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Anthropogenic forcings have reduced the likelihood of heavy precipitation in southern China like the 2019 March-July event by about 60%

Introduction

During March to July 2019, southern China witnessed an extraordinarily long rainy season that was the 3rd wettest on record with total precipitation (1,303 mm) exceeding the climatological (1961-2010) average by 281 mm (Fig. 1a). The so-called 'first rainy season' (FRS), normally spanning from April to June, is the main contributor (40%-50%) to annual precipitation totals over southern China and dominates in the rainfall variability there (Gu et al., 2018). Heavy precipitation can cause flooding and landslides, resulting in huge economic losses (Field C.B. et al., 2012).

Southern China, home to the megacities like Guangzhou and Shenzhen, is highly populated, meaning a high exposure of population and infrastructure to precipitation extremes and resultant hydrological hazards (Burke and Stott, 2017; Li et al., 2018; Zhang et al., 2020). During 6-13 June 2019, over 6 million people across several southern China provinces were affected by heavy rains, floods and landslides. These extremes caused at least 91 deaths, collapsed over 19,000 houses, damaged around 83,000 houses, and affected 419,400 hectares of crops (China Ministry of Emergency Management, 2020). The direct economic loss was estimated to be more than 20 billion RMB (equivalent to 3 billion USD) (China Ministry of Emergency Management, 2020). Understanding the driver for precipitation extremes is a key step toward formulating adaptation and mitigation strategies. This study aims to shed light on this scientific question by addressing potential anthropogenic influences on the probability of extremely wet seasons similar to the March-July 2019 event in this region.

Data and Methods:

The March-July 2019 extreme precipitation event was bounded by 22°-28°N, 110°-120°E over southern China (Fig. 1a). Quality-controlled daily rainfall over 2,400 meteorological stations (Shen et al., 2010) during 1961-2019 were provided by the China National Meteorological Information Center. March-July 2019 precipitation at most rain-gauges in this region was around 150 mm (1mm/day) larger than normal (Fig. 1a).

Raw gauge observations were interpolated onto the 0.56° x 0.83° (same as model resolution) by using bilinear interpolation. These gridded values were area-weight averaged to obtain regional seasonal total precipitation time-series. Then precipitation time-series anomalies were calculated and the positive anomaly of 1.84 mm/day for the March-July 2019 event was used as the threshold (Fig. 1b) for the subsequent attribution analyses.

The HadGEM3-GA6 model (Ciavarella et al., 2018) at an N216 resolution of 0.56° x 0.83° was applied to investigate the role of anthropogenic forcings on the changing risks of the 2019-like seasonal precipitation extremes over southern China. The model outputs include all-forced simulations (historical) conditioned on the observed sea surface temperatures (SST) and sea ice (HadISST (Rayner et al., 2003)) and natural simulations (historicalNat) with anthropogenic signals removed from observed SSTs and with preindustrial forcings. Both historical and historicalNat ensembles consist of 15 members during the historical period (1961-2013), and 525 members for 2019. Accordingly, occurrence probabilities and resultant attribution conclusions are conditioned on the 2019 SST patterns. The 1961-2010 climatology was constructed from the 15-member ensembles.

The Coupled Model Intercomparison Project Phase 5 (CMIP5) models were also included to further corroborate the attribution results. Since the historical runs terminate at the end of 2005, the CMIP5 historical runs were extended through 2006 with the Representative Concentration Pathways 8.5 (RCP8.5) runs. This is because the projected greenhouse gas forcings of RCP8.5 is more consistent with the present realization than the other scenarios (Peters et al., 2013). RCP8.5 simulations for 2009–2028 are used as All and natural-only forcing runs for 1961-1980 are used as Nat (see Table. ES1 for more details). The selection of time periods for both CMIP5 All and Nat simulations is to avoid impacts from major volcano activates like 1991 eruption of Mount Pinatubo. Note that, unlike the HadGEM3-GA6 simulations based on 2019 SSTs, the CMIP5 simulations encompasses a wide range of ocean states. Consequently, the event probabilities estimated hereafter are differently conditioned, such that the results from the two datasets will not be directly comparable.

A Kolmogorov–Smirnoff (K-S) test was applied to test if the distributions of the observed and simulated precipitation anomalies during 1961-2010 are from the same population (Table. ES1). The occurrence probability of events with equivalent or heavier precipitation than the 2019 event (anomaly of 1.84 mm/day with respect to the 1961-2010 climatology) in the entire HadGEM3-GA6 historical and historicalNat (or CMIP5 All and Nat) ensembles are indicated as PALL and PNAT respectively, and the risk ratio (RR) is computed from PALL/PNAT. The RR uncertainty with 90% confidence interval (90% CI) was estimated by identifying the empirical 5^{th} and 95^{th} percentile amongst 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. Note that precipitation anomalies estimated from each model were calculated with their own 1961-2010 climatology, serving to remove the model climatological mean bias (Zhang et al., 2020).

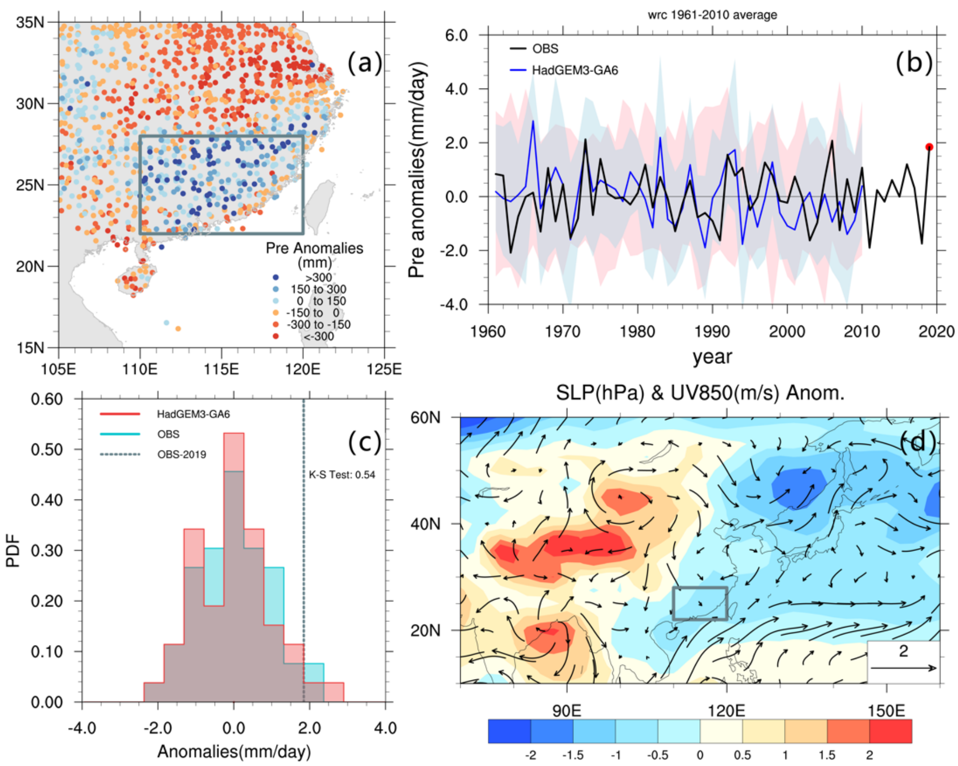

Fig 1: (a) Observed March–July 2019 precipitation anomalies (mm/5month) from rain gauges; (b) Time series of observations and simulated ensemble means of precipitation anomalies (solid lines), and uncertainty bounds of 15 members of HadGEM3-GA6 and 53 members of CMIP5 spread shown as pink and blue shading, respectively. (c) Probability density functions for the precipitation anomalies in the study region during March-July from 1961 to 2010 constructed with data from the HadGEM3-GA6 historical experiments (red) and OBS (green). (d) SLP (shading) and 850-hPa wind (vector) anomalies from NCEP reanalysis in March–July 2019. All anomalies are relative to 1961–2010 climatology. The grey box in (a) and (d) marks the study region.

Results and Discussions:

The domain-averaged seasonal precipitation during March-July 2019 was 1.84 mm/day larger than the 1961-2010 climatology (Fig. 1b), equivalent to a 1-in-28-yr event in the 1961-2019 observations. This prolonged extreme seasonal precipitation event was mainly due to the early onset (by 28 days) and late cessation (by 22 days) of the first rainy season (CMA, 2020).

The event was associated with an anomalous negative sea level pressure (SLP) covering southern China (Fig. 1d) and anomalous westerlies in the southwest of the center of the East Asian westerly jet stream at 200-hPa (Fig. ES1d), indicating an enhanced and southward displaced East Asian westerly jet stream in 2019. This anomalous circulation strengthens the high-level divergence and is conducive to the enhancement of deep convection and precipitation in southern China. The western Pacific subtropical high is enhanced and extended to the southwest (Fig. ES1c). This is accompanied by 850-hPa westerly and southwesterly wind anomalies over southern China and the northeastern portion of Indochina Peninsula (Fig. 1d), which enhances the climatological mean southwesterlies in southern China (Fig. ES1f). The wind anomalies further enhance the water vapor transport from the Indochina Peninsula (Fig. ES1b). This produces anomalous moisture flux convergence over southern China (negative values in Fig. ES1e), providing a favorable moisture environment for abundant precipitation. Meanwhile, the anomalous southwesterlies advect warm air toward southern China. With more evaporation from land, increased water vapor is further enhanced. These conditions are consistent with previous studies finding that above-normal FRS precipitation is often associated with an enhanced and southwestward-extended western Pacific subtropical high and an enhanced Asian westerly jet (Zhang et al., 2009; Gu et al., 2018).

Evaluation of the HadGEM3-GA6 simulations was carried out to see if this model could accurately reproduce the characteristics of precipitation in the study region. The distributions of observed and simulated precipitation anomalies (Fig. 1c) during March-July in 1961–2010 cannot be distinguished based on the K-S test (P-value=0.54; Table. ES1). Note that while precipitation anomalies are reasonably simulated, the HadGEM3-GA6 overestimates actual precipitation values. Moreover, both the HadGEM3-GA6 and CMIP5 models overestimate of seasonal precipitation variability (figures omitted), leading to the underestimation of return periods for the 2019-like precipitation event, particularly for the HadGEM3-GA6 (Table. 1). These results are consistent with the precipitation variability maps shown in Knutson and Zeng (2018).

The probability density functions (PDFs) of the 2019-like persistent precipitation events from both models show the historical simulations shifting toward drier rainy seasons compared to the historicalNat simulations (Fig. 2a, c). This gives the estimated risk ratio of 0.43 [90% CI: 0.31, 0.57] and 0.38 [90% CI: 0.32, 0.44] for CMIP5 and HadGEM3-GA6 ensembles respectively (Table. 1), which implies the anthropogenic forcings have reduced the likelihood of 2019-like extreme seasonal precipitation event over southern China by around 60%. Most of the best estimate of RR values of individual CMIP5 models are less than 1, except the GFDL-ESM2M and GISS-E2-H model (Fig. ES2). Moreover, the changes in return periods also demonstrate that the 2019-like prolonged rainy seasonal precipitation occurs less frequent due to anthropogenic influences and it changes from 1-in-4-yr event for historicalNat simulations to 1-in-9-yr event for Historical simulations (Fig. 2b,d; Table. 1). Although the HadGEM3-GA6 2019 simulations are atmospheric model simulations and conditional to 2019 SST pattern, their attribution results are consistent with the CMIP5 results which takes into account the variability in SST patterns.

The results are consistent with the findings in Zhang et al. (2020) that anthropogenic forcings reduced the probability of long-lasting heavy rainfall in central western China. The reduced probability of persistent heavy rainfall due to anthropogenic forcings could be mainly due to increased aerosols in the climate system (Song et al., 2014; Li et al., 2015; Zhang and Li, 2016; Burke and Stott, 2017). Specifically, by scattering and absorbing solar radiation, aerosols can induce surface cooling through aerosol-radiation interactions, and therefore can lead to reduced precipitation by increasing atmospheric stability. Aerosols also interact directly with cloud by serving as cloud condensation nuclei or ice nuclei, leading to changes in cloud radiative properties and reducing precipitation efficiency (Rosenfeld et al., 2008). In addition, increased aerosols can weaken land-sea thermal contrast and therefore lead to weakening of the monsoon circulation and reduced precipitation over monsoon regions (Dong et al., 2019; Zhou et al., 2020). The impacts of anthropogenic forcings on changing risks of persistent precipitation events are also emphasized by the findings in Ji et al. (2020). They demonstrated that the anthropogenic-induced climate change has reduced the likelihood of extreme flooding by around 34% over the Yellow River basins during summer, consistent with our result. In addition, Lu et al. (2020) used HadGEM3-GA6 to reveal that anthropogenic forcings have reduced precipitation in favor of severe drought development during May-June over southwestern China.

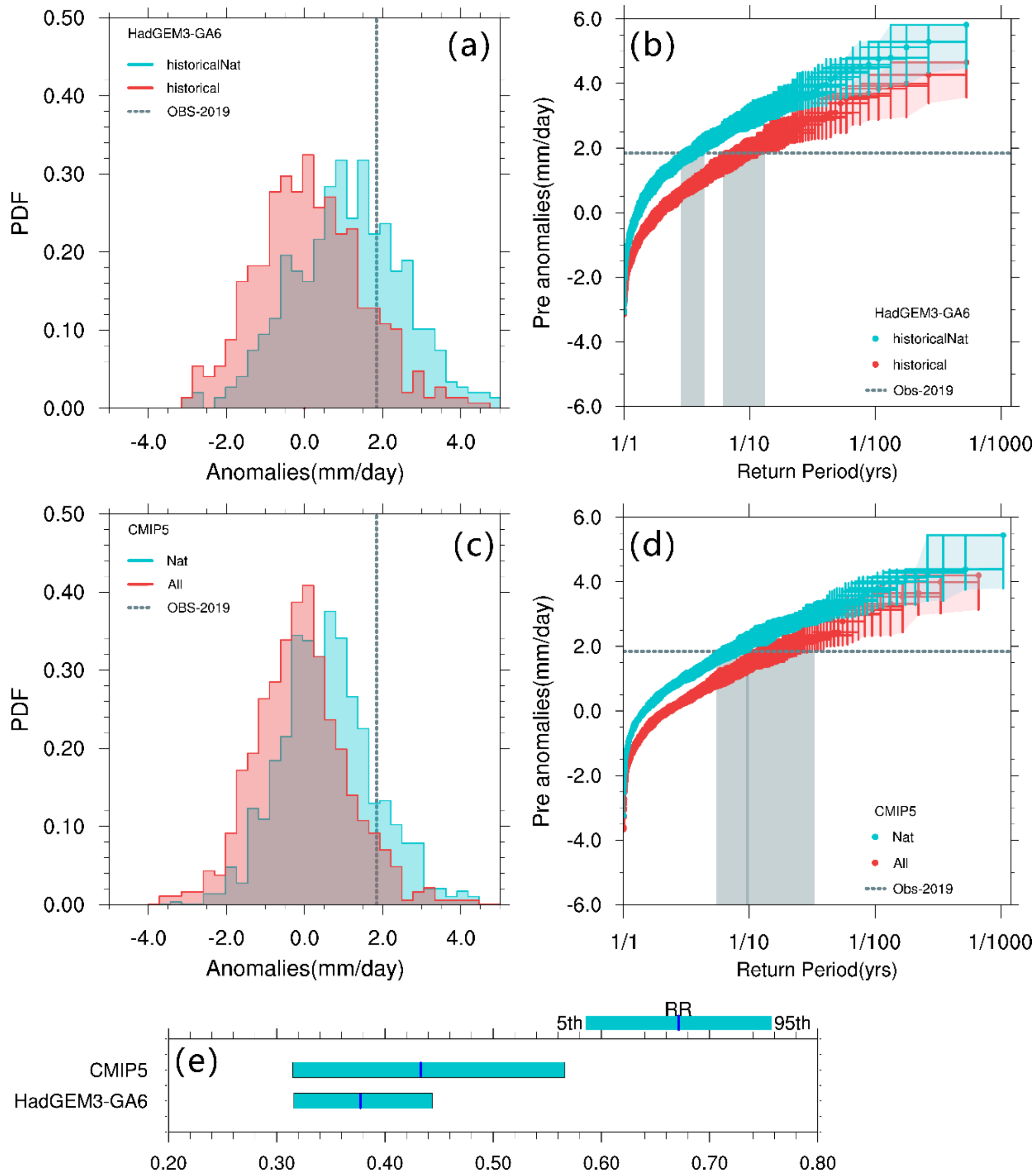

Fig 2: Probability density functions of (a) HadGEM3-GA6 and (c) CMIP5 All (2009-2028) and Nat (1961-1980) ensembles simulations of 2019 March-July precipitation anomalies (mm/day) in the study region. Return period for the (b) HadGEM3-GA6 and (d) CMIP5 All and Nat ensemble simulations. Each marker represents an ensemble member, and the green and red lines are return period for the historical and historicalNat, respectively. The errors bars indicate the 90% confidence interval using bootstrap resampling by 1,000 times. (e) Best estimates (blue lines) and 90% confidence intervals (aqua shadings) of risk ratio for CMIP5 & HadGEM3-GA6.

Table 1: The best estimate and 90% confidence intervals of return period and risk ratio estimated with HadGEM3-GA6 and CMIP5 models.

Models		Return Period (yrs) (90% CI)	Risk Ratio (90% CI)
HadGEM3-GA6	historical	8.78(6.12, 13.17)	0.38(0.32, 0.44)
	historicalNat	3.31(2.83, 4.35)	
CMIP5	All	15.79(9.46, 33.10)	0.43(0.31, 0.57)
	Nat	6.95(5.48, 9.92)	

Conclusions

Using large ensembles of HadGEM3-GA6 and CMIP5 models, anthropogenic influences on changing risks of the 2019 March-to-July-like extreme rainy seasonal precipitation in southern China were quantified. Results based on these two models consistently indicate similar cases are less likely to occur in the current climate compared to the natural world. Specifically, anthropogenic forcings have made the probability of an extreme seasonal precipitation event like 2019 approximately 60% less likely.

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