Modulation of the Intraseasonal Variability of Early Summer Precipitation in Eastern China by the Quasi-Biennial Oscillation

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Abstract. Using the reanalysis and multiple observations, the possible impact of the Madden-Julian Oscillation (MJO) on early summer rainfall in eastern China and its modulation by the Quasi-Biennial Oscillation (QBO) is examined. The composite results show that the suppressed (enhanced) convection anomalies for MJO phases 8-1 (4-5) more concentrated over maritime continent and western Pacific during EQBO (WQBO). As a consequence, more significant wet (dry) anomalies develop in South (eastern) China during MJO phases 8-1 (4-5) configured with easterly (westerly) QBO. The enhancement and expansion of the anomalous tropical convection band do not necessarily correspond to enhancement of the extratropical circulation response to MJO phases 8-1 (4-5) configured with westerly (easterly) QBO. The anomalous high (low) over the maritime continent and western Pacific associated with MJO phases 8-1 (4-5) is intensified (deepened) during easterly (westerly) QBO, leading to large southwesterly (northeasterly) anomalies in South China and coasts, carrying abundant (sparse) moisture. Two anomalous meridional circulation cells are observed for MJO phases 8-1 in the East Asia sector, with downwelling anomalies around 5–20°N, upwelling anomalies around 20–30°N, and another downwelling branch northward of 30°N, which are enhanced during easterly QBO. The anomalous meridional circulation cells are reversed for MJO phases 4-5, which are stronger during westerly QBO with the anomalous downwelling and dry anomalies covering eastern China. The combined impact of MJO phases 8-1 and easterly QBO on the early summer rainfall is noticeable in 1996 and 2020. The enormous rainfall amount appeared along the Yangtze River in 1996 and 2020 due to the extended period of the MJO phases 8-1 under the background of the easterly QBO.

1 Introduction

As the dominant mode on the intraseasonal timescale in the tropics, the Madden-Julian Oscillation (MJO) is characterized by eastward-propagating organized convection systems (Madden and Julian, 1971). The MJO is connected with the coupling convection of mixed Rossby-gravity waves (MRGs), which are initialized in the upper level of the western tropical Indian Ocean (Takasuka et al., 2019, 2021). This coupling convection system, after stimulation, usually propagates along the equator and excites Rossby wave trains (Gill, 1980; Matsuno, 1966) that influences the extratropics (Seo and Son, 2012;

Zhang, 2005). The convection associated with the MJO can excite multiple teleconnections in both the stratosphere and the troposphere (Alexander et al., 2018; Garfinkel and Schwartz, 2017; Garfinkel et al., 2014). These teleconnections can further affect the near surface weather and climate (Jenney et al., 2019; Zheng and Chang, 2019). Recent studies also indicate that the stratosphere can also be modulated by the MJO (Garfinkel et al., 2014; Moss et al., 2016; Yang et al., 2019). The
35 stratospheric sudden warming (SSW) and the northern annular mode can develop following the enhanced convections over the western tropical Pacific (Barnes et al., 2019; Kang and Tziperman, 2018).

The strength of the MJO varies with the season, which is more evident in boreal winter but much weaker in boreal summer (Lafleur et al., 2015; Lu and Hsu, 2017). This difference may be attributed to the surface moistening and strengthened convection in the Intertropical Convergence Zone (ITCZ) in boreal winter, differing from larger static stability and
40 strengthened sinking motion in boreal summer (Wang et al., 2020). Toms et al., (2020) showed that this nonuniformity with the season is also identified for the relationship between the Quasi-Biennial Oscillation (QBO) and the MJO, with the QBO-MJO teleconnection getting maximized in boreal winter. The teleconnection between QBO and MJO in boreal winters has been widely documented in some recent studies (Densmore et al., 2019; Kim et al., 2020a; Klotzbach et al., 2019; Wang and Wang, 2021; Wang et al., 2013). In contrast, the QBO-teleconnection in boreal summer is seldom reported in literature,
45 although the individual influence of the MJO on the surface weather in boreal summer has been analyzed (Bai et al., 2022; Zhang et al., 2009).

The quasi-biennial oscillation (QBO) is described as periodic alternation of easterly and westerly zonal winds in the tropical stratosphere with an average period of 28 months (Baldwin et al., 2001). As an important phenomenon in stratosphere, QBO can influence surface weather and climate by three routes, including polar stratosphere route (Anstey and Shepherd, 2014;
50 Holton and Tan, 1982; Rao et al., 2020b), tropical convection route (Garfinkel and Hartmann, 2011; Son et al., 2017) and subtropical route (Garfinkel and Hartmann, 2011; Rao et al., 2020a). The anomalous high over the Pacific, owing to the QBO wind downward-arching into the troposphere, influence the Asia-Pacific climate (Rao et al. 2020a; Wang et al., 2021). Hu et al. (2022) found that QBO can also influence summer precipitation in China.

The persistent extreme rainfall event is a high-impact weather globally, which usually leads to a fast accumulation of water
55 and even urban waterlogging (Wang and Zhang, 2008; Qian et al., 2013; Zou and Ren, 2015; Rao et al., 2022). During June–July PER events occur in East Asia and the rainbelt usually forms from the Yangtze-Huai Rivers to South of Japan, known as the Meiyu-Baiu (Takaya et al., 2020; Takahashi and Fujinami, 2021; Chen et al., 2021a, 2022). On average, the Meiyu-Baiu rain season persists from late June to early July, and the rainfall in June-July has an evident intraseasonal variance with an averaged cycle of 10–20 days (Ding et al., 2020). Previous studies have established the possible relationship between the
60 tropical MJO and the intraseasonal variability of China rainfall in winter (Jia et al., 2011; Ren and Ren, 2017; Chen et al., 2021b), and the tropical MJO can significantly affect the weather in East China (Jeong et al., 2008; Takahashi et al., 2012; Kim et al., 2020b). It is identified that the MJO impact the precipitation in Southern China via exciting a Rossby wave spreading from tropical Indian Ocean to East Asia along the westerly wind waveguide (Zhang et al., 2009).

Considering that the MJO strength can be modulated by the QBO (Densmore et al., 2019; Klotzbach et al., 2019; Wang and
65 Wang, 2021), recent studies have found that the MJO convection is much stronger during the easterly phase of the QBO at
50 hPa than the westerly phase in boreal winter (Son et al., 2017; Toms et al., 2020). The modulation of QBO on MJO
related precipitation in East Asia in boreal winter was reported in Kim et al. (2020a). They found that EQBO enhances the
MJO-related rainfall anomalies while WQBO weakens in boreal winter. Given that the rainfall is much larger in boreal
summer than in boreal winter (Mao et al., 2022; Wu et al., 2021), a better understanding of the summer rainfall variability is
70 a prerequisite for timely long-range prediction of the weather (Pfahl et al., 2017; Sillmann, 2017). This study is aimed to
explore the impact of the tropical MJO on the summer rainfall in China and its modulation by the QBO. An exploration of
the impact of the MJO on early summer rainfall and its modulation by the QBO can further improve our understanding of the
summer rainfall variability and therefore a better forecast of summer rainfall especially on the long-range timescale (Li, 2016;
Zhu et al., 2017; Liang et al., 2019).

75 This paper is constructed as follows. Following the introduction, section 2 introduces the data and methods employed in this
study. Distribution of circulation and rainfall anomalies for typical MJO phases is shown in section 3. The modulation of the
QBO on the MJO-related rainfall anomalies during early summer in China is discussed in section 4. The physical processes
responsible for the eastern China rainfall variability associated with the MJO and its modulation by the QBO are analyzed in
section 5. Two typical summers (1996 and 2020) are examined in section 6. Finally, summary and discussion is presented in
80 section 7.

2 Data and methods

To investigate the circulation and rainfall anomalies associated with the tropical MJO, several datasets are used in this study.
Daily interpolated outgoing longwave radiation (OLR) spanning from 1979–2021 is provided by the National Atmospheric
and Oceanic Administration (NOAA) with a horizontal resolution of 2.5°×2.5° (Liebmann and Smith, 1996). Further, the
85 European Centre for Medium-Range Weather Forecasts atmosphere reanalysis version 5 (Hersbach et al., 2020) is used for
construction of the composite circulation and moisture patterns. Variables from ERA5 used in this study include the
horizontal winds and vertical velocity at pressure coordinate. ERA5 has a horizonal resolution of 0.25°×0.25° and spans
from 1000–1 hPa at 37 pressure levels. In addition, the CPC daily land precipitation (Chen et al., 2008) is employed to
calculate the composite rainfall anomalies associated with the MJO. The CPC land precipitation has a horizontal resolution
90 of 0.5°×0.5°, covering the timespan of 1979–2021. The geopotential height and specific humidity are derived from NCEP-
NCAR Reanalysis I which have a horizontal resolution of 2.5°×2.5° (Kalnay et al., 1996).

The Real-time Multivariate MJO (RMM) index (Wheeler and Hendon, 2004) is used to define the MJO phase. The RMM
index is the timeseries of the multivariate empirical orthogonal function (MV-EOF) analysis. The MV-EOF is similar to the
traditional EOF analysis but the focused field is not a single variable but a combined one from several different variables
95 (Lee et al., 2013; Li et al., 2019). The variables used for MV-EOF analysis to extract the RMM index include zonal winds at

850 (U850), zonal winds at 200 hPa (U200), and the OLR anomalies meridionally averaged between 15°S and 15°N (Wheeler and Hendon, 2004). The first two principal components (standardized timeseries of the MV-EOFs) are used to define the QBO phases. The two principal components, RMM1 and RMM2 can determine both the MJO strength ($\sqrt[2]{(RMM1)^2 + (RMM2)^2}$) and phase [$\pi \pm$ arctan (RMM2/RMM1)]. The MJO is usually split into eight phases, and

100   every 45° is clustered in one phase (Wheeler and Hendon, 2004). The MJO phases are usually selected only if the amplitude ($\sqrt[2]{(RMM1)^2 + (RMM2)^2}$) is greater than 1.0.

To test the modulation of the QBO on the MJO-related rainfall in Southern China, the QBO index is calculated using the ERA5 zonal winds. The QBO index is defined as the zonal mean zonal winds in the deep tropics (10°S-10°N) at 50 hPa. The index in May-June is used to select the QBO phases: The westerly QBO (WQBO) is defined when the zonal-mean zonal

105   wind anomalies averaged over 10°S-10°N at 50 hPa exceed the 0.7 standard deviations (7 m/s), while the easterly QBO (EQBO) is defined when the zonal-mean zonal wind anomalies fall below -0.7 standard deviations. We also tried to use the threshold of 0.5 standard deviations, and the results are similar but with a lower confidence level than choice of the 0.5 standard deviations. The selected WQBO early summers are 1981, 1983, 1985, 1986, 1988, 1993, 1995, 1999, 2000, 2002, 2009, 2011, 2014, 2017, 2019, and 2021. The selected EQBO early summers are 1982, 1984, 1987, 1992, 1994, 1996, 1998,

110   2010, 2015, 2016, 2018, and 2020.

3 Impact of the tropical MJO on the early summer rainfall in Southern China

Previous studies have indicated that the rainfall anomalies in East Asia is larger and more significant during the MJO phases 8-1 and 4-5 (Zhang et al., 2009). The OLR anomalies and 200 hPa divergence anomalies during MJO phases 8-1 and 4-5 are shown in Figures 1a and 1b. During the MJO phases 8-1, convections are enhanced over the western tropical Indian Ocean

115   but suppressed over the western Pacific and the maritime continent (Figure 1a). As a consequence, anomalous convergence develops over the maritime continent and neighboring areas. In the mirror phases, the convection in the southwest Indian Ocean begins to weaken, while that enhances over most parts of the equatorial Indo-Pacific Oceans, exhibiting a long zonal band tilting from tropical northwest Indian Ocean to southwest Pacific Ocean (Figure 1b). Anomalous divergence appears along this convection band, maximized around east Indian Ocean and the maritime continent.

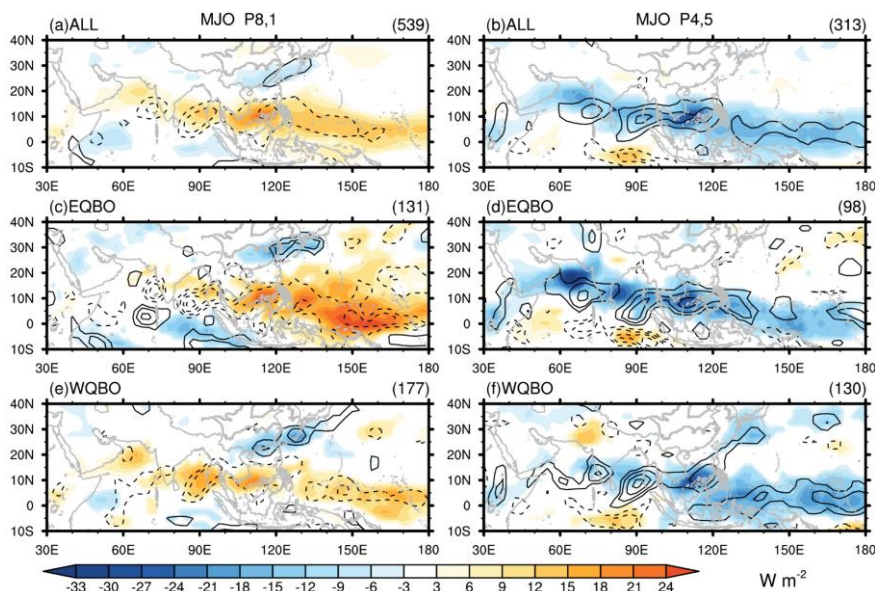



Figure 1. Composite OLR (shadings; units: W/m2) and 200-hPa divergence (contours; units: s-1; interval: 3×10-6) anomalies at the Madden-Julian oscillation (MJO) phases (left) 8-1 and (right) phases 4-5 for (a, b) total days, (c, d) easterly QBO days, and (e, f) westerly QBO days. Only the composite anomalies that are statistically significant at 95% confidence level are shown according to the t-test. The number of days used for each composite map is printed at the top-right corner.

To establish the relationship between the MJO and the early summer rainfall variability in China, Figure 2 shows the composite rainfall anomalies during MJO phases 8-1 and 4-5, respectively. Overall, the MJO has a significant impact on rainfall variability in early summer especially over eastern China (Figure 2a, b). Specifically, South China is wetter during the MJO phases 8-1, while central and northeast China is drier with patches of high significance level (Figure 2a). On the contrary, South China is drier during the MJO phases 4-5, while the rainfall anomalies are insignificant in most parts of northern China (Figure 2b). The significant MJO signal in the rainfall variability is not only identified over China but also observed over northern India and Japan, which is beyond the scope of this study.

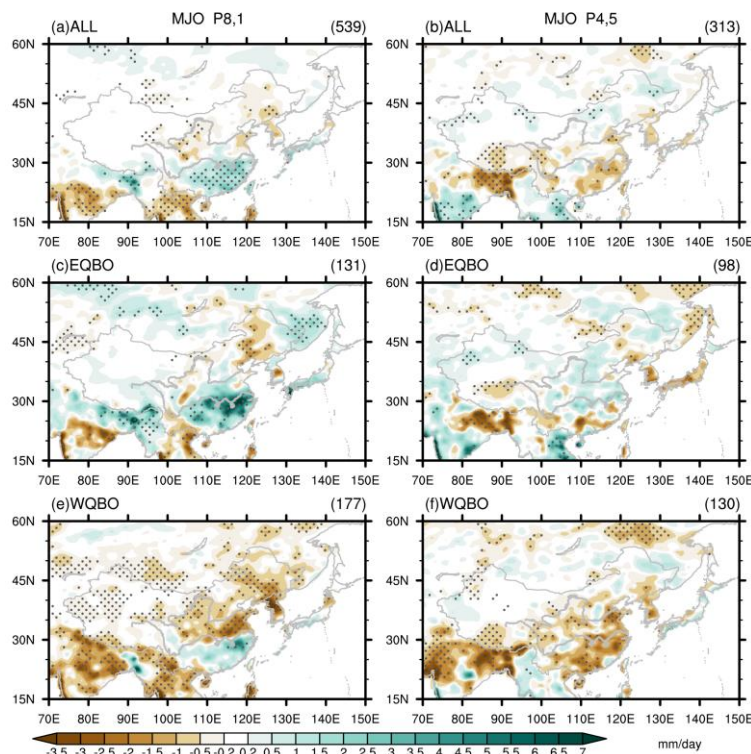



Figure 2. Composite rainfall anomalies (shadings; units: mm/day) at the MJO phases (left) 8-1 and (right) phases 4-5 for (a, b) total days, (c, d) easterly QBO days, and (e, f) westerly QBO days. The dots denote the composite anomalies at 95% confidence level are shown according to the t-test. The number of days used for each composite map is printed at the top-right corner.

4 Modulation of MJO-related rainfall anomalies in early summer by the QBO

To investigate the modulating role of the QBO for the MJO teleconnection in China rainfall during early summer, the composite for MJO phases 8-1 and 4-5 are also shown separately for EQBO and WQBO (Figures 1c–1f, 2c–2f). Compared with the composite for total days of QBO phases in early summer, the suppressed convection anomalies during MJO phases 8-1 are further localized over the western tropical Indian Ocean and maritime continent during EQBO (Figure 1c). The positive OLR anomalies over western Pacific are wider, and the anomalous convergence at 200 hPa is also more organized. In contrast, the convection band for the MJO phases 4-5 is uniformly enhanced during EQBO, which is mainly attributed to the increase in the statistic instability in the lower stratosphere and upper troposphere (Rao et al., 2020a, 2023). The combined MJO phases 4-5 and EQBO lead to an amplification of the enhanced convection with multiple divergence centers at 200 hPa (Figure 1d).

The tropical convection for the MJO phases 8-1 during WQBO is largely suppressed from the tropical Indian Ocean to the tropical western Pacific with the positive OLR anomalies much larger over tropical Indian Ocean than the composite for other conditions (Figure 1e). Previous studies have shown that the thermal forcing in the tropical Indian Ocean usually excites a wave train that is reversed from the forced one by the tropical Pacific forcing (Fletcher and Kushner, 2011; Rao and

150   Ren, 2016, 2020). The multiple positive OLR anomaly centers over the western tropical Indian Ocean, Bay of Bengal, maritime continent, and western Pacific might lead to a net weak extratropical circulation response to the MJO, although the OLR anomalies are amplified. The convections for the MJO phases 4-5 during WQBO are more focused than for other conditions (Figure 1f), and the enhanced convection is mainly located over the eastern tropical Indian Ocean, maritime continent, and western Pacific. Namely, the enhanced convection over western tropical Indian Ocean is missing for the MJO

155   phases 4-5 configured with the WQBO.

In short, the configuration of the MJO phases 8-1 (4-5) and EQBO (WQBO) lead to the more localized OLR anomalies over the Maritime continent and neighboring areas. In contrast, the combination of the MJO phases 4-5 (8-1) and EQBO (WQBO) corresponds to an elongated OLR anomaly band from the western Indian Ocean to the western Pacific with multiple OLR centers.

160   Consistent with the change of the convection associated with the MJO during QBO phases, early summer rainfall anomaly pattern varies (Figure 2c–f). Specifically, the positive rainfall anomalies in South China for MJO phases 8-1 are enhanced during EQBO, and negative rainfall anomalies in northeast China (and even northeast Asia) are relatively stable compared with the composite for total days (Figure 2c vs. Figure 2a). In contrast, the composite rainfall anomalies for MJO phases 8-1 are less organized and insignificant during EQBO than the composite for total days (Figure 2d vs. Figure 2b). The positive

165   rainfall anomalies in South China for MJO phases 8-1 are less significant during WQBO, although the dry anomalies in northern and northeast China are enhanced (Figure 2e). In contrast, dry anomalies in South China for MJO phases 4-5 are strengthened and expand to northern China during WQBO (Figure 2f).

5 Physical analysis of the MJO-related rainfall variation and its modulation by the QBO

The composite horizontal wind and geopotential height anomalies at 850 hPa are shown in Figure 3 for the MJO phases 8-1

170   and 4-5, respectively. As an anomalous cyclone develops over Positive height anomalies develop from tropical Indian Ocean to northwestern Pacific during the MJO phases 8-1, while negative height anomalies replace during the phases 4-5 (Figure 3a, b). As the tropical convections are suppressed from the Indian Ocean to the western Pacific during the MJO phases 8-1, anomalous easterlies appear over the equator, a band of anomalous high controls the South and Southeast Asia in the lower troposphere. Two high centers are prominent, one over the Bay of Bengal, and the other over the Philippine Islands (Figure

175   3a). As a consequence, anomalous southwesterlies over South China and the coastal provinces, which carry more abundant moisture. The circulation pattern associated with the MJO phases 8-1 is highly strengthened during EQBO due to the concentrated thermal forcing (Figure 3c). This altered pattern highly resembles the negative phase of the East Asia-Pacific (EAP) pattern with an anomalous high over the Philippines and an anomalous low over northeast Asia. (Nitta, 1987; Li et al., 2018; Xu et al., 2019). In contrast, the circulation pattern for the MJO phases 8-1 is relatively weaker during WQBO (Figure

180   3e). The anomalous low over northeast Asia is not clearly present, and the anomalous high over the Philippines weakens.

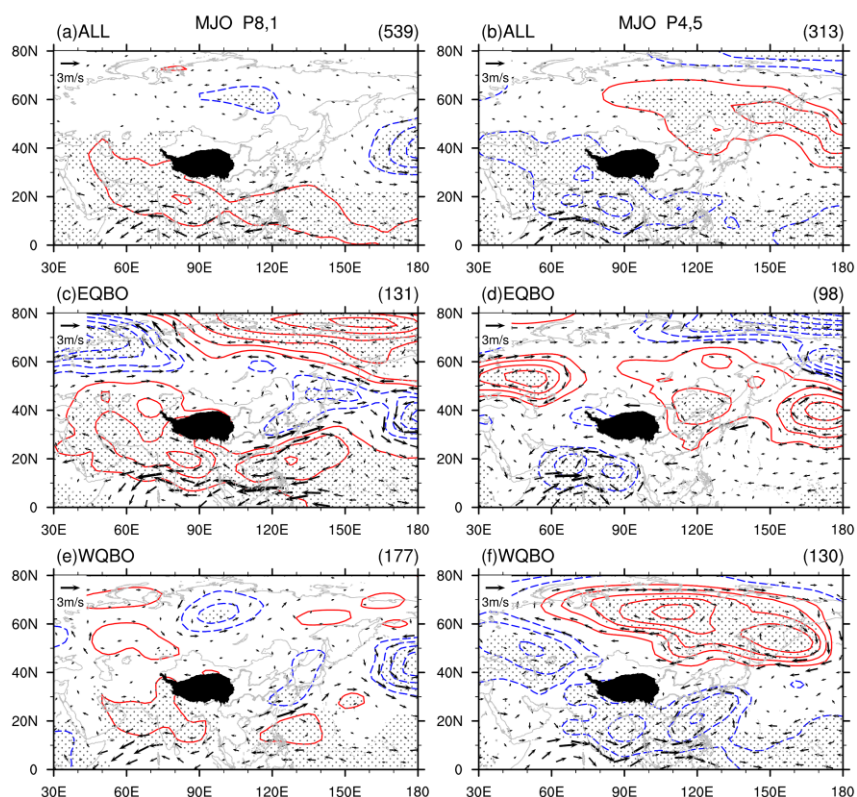



Figure 3. Composite horizontal wind (vectors; units: m/s) and geopotential height (contours; units: gpm; interval: 5) anomalies at 850 hPa during the MJO phases (left) 8-1 and (right) phases 4-5 for (a, b) total days, (c, d) easterly QBO days, and (e, f) westerly QBO days. Note that zero contours are omitted, the positive contours are shown in red, and the negative contours are shown in blue. The dots denote the composite height anomalies at 95% confidence level are shown according to the t-test. The number of days used for each composite map is printed at the top-right corner.

The circulation pattern at 850 hPa during MJO phases 4-5 is nearly contrary to that during phase 8-1 (Figure 3b vs. 3a). Namely, an anomalous low develops over South and Southeast Asia, while an anomalous high develops from northeast Pacific to North Asia (Figure 3b). This tropical anomalous low associated with the MJO phases 4-5 shrinks in its coverage during EQBO, and significant negative height anomalies are mainly situated over tropical Indian Ocean (Figure 3d). Namely, the combination of MJO phases 4-5 and EQBO fail to lead to an enhancement of the circulation variations. In contrast, the tropical circulation anomalies associated with MJO phases 4-5 are stronger during WQBO, when the convection anomalies are more concentrated. Namely, the anomalous low over the Philippines are stronger with northeasterly anomalies prevailing over coastal South China (Figure 3f).

As the two major monsoon systems, the South Asia high (SAH) at 100 hPa and the Western Pacific subtropical high (WPSH) at 500 hPa control the position and intensity of the summer monsoon rainfall band in East Asia (Chen and Zhai, 2016; Guan et al., 2018). The composite of the SAH and WPSH is shown in Figure 4 for the MJO phases 8-1 and 4-5. The SAH is centered over the Tibet in summer (Figure 4a, b), and the WPSH is more sensitive to the MJO phases. The WPSH boundary can extend westward to 122°E during MJO phases 8-1 and 130°E during phases 4-5. Rainfall usually appears to the north of

200   the WPSH, which corresponds to wet anomalies in South China for MJO phases 8-1 and dry anomalies for phases 4-5. The
       SAH is highly enhanced and extends farther eastward during MJO phases 8-1 configured with the EQBO (Figure 4c). The
       WPSH is also strengthened and extends farther westward. This configuration creates a favorable condition for South China
       wetness via enhanced moisture transport in the lower troposphere and intensified divergence in the upper troposphere
       (shown later). The expansion of the SAH is not evident during MJO phases 8-1 configured with WQBO, and the WPSH also
205   retreats to the ocean and South China Sea.

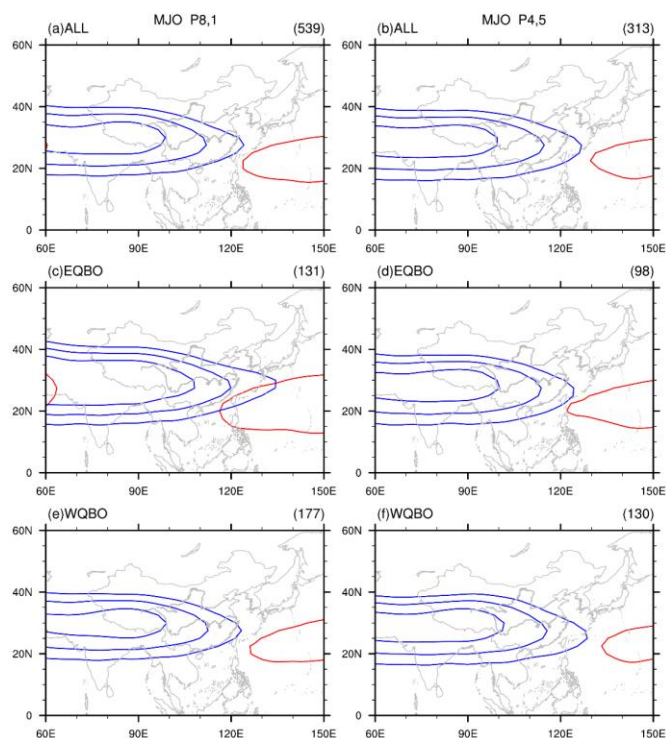



Figure 4. Composited South Asia High (SAH) at 100 hPa and western Pacific high (WPH) at 500 hPa during the MJO phases (left) 8-1 and (right) phases 4-5 for (a, b) total days, (c, d) easterly QBO days, and (e, f) westerly QBO days. Three height contours (16720, 16760, 16800 gpm) are plotted for the SAH, and one contour (5880 gpm) is plotted for the WPSH.

210   Although the WPSH shrinks in its coverage during the MJO phases 4-5 (Figure 4b), it can still be modulated by the phase of
       the QBO. It is observed that the WPSH extends westward to South China Sea and covers the coast of South China during
       MJO phases 4-5 configured with EQBO, which weakens the draught of South China (Figure 4d). The SAH is changed little
       during MJO phases 4-5 from EQBO to WQBO (Figure 4f). In contrast, the WPSH retreats to the ocean, which corresponds
       to the enhancement of the draught in South China.

215   To better understand the rainfall anomalies during the MJO phases 8-1 and 4-5, the vertical cross-sections of the meridional
       circulation averaged from 110–120°E are shown in Figure 5. As the convection is suppressed over the Maritime Continent
       during the MJO phases 8-1, anomalous downwelling develops over the northern tropics from 0–20°N. The convergence is
       clearly present at 200 hPa and 10°N, and anomalous upwelling appears over 20–30°N, which explains the wetness of South

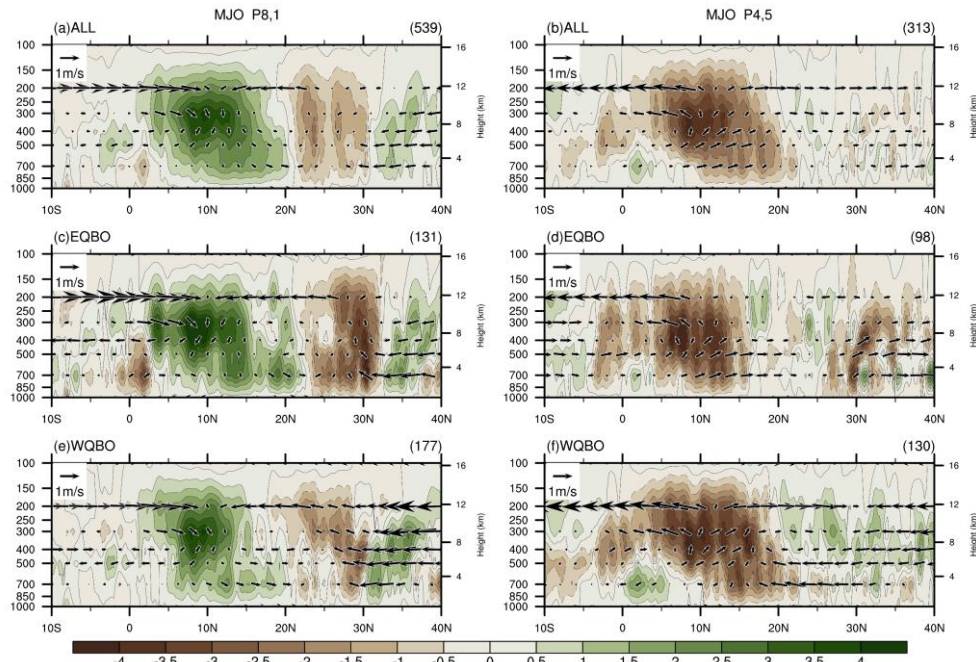
China (Figure 5a). The anomalous downwelling is also present from 30–40°N, which corresponds to the draught of northern
220 China. Namely, two meridional secondary circulation cells are clearly present, one from 10–25°N, and the other from 25–
35°N. With the WPSH and SAH approaching closer during MJO phases 8-1 configured with the EQBO, the anomalous
convergence in lower troposphere and the anomalous divergence in upper troposphere are strengthened, and the anomalous
northerlies are enhanced in the lower troposphere (Figure 5c). In contrast, the anomalous upwelling in the lower troposphere
evidently weakens, and the upwelling band narrows during MJO phases 8-1 configured with WQBO (Figure 5e).

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Figure 5. Composited latitude-pressure cross section of meridional circulation anomalies (vectors; units: m/s, Pa/s) and vertical velocity anomalies (shadings; units: 0.01 Pa/s) averaged from 110–120°E during the MJO phases (left) 8-1 and (right) phases 4-5 for (a, b) total days, (c, d) easterly QBO days, and (e, f) westerly QBO days. The vertical velocity anomalies have been multiplied by -10 to better show the vectors.

230 The anomalous tropical vertical motion during MJO phases 4-5 (Figure 5b) is nearly opposite to that during phases 8-1. As
the convection in the tropics is enhanced, anomalous upwelling occurs in wide regions. The anomalous downwelling is only
seen in the lower troposphere around 25°N and 30°N. The anomalous downwelling is even weaker over South China when
MJO phases 4-5 are configured with EQBO (Figure 5d), which corresponds to insignificant rainfall anomalies in South
China (Figure 2d). In contrast, the anomalous downwelling in eastern China is enhanced during MJO phases 4-5 configured
235 with WQBO (Figure 5f), explaining the dry anomalies (Figure 2f).

In order to examine the moisture conditions associated with the MJO, the vertically integrated moisture flux (VIMF)
anomalies from 1000–300 hPa and the VIMF convergence are shown in Figure 6. Significant anomalous VIMF convergence
anomalies appear in coastal South China during MJO phases 8-1, and weak VIMF appears in parts of northern China (Figure
6a). This pattern intensifies during EQBO: significant anomalous VIMF convergence appears over South China, contrasted

with anomalous VIMF divergence in tropics (Figure 6c). As the strong VIMF band moves farther eastward during WQBO, the anomalous VIMF convergence also moves eastward (Figure 6e), reminiscent of the horizontal wind anomalies at 850 hPa (Figure 3e).
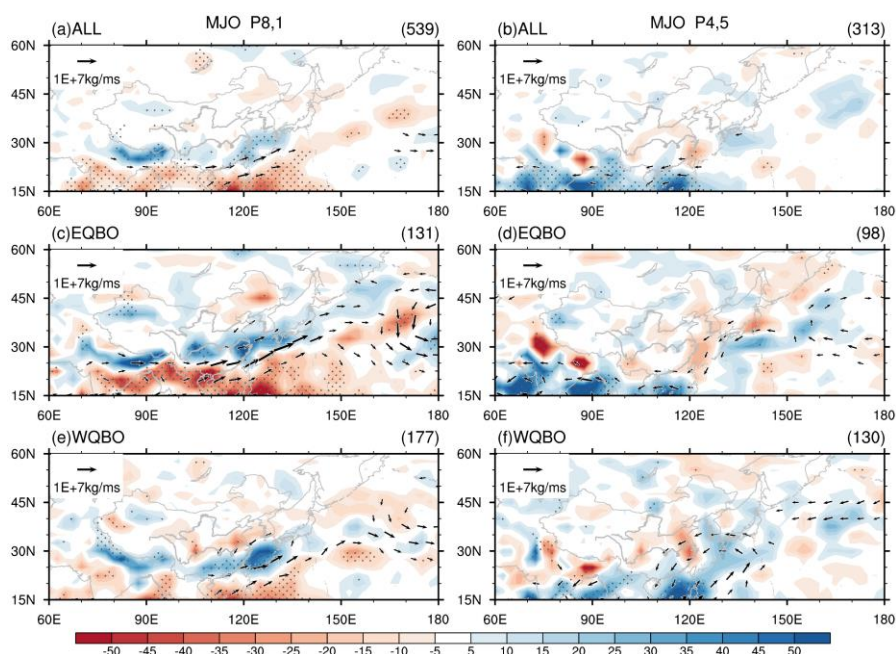
Figure 6. Composited vertically integrated moisture flux (VIMF) anomalies (vectors; units: 107 kg m-1 s-1) and its horizonal convergence (VIMFC) anomalies (shadings; units: kg m-2 s-1) during the MJO phases (left) 8-1 and (right) phases 4-5 for (a, b) total days, (c, d) easterly QBO days, and (e, f) westerly QBO days. Note that only the VIMF lager than 0.5×107 kg m-1s-1 are shown. The VIMFC anomalies that are statistically significant at the 95% confidence level are dotted.

The anomalous moisture divergence is observed over parts of East China during MJO phases 4-5, as the anomalous moisture convergence is observed over South China Sea (Figure 6b). The VIMF and VIMFC patterns associated with the MJO phases 4-5 change limitedly during the EQBO (Figure 6d), while the patterns are enhanced during WQBO (Figure 6e), explaining the significant draught anomalies in eastern China for the MJO phases 4-5 together with the WQBO.

6 Two-case studies

The Meiyu-Baiu is a rainy period in East Asia and has a significant impact on the agricultural growth and production, human societies, ecosystems, and the natural environment (Rao et al., 2022; Feng et al., 2007). Extreme precipitation events take place during Meiyu-Baiu period, which can increase the river flow and lead to heavy economic losses and even high death tolls (Rao et al., 2022; Qian et al., 2013). The MJO can modulate the East Asian summer rainfall, and extreme rainfall events in eastern China usually appear during certain MJO phases (Liang et al., 2021; Wang et al., 2022). Two cases are selected to further verify the possible impact of the MJO phases 8-1 on eastern China heavy rainfall during EQBO. The Meiyu-Baiu average cumulative rainfall exceeded 600 mm in 1996 and 2020, causing enormous economic losses in China.
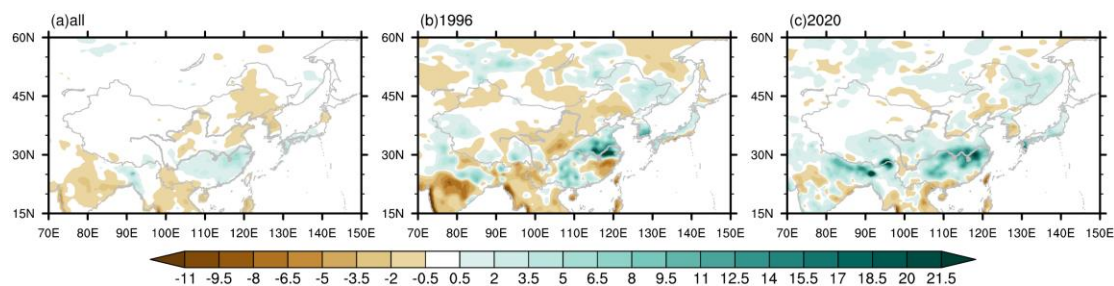
Figure 7. Precipitation anomalies during the MJO phases 8-1 for (a) all years, (b) 1996, and (c) 2020. Note that the central rainfall anomaly magnitude in 1996 and 2000 is nearly 5 times of the composite for all (a).

The composite rainfall anomalies during MJO phases 8-1 for all and case years are shown in Figure 7. Eastern China is characterized by more rainfall in the south and less rainfall in the north (Figure 7a). The wet anomalies mainly develop along the Yangtze River and its south flanks. Compared to the composite of MJO phases 8-1 for all years, the Meiyu-Baiu rainfall band in 1996 and 2020 is biased further northward (Figure 7b, c). Wang et al. (2022) found that the north-south shifts of the 2020 extreme rainfall episodes are probably attributed to the coversion of the MJO from phase 1 to phase 2. With the phase of the QBO considered, the rainfall amplitude associated with the MJO can be further intensified in the composite study and further verified by the two cases in 1996 and 2020.

7 Summary and discussions

The possible impact of the MJO on East Asian winter rainfall and its modulation by the MJO have been widely reported in literature, and the modulation of the East Asian summer rainfall–MJO relation is still not well understood. This study evaluates the relationship between the MJO teleconnection and eastern China rainfall in early summers and its sensitivity to the QBO phase. The main findings in the study are as follows.

I.   The composite convection (OLR) anomaly amplitude can be modulated by the QBO phase. Specifically, the positive OLR anomaly magnitude associated with the MJO phases 8-1 is strengthened especially over tropical Indian Ocean during WQBO, and the suppression convection band covers tropical Indian Ocean, maritime continent, and western Pacific. The positive OLR anomalies for MJO phases 8-1 weaken especially over tropical Indian Ocean and are more concentrated and mainly develop over maritime continent and western Pacific during EQBO. Similarly, the negative OLR anomaly (enhanced convection) band for MJO phases 4-5 extends from tropical Indian Ocean to western Pacific. The negative OLR anomalies for MJO phases 4-5 are amplified especially over tropical Indian Ocean during EQBO, and they weaken and become more concentrated over maritime continent and western Pacific.

II. Eastern China rainfall in early summer is significantly influenced by the MJO. The composite MJO-related rainfall pattern shows that South China is wetter during MJO phases 8-1 with a high significance level, while parts of northern China are drier. Although the tropical convection variations are larger for the MJO phases 8-1 configured with WQBO than that configured with EQBO, the wetness over South China and the Yangtze River Valley is more evident for

EQBO than for WQBO. Similarly, although the negative OLR band is wider for the MJO phases 4-5 configured with EQBO than that configured with WQBO, the drought anomalies over eastern China are broader for WQBO than for EQBO.

290 III. The enhancement and expansion of the tropical maximum convection does not necessarily correspond to strengthened extratropical circulation response. Consistent with MJO-related variations of early summer precipitation in eastern China, the anomalous high (low) over the maritime continent and western Pacific associated with MJO phases 8-1 (4-5) is heightened (deepened) during EQBO (WQBO) when compared with WQBO (EQBO). As a consequence, large southwesterly anomalies prevail in South China and coasts when MJO phases 8-1 are configured with EQBO, carrying

295   abundant moisture. Northeasterly anomalies prevail in the lower troposphere over eastern China and drought occur in eastern China when MJO phases 4-5 are configured with WQBO.

 IV. Two Asian monsoon systems (SAH and WPSH) show somewhat sensitivity to the MJO and QBO phases. The SAH is wide and expands eastward for MJO phases 8-1 configured with EQBO, and meanwhile the WPSH expands further westward to South China Sea. On the contrary, the SAH and/or WPSH size is smaller and the intensity is weaker for

300   MJO phases 4-5 configured with WQBO than other conditions. With the change of the SAH and WPSH, the moisture flux divergence or convergence anomalies are more evident for the two configurations.

 V. Two anomalous meridional circulation cells are observed for MJO phases 8-1 in the East Asia sector, with significant 200-hPa convergence - tropospheric downwelling anomalies around 5–20°N, 200-hPa divergence - upwelling anomalies around 20–30°N, and another upwelling branch northward of 30°N. These two anomalous meridional

305   circulation cells for MJO phases 8-1 are enhanced during EQBO, corresponding to the more significant wet anomalies in South China. The anomalous meridional circulation cells are reversed for MJO phases 4-5, which are stronger during WQBO, with the anomalous downwelling and dry anomalies covering eastern China.

 VI. The combined impact of MJO phases 8-1 and EQBO on the early summer rainfall is noticeable for some typical cases. The enormous rainfall amount appeared along the Yangtze River in 1996 and 2020 due to the extended period of the

310   MJO phases 8-1 configured with EQBO.

The QBO impact the summer rainfall mainly via the tropical convection pathways, as the stratospheric polar pathway is more evident in the Atlantic-Europe sector in winter (Rao et al., 2020a, 2023). The tropical static instability usually enhances in the lower stratosphere and upper troposphere especially over the Indo-Pacific Oceans during EQBO (e.g. Gray et al., 2018; Klotzbach et al., 2019), which modulate the strength and area of the MJO-related convection over western Pacific and South

315 China Sea (Densmore et al., 2019; Klotzbach et al., 2019). Further, the origination of MJO can also be modulated by the QBO (Toms et al., 2020). Besides, previous studies also found that the MJO can also affect the extratropical stratosphere especially in winter (Alexander et al., 2018; Garfinkel and Schwartz, 2017). Due to a pause of the extratropical stratospheric pathway in summer, the MJO-stratosphere links are worth of exploring for a better understanding of the East Asian climate variability in winter. However, the larger area of the convection anomalies does not necessarily correspond to larger

320 circulation anomalies in the Asia-Pacific sector and rainfall anomalies in eastern China. Our results find that the concentrated convection anomalies in the tropics probably have a larger impact on the East Asian climate.

The combined impact of the QBO and MJO on East Asian rainfall in early summer is different from that in winter. Kim et al. (2020a) reported that EQBO amplifies the anomalous rainfall associated with the MJO in winter. This study finds that EQBO is favorable for increase of rainfall associated with MJO phases 8-1, while WQBO is favorable for decrease of

325 rainfall associated with MJO phases 4-5. The seasonal differences in the QBO modulation for the MJO-related rainfall variation is likely related to the seasonal changes in the tropical mean state.

Liang et al. (2021) found that the eastward motion of the MJO is difficult during La Nina than El Nino. Moreover, both the El Nino-Southern Oscillation (ENSO) and QBO phases can impact the eastward motion of the MJO (Sun et al., 2019; Huang and Pegion, 2022). Huang and Pegion (2022) pointed out that La Nina-like cold sea surface temperature (SST) anomalies

330 can weaken the westward-propagating wave activity and confine it in western Pacific, leading to more standing MJO events. The impact of ENSO on the MJO events has been considered in some recent reports (Sun et al., 2019). This study also considers the possible interference of ENSO in the composite for MJO, but a preclusion of the interannual signals associated with ENSO does not significantly change the composite for MJO configured with the QBO.

The QBO-MJO link in boreal winter is reported to intensify in recent years and near future (Kim et al., 2020a). Recent

335 studies also reported that the QBO teleconnections in winter are likely to enhance in the future (Rao et al., 2020b; 2023). This study provides evidence that the MJO teleconnection is also clearly present in early summer, but the future change of the MJO teleconnection in early summer is still unexplored. An evaluation of the state-of-the-art models in reproducing the MJO-China rainfall linkage and its sensitivity to the QBO is left for future study. With high-skill models selecting from the Coupled Model Intercomparison Project, a more confident projection of the MJO teleconnection is also possible in the

340 follow-up study.

Data availability

The CPC land daily precipitation data are available from their website (https://psl.noaa.gov/data/gridded/data.cpc.globalprecip.html). The OLR data are provided by the NOAA (https://psl.noaa.gov/data/gridded/data.olrcdr.interp.html). The ERA5 reanalysis data are provided by the ECMWF

345 (https://cds.climate.copernicus.eu/). The Real-time Multivariate MJO (RMM) index data are provided by the Bureau of Meteorology Australia (BoM) (http://www.bom.gov.au/climate/mjo/). The NCEP-NCAR Reanalysis 1 data are derived from the NOAA (https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html).

Author contributions

ZJ nd JR designed this research. ZF, JR and YW analyzed the data. ZF and YW provided the data analysis methods. ZJ and
350   JY wrote the manuscript draft. JR and QL reviewed and edited the manuscript.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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