Historic Yangtze flooding of 2020 tied to extreme Indian Ocean conditions

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Heavy monsoon rainfall ravaged a large swath of East Asia in summer 2020. Severe flooding of the Yangtze River displaced millions of residents in the midst of a historic public health crisis. This extreme rainy season was not anticipated from El Niño conditions. Using observations and model experiments, we show that the record strong Indian Ocean Dipole event in 2019 is an important contributor to the extreme Yangtze flooding of 2020. This Indian Ocean mode and a weak El Niño in the Pacific excite downwelling oceanic Rossby waves that propagate slowly westward of the equator. At a mooring in the Southwest Indian Ocean, the thermocline deepens by a record 70 m in late 2019. The deepening thermocline helps sustain the Indian Ocean warming through the 2020 summer. The Indian Ocean warming forces an anomalous anticyclone in the lower troposphere over the Indo-Northwest Pacific region and intensifies the upper-level westerly jet over East Asia, leading to heavy summer rainfall in the Yangtze Basin. These coupled ocean-atmosphere processes beyond the equatorial Pacific provide predictability. Indeed, dynamic models initialized with observed ocean state predicted the heavy summer rainfall in the Yangtze Basin as early as April 2020.

Significance

Summer rainfall along the Yangtze River in 2020 was the heaviest since 1961, with devastating socioeconomic impacts. While official forecasts based on tropical Pacific state failed, we show that dynamic models, when initialized with ocean observations globally, succeed in predicting the extreme rainfall. Slowly propagating oceanic Rossby waves in the South Indian Ocean are the source of predictability, which are in turn tied to the record-breaking Indian Ocean Dipole in late 2019. The identification of antecedent subsurface conditions of the Indian Ocean as a key predictor represents an important conceptual advance in Asian summer monsoon dynamics, helping improve disaster preparation that saves lives and properties.

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the North Indian Ocean warming by weakening the background southwest monsoon and suppressing surface evaporation (21–23).

The above ocean-atmospheric coupling processes work well for major El Niño events and provide predictability for Mei-yu rainfall over East Asia (Fig. 1B). A robust Northwest Pacific anomalous anticyclone developed during the summers of 1998 and 2016, each following a major El Niño. A strong anomalous anticyclone and excessive Mei-yu rainfall were not expected for 2020 summer, however, since in the 2019/20 winter (November to January), the Niño3.4 index was marginal at only 0.5 °C (SI Appendix, Fig. S1) as compared to 2.4 °C and 2.6 °C in 1997/98 and 2015/16 winters, respectively. SST anomalies in the equatorial central Pacific (Niño4) were positive and nearly constant in magnitude during May 2018 to May 2020 (SI Appendix, Fig. S1), but the Northwest Pacific anomalous anticyclone did not develop in 2019 summer. Then what caused the pronounced anomalous anticyclone during the 2020 summer? Was it due to unpredictable atmospheric internal dynamics as in August 2016 (24, 25), or did some predictable SST anomalies play a role?

**Atmospheric Model Experiments**

To evaluate the SST effect, we force the state-of-the-art Community Atmosphere Model version 6 (CAM6) with observed monthly SST anomalies (Fig. S1) as compared to the long-term mean (24). The forced CAM6 simulates both the excessive Mei-yu rainfall and low-level anomalous anticyclone over the Northwest Pacific during June 2020, although the anomalous easterlies are too weak over the Bay of Bengal through the South China Sea compared to observations. Mei-yu rainfall anomalies over the Yangtze Basin are over 90 mm/month (Fig. 2B), comparable with observations (Fig. 1A). This indicates that the excessive Mei-yu rainfall and anomalous anticyclone of June 2020 are largely forced by SST anomalies instead of due to internal atmospheric dynamics.

The SST anomalies are positive over the tropical Indian Ocean and a weak La Niña developed over the tropical Pacific in June 2020 (Fig. 2A). To evaluate relative importance of Pacific and Indian Ocean SST anomalies, we conduct another two experiments forced separately by tropical Pacific (referred to as PACIFIC) and Indian Ocean (referred to as INDIAN) SST anomalies. In June 2020, the tropical Indian Ocean is anomalously warm (Fig. 2A). The INDIAN run largely reproduces the results of the GLOBAL run, including positive Mei-yu rainfall anomalies over the Yangtze Basin and negative rainfall anomalies to the south with the anomalous anticyclone (Fig. 2D). In comparison, tropical Pacific anomalies only play a limited role (Fig. 2E). The weak and eastward-displaced anomalous anticyclone south of Japan in the PACIFIC experiment seems forced by depressed rainfall in the equatorial central Pacific as a Rossby wave response (Fig. 2E), due to the rapid transition from El Niño to La Niña in early summer of 2020 (SI Appendix, Fig. S1).

Over the Southwest Indian Ocean, positive SST anomalies induce deep convection with an anomalous cyclonic circulation as well as the northeasterlies (northwesterlies) north (south) of the equator (Fig. 2B and D). Over the North Indian Ocean, the anomalous northeasterlies induce positive SST anomalies by weakening the climatological monsoon westerlies to reduce surface evaporation. The GLOBAL run successfully reproduces the enhanced mid-tropospheric westerly jet in the midlatitudes, which induces adiabatic ascending motion by adverting warm temperature from the Tibetan Plateau through the Yangtze Basin to the North Pacific (Fig. 2C). The adiabatic ascent, together with increased moisture transport by the low-level anomalous anticyclone, sets up a favorable condition for the excessive Mei-yu rainfall. The GLOBAL run does not reproduce all the midlatitude anomalies, including wavy perturbations along the westerly
jet in observations (Fig. 1D) known as the Silk Road Pattern (26–28), because of atmospheric internal dynamics unrelated to SST variability. The model results indicate that the excessive Mei-yu rainfall and anomalous anticyclone of 2020 are largely due to tropical Indian Ocean SST anomalies, with some contribution from the tropical Pacific.

**Indian Ocean Processes**

The next question is what caused the Indian Ocean warming? A major Indian Ocean Dipole (IOD) took place in 2019, with the dipole mode index peaking at 2.1 °C in October (Fig. 3A and SI Appendix, Fig. S1), the highest on record (29, 30). The weak 2019/20 El Niño event probably contributed but by itself cannot explain the record-breaking IOD event of 2019. Over the eastern Indian Ocean, strong easterly/southeasterly wind anomalies (5 m/s) occurred along the equator and the Java–Sumatra coasts during September through November 2019 (Fig. 3A). The equatorial easterly wind anomalies shoal the thermocline, bring cold water to the surface, and amplify the SST cooling along the Java–Sumatra coasts. The ocean cooling strengthens the zonal SST gradient and the easterly/southeasterly winds on the equator/Indonesian coast. This is known as Bjerknes feedback, originally proposed for El Niño growth. The anomalous anticyclonic wind curls associated with the equatorial easterlies force downwelling oceanic Rossby waves that slowly propagate westward south of the equator (Fig. 3B) (31, 32). The downwelling oceanic Rossby waves deepen the thermocline in the South Indian Ocean (Fig. 3B), accompanied by copropagating positive SST anomalies (SI Appendix, Fig. S5A). In September through November 2019, the deepened thermocline causes the sea surface to rise anomalously in the Southwest Indian Ocean centered at 8°S, 75°E (Fig. 3A). At a mooring at 8°S, 67°E, the 20 °C isotherm (a proxy of the thermocline) is shallow at 80 m on average but took a deep dive to 150 m in November 2019 (Fig. 3C), a record of the 14-y deployment (SI Appendix, Fig. S4). The slow-propagating oceanic Rossby waves allow the Southwest Indian Ocean warming to persist through the 2020 summer (SI Appendix, Figs. S1 and S5A). The Southwest Indian Ocean warming intensifies local convection and induces northerly wind anomalies across the equator during 2020 spring to early summer (SI Appendix, Figs. S5 A and B). The Coriolis effect creates an easterly component north and westerly component south of the equator. Over the North Indian Ocean, the anomalous northeasterlies weaken the climatological monsoon westerlies in 2020 summer, reducing surface evaporation and increasing SST (Fig. 2). Indeed, the Indian Ocean warming and the anomalous anticyclone over the Northwest Pacific are coupled with positive feedback known as the Indo-western Pacific Ocean capacitor (Fig. 1 and SI Appendix, Fig. S7A). Both the low-level anomalous anticyclone and enhanced upper-level westerly jet contribute to the heavy rainfall along the Yangtze River.

The anomalous anticyclonic wind curls over the South Indian Ocean begin in 2019 summer and last through the following spring (Fig. 3B). The atmospheric model experiments indicate that the
IOD event causes the anticyclone wind curls through December 2019, while Pacific SST anomalies, notably the warming in the equatorial western Pacific as part of the weak El Niño (SI Appendix, Fig. S5C), contribute to the sustained wind curls thereafter in early 2020 and hence to the record thermocline deepening in the South Indian Ocean (Fig. 3D).

The above coupled ocean-atmospheric processes imply predictability at monthly and longer leads, as oceanic Rossby waves carry the memory of wind forcing in the past and propagate slowly westward. Fig. 4 shows the rainfall anomalies in June 2020 predicted by the North American Multi-Model Ensemble (NMME) (Materials and Methods) at various time leads. The coupled ocean-atmosphere models in NMME allow for skillful forecasts at lead times of one to several months. The multi-model ensemble averages show that the forecasts initialized on 1 June 2020 predict heavy rainfall (above 90 mm/month) over the Yangtze Basin and an anomalous anticyclone over the Northwest Pacific in June 2020 (Fig. 4D), consistent with observations (Fig. 4E). An independent study reports a similar success of the Japan Meteorological Agency dynamic forecast system in capturing enhanced Mei-yu-Baiu rainfall in 2020 (33). As early as April 2020, the NMME predicts the meridional dipole between rainfall decrease and strong El Niño contributed to, but was probably not the deciding factor for, the extreme 2019 IOD event. Historically, ENSO is but one mechanism that triggers IOD (34, 35); a major IOD event took place in 1961 without El Niño. The anticyclonic wind curls associated with the strong IOD and weak El Niño forced downwelling oceanic Rossby waves that slowly propagated westward (Figs. 5A and 3B). The Rossby waves caused the Southwest Indian Ocean to warm as the deepened thermocline increased the temperature of the water upwelled into the surface mixed layer (Figs. 5B and 3B and SI Appendix, Fig. S5A). The persistent Southwest Indian Ocean warming induced an asymmetrical pattern of anomalous atmospheric circulation over the tropical Indian Ocean during 2020 spring to early summer, with the northeasterlies (northwesterlies) north (south) of the equator (Figs. 5B and 2 and SI Appendix, Fig. S5B). Over the North Indian Ocean and the South China Sea, the anomalous northeasterlies weakened the climatological monsoon southwest-erlies during May to June 2020, reducing surface evaporation and increasing SST (Fig. 5B). The Indian Ocean warming in summer 2020 induced the low-level anomalous anticyclone over the Northwest Pacific and intensified the upper-level westerly jet over the Yangtze Basin. The intensified moisture transport by the anomalous anticyclone, together with the anomalous ascending motions induced by the enhanced westerly jet, caused heavy rainfall along the Yangtze River (Fig. 5B).

**Discussion**

Our observational analysis and model experiments show that the historic Yangtze flooding in 2020 summer is due to the combined effect of the record strong IOD and weak central Pacific El Niño in late 2019. Fig. 5 is a schematic of the oceanic and atmospheric processes involved. In fall 2019, a record-breaking IOD, coupled with the easterly wind anomalies through the Bjerknes feedback, developed in the tropical Indian Ocean. By weakening the Walker circulation, a weak El Niño contributed to, but was probably not the deciding factor for, the extreme 2019 IOD event. Historically, ENSO is but one mechanism that triggers IOD (34, 35); a major IOD event took place in 1961 without El Niño. The anticyclonic wind curls associated with the strong IOD and weak El Niño forced downwelling oceanic Rossby waves that slowly propagated westward (Figs. 5A and 3B). The Rossby waves caused the Southwest Indian Ocean to warm as the deepened thermocline increased the temperature of the water upwelled into the surface mixed layer (Figs. 5B and 3B and SI Appendix, Fig. S5A). The persistent Southwest Indian Ocean warming induced an asymmetrical pattern of anomalous atmospheric circulation over the tropical Indian Ocean during 2020 spring to early summer, with the northeasterlies (northwesterlies) north (south) of the equator (Figs. 5B and 2 and SI Appendix, Fig. S5B). Over the North Indian Ocean and the South China Sea, the anomalous northeasterlies weakened the climatological monsoon southwest-erlies during May to June 2020, reducing surface evaporation and increasing SST (Fig. 5B). The Indian Ocean warming in summer 2020 induced the low-level anomalous anticyclone over the Northwest Pacific and intensified the upper-level westerly jet over the Yangtze Basin. The intensified moisture transport by the anomalous anticyclone, together with the anomalous ascending motions induced by the enhanced westerly jet, caused heavy rainfall along the Yangtze River (Fig. 5B).
The official forecasts did not anticipate the extreme Mei-yu rainfall in 2020 summer, but we showed that initialized coupled models successfully predicted the anomalous anticyclone and excessive Mei-yu rainfall over East Asia. In retrospect, the successful multi-model ensemble forecasts would have allowed a lead time of 1 to 3 months in advance for local authorities to implement preventive measures and reduce the loss of lives and properties (Fig. 4 and SI Appendix, Fig. S6). Our study suggests that the successful dynamic prediction is enabled by oceanic Rossby waves in the South Indian Ocean, which are in turn induced by the strong IOD event of 2019 and weak El Niño condition in the western Pacific. The IOD mode of Bjerknes feedback (36) and Indo-western Pacific Ocean capacitor (20) represent major advances in Indian Ocean climate dynamics over the recent decades. While this framework emphasizes ENSO forcing, our results show that other non-ENSO factors are important not only for the IOD but also the Indo-western Pacific Ocean capacitor and, by extension, monsoon rainfall over East Asia. Further research to better understand, model, and observe these factors (e.g., oceanic Rossby waves in the South Indian Ocean) holds the promise of improving seasonal predictions of the East Asia summer monsoon.

In a warming climate, the frequency of extreme IOD and El Niño occurrences increases in most climate models (37, 38). Increased extreme IOD occurrences have profound socioeconomic impacts on the densely populated Asian monsoon region both directly (36, 37) and indirectly, as illustrated in the Yangtze flooding of 2020.

Materials and Methods

Observational Data. We use monthly precipitation from the Climate Prediction Center Merged Analysis of Precipitation (CMAP) (39); monthly air temperature, zonal and meridional winds, vertical velocity, specific humidity, and sea level pressure (SLP) from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset (40); and monthly sea surface height from the NCEP Global Ocean Data Assimilation System (41). Monthly regional SST indices are calculated using the National Oceanic and Atmospheric Administration Optimum Interpolation Sea Surface Temperature version 2 dataset (42), including the Niño 3.4 (5°S to 5°N and 170°W to 120°W), Niño 4 (5°S to 5°N and 160°E to 150°W), and IOD index (anomalous SST gradient between the western [50°E to 70°E and 10°S to 10°N] and southeastern [90°E to 110°E and 10°S to 0°N] equatorial Indian Ocean). The above datasets can be obtained from https://www.esrl.noaa.gov/psd/data/gridded. We focus on a 42-y period from 1979 to 2020 (limited by CMAP’s satellite rainfall estimates). Monthly anomalies are derived relative to the climatological mean (1981 to 2010) after removing the linear trend over the whole period. Monthly ocean temperature data in Fig. 3 are from a buoy of the Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (43) at 8°S, 67°E from 2007 to 2020, obtained from https://www.pmel.noaa.gov/tao/drupal/disdel.

AGCM Experiments. We use the CAM6 to investigate the role of SST forcing in the Yangtze flooding of 2020. CAM6 is the latest global atmosphere model of the NCAR and the atmospheric component of the Community Earth System Model (CESM) version 2.1.2. The model resolution is 0.9° latitude x 1.25° longitude (“f09_f09”) with 30 sigma levels in the vertical. We performed four runs forced with the monthly SST climatology (CONTROL), the detrended monthly SST anomalies for January 2019 to July 2020 globally (GLOBAL), and regionally over the tropical Pacific Ocean (25°S to 25°N, 150°W to 160°E) (Tropical).
Fig. 5. Schematic for physical processes causing the 2020 Yangtze flooding. (A) The record strong IOD (shading) and weak El Niño excite westerly oceanic Rossby waves in the South Indian Ocean in late 2019 and early 2020. (B) Rossby wave-induced Southwest Indian Ocean warming forces an anti-symmetrical wind pattern that is most pronounced in spring 2020. The result is North Indian Ocean warming excites an anomalous anticyclone over the Indo-Northwest Pacific, contributing to the excessive rainfall along the Yangtze River in summer 2020.

120°E to 80°W, PACIFIC and Indian Ocean (25° to 25°N, 40° to 120°E, INDIAN). The CONTROL run has 30 members, and the other experiments have 20 members, each with slightly different initial conditions. The ensemble averages are analyzed. A caveat of imposing partial SST anomalies in limited domains is that it would induce artificial SST gradient and suppress convective responses near the boundaries (120°E, in our case) (Fig. 2 D and E). With global SST forcing, the model captures salient atmospheric anomalies over the summer Indo-western Pacific, consistent with results from long historical simulations beyond the 2020 summer (21, 22, 25).

The model rainfall climatology is too low over the Mei-yu region and too high over the Indo–China Peninsula in June and July (SI Appendix, Fig. S2). In July, the midlatitude westerly jet is displaced about 10° northward compared to observations because of the early onset of deep convection over the tropical Northwest Pacific (44, 45). Regarding interannual variability, the model simulates the low-level anomalous anticyclone and intensifies upper-level westerlies in both June and July (Fig. 2 and SI Appendix, Fig. S3). It captures enhanced rainfall over the Mei-yu region in June (Fig. 2), but not in July of 2020 (SI Appendix, Fig. S3). Similar difficulty in simulating July Mei-yu rainfall variability is reported with the UK Meteorological Office seasonal forecast system (46).

Operational Seasonal Forecasts. We use the NMM2 model (47), based on coupled models in the United States and Canada (https://www.cpc.ncep.noaa.gov/products/NMME/).

Data Availability. AGCM experiments (netCDF) data have been deposited in GitHub (https://github.com/zhengjiangzhou/Yangtze).

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