

Anthropogenic influences on heavy precipitation during the 2019 extremely wet rainy season in Southern China

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1 **Anthropogenic influences on heavy precipitation**
2 **during the 2019 extremely wet rainy season in**
3 **southern China**

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

40 During March to July 2019, southern China witnessed an extraordinarily long rainy season that
41 was the 3rd wettest on record with total precipitation (1,303 mm) exceeding the climatological
42 (1961-2010) average by 281 mm (Fig. 1a). The so-called 'first rainy season' (FRS), normally
43 spanning from April to June, is the main contributor (40%-50%) to annual precipitation totals
44 over southern China and dominates in the rainfall variability there ([Gu et al., 2018](#)). Heavy
45 precipitation can cause flooding and landslides, resulting in huge economic losses ([Field C.B.
46 et al., 2012](#)).

47

48 Southern China, home to the megacities like Guangzhou and Shenzhen, is highly populated,
49 meaning a high exposure of population and infrastructure to precipitation extremes and
50 resultant hydrological hazards ([Burke and Stott, 2017](#); [Li et al., 2018](#); [Zhang et al., 2020](#)). During
51 6-13 June 2019, over 6 million people across several southern China provinces were affected
52 by heavy rains, floods and landslides. These extremes caused at least 91 deaths, collapsed over
53 19,000 houses, damaged around 83,000 houses, and affected 419,400 hectares of crops ([China
54 Ministry of Emergency Management, 2020](#)). The direct economic loss was estimated to be
55 more than 20 billion RMB (equivalent to 3 billion USD) ([China Ministry of Emergency
56 Management, 2020](#)). Understanding the driver for precipitation extremes is a key step toward
57 formulating adaptation and mitigation strategies. This study aims to shed light on this scientific
58 question by addressing potential anthropogenic influences on the probability of extremely wet
59 seasons similar to the March-July 2019 event in this region.

60

61 Data and Methods:

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

67

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

73

74 The HadGEM3-GA6 model ([Ciavarella et al., 2018](#)) at an N216 resolution of 0.56° x 0.83° was
75 applied to investigate the role of anthropogenic forcings on the changing risks of the 2019-like

76 seasonal precipitation extremes over southern China. The model outputs include all-forced
77 simulations (historical) conditioned on the observed sea surface temperatures (SST) and sea
78 ice (HadISST ([Rayner et al., 2003](#))) and natural simulations (historicalNat) with anthropogenic
79 signals removed from observed SSTs and with preindustrial forcings. Both historical and
80 historicalNat ensembles consist of 15 members during the historical period (1961-2013), and
81 525 members for 2019. Accordingly, occurrence probabilities and resultant attribution
82 conclusions are conditioned on the 2019 SST patterns. The 1961-2010 climatology was
83 constructed from the 15-member ensembles.

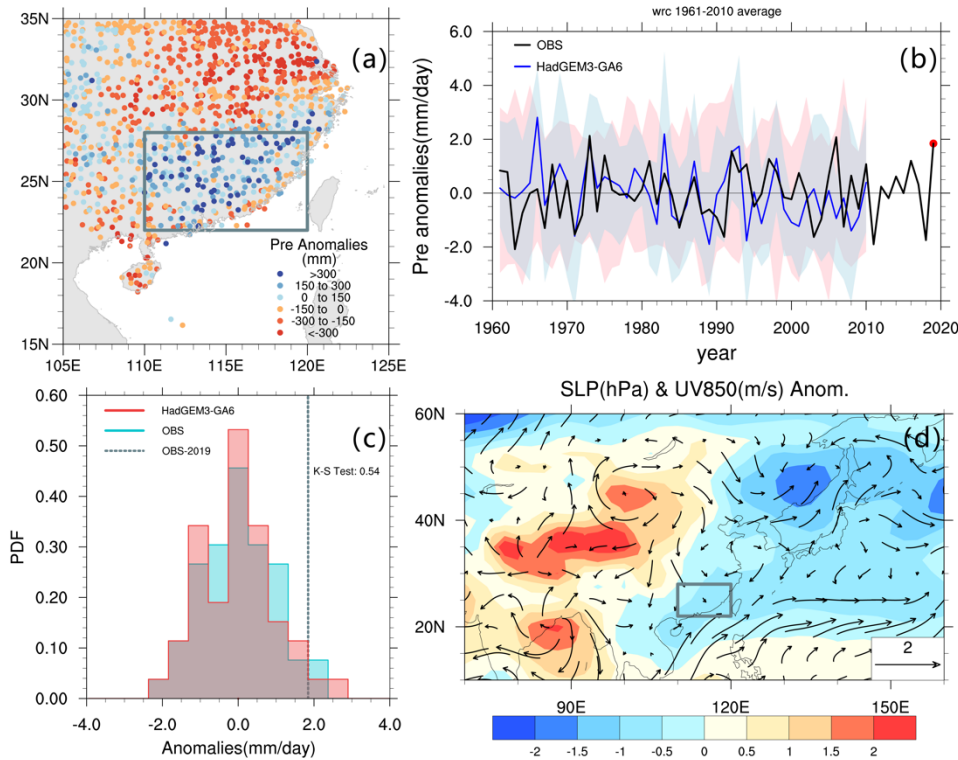
84

85 The Coupled Model Intercomparison Project Phase 5 (CMIP5) models were also included to
86 further corroborate the attribution results. Since the historical runs terminate at the end of
87 2005, the CMIP5 historical runs were extended through 2006 with the Representative
88 Concentration Pathways 8.5 (RCP8.5) runs. This is because the projected greenhouse gas
89 forcings of RCP8.5 is more consistent with the present realization than the other scenarios
90 ([Peters et al., 2013](#)). RCP8.5 simulations for 2009–2028 are used as All and natural-only forcing
91 runs for 1961-1980 are used as Nat (see Table. ES1 for more details). The selection of time
92 periods for both CMIP5 All and Nat simulations is to avoid impacts from major volcano
93 activates like 1991 eruption of Mount Pinatubo. Note that, unlike the HadGEM3-GA6
94 simulations based on 2019 SSTs, the CMIP5 simulations encompasses a wide range of ocean
95 states. Consequently, the event probabilities estimated hereafter are differently conditioned,
96 such that the results from the two datasets will not be directly comparable.

97

98 A Kolmogorov–Smirnov (K-S) test was applied to test if the distributions of the observed and
99 simulated precipitation anomalies during 1961-2010 are from the same population (Table.
100 ES1). The occurrence probability of events with equivalent or heavier precipitation than the
101 2019 event (anomaly of 1.84 mm/day with respect to the 1961-2010 climatology) in the entire
102 HadGEM3-GA6 historical and historicalNat (or CMIP5 All and Nat) ensembles are indicated as
103 PALL and PNAT respectively, and the risk ratio (RR) is computed from PALL/PNAT. The RR
104 uncertainty with 90% confidence interval (90% CI) was estimated by identifying the empirical
105 5th and 95th percentile amongst 1,000-times resampling of model ensemble members by using
106 Monte Carlo bootstrapping procedure ([Christidis et al., 2013](#)). Doing each bootstrap, model
107 ensemble simulations are randomly resampled with replacement to get a set of new data with
108 the same length as the original. Note that precipitation anomalies estimated from each model
109 were calculated with their own 1961-2010 climatology, serving to remove the model
110 climatological mean bias ([Zhang et al., 2020](#)).

111



112

113 **Fig 1: (a) Observed March–July 2019 precipitation anomalies (mm/5month) from rain gauges;**
 114 **(b) Time series of observations and simulated ensemble means of precipitation anomalies**
 115 **(solid lines), and uncertainty bounds of 15 members of HadGEM3-GA6 and 53 members of**
 116 **CMIP5 spread shown as pink and blue shading, respectively. (c) Probability density functions**
 117 **for the precipitation anomalies in the study region during March–July from 1961 to 2010**
 118 **constructed with data from the HadGEM3-GA6 historical experiments (red) and OBS (green).**
 119 **(d) SLP (shading) and 850-hPa wind (vector) anomalies from NCEP reanalysis in March–July**
 120 **2019. All anomalies are relative to 1961–2010 climatology. The grey box in (a) and (d) marks**
 121 **the study region.**

122

123 **Results and Discussions:**

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

128

129 The event was associated with an anomalous negative sea level pressure (SLP) covering
 130 southern China (Fig. 1d) and anomalous westerlies in the southwest of the center of the East
 131 Asian westerly jet stream at 200-hPa (Fig. ES1d), indicating an enhanced and southward
 132 displaced East Asian westerly jet stream in 2019. This anomalous circulation strengthens the
 133 high-level divergence and is conducive to the enhancement of deep convection and
 134 precipitation in southern China. The western Pacific subtropical high is enhanced and

135 extended to the southwest (Fig. ES1c). This is accompanied by 850-hPa westerly and
136 southwesterly wind anomalies over southern China and the northeastern portion of Indochina
137 Peninsula (Fig. 1d), which enhances the climatological mean southwesterlies in southern China
138 (Fig. ES1f). The wind anomalies further enhance the water vapor transport from the Indochina
139 Peninsula (Fig. ES1b). This produces anomalous moisture flux convergence over southern
140 China (negative values in Fig. ES1e), providing a favorable moisture environment for abundant
141 precipitation. Meanwhile, the anomalous southwesterlies advect warm air toward southern
142 China. With more evaporation from land, increased water vapor is further enhanced. These
143 conditions are consistent with previous studies finding that above-normal FRS precipitation is
144 often associated with an enhanced and southwestward-extended western Pacific subtropical
145 high and an enhanced Asian westerly jet ([Zhang et al., 2009](#); [Gu et al., 2018](#)).

146

147 Evaluation of the HadGEM3-GA6 simulations was carried out to see if this model could
148 accurately reproduce the characteristics of precipitation in the study region. The distributions
149 of observed and simulated precipitation anomalies (Fig. 1c) during March-July in 1961–2010
150 cannot be distinguished based on the K-S test (P-value=0.54; Table. ES1). Note that while
151 precipitation anomalies are reasonably simulated, the HadGEM3-GA6 overestimates actual
152 precipitation values. Moreover, both the HadGEM3-GA6 and CMIP5 models overestimate of
153 seasonal precipitation variability (figures omitted), leading to the underestimation of return
154 periods for the 2019-like precipitation event, particularly for the HadGEM3-GA6 (Table. 1).
155 These results are consistent with the precipitation variability maps shown in [Knutson and Zeng](#)
156 [\(2018\)](#).

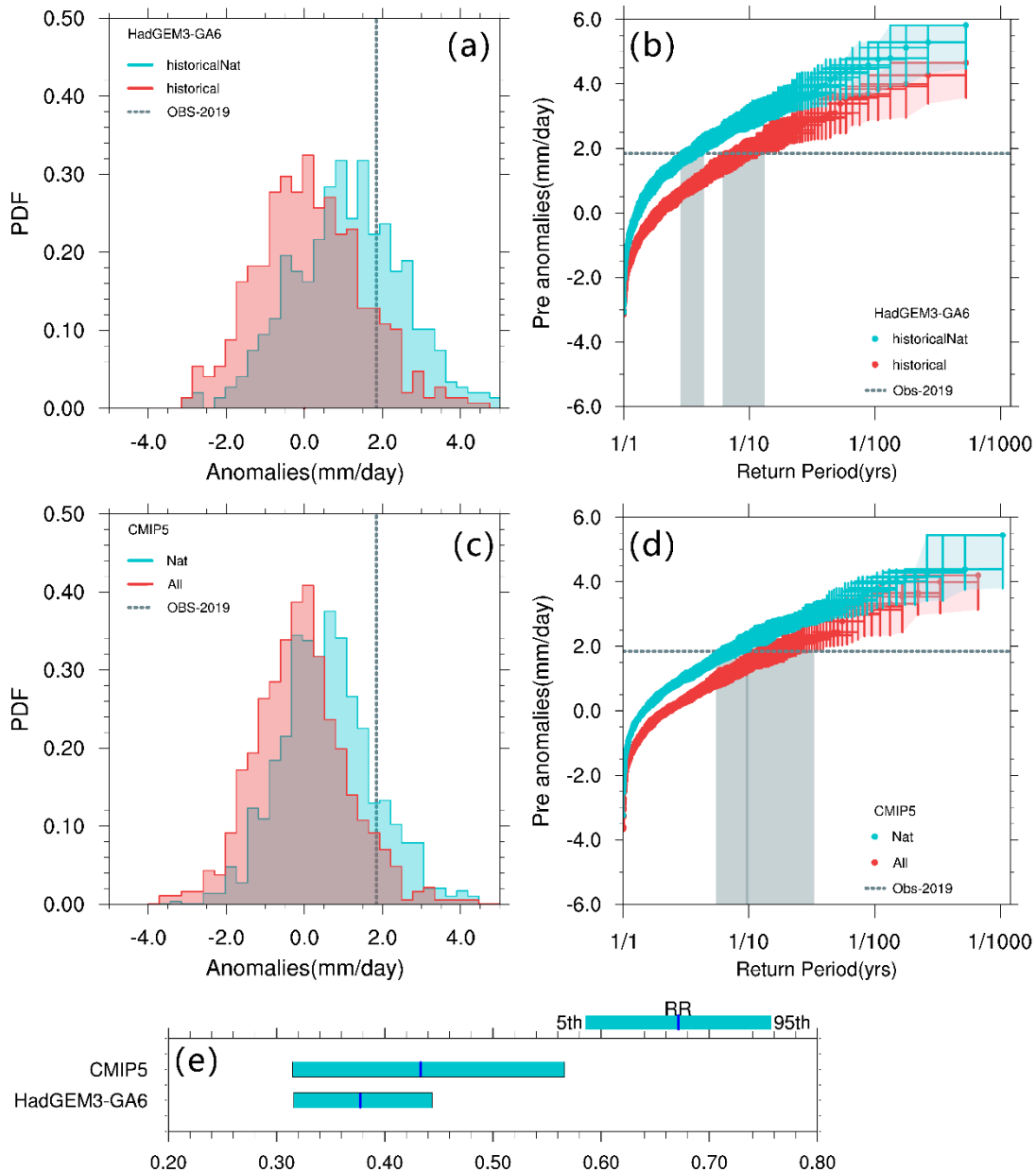
157

158 The probability density functions (PDFs) of the 2019-like persistent precipitation events from
159 both models show the historical simulations shifting toward drier rainy seasons compared to
160 the historicalNat simulations (Fig. 2a, c). This gives the estimated risk ratio of 0.43 [90% CI:
161 0.31, 0.57] and 0.38 [90% CI: 0.32, 0.44] for CMIP5 and HadGEM3-GA6 ensembles respectively
162 (Table. 1), which implies the anthropogenic forcings have reduced the likelihood of 2019-like
163 extreme seasonal precipitation event over southern China by around 60%. Most of the best
164 estimate of RR values of individual CMIP5 models are less than 1, except the GFDL-ESM2M
165 and GISS-E2-H model (Fig. ES2). Moreover, the changes in return periods also demonstrate
166 that the 2019-like prolonged rainy seasonal precipitation occurs less frequent due to
167 anthropogenic influences and it changes from 1-in-4-yr event for historicalNat simulations to
168 1-in-9-yr event for Historical simulations (Fig. 2b,d; Table. 1). Although the HadGEM3-GA6
169 2019 simulations are atmospheric model simulations and conditional to 2019 SST pattern,
170 their attribution results are consistent with the CMIP5 results which takes into account the
171 variability in SST patterns.

172

173 The results are consistent with the findings in [Zhang et al. \(2020\)](#) that anthropogenic forcings

174 reduced the probability of long-lasting heavy rainfall in central western China. The reduced
175 probability of persistent heavy rainfall due to anthropogenic forcings could be mainly due to
176 increased aerosols in the climate system ([Song et al., 2014](#); [Li et al., 2015](#); [Zhang and Li, 2016](#);
177 [Burke and Stott, 2017](#)). Specifically, by scattering and absorbing solar radiation, aerosols can
178 induce surface cooling through aerosol-radiation interactions, and therefore can lead to
179 reduced precipitation by increasing atmospheric stability. Aerosols also interact directly with
180 cloud by serving as cloud condensation nuclei or ice nuclei, leading to changes in cloud
181 radiative properties and reducing precipitation efficiency ([Rosenfeld et al., 2008](#)). In addition,
182 increased aerosols can weaken land-sea thermal contrast and therefore lead to weakening of
183 the monsoon circulation and reduced precipitation over monsoon regions ([Dong et al., 2019](#);
184 [Zhou et al., 2020](#)). The impacts of anthropogenic forcings on changing risks of persistent
185 precipitation events are also emphasized by the findings in [Ji et al. \(2020\)](#). They demonstrated
186 that the anthropogenic-induced climate change has reduced the likelihood of extreme
187 flooding by around 34% over the Yellow River basins during summer, consistent with our result.
188 In addition, [Lu et al. \(2020\)](#) used HadGEM3-GA6 to reveal that anthropogenic forcings have
189 reduced precipitation in favor of severe drought development during May-June over
190 southwestern China.
191



192
 193 **Fig 2: Probability density functions of (a) HadGEM3-GA6 and (c) CMIP5 All (2009-2028) and**
 194 **Nat (1961-1980) ensemble simulations of 2019 March-July precipitation anomalies**
 195 **(mm/day) in the study region. Return period for the (b) HadGEM3-GA6 and (d) CMIP5 All**
 196 **and Nat ensemble simulations. Each marker represents an ensemble member, and the green**
 197 **and red lines are return period for the historical and historicalNat, respectively. The errors**
 198 **bars indicate the 90% confidence interval using bootstrap resampling by 1,000 times. (e)**
 199 **Best estimates (blue lines) and 90% confidence intervals (aqua shadings) of risk ratio for**
 200 **CMIP5 & HadGEM3-GA6.**

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

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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)	

209

210

211 Conclusions

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

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