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Anthropogenic Influence on 2022 Extreme January–February Precipitation in Southern China

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The precipitation in January–February 2022 in southern China was the second-largest amount since 1961. Anthropogenic influence reduced the likelihood of extreme events like 2022 by about 50% (55%) in HadGEM3 (CMIP6).

From January to February (J–F) 2022, southern China (SC) experienced abnormally heavy precipitation, with the regionally averaged total precipitation reaching 248 mm, making it the second-largest value since 1961. This extreme event resulted in significant damage to transportation, power supply, and crop production. About 6.092 million people and 422,300 ha of crop area were affected, leading to a direct economic loss of 7.89 billion CNY. As a result, it was identified as one of the top 10 natural disasters in 2022 by the Department of Emergency Management in China (https://www.mem.gov.cn/xw/yjglbgzdt/202301/t20230112_440396.shtml). This extreme precipitation event was attributed to the internal atmospheric dynamics (Ma et al. 2022). In this study, we assess how anthropogenic activity has changed the likelihood of extreme precipitation events similar to the J–F 2022 event over SC.

Previous studies have focused on summer extreme precipitation (Zhang et al. 2020; Li et al. 2021) and showed that anthropogenic warming has affected extreme precipitation over East Asia (Ma et al. 2017), intensifying the probability of short-term extreme

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precipitation events (Westra et al. 2014; Dong et al. 2020, 2021; Sun et al. 2022), while less attention was given to winter counterparts over SC (Hu et al. 2021). The objective of this study is to investigate whether anthropogenic influence has altered the likelihood of unusual precipitation in 2022 J–F.

Data and methods

Daily gauge precipitation observations from approximately 2,400 stations across China were obtained from the China Meteorological Administration (CMA) for the period 1961–2022. Monthly wind and sea level pressure fields from the ERA5 reanalysis provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al. 2020) were used to analyze circulation characteristics.

To assess anthropogenic and natural factors' influences on the probability of the exceptional precipitation event in SC during J–F 2022, we used the Met Office HadGEM3-GA6-N216 model (referred to as HadGEM3 hereafter) simulations at a horizontal resolution of 0.56° × 0.83° and 85 vertical levels (Ciavarella et al. 2018). The HadGEM3 model simulations are forced by observed sea surface temperature (SST)/sea ice extent (SIE) and therefore attribution of events is conditioned to SST/SIE. Both natural and anthropogenic forcing (ALL) and natural forcing (NAT) experiments were used. The details of the model can be found in Christidis et al. (2013). The ensemble simulations consisted of 15 members for 1960–2013 with ALL forcings, and 525 members for 2022 with ALL and NAT forcings (ALL_{2022} and NAT_{2022}).

Meanwhile, we utilized simulations from climate models that participated in the Coupled Model Intercomparison Project phase 6 (CMIP6) and Detection and Attribution Model Intercomparison Project (DAMIP) (Eyring et al. 2016; Gillett et al. 2016) under all anthropogenic and natural forcing combined (ALL), well-mixed greenhouse gas forcing (GHG), anthropogenic aerosol forcing (AA), and natural forcing (NAT) to assess the anthropogenic influence on the likelihood of the 2022 event (more details of model information are listed in Table ES1). CMIP6 model simulations are coupled model simulations and therefore we cannot use a specific year to represent 2022. We specify a period around our target year to represent 2022. Since historical simulations stopped in 2014 in CMIP6, we need to merge historical simulations with SSP2–4.5 future scenario simulations for 2015–26. But the NAT simulations (DAMIP) stopped in 2020, and therefore there are no NAT future scenario simulations. Thus, in order to have enough samples to give a robust estimate of PDFs, we used a 15-yr window of 2006–20 in ALL, GHG, AA, and NAT as ALL_{2022}, GHG_{2022}, AA_{2022}, NAT_{2022} in CMIP6/DAMIP simulations with a total 405 sample points (see details in the online supplemental material).

In the 2022 J–F event, the excessive precipitation was mainly concentrated over the region of (20.5°–27°N, 106°–119°E) (Fig. 1a). To evaluate the model performance, we calculated the SC precipitation index (SCPI), defined as the normalized regional-averaged precipitation anomaly in J–F with respect to the climatological period of 1961–2005. Except for quantile–quantile (QQ) and kernel density estimation (KDE) plots, a two-sample Kolmogorov–Smirnoff (KS) test with a significance level of 0.05 was used to test whether the observed and simulated SCPI during 1961–2013 were from the same distribution.

The generalized extreme value (GEV) distribution was used to fit the precipitation indices and estimate the occurrence probability and return periods for both observations and simulations. The probability of an event, which is equivalent to or heavier than the J–F 2022 event, was defined as P_{ALL} and P_{NAT} for ALL and NAT, forcing experiments, respectively. The probability ratio ($PR_{ALL} = P_{ALL}/P_{NAT}$,) is calculated to quantify the anthropogenic influences. Similarly, we used $PR_{GHG} = P_{GHG}/P_{NAT}$ and $PR_{AA} = P_{AA}/P_{NAT}$ to denote the GHG or AA forcing influences. The 90% confidence interval (90% CI) was obtained by using 1,000 bootstrap resampling.

Results

The J–F time-averaged precipitation for 1961–2005 was about 117 mm in SC. However, during J–F in 2022, the regional mean precipitation was about 248 mm over SC, and it was the second-highest value since 1961 with the anomaly being about 2.3 standard deviations (2.3σ, used as the threshold for the 2022 event) above the climatology in the period of 1961–2005 (Figs. 1a,b). There are two dynamical drivers for this precipitation anomaly. One is the wave train propagating along the South Asian jet that intensifies the India–Burma trough. It enhances the SCP through exciting anomalous strong moisture transport from the Bay of Bengal and ascending motion. The other is the positive geopotential height anomaly over eastern Siberia that prompts southward cold air intrusion and convergence over the SC region (Fig. 1c) (Ma et al. 2022). The observed SCPI in 2022 J–F corresponds to a 1-in-31-yr (18–143 yr) event (Fig. 1d).

Both the HadGEM3 and CMIP6 simulations reasonably well capture the variability of observed SCPI for the period 1961–2013, as shown in Figs. 2a and 2b, and probability density functions (PDFs) in simulations are comparable to that observed (Figs. 2c,d). Moreover, the observed precipitation indices fall within the range of those simulated by the models. We applied the QQ and KDE plots to test the distribution between the simulations and observations. Results show the simulations of HadGEM3 and CMIP6 follow the same distribution as observations (not shown). PDFs of SCPI exhibit similar distributions between model simulations and observations (Figs. 2c,d) with p values of 0.50 and 0.33, respectively, according to the two-sample KS test. These results suggest that both HadGEM3 and CMIP6 models can be considered reliable for the attribution of the 2022 J–F extreme precipitation event over SC.

Figures 2e and 2f show the GEV-fitted PDFs for the 2022-like event under different external forcings. In both two sets of model simulations, PDFs of SCPI exhibit a drying shift from NAT to ALL. This shift indicates that the observed extreme precipitation event like 2022 is less

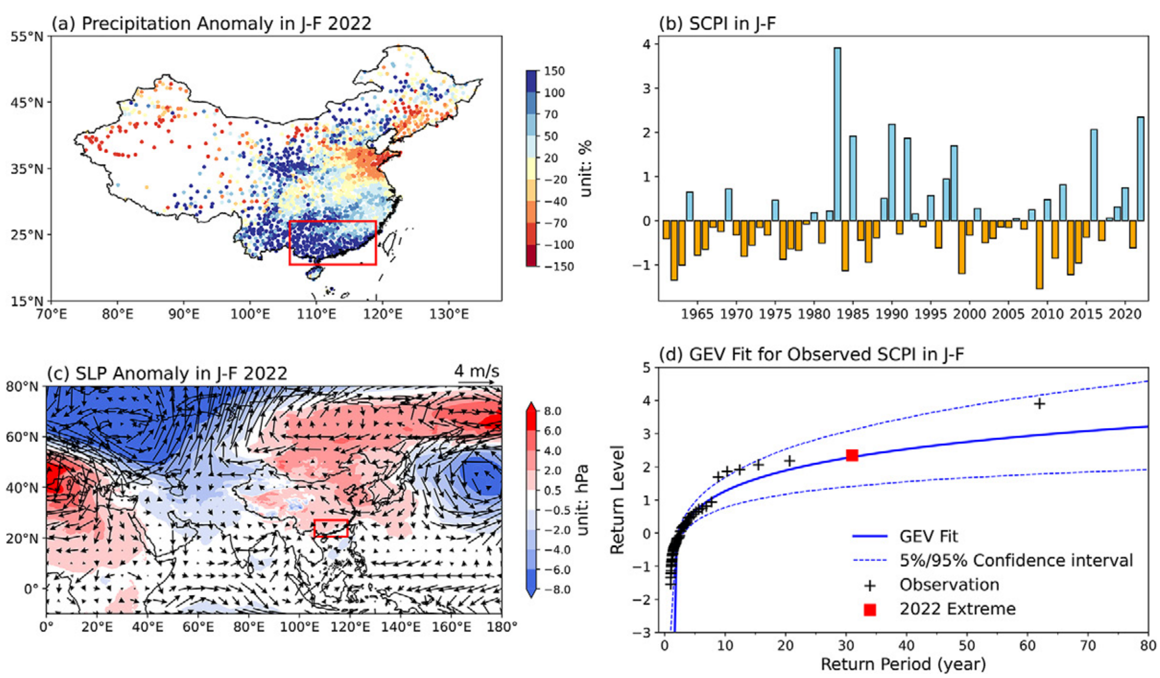

Fig. 1. (a) Percentage anomalies of observed precipitation in 2022 J–F relative to the 1961–2005 climatology. (b) Observed SCPI in each J–F for 1961–2022. (c) Spatial distribution of the sea level pressure anomaly (shading; hPa) and 850-hPa wind anomaly (vector; m s^{-1}). (d) GEV fit (blue solid line) of observed SCPI with 90% CI. The crosses are estimated from the empirical distributions of the observed precipitation index with the red square denoting the 2022 event.

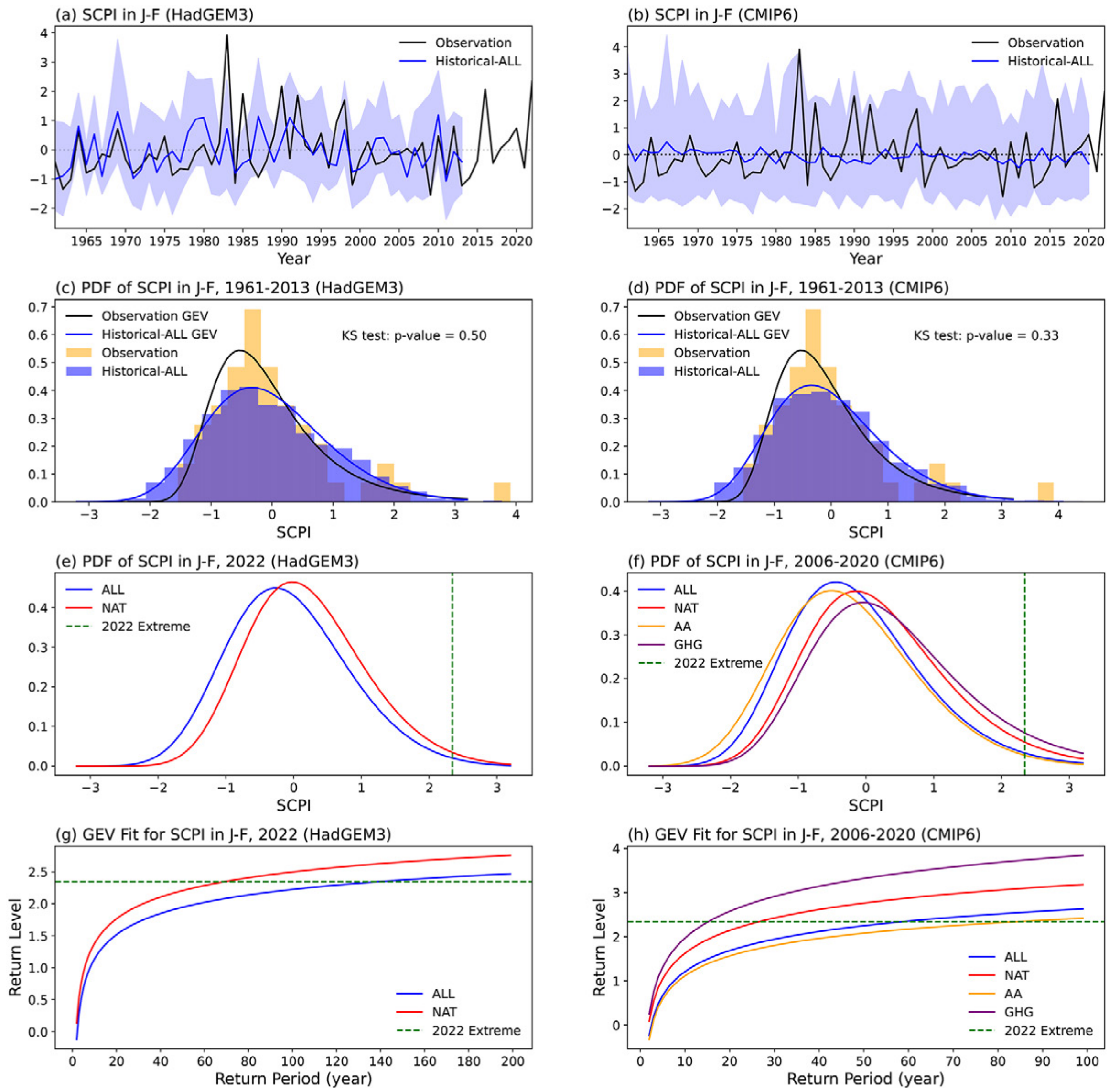

Fig. 2. (a),(b) Time series of observed (black) and simulated ensemble mean (blue) SCPI for 1961–2022, with (a) 15-member and (b) 27-member spread shown as light blue shading in HadGEM3 and CMIP6 simulations, respectively. (c),(d) SCPI original (bar) and GEV fitted PDFs (solid line) of observations (yellow bar and black line) and historical ALL simulations (blue bar and blue line) for 1961–2013 in HadGEM3 in (c) and CMIP6 in (d). The *p* value for the KS test is on the top right. (e),(f) GEV fitted PDFs of SCPI in 2022 based on ALL (blue) and NAT (red) ensembles in HadGEM3, and ALL (blue), NAT (red), GHG (purple), and AA (yellow) in CMIP6 simulations. The dashed green line denotes the observed 2022 event. (g),(h) As in (e) and (f), but for return periods.

likely to occur with anthropogenic influence (Table 1). The estimated occurrence probability decreased from 1.3% (1.3%–1.7%) in NAT to 0.7% (0.6%–0.9%) in ALL, with a PR_{ALL} of 0.50 (0.41–0.60) in HadGEM3 simulations. The return period is significantly increased from ~77 years in NAT to ~143 years in ALL (Fig. 2g). Similarly, in CMIP6 simulations, the estimated occurrence probability decreased from 3.8% (2.6%–4.8%) in NAT to 1.7% (1.0%–2.4%) in ALL, with a PR_{ALL} of 0.45 (0.38–0.53) and the return period increased from ~26 years in NAT to ~59 years in ALL (Fig. 2h). These results suggest that anthropogenic influence reduced the likelihood of extreme event like 2022 by about 50% (55%) in HadGEM3 (CMIP6).

Furthermore, the GHG forcing leads to a rightward shift of PDFs to a wetter climate relative to NAT (Fig. 2f), while the AA forcing shifts to a drier world. The estimated P_{GHG} and P_{AA} indicate that a ~26-yr event becomes a ~15-yr event with PR_{GHG} = 1.75(1.60–2.00) in GHG and a ~83-yr event in AA with PR_{AA} = 0.31 (0.24–0.37).

How does anthropogenic influence reduce the likelihood of extreme events like 2022? The J–F differences of ensemble mean precipitation and atmospheric circulations between ALL and NAT experiments are analyzed (Fig. ES1 in the supplemental material). Decreases in precipitation occur in both HadGEM3 and CMIP6 simulations over SC (Figs. ES1a,b), accompanied by anomalous positive sea level pressure (SLP) and an anomalous anticyclonic circulation over SC (Figs. ES1c,d).

Table 1. Attribution results for the 2022 J–F event with probability ratio (PR_{ALL}, PR_{GHG}, and PR_{AA}), exceedance probability from ALL (P_{ALL}), GHG (P_{GHG}), AA (P_{AA}), and NAT (P_{NAT}), and the 90% confidence intervals (CI) in parentheses in HadGEM3 and CMIP6 simulations.

	HadGEM3	CMIP6
PR_{ALL}	0.50 (0.41–0.60)	0.45 (0.38–0.53)
PR_{GHG}	—	1.75 (1.60–2.00)
PR_{AA}	—	0.31 (0.24–0.37)
P_{ALL} (%)	0.7 (0.6–0.9)	1.7 (1.0–2.4)
P_{GHG} (%)	—	6.7 (5.1–7.9)
P_{AA} (%)	—	1.2 (0.5–1.9)
P_{NAT} (%)	1.3 (1.3–1.7)	3.8 (2.6–4.8)

The two most important anthropogenic forcings are greenhouse gases and atmospheric aerosols and they can have different effects on SC J–F precipitation. According to the CMIP6 results, compared to the NAT, the GHG simulation is shifting rightward to a wetter climate, while the AA distribution is marked by a flatter distribution with shifting to a drier region (Fig. 2f). A further comparison of AA and GHG with the NAT experiments reveals the impact of different anthropogenic forcings. Through aerosol radiation and cloud interactions, there is a positive SLP anomaly in most of the mid-to-high latitudes of East Asia, with an anomalously strong Siberian high together with changes in the Walker circulation over the eastern Indian Ocean, Maritime Continent, and western Pacific Ocean (Takahashi et al. 2018) and with a weakening of anomalous anticyclonic circulation over the western North Pacific (WNP), which leads to anticyclone anomaly over the SC, so a reduction in J–F precipitation happened in SC (Fig. ES2a). On the other hand, over SC, the effect of nonabsorbing aerosols is dominant. The solar flux at the surface is significantly reduced directly by the scattering of nonabsorbing aerosols and indirectly by the intensification of shortwave cloud forcing. Accordingly, the surface air temperature in SC is reduced, which leads to the moisture transport decreasing, so the precipitation is also significantly reduced in South China (Huang et al. 2007; Jiang et al. 2017) (Fig. ES2c).

On the other hand, GHG contributes to an increase in precipitation over SC (Fig. ES2b). This is partly related to the GHG-induced increase of moisture in the atmosphere associated with warming (Guo et al. 2023) and is also associated with an anomalous negative SLP in the midlatitudes, where the Baikal trough deepens and favors the cold air to SC. The anomalous anticyclonic circulation in the WNP subtropical region caused the convergence of warm and moist air from the southern flank of the Philippine high, contributing to the SC precipitation increase (Fig. ES2d). The impacts from aerosols overwhelm the impacts from GHG changes, leading to a decrease of precipitation from NAT to ALL in CMIP6/DAMIP simulations.

Conclusions

We conducted an assessment of the anthropogenic influence on the likelihood of the 2022 extreme wet J–F in SC using two sets of model simulations. The analysis reveals that anthropogenic activities have reduced the likelihood of extreme events like 2022 by about 50% (55%) in HadGEM3 (CMIP6) simulations. Analyses of single forcing experiments using CMIP6 model ensembles demonstrate different roles of changes in GHG and AA in J–F precipitation over SC with GHG forcing inducing an increase and AA forcing inducing a decrease, similar to previous studies in warm season (Sun et al. 2022; Guo et al. 2023; Hu et al. 2023). However, the magnitude of the AA-induced precipitation decrease is larger than that of the GHG-induced increase (Cao et al. 2022), leading to the reduced likelihood of a J–F precipitation event similar to that of 2022 in SC by the combined effect of anthropogenic forcing.

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Data availability statement. The following data are available online: the CMIP6 GCM simulations (https://esgf-node.llnl.gov/projects/cmip6/) and the homogenized station data in China (http://data.cma.cn/).

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