (i.e., SSP126, SSP245, SSP370, and SSP585) based on the ensemble mean of the 9 (10) Coupled Model Intercomparison Project Phase 6 (CMIP6) models during 2000–2100 in central and eastern China. The probabilities are computed as the percentages between the number of surpassing the 2021 EPEs and the number of ensemble members multiplied by 10 years.

Rx5day anomalies in central and eastern China showed a decreasing trend and fluctuated within the range of internal variability (i.e., ±1 standard deviation of the summer Rx5day during 1861–1910). However, with the increase in global GHG emissions, the decreasing trend of summer Rx5day anomalies in central and eastern China became an increasing trend and is likely to start exceeding the range of internal variability (reaching outside the gray box in Figure 8). In central (eastern) China, the emergence time of summer Rx5day under SSP126, SSP245, SSP370, and SSP585 is estimated as 2042 (2036), 2056 (2048), 2035 (2050), and 2023 (2039), respectively.

We further compared the occurrence probabilities of precipitation extremes such as the 2021 EPEs between the future and historical periods (Figure 9). In comparison with historical NAT forcing, the probability density curves of the summer Rx5day PPA time series under the four future scenarios are clearly shifted toward the right, indicating that the occurrence probabilities of events such as the 2021 EPEs in central and eastern China are likely to increase in the future, irrespective of the chosen scenario. The RR (i.e., ratio of occurrence probability between the future warming period and the historical ALL forcing period, where ratios greater than 1 indicate a larger occurrence probability in the future) shows that all three future warming periods (i.e., 2021–2050, 2051–2080, and 2081–2100) and all four future scenarios have estimated RRs larger than 1. By the end of the 21st century, the RR of precipitation extremes like the 2021 EPE in central/eastern China under SSP585 is estimated to be 14 (9–19)/15 (9–20) (Figures 9c and 9d). This indicates that the future occurrence probability of such event in central (eastern) China under SSP585 is estimated to be 14 (15) times larger than under historical climate conditions.

Why is the likelihood of precipitation extremes such as the 2021 EPEs in central and eastern China projected to increase under future warming? From the perspective of physics, thermodynamic drivers (e.g., moisture convergence and surface evaporation) mainly contribute to the intensification of precipitation extremes in the Asian monsoon region under future GHG emission scenarios, while dynamic drivers (e.g., changes in circulation related to the monsoon) are relatively weak (Chang et al., 2022; Hsu et al., 2012; Li et al., 2022; Seo et al., 2013; You et al., 2022; Zou & Zhou, 2022). In Figures 10a–10d, central and eastern China are projected to experience increasing precipitation during 2071–2100 under the four future GHG emission scenarios, with the largest increase in precipitation under the SSP585 scenario. If we consider projections of the thermodynamic effect, enhanced evaporation due to the increase in surface temperature is seen to increase water vapor content under the moderate-high emission scenarios (Figures 10f–10h). For the dynamic effect, the intensified southwesterly wind under the moderate-high emission scenarios conveys abundant water vapor to central and eastern China. Both thermodynamic and dynamic effects are thus expected to contribute to the projected increase in precipitation, but the increase is principally driven by the thermodynamic effect (Chang et al., 2022; Chen et al., 2020; Seo et al., 2013).

4. Discussion

The 2021 EPEs in central and eastern China were connected with TIF. However, our attribution and projection of the occurrence probabilities of precipitation extremes like the 2021 EPEs do not identify typhoon activity in the climate model simulations, due to that both typhoon and typhoon-induced precipitation simulations have large uncertainty. For typhoon simulations, the presently known sources of uncertainty include model parameterizations, model resolution, future sea surface temperature patterns, related environmental climate parameters, and the choice of typhoon detection methods (Cha et al., 2020; Emanuel, 2021; Murakami et al., 2012; Patricola & Wehner, 2018; Reed & Jablonowski, 2011; Torn, 2016; F. Zhang et al., 2016). Consequently, the attribution of typhoon activity and typhoon-induced precipitation to ACC in historical and future periods is controversial (Knutson et al., 2019, 2020).

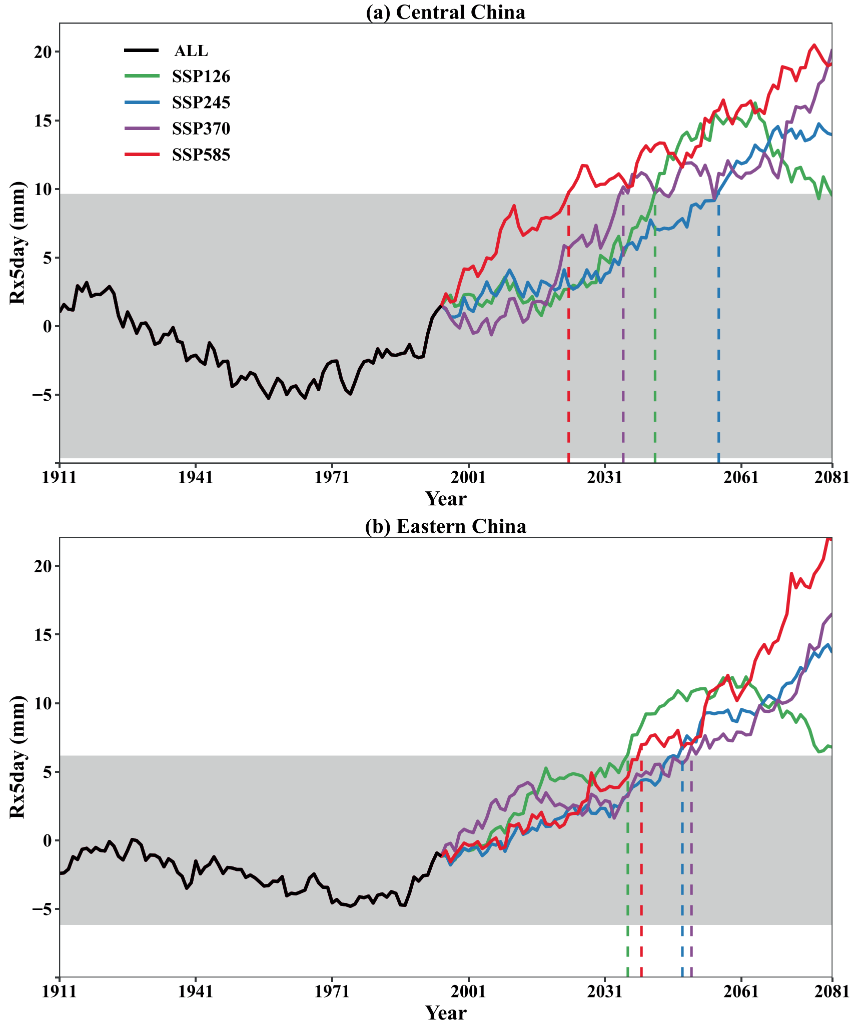

Figure 8. Changes in the 20-year running mean of the summer Rx5day (unit: mm; solid lines) under ALL (black line) and different future scenarios (i.e., SSP126, SSP245, SSP370, and SSP585; color lines) based on the ensemble mean of the 9 (10) Coupled Model Intercomparison Project Phase 6 (CMIP6) models in central and eastern China (see Equation 7). The horizontal gray shadings denote the range of internal variability, which is the ±standard deviation of the summer Rx5day during 1861–1910. The vertical dashed lines denote the emergence time of anthropogenic climate change.

In addition to typhoon simulations, there are large uncertainties for climate models to simulate extreme precipitation (Hawkins & Sutton, 2011; Kent et al., 2015; Knutti and Sedla'ček 2013; Ma & Xie, 2013; Salman et al., 2022; Tian et al., 2021; Xiang et al., 2021; Yue et al., 2021). The uncertainties in simulating precipitation extremes can be attributed to two main sources: internal variability and model uncertainty (John et al., 2022; Kim et al., 2020; Yip et al., 2011). Besides, our limited understanding of the key physical processes that dominate the responses of precipitation extremes simulated by climate models contributes to the model uncertainty and the uncertainty in simulating precipitation extremes (John et al., 2022). Given the large uncertainty in simulating both typhoons and extreme precipitation, it is also a considerable challenge to obtain accurate typhoon-induced extreme precipitation estimates, and then use them to quantify the impacts of ACC on the 2021 EPEs in this study.

Here, our attribution and projection of the occurrence probabilities of precipitation events such as the 2021 EPEs were conducted without identifying typhoon-induced EPEs in climate models. Nevertheless, this caveat does not alter our principal conclusion that ACC can intensify the occurrence probability of such 2021 EPEs. Climate warming has been shown to intensify typhoons and shift their tracks northward in the WNP (Feng et al., 2021; Hong et al., 2021; Song & Klotzbach, 2018; Wang, Gu, & Guan, 2023; H. Zhao et al., 2022), which is conducive to intensifying the EPEs triggered by typhoons in central and eastern China. Meanwhile, Utsumi and Kim (2022)

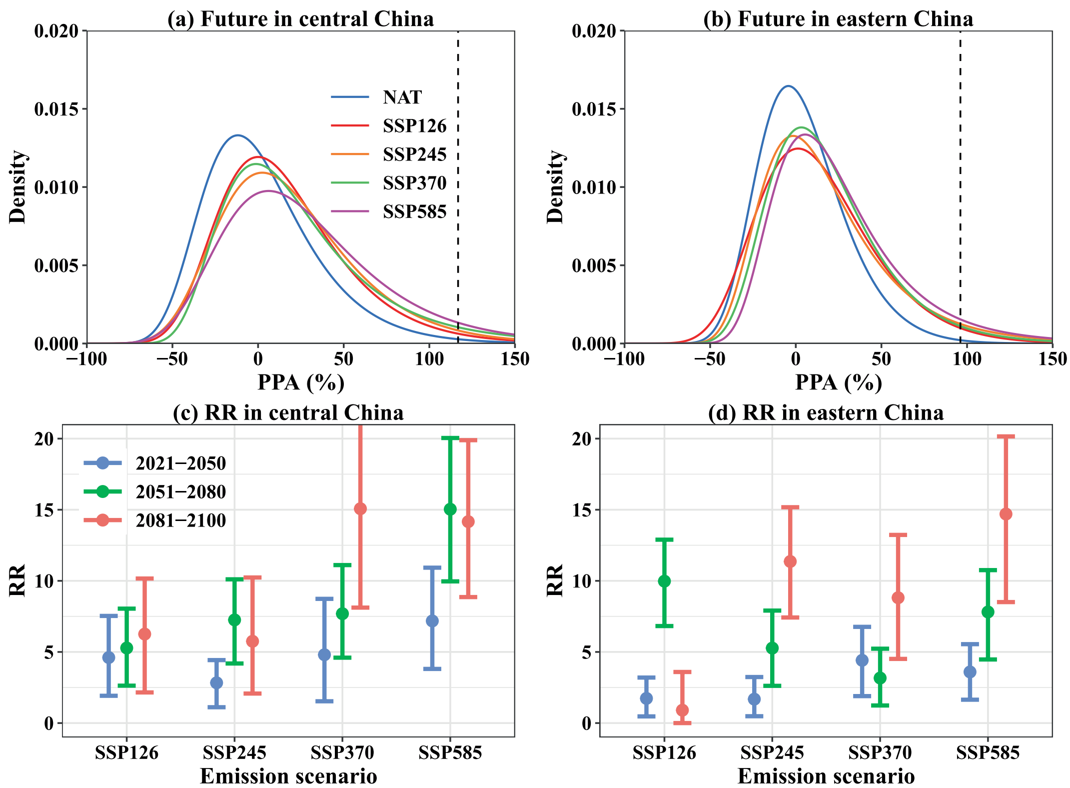

Figure 9. The generalized extreme value (GEV) probability density curves of the summer Rx5day percentage precipitation anomaly (PPA) (unit: %) under different forcings (i.e., SSP126, SSP245, SSP370, and SSP585) with 270–300 samples during 2071–2100 (a and b) and risk ratio (RR) during the three future periods (i.e., 2021–2050, 2051–2080, and 2081–2100; c and d) in central and eastern China. Each model under a given forcing has 30 summer Rx5day PPA values (i.e., 30 samples) during 2071–2100. Hence, the four future scenarios provide 180 (200) samples from 9 (10) models (see Table 1) during 2081–2100. The dashed vertical lines in panels a and b show the PPA locations of the 2021 extreme precipitation events (EPEs). In panels c and d, the best estimates (dots) and 90% confidence interval (CI) (error bars) were estimated via 1,000-member bootstrap.

found that ACC has considerably intensified the tropical cyclone-induced EPEs in eastern China. Here, our purpose is to evaluate the role of ACC in the likelihood of precipitation extremes with a magnitude similar to that of the 2021 EPEs. Therefore, our attribution and projection employed not typhoon-induced EPEs, but all EPEs, which is consistent with other similar studies (Lu et al., 2021; W. Zhang et al., 2020; C. Zhou et al., 2018). For example, W. Zhang et al. (2020) employed all summer EPEs during 1961–2018 to quantify ACC's contribution to the likelihood of the 2018 summer EPE (in central western China) induced by the westward extension of the WPSH and increased low-level southerly winds.

Finally, some limitations of the study should be noted. First, this study uses the mixed population of EPEs to conduct attribution and projections of the likelihood of 2021-like EPEs, but future attribution analyses could instead use reliable simulations of typhoon activity and typhoon-induced precipitation. Second, a limited number of CMIP6 models were used in this study and the spatial resolution of these models is coarse, which may cause uncertainty in EPE simulations (John et al., 2022). Future work on the historical attribution and future projection of the likelihood of 2021-like EPEs could directly employ high-resolution large-sample simulations to better understand changing typhoon behavior.

5. Summary

Focusing on the 2021 EPEs in central and eastern China, we carried out the attribution of the occurrence probabilities of precipitation extremes like these events to ACC in the past and future. During 1961–2021, the Rx5day PPA of the 2021 EPE in central China occurred under no linear trend in the region-averaged Rx5day PPA, while eastern China experienced the Rx5day PPA of the 2021 EPE in the context of a significant linear

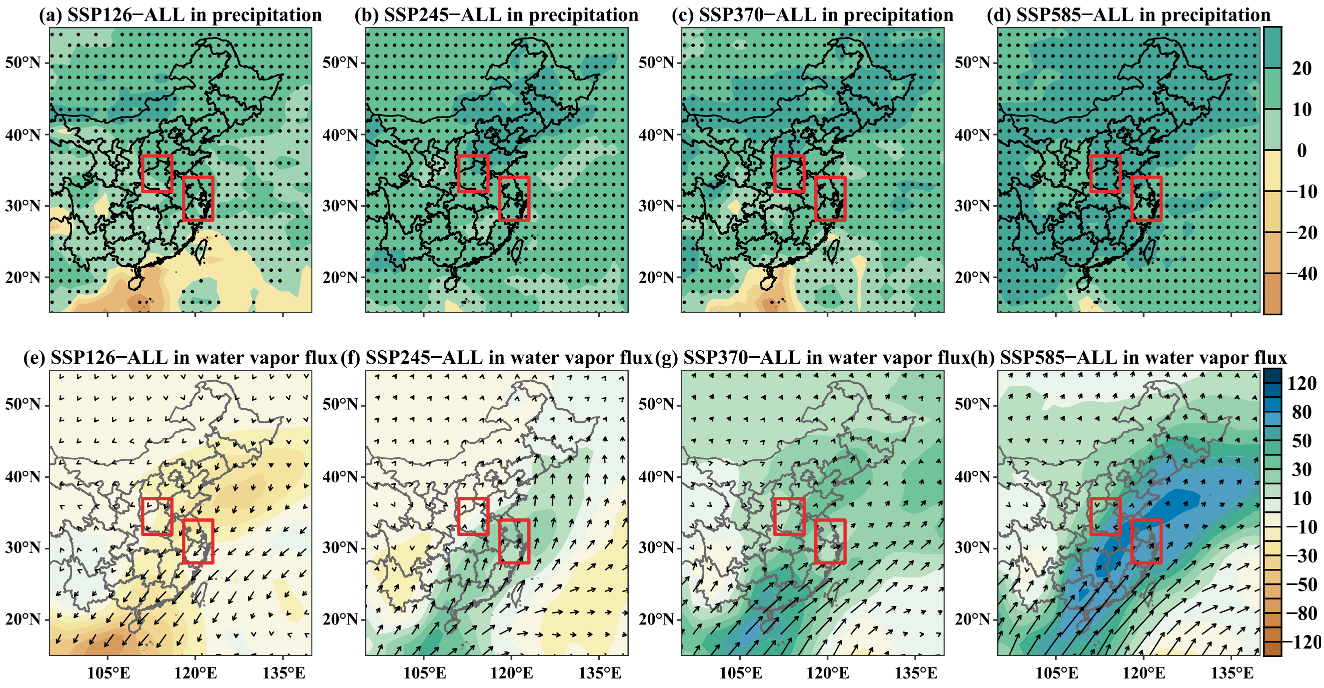

Figure 10. Spatial patterns of relative changes (%) in summer mean Rx5day (a–d) and water vapor flux (e–h) between future and historical climate conditions. In panels a–d, the color shadings represent the percentage difference in summer mean Rx5day between the period 2071–2100 in the four future scenarios and the period 1961–2020 in the historical ALL forcing. The dots in panels a–d represent locations where the signs of more than 60% of the Coupled Model Intercomparison Project Phase 6 (CMIP6) models are consistent with the sign of the ensemble mean of 9 (10) CMIP6 models. Panels e–h are the same as panels a–d but for water vapor flux, and the units of the arrow vectors and shaded areas are 40 kg m^{-1} s^{-1} and kg m^{-1} s^{-1}, respectively.

increasing trend in the region-averaged Rx5day PPA at a rate of 4.44%/decade (90% CI: 3.11%–5.79%/decade; $p < 0.05$). From the scaled GEV distribution, we detected a slightly negative (significantly positive) correlation or no association of the Rx5day PPA time series in central (eastern) China with GMTA, implying that global warming might have no (a detectable) contribution to the occurrence probability of precipitation extremes like the 2021 EPE in central (eastern) China. Based on the CMIP6 model simulations, attribution results showed that the occurrence probability of precipitation extremes like the 2021 EPE in central/eastern China decreased/increased by approximately +47% (−23% to 89%)/+55% (−45% to +201%) due to ACC. By the end of the 21st century, the occurrence probability of precipitation extremes similar to the 2021 EPE in central (eastern) China under SSP585 is projected to be 14 (15) times larger than the occurrence probability under historical climate conditions.

In the historical period, GHG forcing has led to global warming and enhanced water vapor content in the atmosphere, which has been conducive to the increasing occurrence of EPEs. However, the cooling effect of AER forcing has led to a decrease in atmospheric water vapor content and reduced the land-sea thermal contrast and the East Asian Summer Monsoon (Jiang et al., 2015; Lau, 2016; Lu et al., 2021; Wu et al., 2016), both of which have restricted the occurrence of EPEs. Thus, the GHG-induced increase in the likelihood of precipitation extremes like the 2021 EPEs has been counterbalanced by the AER-induced decrease, and this offset has likely been more significant in central China compared with eastern China, leading ACC to decrease (increase) the occurrence probabilities of precipitation extremes similar to the 2021 EPEs in central (eastern) China. If the moderate-high future emission scenarios are accurately representing what is going to happen in reality, the evaporation and southwesterly wind under such emission scenarios will enhance and intensify, respectively. Then, ACC is likely to lead to a considerable increase in the occurrence probabilities of precipitation extremes similar to the 2021 EPEs in central and eastern China.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The daily observed gridded precipitation data were obtained from the China Meteorological Data Service Center (http://www.nmic.cn/en) but are currently not available at this website. These data in our study regions are available in Wang, Gu, Slater, et al. (2023). Daily precipitation and other meteorological parameters from the CMIP6 are available through https://esgf-node.llnl.gov/search/cmip6/. The GMTA on which this article is based are available in GISTEMP Team (2022).

Acknowledgments

This study is supported by the following projects: the National Natural Science Foundation of China (Grants U1911205, 42371041, 41901041, 42001042, and 52209025), the Pre-research Project of SongShan Laboratory (Grant YYYY062022001), Guiding project of Scientific Research Plan of Education Department of Hubei Province (Grant B2022265), the open funding from Guangdong-Hong Kong Joint Laboratory for Water Security (Grant 2020B1212030005), and the open funding from State Key Laboratory of Water Resources and Hydropower Engineering Science (Wuhan University) (Grant 2021SWG01). Xihui Gu is supported by the China Scholarship Council. Louise J. Slater is supported by UKRI (MR/V022008/1 and NE/S015728/1).

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