EXPLAINING EXTREME EVENTS OF 2018

From a Climate Perspective

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EXPLAINING EXTREME EVENTS OF 2018 FROM A CLIMATE PERSPECTIVE

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COVER CREDIT: iStock.com/Alena Kravchenko—River Thames receded during a heatwave in summer 2018 in London, United Kingdom.

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THE LATE SPRING DROUGHT OF 2018 IN SOUTH CHINA

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HadGEM3-A indicates that anthropogenic forcing has increased the likelihood of the 2018 late spring drought in South China approximately 17 times, and such events do not occur in CAM5 without human influence.

Late spring (April–May) is normally the end of the dry season in South China, but 2018 was an exception. An extreme drought condition developed over South China (22°–29°N, 105°–120°E; box in Figs. 1a–c) during the late spring in 2018, affecting the provinces of Guangdong, Fujian, Jiangxi, Guizhou, and part of Hunan. South China received only about 40% of the 1951–2018 mean precipitation over Guangdong and Fujian provinces (Fig. 1a). The surface temperature reached 2.8°C above normal (1951–2018 mean) at a maximum (Fig. 1b), with record-breaking hot days in May reported in Guangdong, Jiangxi, and Fujian provinces. More than half stations over South China experienced a record-breaking drought seen from the anomalies in precipitation and the difference between precipitation and reference evapotranspiration (Pr-ET) (Figs. 1a,c). The 2018 late spring was ranked as the third year with extreme deficit rainfall (−2.6 mm day^{−1} less), the warmest year (2.0°C warmer) for 1951–2018 (Fig. 1d),

and the second driest year on record (−2.8 mm day^{−1} less) measured by Pr-ET. It reported that this drought has resulted in shrinking reservoirs and water shortages (www.gdsw.gov.cn/zwgk/tjxx.html; <http://slt.fujian.gov.cn/xxgk/tjxx/swxb/>). The acreage and yield for early rice, which is mainly planted in South China, was reduced respectively by 350 thousand hectares and 1.28 million tons relative to 2017 (National Bureau of Statistics of China; www.stats.gov.cn/tjsj/zxfb/201808/t20180824_1618794.html).

Observations show that South China has experienced a drying trend in late spring since the 1950s (Xin et al. 2006; Qiu et al. 2009; Li et al. 2018). The internal variation, such as the interdecadal changes of North Atlantic Oscillation (Xin et al. 2006) and an increase in protracted El Niño events accompanied by a reduction in La Niña episodes (Qiu et al. 2009), and anthropogenic aerosol forcing (Kim et al. 2007) were documented to be contributing to this drying trend. So far it is still unclear whether the attribution of anthropogenic forcing is detectable in the extreme late spring drought events over South China. This study will investigate the cause of the 2018 late spring drought in South China, and will assess the contribution of anthropogenic climate change on the likelihood of the 2018 late spring drought over South China by both examining drought indices and associated circulation.

DATA AND METHODS. The observational and reanalysis datasets used in this study are 1) monthly surface air temperature and precipitation observations at 839 stations for 1951–2018 provided by the National Meteorological Information Center at the China Meteorological Administration (the station data are further area-weighted interpolated to a 0.5° grid cell) and 2) monthly circulation data from the Japanese 55-Year Reanalysis for 1959–2018 (JRA-55;

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FIG. 1. The anomalies of (a) precipitation (%), (b) surface air temperature (°C), and (c) the difference between precipitation and reference evapotranspiration (Pr-ET; mm day⁻¹) in April–May 2018 relative to 1951–2018. The dots are the percentile ranks of April–May anomalies in 2018 at each station. Shadings are the anomalies based on the gridded data from the station observations. (d) Observed April–May mean surface air temperature (blue; °C), precipitation (black; mm day⁻¹), and Pr-ET (red; mm day⁻¹) anomalies regional averaged over South China [red box in (a)–(c)], where the dots denote the year 2018. (e) Return periods and 95% confidence intervals for April–May mean Pr-ET averaged over South China, where the red line denotes the year 2018. (f) April–May mean sea level pressure (shading; Pa) and 850-hPa winds (vector; m s⁻¹) anomalies in 2018 relative to 1959–2018.

Ebita et al. 2011). Reference evapotranspiration is calculated from surface temperature using the Hamon formulation (Haith and Shoemaker 1987).

We use outputs of two ensembles of simulations for the actual climate with all external forcing (“Factual”) and for a hypotheticals natural climate without the ef-

fect of human influence (“Counterfactual”) from two atmospheric general circulation models (Stone et al. 2019). One is HadGEM3-A-N216 from the Met Office HadGEM3-A-based operational event attribution system on a $0.83^\circ \times 0.56^\circ$ grid (Christidis et al. 2013; Ciavarella et al. 2018). The other one is CAM5 from CLIVAR C20C+ Detection and Attribution project on a $1^\circ \times 1^\circ$ grid (Angélil et al. 2017). 15 (50) members of historical simulations for 1960–2013 (1959–2017) and 525 (200) members for 2018 April–May were conducted for each experiment in HadGEM3-A (CAM5).

Two drought indices are used in this study, namely April–May mean Pr-ET and precipitation (Pr) averaged over the land grids in South China (22° – 29° N, 105° – 120° E), considering that precipitation deficit is the primary cause for agricultural failures and hydrological water shortages, and Pr-ET measures the balance between moisture supply and demand in the atmosphere. A circulation index is defined as the 850-hPa zonal winds (U850) averaged over 5° – 20° N, 90° – 120° E, a key region to define the South China Sea summer monsoon onset (Wang et al. 2004). Generalized extreme value (GEV) distribution is used to fit the April–May mean Pr, Pr-ET, and U850 distribution to estimate the return periods of drought events.

For the detection and attribution study, the following steps are carried out to make simulations and observations comparable. 1) We first extract the Pr, Pr-ET, and U850 indices in each experiment. This yields 525 (200) samples for year 2018 and 810 (2950) for the “historical” experiment from HadGEM3-A-N216 (CAM5). 2) Then we construct GEV distributions using all indices from the samples from this historical experiment, and derive the thresholds for the drought events in HadGEM3-A-N216 and CAM5, which have the same return periods as the year 2018 in observation. 3) Finally, the GEV probabilities of all simulated drought indices for year 2018 are derived from the Factual and Counterfactual experiments, and the risk ratio of such an event is calculated to see whether the anthropogenic forcing is detectable. The uncertainty of risk ratio is estimated via bootstrapping 1,000 times with showing the 5th–95th percentile ranges. We resample all model years with replacement and calculate the risk ratio for each bootstrap realization.

RESULTS. The return period of the 2018 late spring drought in observation is about once-in-66 years (Fig. 1e) and once-in-47 years based on Pr-ET and Pr, respectively. The dry condition in 2018 late spring was associated with an anomalous high sea level pressure

(SLP) covering the Bay of Bengal and Southeast Asia, accompanied with easterly anomalies to its south flank (Fig. 1f). It prohibited the transition of low-level winds over the Bay of Bengal from easterlies to westerlies during April–May, thus delayed the onset of South China Sea summer monsoon (SCSSM) and the South China rainy season. Studies showed that the pre-rainy season onset began on 7 May 2018, 31 days later than the normal (www.cma.gov.cn/root/7/auto13139/201903/t20190319_517664.html; Liu and Zhu 2019; Wang et al. 2016). A prominent feature of the low-level circulation anomalies is the anticyclonic circulation anomalies over the north Indian Ocean, demonstrating a weakened Walker circulation in late spring. At middle and high levels, the western North Pacific subtropical high was enhanced and westerly jet stream was weaker than the normal (Liu and Zhu 2019). These large-scale circulation anomalies are consistent with previous studies finding that a weakened Walker circulation is unfavorable for the airflow from the Indian Ocean into the SCS and easterly retreat of western North Pacific subtropical high, inducing a late SCSSM onset and South China late spring rainfall deficit (Feng and Hu 2014; Luo et al. 2016; Zhou and Chan 2007; Qiu et al. 2009). The U850 in 2018 April–May was only -1.7 m s^{-1} , which is about -1.8 m s^{-1} less than 1959–2017 mean, with a return period about 70 years.

ATTRIBUTION OF THE ANTHROPOGENIC FORCING ON 2018 LATE-SPRING DROUGHT.

Models reasonably represent the variation of South China drought for the period 1960–2013. It shows that the two models well simulate the ranges of observed anomalies both from yearly variation (see Figs. ES1a,b in the online supplemental material) and the dry tail as seen in the observation (Figs. ES1c,d), particularly for HadGEM3-A-N216. The correlation coefficient of Pr-ET between the ensemble mean for the Factual run of HadGEM3-A-N216 and observation is 0.29 for 1960–2013, statistically at 95% confidence level (Figs. ES1a,b). The climate mean distribution of 850-hPa winds in April–May can also be well simulated by models (Figs. ES3a,b). The thresholds at 2.4 (1.3) mm day^{-1} in Pr-ET and 4.7 (3.6) mm day^{-1} in Pr with the same return periods of observation are derived from HadGEM3-A-N216 (CAM5) for attribution, respectively. The difference between the two models indicates great uncertainty arising from model structure and the importance of multimodel comparison for attribution study.

An overall mean shift of Pr-ET toward a drier condition in Factual relative to Counterfactual is

simulated both by HadGEM3-A-N216 and CAM5 for year 2018 (Figs. 2a,b), demonstrating increases in the probability of such drought events over South China with anthropogenic forcing. The likelihood of such drought events defined by Pr-ET is around 9.9% (P1) (8.2%–11.5%) from the 525 samples of 2018 in the Factual experiment but only 0.6% (P0) (0.05%–0.9%) in the Counterfactual experiment of HadGEM3-A-N216. The risk ratio (P1/P0) is approximately 17 (10–165), suggesting that human influences have increased the risk of such a drought event by 17 (10–165) times in year 2018 in HadGEM3-A-N216. The increase in the risk of such droughts event in 2018 is mainly caused by a higher probability of extreme precipitation deficit with human impact, which is 12.2% (5.3%–12.0%) in Factual but only 1.5% (0.6%–2.1%) in Counterfactual, with a risk ratio around 8.0 (5–19) (Fig. 2b). U850 also shows a shift toward an extreme weak tail (Fig. 2c). The events with U850 such as observed in 2018 never occur from the 525 members of HadGEM3-A-N216 either in the Factual or Counterfactual experiment. By lowering the threshold of U850 from one-in-70 years (-2.1 m s^{-1}) to one-in-20 years (-1.0 m s^{-1}), the likelihood of such events is about 0.1% in the 2018 Factual experiment, whereas it still never occurs in the 2018 Counterfactual experiment. CAM5 also supports the results from HadGEM3-A-N216, while the events similar to 2018 never occur in the Counterfactual world. Thus, risk ratio cannot be obtained from CAM5.

The width for GEV distributions of the three indices in Factual is comparable with that in Counterfactual, but with a shift in mean states toward a weaker magnitude. It demonstrates that the mean state of circulation in Factual is weaker than that in Counterfactual, which increases the likelihood of extreme weak U850 events and thus extreme drought in South China. Therefore, the 850-hPa wind difference between 2018 Factual and Counterfactual is examined (Figs. 2d,h). Their differences show the similar anomalies as observed in 2018, with anomalous lower-level divergence over the Maritime Continent, suggesting that anthropogenic forcing plays an importance role in the weakened Walker circulation in 2018 late spring. Thus, anomalous easterly winds are seen over (5° – 20°N , 90° – 120°E), increasing the likelihood of extreme weak U850 in the Factual experiment (Figs. 2c,g).

Under anthropogenic forcing, an El Niño-like SST warming pattern over the tropical Pacific Ocean under global warming and east–west SST gradients over the tropical Indo-Pacific Ocean are seen in 2018 late spring. Those SST anomaly patterns could both con-

tribute to a weakened Walker circulation (Figs. 2d,h, Held and Soden 2006; Tokinaga et al. 2012). Consequently, the anomalous easterly winds are shown over the north Indian Ocean under anthropogenic forcing in the two models, increasing the likelihood of extreme late onset of the East Asian summer monsoon. In comparison, the circulation difference between Factual and Counterfactual is much stronger in HadGEM3-A-N216 relative to CAM5.

We further investigated the results from the full historical simulations to verify the robustness of the attributable results. The shifts toward the extreme weak tail of Pr-ET, Pr, and U850 under anthropogenic forcing can also be detected (Fig. ES2). In historical simulation, the risk ratio of the 2018 drought event estimated by Pr-ET is about 8 (2–42) and 75 (36–1389) in HadGEM3-A-N216 and CAM5, respectively, and 4 (2–14) and 58 (33–432) estimated by Pr. Similar to Fig. 2d, there is a weaker Walker circulation with easterly winds anomalies to the south of Bay of Bengal in the Factual experiment relative to the Counterfactual experiment associated with the same non-uniform distribution of SST warming under anthropogenic forcing (Figs. ES3c,d). A parallel analysis using the CAM5 simulations is similar to those based on the HadGEM3-A-N216, supporting that our findings have less model dependence.

CONCLUSIONS. An exceptional rainfall deficit combined with record-breaking warm temperatures ranked 2018 late spring as the second driest year since 1951. The extremely late onset of the SCSSM in 2018 played a major role, characterized by easterly anomalies to the south of the Bay of Bengal. We find that anthropogenic forcings have increased the likelihood of the observed 2018 late spring drought in South China by 17 times in HadGEM3-A-N216, and such events similar to 2018 would never occur in the CAM5 Counterfactual experiment. A weakening of the Walker circulation in late spring under anthropogenic forcing increases the likelihood of extreme weak westerly winds and then the occurrence of extremely late onset of SCSSM, and subsequently extreme drought over South China. The increase in drought risk of South China poses serious challenges for decision makers and the society as whole for water resource management and economic development.

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FIG. 2. GEV distributions of the April–May mean (a) Pr-ET and (b) precipitation (mm day⁻¹) averaged over South China with (Factual; red) and without (Counterfactual; blue) anthropogenic climate changes constructed for 2018 with HadGEM3-A. (c) As in (a) and (b), but for the 850-hPa zonal wind averaged over the red box in Fig. 1f. The gray lines denote the thresholds of drought events as observed in year 2018 except in (c), which shows the U850 with a 20-yr return period. (d) Difference in April–May mean 850-hPa winds and sea surface temperature (SST) between the 525 members mean of the Factual and Counterfactual experiments for the year 2018. To show the impact of non-uniform distribution in SST warming with anthropogenic forcing on circulation changes, we first get the SST difference between Factual and Counterfactual and then remove its area-average mean over 40°S–40°N. (e)–(h) As in (a)–(d), but for the results from CAM5.

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