Indispensable Role of the Madden-Julian Oscillation in the 2019 Extreme Autumn Drought Over Eastern China

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Abstract Eastern China suffered an extensive drought during autumn (September–October 2019) with precipitation deficits reaching as high as 70% of the climatology, the worst on record since the 1980s. Concurrent with this extreme drought, the tropical Indo–Pacific oceans experienced a central–Pacific (CP) El Niño event with the westernmost location, and the third–ranking positive Indian Ocean Dipole (IOD) event. However, the CP El Niño associated convection anomalies are unexpectedly absent over the western equatorial Pacific, leading to the decoupling of traditional atmospheric–oceanic connections between the tropical Pacific and Indian Oceans. A strong Madden–Julian oscillation (MJO) event stayed in the western Indian Ocean for 32 days during September–October 2019, nearly triple the frequency of climatology. This extraordinary long–lasting MJO activity suppressed the western Pacific convection associated with the CP El Niño and simultaneously enhanced the local IOD–related sea surface temperature anomalies via the atmospheric forcing. The MJO associated convection over the Indian Ocean can excite an anomalous cyclone in the western North Pacific, producing persistently extensive precipitation deficiencies over eastern China. It highlights that the abnormal MJO activity plays a crucial role on the Indo–Pacific atmospheric–oceanic features and the extreme precipitation deficits over eastern China.

1. Introduction

In the densely populated East Asian region, autumn is the key period for crop harvest and sowing winter wheat, in which droughts and floods frequently cause enormous damage to agricultural production and people’s lives (Barriopedro et al., 2012; Yang et al., 2012; Zhou et al., 2018). In autumn 2019, the widespread and persistent drought struck eastern China (Figure 1), which created about $4.4 billion damages and nearly 2,953,000 citizens suffered from water shortages in six provinces (Ministry of Emergency Management of the People’s Republic of China: Ten natural disasters of 2019 in China, website: http://www.mem.gov.cn/xw/bndt/202001/t20200112_343410.shtml). It was the driest year on record over eastern China in the recent four decades. At present, the underlying mechanisms driving the 2019 extreme autumn drought over eastern China remain elusive. Better understanding of the physical mechanisms that led to this disastrous drought provides valuable input for assessing potential predictability of extreme droughts over eastern China.

This extreme autumn drought coincided with evident sea surface temperature (SST) anomalies in the Indo–Pacific oceans. An obvious SST warming occurred in the central Pacific during 2019, which has been identified as a moderate El Niño event by the Climate Prediction Center (CPC). This warming event can be classified into a typical central–Pacific (CP) El Niño event with its warming center located west of the dateline (Ashok et al., 2007; Kao & Yu, 2009; Kug et al., 2009; Ren & Jin, 2011). Impacts of El Niño–Southern Oscillation (ENSO) on autumn precipitation variability over eastern China have been extensively demonstrated (Huang & Wu, 1989; Wang et al., 2000; Zhang et al., 2011). Earlier researches have shown that more moisture can be transported into eastern China by anomalous southwesterly winds associated with the enhanced anticyclone over the western North Pacific (WNP) during El Niño developing autumn, leading to precipitation surplus there (Wang et al., 2000; Zhang et al., 1999). Opposite–signed anomalies in precipitation are reported to appear during La Niña autumns. Recent observational analyses documented that the autumn precipitation responses to El Niño exhibit a high degree of uncertainty mainly due to inter–El Niño variations in its SST anomaly patterns (Zhang et al., 2011, 2013, 2014; Gu et al., 2015). Distinct from traditional eastern–Pacific (EP) El Niño events, the CP El Niño usually excites an anomalous cyclone over the WNP and therefore produces precipitation deficits over eastern China during autumn (Zhang...
et al., 2011, 2013). These different precipitation responses lead to more frequent autumn drought over eastern China since the 1990s when the CP El Niño has become a dominant mode of ENSO warm phase versus the EP El Niño (Zhang et al., 2014).

Simultaneously, a dipole SST anomaly structure is observed between the western tropical Indian Ocean and the Sumatra–Java coast, which is a typical SST anomaly pattern of positive Indian Ocean Dipole (IOD) events (Saji et al., 1999; Webster et al., 1999). IOD–related diabatic heating anomaly can affect temperature and precipitation over East Asia by modulating the intensity and location of the anomalous anticyclone over the WNP (e.g., Doi et al., 2020a; Guan and Yamagata, 2003; Nitta, 1987; Ratna et al., 2021; Saji et al., 1999; Watanabe & Jin, 2002; Xie et al., 2009; Yang et al., 2007). However, the Indian Ocean Dipole (IOD) usually takes place coherent with ENSO event, and therefore it is difficult to isolate its relatively pure climate impact (Zhang et al., 2015).

What is the explicit role of the CP El Niño as well as the co–occurred IOD event in fostering this severe drought deserves attention for understanding the formation of the extreme autumn drought in 2019. Nevertheless, the CP El Niño associated convection anomalies are counterintuitively absent over the western equatorial Pacific, leading to the decoupling of traditional atmospheric–oceanic connections between the

Figure 1. (a) The precipitation anomalies (shaded, mm) and precipitation anomaly percentages (contour) in autumn September–October 2019, superimposed by 2-months Standardized Precipitation Index (SPI) (the yellow, red, purple dots indicate the moderate, severe and extreme droughts, respectively). Magenta box denotes the region of eastern China (25–34°N, 114–119°E). (b) Daily precipitation averaged in eastern China from September 1 to October 31 (pink bars for 2019 and black dots for the climatology), and the accumulated precipitation (red for 2019 and gray for the climatology). (c) Time series of September–October precipitation anomaly (mm) averaged over eastern China from 1979 to 2019.

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tropical Pacific and Indian Ocean (see our detailed discussion in Section 3). Concurrent with the autumn drought and Indo–Pacific SST anomalies in 2019, a strong and prolonged Madden–Julian oscillation (MJO) event appeared over the tropical Indian Ocean, which can also bring about extra–tropical climate anomalies. For example, the precipitation over East Asia varies significantly with respect to the MJO phase (Jeong et al., 2008). Persistent active MJO in the tropical eastern Indian Ocean may enhance subsidence flow in Yunnan Province, contributing to the severe autumn drought there in 2009 (Lü et al., 2012). Therefore, what kind of role does the abnormal MJO activity play in this extreme autumn drought is now unclear.

This study tries to demonstrate the main mechanism that drives the worst autumn drought on record through analyzing the anomalous circulation and oceanic thermal features. Our findings show that MJO plays an indispensable role on the precipitation deficiencies over eastern China during September–October 2019. The remainder of the study is organized as follows. Section 2 illustrates data, methods and definition of indices used in this study. Section 3 describes the atmospheric and oceanic thermal features during the autumn drought and the possible contributors. Finally, the major conclusions are summarized and discussed in Section 4.

1.1. Data and Method

The monthly SST datasets used in this study is the monthly Hadley Center Sea Ice and Sea Surface Temperature data set (HadISST) with resolution of 1° × 1° (Rayner et al., 2003). Atmospheric circulations are examined based on the National Center for Environmental Prediction/National Center for Atmospheric Research–Department of Energy (NCEP/NCAR DOE) Reanalysis 2 (2.5° × 2.5°, Kalnay et al., 1996). Monthly global precipitation is taken from Climate Prediction Center Merged Analysis of Precipitation (CMAP, Xie & Arkin, 1997) with resolution of 2° × 2°, daily land precipitation from CPC Global Unified Gauge–Based Analysis of Daily Precipitation with resolution of 0.5° × 0.5° is also used to display the extreme character of this drought (https://psl.noaa.gov/). The convection condition is investigated by using the outgoing longwave radiation (OLR) from National Oceanic and Atmospheric Administration (NOAA) (Liebmann & Smith, 1996). Our analyses cover the period of 1979–2019 and anomalies for all variables were computed as the deviations from the climatological mean in the entire study period. Autumn in this study is defined as September and October, when eastern China experiences the most serious precipitation deficits. The intra–seasonal variability is extracted by employing 20–90–day Lanczos band–pass filtering with 201 weights (Duchon, 1979) after the climatological annual cycle is removed (annual mean plus first three leading harmonics).

El Niño events are identified according to the CPC’s definition based on a threshold of 0.5 C of the Niño3.4 index (averaged SST anomaly in the domain of 5°S–5°N, 120°W–170°W) for five consecutive months. The intensity of CP El Niño events are described as the normalized CP Index (CPI) defined by Ren and Jin (2011) as follows,
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2. Results

Figure 1 shows the temporal and spatial characteristics of precipitation anomalies over eastern China during autumn 2019. During September and October, the precipitation deficits appear over eastern China east of about 110°E, with the intensity ranging from 30% to 70% of the climatology (Figure 1a). In about 45 days the precipitation was obviously fewer than half of the climatology from September 1 to October 31, among which Eastern China experiences little to no precipitation for as long as 30 days (Figure 1b). The cumulative precipitation was only 60 mm, nearly one third of the climatological value. The drought condition is also measured by the SPI, indicating that the severe drought struck most of eastern China (Figure 1a). Here a 2-months time scale is selected to focus on the seasonal to interannual drought. Drought classification according to the SPI value is based on the definition by the Climate Data Guide (https://climatedataguide.ucar.edu/climate-data/standardized-precipitation-index-spi). Moderate drought denotes events with SPI values ranging from −1.0 to −1.49, while severe drought has values from −1.50 to −1.99, extreme drought has values less than −2.0.

Figure 3. SSTA in regression onto the precipitation anomalies over eastern China (shaded, °C), and in autumn 2019 (contours, °C, blue lines for negative values in −0.7, −0.5 and −0.3, and red lines for positive values in 0.5, 0.7 and 0.8). The regression pattern was multiplied by −1 to focus on the SST anomalies related to precipitation deficits over eastern China. Dots show the regression significant at the 95% confidence level. SSTA, sea surface temperature anomalies.
Associated with the WNP anomalous cyclone, anomalous northerly winds over eastern China tend to inhibit the moist air from tropical seas and reduce precipitation there. This autumn also witnessed evident SST anomalies in the tropical Pacific and Indian oceans (Figure 3). A remarkable SST warming occurred in the central Pacific, which has been identified as a moderate CP El Niño event by the CPC. This SST pattern is analogous to the regression onto the eastern China autumn precipitation that in 2019, suggesting that the precipitation deficits are closely related to the CP warming. CP El Niño events are usually accompanied with the anomalous cyclone over the WNP and reduced precipitation over most regions of eastern China during autumn (Figure 4a). It is consistent with our previous studies (Zhang et al., 2011, 2013, 2014) that the CP El Niño can excite convection anomalies over the western-to-central Pacific and thus WNP cyclonic anomalies as a Rossby wave response (Matsuno, 1966; Gill, 1980). Among eight CP El Niño events in record, the SST warming center was 165°E in 2019 autumn with the most westward location and the CPI reaches as high as 1.73 with the strongest intensity (Figure 4b). Here the precipitation (Figure 2b). Associated with the WNP anomalous cyclone, anomalous northerly winds over eastern China tend to inhibit the moist air from tropical seas and reduce precipitation there. This autumn also witnessed evident SST anomalies in the tropical Pacific and Indian oceans (Figure 3). A remarkable SST warming occurred in the central Pacific, which has been identified as a moderate CP El Niño event by the CPC. This SST pattern is analogous to the regression onto the eastern China autumn precipitation that in 2019, suggesting that the precipitation deficits are closely related to the CP warming. CP El Niño events are usually accompanied with the anomalous cyclone over the WNP and reduced precipitation over most regions of eastern China during autumn (Figure 4a). It is consistent with our previous studies (Zhang et al., 2011, 2013, 2014) that the CP El Niño can excite convection anomalies over the western-to-central Pacific and thus WNP cyclonic anomalies as a Rossby wave response (Matsuno, 1966; Gill, 1980). Among eight CP El Niño events in record, the SST warming center was 165°E in 2019 autumn with the most westward location and the CPI reaches as high as 1.73 with the strongest intensity (Figure 4b). Here the precipitation (Figure 2b). Associated with the WNP anomalous cyclone, anomalous northerly winds over eastern China tend to inhibit the moist air from tropical seas and reduce precipitation there. This autumn also witnessed evident SST anomalies in the tropical Pacific and Indian oceans (Figure 3). A remarkable SST warming occurred in the central Pacific, which has been identified as a moderate CP El Niño event by the CPC. This SST pattern is analogous to the regression onto the eastern China autumn precipitation that in 2019, suggesting that the precipitation deficits are closely related to the CP warming. CP El Niño events are usually accompanied with the anomalous cyclone over the WNP and reduced precipitation over most regions of eastern China during autumn (Figure 4a). It is consistent with our previous studies (Zhang et al., 2011, 2013, 2014) that the CP El Niño can excite convection anomalies over the western-to-central Pacific and thus WNP cyclonic anomalies as a Rossby wave response (Matsuno, 1966; Gill, 1980). Among eight CP El Niño events in record, the SST warming center was 165°E in 2019 autumn with the most westward location and the CPI reaches as high as 1.73 with the strongest intensity (Figure 4b). Here the
The observation and modeling experiments suggest that the precipitation deficits become more severe when the CP El Niño shifts farther westward (Zhang et al., 2013). Based on the previous studies, some studies argue that the CP El Niño related warming in 2019 contributes to this severe drought (Ma et al., 2020; Xu et al., 2020). Simultaneously, a strong positive IOD event was observed in tropical Indian Ocean during autumn 2019 (Figure 3). A line of researches suggested that the IOD can be triggered by the ENSO variability (Li et al., 2003; Schott et al., 2009; Stuecker et al., 2017) and oceanic condition across Indian Ocean and Pacific Ocean in 2019 has been widely discussed (Doi et al., 2020b; Du et al., 2020; Lu et al., 2020). ENSO–IOD relationship exhibits a certain degree of uncertainty in recent 20 years, mainly owing to the inter–ENSO variability associated with CP El Niño (Teng et al., 2020; Zhang et al., 2015). Different from conventional El Niño events, the IOD response is more sensitive to the zonal location of CP El Niño, rather than its intensity (Zhang et al., 2015). A farther eastward CP El Niño event tends to coincide with a stronger IOD event ($r = 0.82$, significant at the 95% confidence level) (Figure 4c). However, for 2019 the westernmost located CP El Niño event is co–occurred with a strong IOD event, in sharp contrast with other CP El Niño events. So,
the traditional atmospheric–oceanic connection between the tropical Pacific and the Indian oceans seems to be absent in autumn 2019.

To detect the uniqueness for the condition during autumn 2019, we in Figure 5 show the OLR anomalies over the western tropical Pacific for all CP El Niño events. In normal conditions, the associated deep convection can be excited west of SST warming center (Figure 5c). Unexpectedly, the convection is suppressed over the western and central Pacific in autumn 2019, opposite in sign with all the other CP El Niño autumns (Figure 5a; red dashed line in Figure 5c). Positive OLR anomalies appear throughout September and October over the western tropical Pacific (Figure 5b). The absence of the convection of the CP El Niño suggests that the WNP anomalous cyclone and precipitation deficits should not be produced by the simultaneous CP warming. Therefore, the CP El Niño in autumn 2019 exhibits an abnormal feature in its teleconnection to the WNP circulation and IOD.

One may argue that the precipitation deficits could be a response to the strong positive IOD event. To detect its possible role, we show the regressed low–level wind and precipitation anomalies on the IOD index (Figure 6a). A positive IOD event usually coincides with anomalous easterly over the tropical Indian Ocean and anomalous westerly over the tropical western Pacific. The precipitation is increased over the tropical western Indian Ocean and the central Pacific, and decreased over the Indo–Pacific warm pool, resembling

Figure 6. Regressed precipitation (shaded, mm) and 850 hPa wind anomalies (vector, m/s) upon (a) the raw IOD index and (b) the partial IOD index when linearly removing the Niño 3.4 associated impact. Dots and black vectors indicate the coefficients of precipitation and wind anomalies are statistically significant at 95% confidence level.
the ENSO associated anomaly pattern. Over East Asia, no significant precipitation anomalies are observed, suggesting that the IOD seems to have minor impact on the precipitation deficits over eastern China. Considering the co–occurrence of the ENSO and IOD, we furthermore examine the possible role from the IOD by linearly removing the ENSO signal (Figure 6b). The corresponding responses remain largely the same over the Indian Ocean and eastern China. These statistical results indicate that the extreme precipitation deficits during autumn 2019 could not be attributed to the concurrent IOD event.

Very interestingly, the autumn 2019 has seen an abnormally persistent MJO activity. The MJO does not propagate eastward from the tropical Indian Ocean to western Pacific as usual (Madden & Julian, 1971; Salby & Hendon, 1994), staying in Phases 8 and 1 for consecutive 32 days, more than triple that of the climatology (8.2 days for climatology of 1979–2018) (Figure 7a and light bars in 7b). MJO days in Phases 8 and 1 decrease to 14 days for 2019 and 3.5 days for climatology when taking threshold value 0.5 standard deviation. The following analyses are based on MJO amplitude greater than 1. In response to the MJO forcing in Phases 8 and 1, a dipole structure of the convective anomalies appear over the Indian Ocean with the enhanced and sup-

Figure 7. (a) The phase space diagram of Madden–Julian oscillation (MJO) from September to October 2019. (b) September–October total MJO active days in Phases 8 and 1 respectively for 2019 (light and dark pink bar; day) and climatological mean (light and dark blue bar; day). The active days are selected when the MJO amplitude \( \sqrt{RMM1^2 + RMM2^2} \) exceeds 1 (light bars) and for comparison we also show the active days based on 0.5 standard deviation (dark bars). (c) Composite 20–90–days filtered precipitation (shaded; mm/day), OLR (W/m², red and blue lines indicate positive and negative values, respectively) and 850 hPa wind anomalies (vectors; m/s) of active MJO days in Phases 8 and 1. The historical mean number of MJO days in Phases 8 and 1 is 8.2 days as shown in the upper-right corner in (c). (d) Longitude–height plot of the equatorial (5°S–5°N average) 20–90–day filtered specific humidity (shaded, 10⁻² g/kg) and 850–hPa wind anomalies for MJO Phases 8 and 1, superimposed by the moisture flux divergence anomalies (only positive values are plotted marked as red solid lines). The vertical velocity has been multiplied by a factor of –100. Dots in (c) denote values exceeding the 95% confidence level. Vectors in (c) and (d) are only shown when they are significant at the 95% confidence level.
pressed convection over the western Indian Ocean and the Maritime continent to western Pacific Ocean, respectively (Figure 7c). As revealed by previous studies (Hoskins & Karoly, 1981; Rui & Wang, 1990; Zhang, 2013; Zhang et al., 2009), both atmospheric circulation analyses and numerical simulations show that strong convection of the MJO will generate teleconnection pattern through Rossby wave train along subtropical westerly winds. When MJO is in Phases 8 and 1, the low–level anomalous cyclone forms over the WNP as a Rossby wave response in favor of precipitation deficits in East Asia (Figure 7c). The extraordinarily long–lasting active MJO (staying in Phases 8&1, Figure 7) could lead to the extremity of the precipitation deficits over eastern China. Meanwhile, this abnormal MJO activity also excites the downward motion over the western Pacific, which brings about remarkable dry air in middle troposphere and corresponding divergence in low level (Figure 7d). So, the CP El Niño associated convection can be suppressed by the persistent MJO activity despite of the relatively high intensity of the warming SST anomaly (Figure 5). The longest–lasting active MJO can also enhance the local IOD–related SST anomalies via the low–level easterly anomalies (Figure 7c). In turn, prolonged MJO in 2019 might be related to positive IOD (Wilson et al., 2013). SST anomalies associated with positive IOD suppress MJO development in the eastern Indian Ocean and enhance in the western Indian Ocean (Wilson et al., 2013), contributing to the maintenance of MJO in Phases 8 and 1 in 2019. The above relationship is also observed in models (Seiki & Takayabu, 2007a,b; Sooraj et al., 2009; Benedict et al., 2015). However, the two–way interactions between MJO and the underlying SST anomalies remain challenging and reasons for MJO activity in 2019 deserve furthermore study.

3. Conclusion and Discussion

In the present study, we demonstrate that the severe precipitation deficiencies in autumn 2019 over eastern China was largely attributed to the abnormal long–lasting MJO activity over the Indian Ocean. Although the westernmost located CP El Niño event and strong positive IOD event co–occur with the disastrous drought in autumn 2019, no effective convection was observed over tropical western Pacific west of the SST warming center of the CP El Niño, leading to the absence of traditional atmospheric–oceanic connections between the tropical Pacific and Indian oceans. Observations show that the MJO triggered anomalous downward motion over the tropical western Pacific, which is prone to suppress the convection associated with the CP El Niño. The MJO excited anomalous easterly wind over the tropical Indian Ocean is also in favor of maintaining of the positive IOD event. Therefore, we highlight the indispensable and crucial role of the abnormal MJO activity not only on the East Asian climate, but also on the atmospheric–oceanic interaction over the Indo–Pacific Oceans.

During the past 40 years, another similar long–lasting MJO activity is found to occur in autumn 1994 (Figure 8). Under the large scale Indo–Pacific SST anomaly condition (CP El Niño and positive IOD), the active MJO stays in Phases 8 and 1 for 28 days. This abnormal persistent MJO could also contribute to the precipitation deficits over most region of eastern China, despite some difference for the anomaly center compared to those in 2019 (Figure 9). The result above hints to the potential predictability of future extreme droughts over eastern China analogous to 2019 event in advance if the MJO prediction skill would be significantly improved. In a warming world, the MJO are projected to become more active (Rushley et al., 2019). These evidences call for attentions to the MJO activity over the Indian Ocean, which would increase risk of the autumn droughts over eastern China.
Data Availability Statement

All data in this study are publicly available and cited in the reference. SST at https://www.metoffice.gov.uk/hadobs/hadisst/data/HadISST_sst.nc.gz. Daily precipitation from CPC at https://psl.noaa.gov/data/gridded/data.cpc.globalprecip.html. Monthly precipitation from CMAP at https://psl.noaa.gov/data/gridded/data.cmap.html. Monthly SLP at https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.surface.html. Daily wind at https://psl.noaa.gov/data/gridded/data.ncep.reanalysis2.pressure.html. Daily specific humidity at https://psl.noaa.gov/data/gridded/data.ncep.reanalysis2.pressure.html. Daily OLR at https://psl.noaa.gov/data/gridded/data.orlcrdr.interp.html.

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