

# Was the Record-Breaking Mei-yu of 2020 Enhanced by Regional Climate Change?

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**DOI:** 10.1175/BAMS-D-21-0187.1

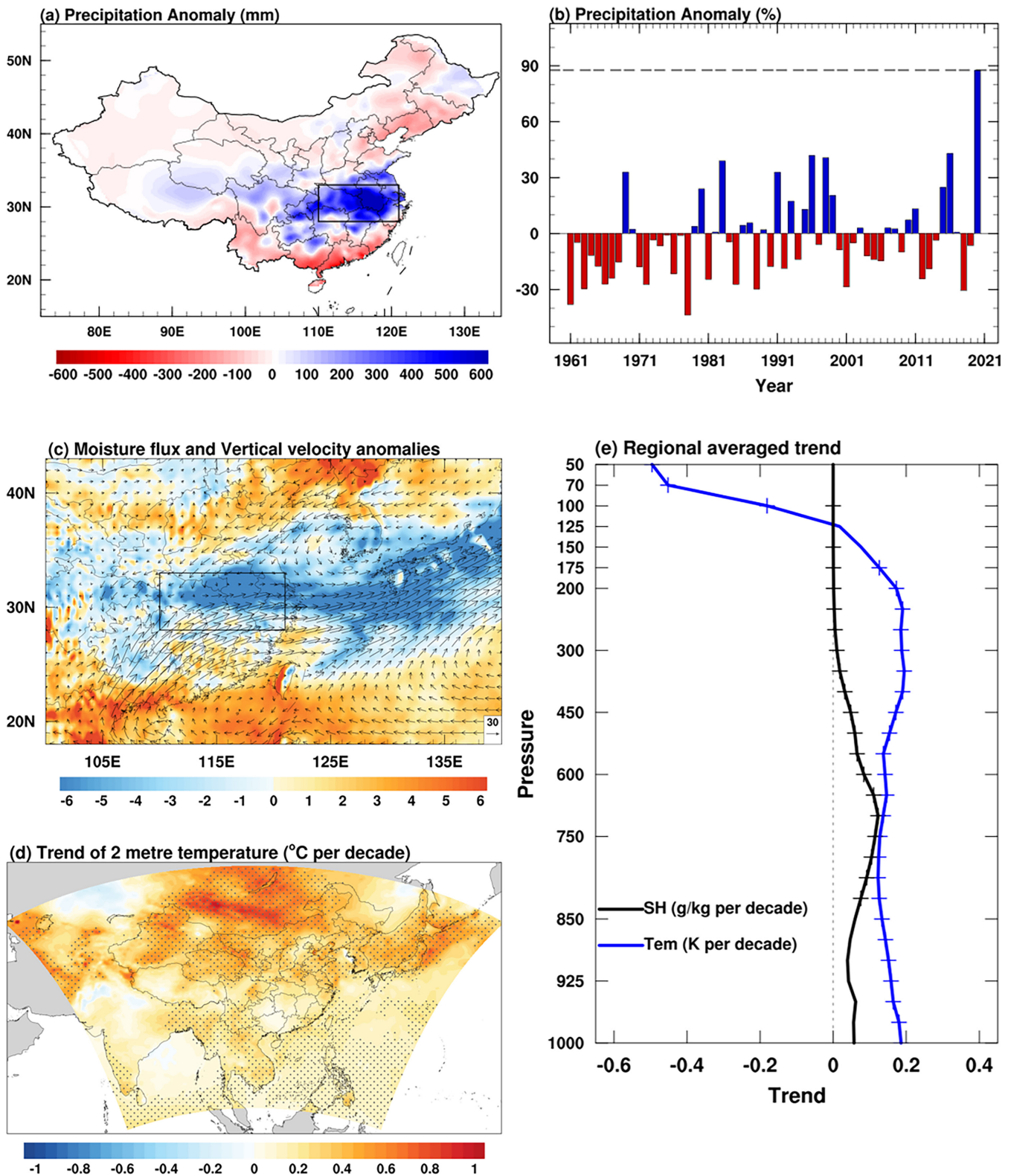
A supplement to this article is available online (10.1175/BAMS-D-21-0187.2)

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The record-breaking mei-yu rainfall amount of 2020 around the Yangtze River decreased by approximately 9.2%–14.1% due to the post-1980 regional climate change in Asia.

In 2020, the middle and lower reaches of the Yangtze River (MLYR; 28°–33°N, 110°–121°E) in China suffered an unexpected long-persisting mei-yu season, and both the duration and rainfall amount reached the highest record since 1961 (Wei et al. 2020). In particular, the average cumulative precipitation for the period of 1 June to 31 July exceeded +750 mm with a maximum value of 1720 mm, and the precipitation anomaly reached +350 mm (Fig. 1a), which was about 88% more than 1980–2010 climatology in this region (Fig. 1b). The corresponding extreme precipitation caused severe flooding over the MLYR region, affecting 63.46 million people and resulting in a direct economic loss of over 178.96 billion Yuan (<https://www.chinanews.com/sh/2020/08-14/9264482.shtml>).

This super mei-yu was primarily driven by the enhanced upward movement and moisture flux (Fig. 1c). They were caused by the abnormal East Asian westerly jet in the upper level and the southwesterly jet in the lower level, which were associated with abnormal position and intensity of the western Pacific subtropical high (Ding et al. 2021). These circulation anomalies coincided with the North Atlantic Oscillation (NAO; Liu et al. 2020), North Atlantic SST anomaly (Zheng and Wang 2021), the strong preceding Indian Ocean dipole (IOD; Takaya et al. 2020; Z.-Q. Zhou et al. 2021), a rap-



**Fig. 1.** (a) The observed rainfall anomalies relative to 1981–2010 climatology. The black box denotes the MLYR region ( $28^{\circ}$ – $33^{\circ}\text{N}$ ,  $110^{\circ}$ – $121^{\circ}\text{E}$ ). (b) Time series of accumulated rainfall percentage anomalies for the black box in (a) during 1 Jun to 31 Jul relative to 1981–2010. (c) 500-hPa vertical velocity anomalies (shading;  $10^{-2} \text{ Pa s}^{-1}$ ; negative values denote upward motion) and 850-hPa moisture flux anomalies (vectors;  $\text{g m}^{-1} \text{ s}^{-1} \text{ Pa}^{-1}$ ) during 1 Jun to 31 Jul relative to 1981–2010. (d) Model domains and trend of 2-m temperature during 1980–2020, where the dotted area is the region exceeding the 95% confidence level. (e) Vertical profiles of regional-mean air temperature (Tem) and specific humidity (SH) trend over the model domain, where the 95% confident level of area-average field are marked with a plus sign (+).

idly developing La Niña (Z.-Q. Zhou et al. 2021), and an exceptionally persistent MJO active phase in the Indian Ocean (Zhang et al. 2021). Besides, the air temperature in Asia has been increasing rapidly (e.g., Huang et al. 2012; Kawase et al. 2020) and it is possible that climate change contributed to the extreme rainfall in 2020.

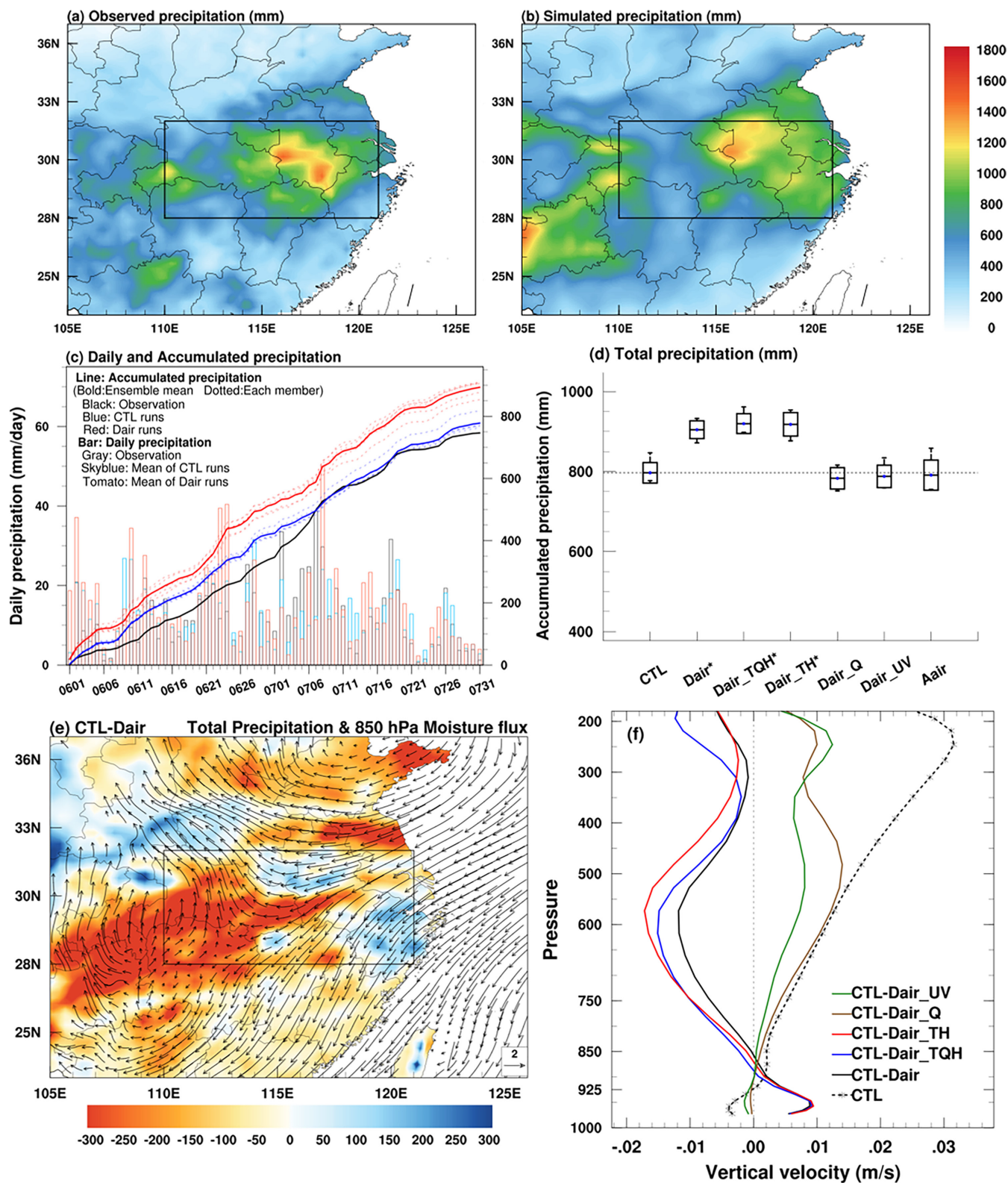
When attributing a specific extreme event to climate change, the approaches are important to extend the chain of complex physical causality. Generally, an “absolute” approach assesses overall changes in event likelihood, but the contribution of specific aspect of climate change is not considered (Swain et al. 2020). The “ingredient-based” approach with both absolute and conditional frameworks can ascertain the most essential physical conditions and then assess changes in the probability of these conditions (Swain et al. 2020). The “storyline” approach (Shepherd et al. 2018) typically uses a regional model to simulate an observed event under different boundary forcing and can offer better understanding of local-scale processes such as thermodynamical and dynamical changes (Meredith et al. 2015a,b). In this study, we will apply the storyline approach to evaluate the impact of climate change on the extreme rainfall event on a physically based causal narrative.

### Data and methods.

The gauge observations of daily precipitation during 1961–2020, using ~824 stations over China with rigorous quality control (Cao et al. 2016), are obtained from the China Meteorological Administration to examine this mei-yu event from the perspective of climate. The quasi-real-time hourly precipitation data collected from ~2400 stations, with quality control performed for the hourly precipitation from the Chinese hourly gauge network (Shen et al. 2010), are used to validate the simulated precipitation.

We investigate the impact of post-1980 regional climate change on the super-mei-yu using the Weather Research and Forecasting (WRF) model. The initial conditions and boundary meteorological fields (IBCs) are obtained from the National Centers for Environmental Prediction final analysis (NCEP/FNL) data with 1° horizontal resolution and 6-h temporal intervals. The model domain centers at 30°N, 105°E with grid numbers of 280 × 220 and spacings of 27 km (Fig. 1d). The unevenly spaced terrain-following vertical coordinate levels are used with 38 vertical layers up to 50 hPa. To better capture this mei-yu rainfall, a series of parameterization schemes are tested and the final main physical options are listed in Fig. S1b in the online supplemental material.

Two series of ensemble simulations are carried out to assess the sensitivity of the extreme mei-yu rainfall to regional climate change. One ensemble of simulations is driven with realistic IBCs based on the NCEP/FNL data (CTL runs), and the other has the identical setup, except that trend of the post-1980 regional climate change estimated by the fifth generation European Centre for Medium-Range Weather Forecasts atmospheric reanalysis data is removed from the IBCs. The method of subtracting the climate change trend is usually used to evaluate the impact of climate change by the “storyline” approach (Swain et al. 2020). It has been useful for extreme rain events in the United States (e.g., Wang et al. 2018), Japan (e.g., Kawase et al. 2020), India (e.g., Cho et al. 2016), and over the Black Sea and Mediterranean region (e.g., Meredith et al. 2015a,b). Note that the trend in climate change includes both anthropogenic global warming and natural decadal variability, but the atmosphere warming and moistening in Asia can be largely attributed to human activities (Zhang et al. 2019). Based on the adjusted variables, six sensitivity experiments, including the Dair, Dair\_TQH, Dair\_TH, Dair\_Q, and Dair\_UV runs, are set and more information can be found in Fig. S1b. All simulations are conducted from 25 May to 1 August 2020, and the days before 1 June are considered as a spin-up period (Zhong et al. 2007; Jerez et al. 2020).



**Fig. 2.** (a) Gauge-analyzed total precipitation from 1 Jun to 31 Jul 2020. (b) As in (a), but for the ensemble means of precipitation from CTL runs. (c) Time series of regional-averaged daily (bar) and accumulated precipitation (line) over the MLYR region. (d) The minimum, maximum, and mean total precipitation and the standard deviations simulated by each experiment. The x-axis labels marked with an asterisk (\*) indicate a significant difference from CTL runs at 95% confidence interval by a *t* test. (e) Difference of total precipitation (shading, mm) and 850-hPa moisture flux (vectors;  $\text{g m}^{-1} \text{s}^{-1} \text{Pa}^{-1}$ ) between the CTL runs and Dair runs. (f) Vertical profiles of regional-mean vertical velocity of CTL runs ( $\text{m s}^{-1}$ ) and the difference in the vertical velocity ( $10^{-1} \text{ m s}^{-1}$ ) compared with CTL runs.

This study aims to conduct several months of regional climate simulation to evaluate the effects of climate change on the long-persisting mei-yu season of 2020. To reduce and assess the uncertainties, each experiment adopts a piecewise-integration method (Zhang et al. 2008) and has six ensemble runs with different microphysical parameterizations (see Fig. S1b). This setup gives a high signal-to-noise ratio, which allowing fewer members and better understanding of thermodynamical and dynamical responses of climate change (Meredith et al. 2015a,b). Experiments with realistic IBCs show that the piecewise-integration method can effectively reduce simulated precipitation biases compared with the continuous-integration method (Figs. S1c,d).

## Results.

The climate in Asia became warmer and more humid from 1980 to 2020 (Fig. 1d and Fig. S1a). During this time, the temperature increases are most apparent in mid- and high-latitude regions, while specific humidity increases are clearest over the ocean. The climate warms most in the lower and upper atmosphere and humidity increases are greatest in the middle atmosphere (Fig. 1e).

The ensemble mean of six CTL runs reasonably captures the intensity and location of the accumulated precipitation amount during the extreme rainfall event (Figs. 2a,b). Also, the CTL runs well reproduces the cumulative process of precipitation of the heavy rainfall event (Fig. 2c). Specifically, the simulated regional-mean total precipitation amount is 777.9 mm with a standard deviation of 17.3 mm and a high signal-to-noise ratio of 45.0. Compared with observations, the total precipitation bias is 31.6 mm, which only accounts for approximately 4.2% of observed precipitation.

The difference in the total precipitation between the ensemble mean of CTL runs and Dair runs shows that post-1980 climate change decreases precipitation over the MLYR (Fig. 2e). Comparing the timing evolution of the accumulated precipitation between CTL runs and Dair runs, we can see that the difference in ensemble mean precipitation starts at 1 June and increases gradually to the end of the heavy precipitation event (Fig. 2c). The difference is  $-107.7$  mm at 31 July (Fig. 2d), which is equivalent to  $-11.9\%$  ( $-14.1\%$  to  $-9.2\%$ ) relative to the Dair runs (Fig. S2a). Further, the influence of climate change on this extreme event mainly occurs through the temperature and geopotential, while the effects of relative humidity and horizontal winds are very small (Fig. 2d).

To understand the pronounced changes in precipitation, we further address the relative roles of thermal and dynamical changes induced by the climate change. Comparatively, the equivalent potential temperature (Fig. S2c) and the water vapor mixing ratio (Fig. S2d) are increasing significantly in the lower and middle atmosphere, but decreasing in the upper atmosphere, indicating the enhanced atmospheric thermal instability and humidity in the CTL runs. However, these local thermal changes do not induce increased precipitation, probably because of the maximum warming and moistening at  $\sim 850$  hPa, which cause more stable stratification conditions in the lower atmosphere. Dynamical changes show that the climate change induces northeast–southwest direction moisture flux and wind field anomaly and a strong downward movement (Fig. 2e and Fig. S2b), which is opposite to the circulation anomalies of East Asian summer monsoon (EASM) circulation (Fig. 1c). The differences in vertical velocity profiles show a clear weakened upward movement in the CTL runs and the change of vertical movement is consistent with the change of precipitation (Fig. 2f). This demonstrates that the climate change decreases the precipitation mainly by the circulation anomalies related to dynamical changes, which indicates the weakened large-scale background EASM circulations. The weakening EASM may be associated with the increased static stability in the vertical atmosphere (Held and Soden 2006; Liu et al. 2013), land–sea thermal contrast (Kamae et al. 2014), and spatial inconsistency of global warming (Zuo et al. 2012).

## Conclusions.

This study evaluates the contribution of regional climate change to the super-2020 mei-yu rainfall event over the MLYR region by a “storyline” approach. The model reasonably captures the spatial distribution and cumulative process of total precipitation amount. Sensitivity experiments indicate that the post-1980 regional climate change in IBCs reduces the total precipitation by approximately 9.2%–14.1%. The weakened precipitation is mainly attributed to the EASM circulation anomalies associated with dynamical changes. This is consistent with T. Zhou et al. (2021), who showed that anthropogenic forcing reduced the probability of the 2020 extreme rainfall through weakening the EASM circulation caused by anthropogenic aerosols. Therefore, precipitation changes in China are related not only to changes in atmospheric temperature and moisture, but also to changes in the background atmosphere circulations. This study demonstrates that regional climate change in Asia is unfavorable for this rainfall event, and thus extreme external forcings, such as the IOD, NAO, and El Niño–Southern Oscillation (ENSO), on such events may play the dominant roles (e.g., Ding et al. 2021; Z.-Q. Zhou et al. 2021; Liu et al. 2020). Future work is required to evaluate the influence of global warming or climate change in specific external forcings (e.g., ENSO and IOD) on the 2020 rainfall event.

**Acknowledgments.** This work was supported by National Natural Science Foundation of China (41905013, 41930759, 42075105, 41805116) and the CAS “Light of West China” Program. Meteorological data were obtained from the China Meteorological Administration (<http://data.cma.cn/en/>). We would like to gratefully thank the above organization providing data.

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