Interannual variations of the influences of MJO on winter rainfall in southern China

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Abstract

The influences of Madden-Julian Oscillation (MJO) on the winter rainfall in southern China exhibit prominent interannual variations. In general, when MJO is active over the Indian Ocean (western Pacific), winter rainfall in southern China increases (decreases) substantially; however, it also decreases (increases) significantly in some winters. The anomalous atmospheric circulation, especially the intraseasonal and low-frequency circulation anomalies, like are responsible for these variations. Both the intraseasonal and low-frequency circulation anomalies are almost opposite between wetter and drier winters MJO is active over the Indian Ocean and the western Pacific, which leads to the different moisture convergences in southern China. As a result, the influences of MJO over the same region on winter rainfall in southern China are different. When MJO is active over the Indian Ocean, the moisture convergence (divergence) in wetter (drier) winters is dominated primarily by the meridional (zonal) moisture convergence (divergence) and advection. When MJO is active over the western Pacific, in both wetter and drier winters, the anomalous moisture divergence is controlled by the meridional moisture divergence and advection. Therefore, it is not only the location and intensity of MJO activity that are important; the anomalous circulation and moisture on different timescales (in particular the intraseasonal and low-frequency timescales) should be considered in the operational weather forecast when using MJO as a predictor.

1. Introduction

Winter rainfall in China is less than that in summer, and it mainly occurs in southern China. Anomalous rainfall, especially extreme rainfall events, also causes severe damage (He et al 2006, Gao and Yang 2009, Wen et al 2009, Yuan et al 2014). Therefore, an accurate extended-range weather forecast is necessary and important. Madden-Julian Oscillation (MJO) is the most prominent component of tropical atmospheric intraseasonal variability and is characterized by eastward propagation from the Indian Ocean to the central Pacific (Madden and Julian 1971, 1972, 1994, Zhang 2005). As a bridge between weather and climate variations, MJO has significant influences on the weather and climate around the world (Zhang 2013, Li et al 2014a, Taraphdar et al 2018, Jenney et al 2019). Thus, MJO is a fundament of sub-seasonal to seasonal prediction and has been used widely in operational weather forecast (Zhang 2013, Krishnamurthy and Sharma 2017, Ren and Ren 2017).

Accompanying the eastward propagation of MJO convection from the Indian Ocean to the Pacific, rainfall in China shows systematic and substantial changes (He et al 2011, Ren and Shen 2016). When MJO is active over the Indian Ocean (Maritime Continent), spring rainfall increases over the mid-lower Yangtze River Basin (South China) (Bai et al 2013). Rainfall in the pre-flood season (Apr. to Jun.) in South China is enhanced (weakened) when MJO is active over the Maritime Continent (western Pacific) (Zhang et al 2011), and the response of rainfall lags MJO activity about 1–2 pentads (Li et al 2014a). Summer rainfall in southeastern China increases
(decreases) by about 15% (13%) relative to the climatological mean when MJO is active over the Maritime Continent (western Pacific) (Zhang et al. 2009). Based on the composite analysis, Jia et al. (2011) found that winter rainfall in China is strengthened when MJO is active over the Indian Ocean, whereas it is weakened when MJO enters the western Pacific. The systematic and substantial changes of winter rainfall in eastern China that are associated with the eastward propagation of MJO were also identified by Liu and Yang (2010) using correlation analysis. MJO influences rainfall in China by modulating the circulation and moisture transport through local and remote mechanisms (Zhang et al. 2009, Liu and Yang 2010, Jia et al. 2011). Rossby wave excited by the enhanced MJO convection over the Indian Ocean could enhance the rainfall in China (Zhang et al. 2009, Li et al. 2014a). MJO could reduce the moisture transport towards southeastern China via regulating the meridional circulation when MJO is active over the western Pacific (Zhang et al. 2009, He et al. 2011). The extreme rainfall events (ERE) in China are also closely related to MJO activity (Hsu et al. 2016, Lee et al. 2017). The probability of winter EREs in southern China increases (reduces) by about 30%–50% (20%–40%) when MJO is active over the Indian Ocean (western Pacific) (Ren and Ren 2017). When boreal summer intraseasonal oscillation is active over the Indian subcontinent and Bay of Bengal, summer EREs in the Yangtze River Basin increase by about 35%–45% (Ren et al. 2018).

In boreal winter, rainfall is mainly located over the southern China (21°–31°N, 110°–122°E, figure S1(a)) (available online at https://stacks.iop.org/ERL/15/114011/mmedia), and the daily mean rainfall exceeds 2 mm day⁻¹ in most parts of southern China. Winter rainfall over the southern China can account for more than 20% of the annual mean rainfall (figure S1(b)) and exhibit pronounced daily variability (figure S1(c)). Rainfall in southern China shows systematic and substantial changes corresponding to the MJO activity, and the influences of MJO on winter rainfall in southern China are more pronounced when MJO is active over the Indian Ocean and western Pacific than over other areas (Jia et al. 2011, Chen et al. 2020). Climatologically, winter rainfall in southern China is significantly enhanced (weakened) when MJO is active over the Indian Ocean (western Pacific) (figure S2). The influences of MJO on winter rainfall in southern China, however, are unstable and vary from year to year (figure 1). Why the effects of MJO show prominent interannual variations and what causes these variations remains unknown? Most of the previous studies that investigated the influences of MJO on rainfall in China were conducted from the perspective of climatology or some cases study, while the interannual variations of the influences of MJO on rainfall have not been examined in detail. In this study, we aim to explore these issues using reanalysis data and statistical methods. The rest of this paper is organized as follows. Datasets and methods used in this study are described in section 2. The variations of MJO influences and relevant mechanisms are explored in section 3, followed by a summary and discussion in section 4.

2. Data and methods

Daily rainfall data from more than 2000 stations in China were collected and compiled by the National Meteorological Information Center of the China Meteorological Administration. Daily horizontal winds and specific humidity at different pressure levels with a horizontal resolution of 1.5° × 1.5° were obtained from the ERA-Interim global atmospheric reanalysis datasets (Dee et al. 2011). Monthly sea surface temperature (SST) data with a horizontal resolution of 2.0° × 2.0° were derived from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST V5 (Huang et al. 2017). Daily real-time multivariate MJO (RMM) index developed by Wheeler and Hendon (2004) was downloaded from the website of the Australian Bureau of Meteorology. This index divides MJO life cycle into eight phases, and phases 2–3 (6–7) denote MJO activity over the Indian Ocean (western Pacific). The datasets during the period from 1 January 1979 to 31 December 2017 were used in this study. The winter refers to the period from November to following March, and the winter of 1979 refers to the 1979/1980 winter.

The anomaly of a given variable was generated by removing its climatological mean and long-time linear trend. The anomaly of a variable (<A>) can be divided into three components according to the timescales: the high-frequency component (A′, with a period < 30 d), intraseasonal oscillation (ISO/MJO) component (A′′, with a period during 30–90 d), and low-frequency component (A, with a period > 90 d). The high-frequency and ISO/MJO signals were obtained by using Lanczos high-pass and bandpass filter with 201 d smoothing (Duchon 1979). Composites of anomalous rainfall and atmospheric circulation were carried out in phases 2–3 and 6–7 of MJO, considering only strong MJO events (RMM index >1). The significance of the composite results was evaluated with a two-tailed Student’s t-test.

3. Results

3.1. Characteristics of rainfall anomalies

On climate mean state, winter rainfall in southern China is significantly enhanced in phases 2–3 of MJO (figure S2(a)), whereas it is prominently weakened in phases 6–7 (figure S2(b)). To analyze the variations of the impacts of MJO, rainfall index for phases 2–3 (6–7) of MJO is defined as the average of the rainfall anomalies over 21°–31°N, 110°–122°E when MJO is
Figure 1. Standardized rainfall indices for phases (a) 2–3 and (b) 6–7 of MJO from 1979 to 2016. Dashed lines denote the ±0.75 standard deviations.

in phases 2–3 (6–7). The standardized rainfall indices for phases 2–3 and 6–7 of MJO in winters from 1979 to 2016 are presented in figures 1(a) and (b), respectively. As can be seen, the rainfall anomalies exhibit noticeable interannual variations in both phases 2–3 and 6–7, which reflects the interannual variations of the influences of MJO on winter rainfall in southern China. Abnormal winters with excessive/deficient rainfall in southern China (referred as wetter/drier winters) when MJO is active over the Indian Ocean and western Pacific are defined as the rainfall indices for phases 2–3 and 6–7 exceeding ±0.75 standard deviations. The identified winters are listed in table 1.

Composite rainfall anomalies in abnormal rainfall winters when MJO is active over the Indian Ocean are provided in figures 2(a) and (b). Winter rainfall in China is enhanced significantly in wetter winters with the maxima exceeding 4 mm day\(^{-1}\), which is almost twice the climatological mean when MJO is active over the Indian Ocean (figure 2(a)). The remarkable negative rainfall anomalies in drier winters are located mainly over the South China and have much weaker magnitudes (figure 2(b)). Daily mean rainfall anomaly over southern China in wetter (drier) winters is 2.81 (−0.84) mm day\(^{-1}\) (table S1). The differences in the number of MJO activity days (days with RMM index >1) and intensity of MJO between wetter and drier winters are not significant (table S1), which suggests that the interannual variations of MJO influences are not closely related to the activity days and intensity of MJO.

Figures 2(c) and (d) provide the composite rainfall anomalies in abnormal rainfall winters when MJO is active over the western Pacific. Anomalous rainfall is mainly located over southern China, and its intensity is comparable between wetter and drier winters. Significant negative rainfall anomalies occur over almost all of southern China in drier winters (figure 2(d)), whereas significant positive rainfall anomalies are mainly over the northern parts of southern China in wetter winters (figure 2(c)). The difference of MJO intensity in phases 6–7 between wetter and drier winters is also not prominent, but the number of MJO activity days in drier winters are significantly higher in drier winters than that in wetter winters (table S1).

The above analysis demonstrates the noticeable interannual variations of the influences of MJO on winter rainfall in China. A question for what physical processes lead to the interannual variations is raised. We will investigate this issue via large-scale circulation and moisture transport analysis in the following parts.

3.2. Causes of the rainfall variations

3.2.1. In phases 2-3

Composite anomalous circulation at 850 hPa in wetter and drier winters are shown in figure 3. When MJO is active over the Indian Ocean (figures 3(a) and (b)), anomalous circulation in the tropics is similar between wetter and drier winters, whereas the anomalous circulation over the extratropics differs significantly. Southern China is dominated by significant southwesterly in wetter winters for phases 2–3 (figure 3(a)), which induces to the significant convergence in southern China. Thus, rainfall increase significantly. However, anomalous
**Table 1.** Wetter and drier winters for phases 2–3 and 6–7 of MJO.

| MJO phases | wetter/drier | winters               |
|------------|--------------|-----------------------|
| 2–3        | wetter       | 1981, 1982, 1989, 1991, 1997, 2006, 2015 |
|            | drier        | 1979, 1983, 1985, 1992, 1994, 1998, 2003, 2010, 2012, 2014 |
| 6–7        | wetter       | 1982, 1984, 1985, 2001, 2004, 2009, 2016 |
|            | drier        | 1983, 1991, 1992, 1995, 1996, 2006, 2007, 2008, 2012 |

*Figure 2.* Composite rainfall anomalies (mm day\(^{-1}\)) in (a, c) wetter and (b, d) drier winters for phases (a, b) 2–3 and (c, d) 6–7 of MJO. Results exceeding the significance test at 90% confidence level are dotted.

Circulation and its divergence are not significant over southern China in drier winters (figure 3(b)).

We further analyzed the anomalous circulations on different timescales. The high-frequency circulation over southern China is not significant in wetter winters (figure S3(a)), whereas the significant high-frequency southwesterly over southern China in drier winters leads to the divergence south of 26°N (figure S3(b)). The intraseasonal circulation over southern China is significant in both wetter and drier winters when MJO is in phases 2–3, but their intensity and distribution pattern differ from each other prominently. Strong southwesterly prevail over southern China in wetter winters, which induces the strong convergence there (figure S4(a)). However, southern China is dominated by an anomalous cyclonic circulation in drier winters, which leads to the divergence (convergence) to the north (south) of 26°N (figure S4(b)). On low-frequency timescale, anomalous southerlies lead to the strong convergence over southern China in wetter winters (figure S5(a)), but anomalous northerlies induce the divergence over southern China in drier winters (figure S5(b)). The intensity of anomalous intraseasonal and low-frequency circulation over southern China is much stronger in wetter winters, which leads to the strong asymmetric in rainfall anomalies between wetter and drier winters (figures 2(a) and (b)).

The direction of the low-frequency meridional wind is almost opposite over southern China and adjacent sea between drier and wetter winters, which suggests that the rainfall anomalies may be closely linked with the meridional wind. To analyze this issue, we define a meridional wind index as the anomalous meridional wind at 850 hPa averaged over 15°–30°N, 115°–125°E. The standardized rainfall index and meridional wind index on different timescales are shown in figure 4. It is found that the rainfall index is closely related to the meridional wind index, stronger northerly (southerly) corresponding to the less (more) rainfall in southern China (figure 4(a)), and this close relationship mainly stems from the low-frequency meridional wind (figure 4(d)). The intraseasonal meridional wind index is also...
significantly related to the rainfall index with a relatively lower correlation coefficient (figure 4(c)). The relationship between high-frequency meridional wind and rainfall anomalies is not significant (figure 4(b)).

Anomalous circulation could result in anomalous moisture transportation. Specifically, anomalous southwesterly over the southern China in wetter winters can transport more moisture from the Indian Ocean, South China Sea, and western Pacific into the mainland China and thus induce strong moisture convergence over the southern China (figure 5(a)). The moisture transport and its divergence are not prominent over southern China in drier winters. The divergence of moisture south of 26°N may account for the significant weakened rainfall there (figure 5(b)). Moisture flux divergence can be written as follows (gravitational acceleration \( g \) is omitted),

\[
M_{\text{div}} = q \frac{\partial u}{\partial x} + u \frac{\partial q}{\partial x} + q \frac{\partial v}{\partial y} + v \frac{\partial q}{\partial y}
\]  

where, \( q \), \( u \) and \( v \) represent the specific humidity, zonal wind, and meridional wind, respectively. \( M_{\text{div}} \) is the moisture flux divergence, and the four terms on the right-hand side of equation (1) are (from left to right) zonal moisture advection, meridional moisture divergence, and meridional moisture advection (Ren et al. 2018).

Figure 6(a) shows individual terms in equation (1) averaged over the southern China under different conditions. Zonal (meridional) moisture flux leads to the moisture divergence (convergence) in both wetter and drier winters for phases 2–3 of MJO. The moisture convergence (divergence) in wetter (drier) rainfall winters is mainly attributed to the effects of meridional (zonal) moisture convergence (divergence).

The raw specific humidity, zonal and meridional velocities can be further decomposed into three components according to their timescales, the high-frequency (with a period <30 d) component, ISO/MJO (30–90 d) component, and low-frequency background state (LFBS; with a period >90 d) component following Chen et al. (2016), (2020):

\[
q = q^* + q' + \bar{q} \quad u = u^* + u' + \bar{u} \quad v = v^* + v' + \bar{v}
\]  

(2)

where the asterisk, prime, and overbar denote the high-frequency, ISO/MJO, and LFBS components, respectively. It is worth noting that the LFBS is the sum of low-frequency anomaly and the climatological mean (\( A = \bar{A} + \Delta \), where \( \bar{A} \) is the climatological mean).

Thus, zonal and meridional moisture divergence can be further decomposed as:

\[
\frac{\partial q\bar{u}}{\partial x} = q^* \frac{\partial \bar{u}}{\partial x} + q' \frac{\partial \bar{u}}{\partial x} + q \frac{\partial \bar{u}}{\partial x} + q^* \frac{\partial u^*}{\partial x} + q' \frac{\partial u'}{\partial x} + q \frac{\partial u}{\partial x}
\]

\[
\frac{\partial qv}{\partial y} = q^* \frac{\partial v^*}{\partial y} + q' \frac{\partial v'}{\partial y} + q \frac{\partial \bar{v}}{\partial y} + q^* \frac{\partial \bar{v}}{\partial y} + q' \frac{\partial \bar{v}}{\partial y} + q \frac{\partial \bar{v}}{\partial y}
\]  

(3)

Individual terms on the right-hand side of equations (3) and (4) averaged over southern China in wetter and drier winters are shown in figure S6. Zonal moisture divergence over the southern China in drier winters is mainly induced by the LFBS moisture divergence caused by ISO zonal wind, followed by the LFBS moisture divergence caused by LFBS zonal wind (figure S6(a)). Zonal moisture divergence in wetter winters is dominated by the LFBS moisture divergence caused by LFBS zonal wind. The stronger meridional moisture convergence in wetter winters is mainly attributed to the LBFS moisture convergence caused by the LFBS, ISO, and high-frequency meridional wind (figure S6(b)). ISO meridional wind also leads to LBFS moisture convergence in drier winters, but its effects are offset by other terms of moisture flux divergence (figure S6(b)).
3.2.2. In phases 6-7
When MJO is in phases 6–7, significant anomalous southerly (northerly) is over southern China in wetter (drier) winters, and southern China is dominated by prominent convergence (divergence; figures 3(c) and (d)). High-frequency circulation at 850 hPa over southern China is not significant in both wetter and drier winters, although it leads to the convergence (divergence) in wetter (drier) winters (figures S3(c) and (d)). Whereas, ISO and low-frequency winds over southern China are significant and characterized by opposite direction and similar amplitude between wetter and drier winters (figures S4(c), (d), S5(c) and (d)), which lead to the convergence (divergence) over southern China in wetter (drier) winters. There is an anomalous ISO anticyclonic circulation over southern China and the East China Sea in wetter winters, which leads to the divergence over Guangdong province and convergence over the Yangtze River Basin (figure S4(c)). Winter rainfall in China during phases 6–7 is also closely linked to the meridional winds over the southeast China and adjacent sea regions (figure 4(e)), and this significant relationship is also mainly contributed by the low-frequency and intraseasonal flows (figures 4(g) and (h)). Meanwhile, the effects of high-frequency meridional winds are also prominent (figure 4(f)).

Significant southwest winds can lead to the strong moisture convergence over the southern China in wetter winters (figure 5(c)), while the pronounced northeast flows induce the significant moisture divergence in drier winters (figure 5(d)). The anomalous circulation and moisture transport are significant both in wetter and drier winters and their magnitude is comparable between the two conditions, which differ from the results when MJO is active over the Indian Ocean. Each term in equation (1) averaged over southern China for phases 6–7 in wetter and
drier winters are shown in figure 6(b). The strong moisture convergence in wetter winters is induced by the meridional moisture convergence and advection. While the moisture divergence in drier winters is mainly controlled by meridional moisture divergence, and the effects of meridional moisture advection are relatively weaker.

The meridional moisture divergence and advection can be decomposed as the combined effects of moisture and meridional wind on different timescales as in equations (4) and (5).

\[
\frac{\partial q}{\partial y} = v' \frac{\partial q'}{\partial y} + v' \frac{\partial q^*}{\partial y} + v' \frac{\partial q}{\partial y} + v' \frac{\partial q^*}{\partial y} + v' \frac{\partial q'}{\partial y} + \bar{v} \frac{\partial \bar{q}}{\partial y} + \bar{v} \frac{\partial \bar{q}^*}{\partial y} + \bar{v} \frac{\partial \bar{q}'}{\partial y}.
\]

The terms on the right-hand side of equations (4) and (5) averaged over southern China in wetter and drier winters are shown in figure S7. The strong meridional moisture convergence in wetter winters is mainly induced by the LFBS moisture convergence caused by LFBS meridional wind and followed by the ISO moisture convergence caused by LFBS meridional wind (figure S7(a)). While the ISO meridional wind leads to the LFBS moisture divergence in wetter winters. The stronger meridional moisture divergence in drier winters mainly stems from the LFBS moisture divergence caused by ISO, LFBS, and high-frequency meridional wind in wetter winters. Whereas, it is mainly induced by the LFBS moisture advection caused by LFBS meridional wind in drier winters (figure S7(b)).

4. Summary and discussion

The results of this investigation show that the influences of MJO on winter rainfall in southern China exhibit outstanding interannual variations in both phases 2–3 and 6–7 of MJO. The magnitude of rainfall anomalies in southern China shows noticeable asymmetric features between the wetter and drier winters in phases 2–3. The amplitude of rainfall anomalies in wetter winters is much stronger than that in drier winters. The magnitude of rainfall anomalies in southern China between wetter and drier winters in phases 6–7 of MJO is comparable, but the region of negative anomalous rainfall is larger than that of positive anomalies. Anomalous large-scale circulation and moisture transport are responsible for the interannual variations of the influences of MJO. The anomalous circulation associated with the interannual variations of rainfall anomalies is dominated by the ISO and low-frequency circulation, and the high-frequency circulation also contributes to the rainfall anomalies in phases 6–7 of MJO. When MJO is active in phases 2–3, the zonal (meridional) moisture flux is the main contributor to the moisture divergence (convergence) in drier (wetter) winters. However, the moisture flux anomalies related to the variations of rainfall anomalies in phases 6–7 are dominated by the...
meridional component of moisture flux, which leads to the moisture convergence (divergence) over southern China in wetter (drier) rainfall winters.

Winter rainfall in southern China exhibits opposite features when MJO is active over the Indian Ocean and western Pacific on climatology, but the correlation coefficient of rainfall index for phases 2–3 and 6–7 is only −0.06, which suggests this opposite characteristic is unstable and does not occur during some years. In 19 of the winters (form 1979 to 2017), the rainfall exhibited opposite anomalies during phases 2–3 and 6–7; and in 9 of the winters, the rainfall is enhanced (weakened) in both phases 2–3 and 6–7; and in winter of 1985, rainfall is weakened (enhanced) in phases 2–3 (6–7).

There are evident interactions among circulations on different timescales (Hsu et al. 2011, 2018). The low-frequency circulation can modulate the high-frequency and intraseasonal circulation as their background, but high-frequency and intraseasonal circulation also affect the evolution of low-frequency circulation. Under different low-frequency background state, MJO that in the same phase will exert different influences on winter rainfall in southern China. The activity of MJO is regulated by the LFBS. Meanwhile, LFBS can reinforce or offset the influences of MJO (Chen et al. 2020, Kim et al. 2020). Therefore, the influences of MJO on winter rainfall in southern China show pronounced interannual variations. The high-frequency circulation is also modified by MJO and low-frequency and will contribute to the interannual variations of MJO influences, especially when MJO is active over the western Pacific.

Some interannual variations signal, such as El Niño-southern oscillation (ENSO) and quasi-biennial oscillation (QBO), can influence the weather and climate variability and also modulate the impacts of MJO on rainfall via regulating the LFBS circulation (Moon et al. 2011, Cheung et al. 2016, Chen et al. 2020, Kim et al. 2020). The correlation coefficients between Niño 3.4 index and the rainfall index for phases 2–3 and 6–7 are 0.37 and 0.38, respectively, with both exceeding the 95% confidence level. This demonstrates the close relationship between ENSO and winter rainfall in China (Yuan et al. 2014), but this relationship is also unstable. The anomalies of Niño 3.4 index under different conditions are listed in table S2. The enhanced or weakened rainfall in southern China can be observed in both El Niño and La Niña winters no matter in phases 2–3 or 6–7 of MJO. The rainfall in phases 2–3 of MJOis enhanced in some El Niño winters (e.g. 1982, 1991, 1997, 2015, and 2009), but it is also weakened in 1986, 1994, and 2002 El Niño winters. This phenomenon also exists for phases 6–7 of MJO. To further explore the role of ENSO in the variations of MJO influences, we remove the El Niño in wetter winters and La Niña in drier winters from the composite low-frequency circulations (figure S8). The anomalous circulation is similar to that in figure S5, which indicates that ENSO is not the only factor affecting the influences of MJO. After removing the effects of ENSO, the anomalous southwesterly over the southern China is weakened noticeably in wetter winters, especially in phases 2–3, whereas no significant change occurred in the anomalous northeasterly over the southern China. ENSO can look quite different from time to time (Johnson 2013), which may induce quite different lower-frequency circulation anomalies for a relatively small region. Therefore, ENSO is an important factor regulating the influences of MJO, but its effects are uncertain and vary with MJO phases and with ENSO events. These findings in this paper will improve our understanding of the influences of MJO and provide a scientific basis for improving the forecast accuracy. When we predict the weather and climate variations based on MJO, not only the phases and intensity of MJO but also the circulation on different timescales, especially the low-frequency, should be considered.

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Data availability statement

The daily rainfall from stations in southern China was provided by the National Meteorological Information Center of the China Meteorological Administration (http://data.cma.cn/). Daily atmospheric data were obtained from the ERA-Interim global atmospheric reanalysis datasets (www.ecmwf.int/en/research/climate-reanalysis). Monthly SST data were from the NOAA Extended Reconstructed SST V5 (www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.v5.html). The daily real-time multivariate MJO (RMM) index was downloaded from the website of the website of the Australian Bureau of Meteorology (www.bom.gov.au/climate/mjo/).

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