Diversity of the Global Teleconnections Associated with the Madden–Julian Oscillation

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(Manuscript received 15 May 2020, in final form 21 September 2020)

ABSTRACT: A recent study has revealed that the Madden–Julian oscillation (MJO) during boreal winter exhibits diverse propagation patterns that consist of four archetypes: standing MJO, jumping MJO, slow eastward propagating MJO, and fast eastward propagating MJO. This study has explored the diversity of teleconnection associated with these four MJO groups. The results reveal that each MJO group corresponds to distinct global teleconnections, manifested as diverse upper-tropospheric Rossby wave train patterns. Overall, the teleconnections in the fast and slow MJO are similar to those in the canonical MJO constructed by the real-time multivariate MJO (RMM) indices, while the teleconnections in the jumping and standing MJO generally lose similarities to those in the canonical MJO. The causes of this diversity are investigated using a linearized potential vorticity equation. The various MJO tropical heating patterns in different MJO groups are the main cause of the diverse MJO teleconnections, as they induce assorted upper-level divergent flows that act as Rossby-wave sources through advecting the background potential vorticity. The variation of the Asian jet could affect the teleconnections over the Pacific jet exit region, but it plays an insignificant role in causing the diversity of global teleconnections. The numerical investigation with a linear baroclinic model shows that the teleconnections can be interpreted as linear responses to the MJO's diabatic heating to various degrees for different MJO groups, with the fast and slow MJO having higher linear skill than the jumping and standing MJO. The results have broad implications in the MJO's tropical–extratropical interactions and the associated impacts on global weather and climate.

KEYWORDS: Madden-Julian oscillation; Rossby waves; Teleconnections

1. Introduction

The Madden–Julian oscillation (MJO), named after [Madden and Julian \(1971, 1972\)](#), is the dominant mode of tropical atmospheric variability ([Zhang 2005](#)). The MJO can significantly affect the global weather and climate systems ([Zhang 2013](#)), bridging the weather and climate and providing foundation for “seamless prediction” ([Hurrell et al. 2009](#); [Brown et al. 2012](#)).

One way for MJO to affect the global weather and climate systems is through exciting teleconnections. The diabatic heating of the MJO can induce Rossby wave trains that propagate from low latitudes into high latitudes, forming global teleconnections in both hemispheres ([Weickmann 1983](#); [Weickmann et al. 1985](#); [Lau and Phillips 1986](#); [Knutson and Weickmann 1987](#); [Ferranti et al. 1990](#); [Weickmann and Khalsa 1990](#); [Hsu 1996](#); [Higgins and Mo 1997](#); [Matthews et al. 2004](#); [Moon et al. 2011](#); [Roundy 2012](#); [Seo and Son 2012](#); [Adames and Wallace 2014](#)). These MJO-related teleconnections have significant impacts on the global precipitation ([Donald et al. 2006](#)) and surface temperature ([Seo et al. 2016](#)). Moreover, the MJO-related teleconnections can interact with other major regional climate modes, such as the Pacific–North American pattern (PNA) ([Mori and Watanabe 2008](#); [Adames and Wallace 2014](#); [Seo and Lee 2017](#); [Tseng et al. 2018](#)) and North Atlantic

Oscillation (NAO) ([Cassou 2008](#); [Lin et al. 2009](#); [Yadav and Straus 2017](#)), thereby affecting the regional weather and climate variability.

As the MJO's convection activities and the associated diabatic heating are sources for exciting the teleconnections, understanding how the MJO's convection propagate and evolve is crucial for foreseeing the MJO teleconnections. The MJO is commonly described by the leading modes of empirical orthogonal function (EOF) of some atmospheric variables, and its evolution phases can be constructed by the associated principal components (PCs) ([Matthews et al. 2004](#); [Wheeler and Hendon 2004](#); [Ventrone et al. 2013](#); [Adames and Wallace 2014](#); [Kiladis et al. 2014](#)). The corresponding phase composites can reveal the typical life cycle of the MJO. Another way to describe the typical MJO life cycle is to construct time-lagged correlation (or regression) maps based on indices defined as some area-averaged atmospheric variables [e.g., area-averaged outgoing longwave radiation (OLR)]. The typical MJO depicted by these methods can be regarded as canonical MJO.

The definitions of canonical MJO are useful for studying the most typical structure and evolution of the MJO, but not every MJO event has a life cycle similar to that of the canonical MJO. A recent study has revealed that the propagation tracks of MJO convection exhibit diversity during boreal winter ([Wang et al. 2019](#)), and there exist four archetypes of MJO: the standing MJO, the jumping MJO, the slow eastward propagating MJO, and the fast eastward propagating MJO. The time–longitude evolution of convection anomalies associated with these four types of MJO is presented in [Fig. 1](#). It shows that each type of MJO exhibits a distinct life cycle: both the fast

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DOI: 10.1175/JCLI-D-20-0357.1

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FIG. 1. The time-longitude evolution of equatorial (10°S – 10°N averaged) intraseasonal OLR anomalies (shading; W m^{-2}) and intraseasonal 200-hPa velocity potential anomalies (contour with interval of $1 \times 10^6 \text{ m}^2 \text{ s}^{-1}$) for (a) fast, (b) slow, (c) jumping, and (d) standing MJO. Only the OLR anomalies above the 95% confidence level are shaded. The positive contours (solid contours) start from $2 \times 10^6 \text{ m}^2 \text{ s}^{-1}$, the negative contours (dashed contours) start from $-2 \times 10^6 \text{ m}^2 \text{ s}^{-1}$, and the zero contours are omitted. The regions where the velocity potential anomalies are above the 95% confidence level are stippled. The number of MJO events for each MJO group is indicated in parentheses.

and slow MJO show systematic eastward propagation from the Indian Ocean (IO) to the western Pacific (WP), but the fast MJO propagates faster; both the jumping and standing MJO cannot propagate through the Maritime Continent (MC), but the convection anomalies in the jumping MJO exhibit some jumps from IO to WP.

The diverse propagation tracks of convection anomalies in different MJO groups imply assorted evolution of MJO-related teleconnections. However, a thorough investigation of teleconnections associated with these four MJO groups is absent, although some previous studies have already revealed the diversity of MJO teleconnections (Yadav and Straus 2017; Chen and Wang 2018a). Therefore, one goal of this study is to unveil the diversity of global teleconnections associated with the four MJO groups. An important issue is how the teleconnections in the four MJO groups differ from those in the canonical MJO.

Another goal is to assess the causes of MJO teleconnection diversity. An important issue is what are the factors controlling

the diversity of MJO teleconnection. Previous studies have shown that the MJO-related teleconnection can be largely considered as circulation responses to the MJO's tropical diabatic heating (Matthews et al. 2004; Seo and Son 2012). Thus, one question is how the diversity of the MJO's tropical convection anomalies affect the teleconnection diversity. Since the teleconnection will have higher predictability if it can be well explained by linear dynamics, a further question is to what extent the MJO teleconnections can be interpreted as linear circulation responses to the MJO's tropical diabatic heating. On the other hand, the extratropical circulation associated with the MJO is more than direct response to the tropical forcing, as the MJO's extratropical circulation anomalies could extract energy from the background mean flow by barotropic conversion (Hsu 1996; Mori and Watanabe 2008). Seo and Son (2012) further showed that the MJO's circulation anomalies were somewhat sensitive to the background mean flow. Therefore, another question is whether the variation of the

background flow could contribute to the MJO teleconnection diversity.

Given the broad impacts of MJO teleconnections, the results of this study will have significant implications in predicting the global weather and climate. The rest of the manuscript is organized as follows. Section 2 describes the datasets, the methods, and the numerical model used in this study. Section 3 presents the observed features of the teleconnections associated with the four MJO groups and the comparisons to the canonical MJO. The causes of the MJO teleconnection diversity will be explored in section 4. Section 5 gives the conclusions and discussion.

2. Data and methodology

a. Data and method

The atmospheric data used in this study include the 4 times daily ERA-Interim reanalysis dataset (Dee et al. 2011), with a 2.5° longitude $\times$ 2.5° latitude horizontal resolution and a period from 1979 through 2013. The daily mean is calculated from the four daily records. To represent the large-scale convection over the tropical region, the daily averages of outgoing longwave radiation (OLR) data on a 2.5° square grid, sourced from the NCEP/NOAA interpolated OLR dataset (Liebmann and Smith 1996), were used here. The real-time multivariate MJO (RMM) indices of Wheeler and Hendon (2004) are obtained from the website of Australian Bureau of Meteorology (<http://www.bom.gov.au/climate/mjo/>). Following Wang et al. (2019), we focus on the MJO events in the boreal winter from November to April (NDJFMA), as the MJO is most prominent during this season (Kikuchi et al. 2012). In this study, the daily anomalies are obtained by removing the time mean and first three harmonics of the climatological seasonal cycle. To obtain the intraseasonal signals, a 20–70-day Lanczos bandpass filter (Duchon 1979) is applied to the daily anomalies.

The methods of selection and classification of MJO events are exactly the same as those in Wang et al. (2019). The readers can refer to that reference for details. In this study and the previous study (Wang et al. 2019), only the MJO events that initiate over the IO are considered, as the IO is an active center for the MJO and the majority of MJO events initiate over the IO (Zhang and Ling 2017). The MJO events are selected when the box-averaged OLR over the eastern IO (10°S – 10°N , 75° – 95°E) is below one standard deviation for 5 successive days, and there are total 103 selected cases. These selected MJO events are then classified into four clusters using the k -means cluster analysis. The number of clusters is optimally determined by the mean silhouette value that measures how well the clusters are classified (Wang et al. 2019). Additionally, 13 events have been removed as their silhouette values are lower than 0.06, and this step could eliminate those MJO events that are not well classified and may have overlaps over different clusters. Finally, 90 remaining events are retained.

It should be noted that the selection of MJO events here is based on the total intraseasonal signals that contain both eastward and westward propagating signals. If the MJO is defined as eastward propagating planetary-scale signals on the

wavenumber–frequency domain (Wheeler and Kiladis 1999; Roundy and Frank 2004a), then the “MJO” events selected here are not MJO alone, and they may contain interferences from the westward propagating signals (e.g., equatorial Rossby wave) as documented by Roundy and Frank (2004b). Nevertheless, these selected intraseasonal oscillation events are still loosely defined as “MJO” in this study, following the conventional notion that was set up in the previous works (Kim et al. 2014; Feng et al. 2015; Chen and Wang 2018a). The resulting MJO clusters actually describe the characteristics of convection signals associated with the MJO, even when these signals may also include the effects of interference associated with equatorial Rossby waves. This definition of the MJO here, on the other hand, could have advantages in representing the MC barrier effect, as it requires both eastward and westward propagating signals to represent the attenuation of MJO over the MC (Zhang and Hendon 1997; Chen and Wang 2018b).

In the following study, the composite analysis on these four MJO groups will be performed. A two-tailed Student’s t test will be used to test the significance of the composited anomalies. The degree of freedom of the t test is $n - 1$, where n is the sample size.

b. Linear baroclinic model

The linear baroclinic model (LBM) developed by Watanabe and Kimoto (2000) is used here to study the causes of MJO teleconnection diversity. The model consists of primitive equations linearized about a background basic state. The model has a horizontal resolution of T42 and 20 vertical levels in σ coordinates. The zonally asymmetric climatological monthly mean data derived from the ERA-Interim are used for calculating the background basic state. The biharmonic diffusion with time scale of 6 h is used for damping the smallest waves, and the vertical diffusion with time scale of 1000 days is used to remove the noise arising from vertical difference. Following Tseng et al. (2020), the time scale for the Newtonian cooling and Rayleigh friction is 20 days for all vertical layers except the top layer and the bottom three layers, which have a time scale of 0.5 days.

The model is solved with time-dependent external heating rate anomalies derived from the observed apparent heat source associated with the MJO. The apparent heat source is defined as the budget residual of the thermodynamic energy equation (Yanai et al. 1973):

$$Q_1 = \frac{ds}{dt}, \quad (1)$$

where $d/dt = (\partial/\partial t) + u(\partial/\partial x) + v(\partial/\partial y) + \omega(\partial/\partial p)$ and $s = C_p T + gz$ is the dry static energy. The heating rate Q_1/C_p is calculated using the daily data, and then the heating rate anomalies are obtained by using the method described in this section.

3. Observed diversity of the MJO-related teleconnections

In this section, the features of global teleconnections associated with the four types of MJO will be explored. Since the

Canonical MJO

FIG. 2. Phase composites of 200-hPa normalized daily geopotential height anomalies (contour) and the intraseasonal OLR anomalies (shading; W m^{-2}) for the canonical MJO. The phase spaces are expanded by the RMM indices (Wheeler and Hendon 2004). Only the OLR anomalies significant at 95% confidence level are shaded. The contour interval is 0.15. The region where normalized geopotential height anomalies are significant at the 95% confidence level are stippled. The solid contours denote positive values, the dashed contours denote negative values, and the thick solid contours denote zero contours. The number of days for each MJO phase (when RMM amplitude is greater than 1.0) is indicated in parentheses.

MJO circulation anomalies have equivalent barotropic structures in the extratropics with maximum amplitudes at the upper troposphere (Moon et al. 2011), upper-tropospheric (i.e., 200 hPa) circulation anomalies are utilized to represent the MJO teleconnections, which could well capture the features of MJO global teleconnections.

a. Teleconnections associated with the canonical MJO

For comparison, we first examine the circulation features of the canonical MJO. Figure 2 shows the phase composites of

normalized daily geopotential height anomalies at 200 hPa. The phases of canonical MJO are expanded by the RMM indices, and the composites are made only when the amplitudes of RMM indices are greater than 1.0. The normalized anomaly at each grid point is obtained through dividing the daily anomaly by the corresponding standard deviation at that grid point. The use of normalized anomaly is because it could well depict circulation features in both tropics and extratropics. Also shown in Fig. 2 are the composited intraseasonal OLR anomalies. Note that the geopotential height anomalies are not

intraseasonally filtered, as the circulation outside the MJO tropical heating region may have frequencies other than the intraseasonal band.

At phase 8 (Fig. 2a), there are suppressed convection anomalies over the MC region. The corresponding tropical circulation response resembles the Gill–Matsuno pattern (Matsuno 1966; Gill 1980), with Kelvin wave low pressure anomalies to the east of the suppressed convection and a Rossby wave cyclone pair to the west, consistent with previous results (Wang and Rui 1990; Hendon and Salby 1994; Maloney and Hartmann 1998; Adames and Wallace 2014; Chen and Wang 2017). To the east of the MC suppressed convection, there is an anticyclone pair straddling the equator. This anticyclone pair, attributed partly to the enhanced convection over equatorial central Pacific and partly to the MC suppressed convection (Monteiro et al. 2014), forms a quadrupole vortex structure (Hendon and Salby 1994; Kiladis et al. 2005; Monteiro et al. 2014) together with the cyclone pair to the west of the MC suppressed convection. In the extratropics, the most noticeable feature is a PNA-like pattern over the northern Pacific and North America. There are also wave train patterns over the Eurasian continent. The extratropical circulations in the Southern Hemisphere are less wavy, but the circulation anomalies can still reach the Antarctic region, which could potentially affect the Antarctic sea ice (Lee and Seo 2019).

At phase 1 (Fig. 2b), the MC suppressed convection propagates eastward into the WP, and there is enhanced convection emerging in the IO, which induces a Kelvin wave high to its east. In the extratropics, there are Rossby wave trains emanating from the flanking Rossby wave cyclone associated with the MC–WP suppressed convection into the middle and high latitudes in both hemispheres, and the PNA-like pattern evolves and begins to collapse. At phase 2 (Fig. 2c), the IO enhanced convection strengthens and propagates eastward, while the WP suppressed convection weakens. The tropical and extratropical circulation anomalies exhibit continuous evolution, but it should be noted that it takes about 10–15 days for the extratropical circulation to fully develop in response to the tropical heating (Tseng et al. 2019, 2020).

At phase 3 (Fig. 2d), the IO enhanced convection matures and the associated Gill–Matsuno pattern emerges. The WP suppressed convection significantly weakens and moves into the central Pacific, but the associated Rossby cyclonic gyres do not decay significantly. This is because these Rossby cyclonic gyres can be enhanced by the enhanced IO convection (Monteiro et al. 2014). In both hemispheres, there are Rossby wave trains emanating from the flanking Rossby wave anticyclone associated with the IO enhanced convection. In northern Pacific, there is an emerging wave pattern resembling the PNA pattern, except its location is shifted westward.

From phase 4 (Fig. 2e) the MJO enters into its another half life cycle. The anomalous convection patterns in phases 4–7 (Figs. 2e–h) are out of phase with phase 8 and phases 1–3 (Figs. 2a–d). Note that the circulation anomalies in the two half life cycles are generally out of phase, but there are also some notable discrepancies.

b. Diversity of MJO teleconnections

Unlike the canonical MJO, it is impracticable to define evolution phases for the four MJO groups identified in

section 2. However, since phase 3 of the canonical MJO has strongest enhanced convection over the IO (Fig. 2d) and each MJO group has maximum enhanced convection over the IO around day 0 (Fig. 1), we can make a composite from day –2 to day 2 for each MJO group analogous to the phase 3 composite of the canonical MJO. Accordingly, we define the period from day –17 to day –13 as pentad 1, from day –12 to day –8 as pentad 2, and so on. Therefore, we obtain eight pentads from day –17 to day 22, mimicking the eight phases of the canonical MJO. Figures 3–6 show the composited maps of the eight pentads for the four MJO groups. The sample size n of each pentad composite for a particular MJO group is $5 \times k$, where k is the case number (shown in Fig. 1) of that MJO group. Since the data in adjacent days within a pentad may have persistency and may not be independent, the use of $5 \times k - 1$ as degree of freedom could be an overestimate. Thus, a more conservative estimate is used here by taking the degree of freedom as $k - 1$, assuming each pentad has one degree of freedom. It should be noted that this alternative measure could also underestimate the degree of freedom, and correspondingly a 90% confidence level is used in Figs. 3–6.

For the fast MJO (Fig. 3), the evolution of tropical convection anomalies is similar to that of the canonical MJO (Fig. 2), and the major circulation features of the fast MJO show some similarities to those of the canonical MJO. Note that the details of the anomalous tropical convection patterns are not exactly the same between the two MJOs, and there exist discrepancies in circulations. To quantify the similarities of the circulations between the canonical MJO and the fast MJO, the second column of Table 1 shows the pattern correlation coefficients between the canonical MJO and the fast MJO over the global area, the Northern Hemisphere, and the Southern Hemisphere, respectively. For the global area (first number), the average pattern correlation is about 0.58. The highest similarities between the fast MJO and canonical MJO occur on pentads 3–4 (phases 2–3), with correlation coefficients exceeding 0.7. Further examination of Table 1 reveals that the pattern correlation shows some sensitivity to the domain. The pattern correlation coefficients for the Southern Hemisphere region are the highest during pentads 1 and 3–4 (phases 8 and 2–3), while the pattern correlations for Northern Hemisphere region are the highest during pentads 5–6 and 8 (phases 4–5 and 7).

For the slow MJO (Fig. 4), the tropical convection anomalies propagate eastward at a slower speed compared to the canonical MJO and the fast MJO, and the zonal scales of the convection anomalies are also smaller. For the global area, the average pattern correlation (third column in Table 1) is about 0.57. The highest similarity between the slow MJO and canonical MJO occurs in pentad 6 (phase 5), with pattern correlation coefficient approaching 0.7. Comparing the slow and fast MJO on the global scale, it shows that the teleconnections in the fast MJO are more similar to those in the canonical MJO in pentads 2–4 as measured by the pattern correlation, whereas the teleconnections in the slow MJO are more similar to those in canonical MJO in pentads 1 and 6. But on average, differences between fast and slow events on global domain are not large when they are compared to the canonical events.

fast MJO

FIG. 3. As in Fig. 2, but for the time-lagged composites of the fast MJO. Shown are sequential composited maps from pentad 1 (from day -17 to day -13) to pentad 8 (from day 18 to day 22). A 90% confidence level is used for the significance test.

For the jumping and standing MJO (Figs. 5 and 6), the propagation patterns of tropical convection anomalies are dramatically changed compared to the canonical MJO. The enhanced convection anomalies in the jumping and standing MJO could not propagate across the MC, and there are discontinuous developments of enhanced convection anomalies from the IO to the WP (e.g., Figs. 5d,e) in the jumping MJO. Consequently, the circulation patterns in the jumping (Fig. 5) and standing MJO (Fig. 6) significantly differ from those in the canonical MJO. This is also manifested in Table 1 in that the pattern correlation coefficients to the canonical MJO are generally low for the jumping and standing MJO. The circulation differences between the jumping and standing MJO are also apparent.

In summary, there is diversity in the MJO teleconnections and each MJO group exhibits distinct evolution of teleconnections. Overall, the teleconnections in the fast MJO and slow MJO are similar to those in the canonical MJO, while the teleconnections in the jumping and standing MJO generally lose similarities to those in the canonical MJO.

4. Causes of the MJO teleconnection diversity

It has been shown that there is diversity in the MJO-associated global teleconnections, manifested in various upper-tropospheric Rossby wave train patterns associated with different MJO groups. In this section, the causes of this diversity will be explored.

slow MJO

FIG. 4. As in Fig. 3, but for the slow MJO.

a. The linear dynamical framework

To study the diversity of Rossby wave trains associated with the MJO, consider the vorticity equation and thermodynamic equations on pressure level:

$$\frac{\partial}{\partial t}(\zeta + f) + \mathbf{V} \cdot \nabla(\zeta + f) = f \frac{\partial \omega}{\partial p}, \quad (2)$$

$$\frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T - S_p \omega = Q/C_p, \quad (3)$$

where $\zeta = (\partial v/\partial x) - (\partial u/\partial y)$ is the vertical component of the relative vorticity and f the planetary vorticity; $\mathbf{V}$ is the horizontal wind vector and ω the vertical velocity, and S_p is the static stability parameter, which is only a function of pressure. Combining Eqs. (2) and (3), we obtain

$$\frac{\partial q}{\partial t} + \mathbf{V} \cdot \nabla q = -\frac{f}{C_p} \frac{\partial}{\partial p} \left(\frac{Q}{S_p} \right) + \text{res}, \quad (4)$$

where $q = \zeta + f - (\partial/\partial p)[(f/S_p)T]$ is the approximation of (perturbation) Ertel potential vorticity (PV). If the geostrophic approximation is used with f being constant in the third term, q is exactly the quasigeostrophic PV. The residual term on the right-hand side of Eq. (4) includes damping due to friction and radiation cooling, and the ageostrophic effect $(\partial f \mathbf{V} / \partial p) \cdot \nabla(T/S_p) - v(\partial/\partial p)(T/S_p)(\partial f/\partial y)$ that vanishes if the geostrophic approximation is used with f being constant. In calculation, the residual term also includes errors that come from data resolution, assimilation increments, numerical errors, etc. Equation (4) can be overall balanced without considering the residuals when daily data are used.

jumping MJO

FIG. 5. As in Fig. 3, but for the jumping MJO.

Linearizing Eq. (4) gives

$$\frac{\partial q'}{\partial t} + \bar{\mathbf{V}} \cdot \nabla q' + \mathbf{V}' \cdot \nabla \bar{q} \approx -\frac{f}{C_p} \frac{\partial}{\partial p} \left(\frac{Q'}{S_p} \right) + \text{res}', \quad (5)$$

where the overbar denotes the background state and the prime the perturbation. After decomposing the wind vectors into the rotational part and the divergent part and neglecting the residual term, Eq. (5) becomes

$$\frac{\partial q'}{\partial t} + \bar{\mathbf{V}}_\psi \cdot \nabla q' + \mathbf{V}'_\psi \cdot \nabla \bar{q} \approx -\frac{f}{C_p} \frac{\partial}{\partial p} \left(\frac{Q'}{S_p} \right) - \mathbf{V}'_\chi \cdot \nabla \bar{q} - \bar{\mathbf{V}}_\chi \cdot \nabla q', \quad (6)$$

where $\mathbf{V}'_\psi$ and $\mathbf{V}'_\chi$ are the rotational part and the divergent part of the horizontal wind perturbation, and $\bar{\mathbf{V}}_\psi$ and $\bar{\mathbf{V}}_\chi$ are the

background rotational part and divergent part of the horizontal wind.

The right-hand side of Eq. (6) can be considered as Rossby wave sources (Sardeshmukh and Hoskins 1988; Hoerling 1992). The first term represents the generation of Rossby wave by vertical gradient of diabatic heating. The second term is the advection of background PV by perturbation divergent wind, and the third term is the advection of perturbation PV by background divergent wind. Since the third term is much smaller than other terms, it will not be further considered in this study.

According to Eq. (6), the diversity of the MJO teleconnection could be affected by two factors: the variation of the MJO diabatic heating and the variation of background flow. The MJO diabatic heating has two effects: a direct effect and an indirect effect. The direct effect is that the

standing MJO

FIG. 6. As in Fig. 3, but for the standing MJO.

vertical gradient of diabatic heating could directly induce PV anomalies, as manifested in the first term on the right-hand side of Eq. (6). The indirect effect is that the MJO's tropical convection anomalies could induce divergent wind anomalies that act like Rossby wave sources by advecting background PV, as manifested in the second term on the right-hand side of Eq. (6). As indicated by the second and third term on the left-hand side of Eq. (6), the variation of background flow could affect the propagation of the Rossby wave (Hoskins and Karoly 1981; Hoskins and Ambrizzi 1993) and the energy conversion between the background flow and the perturbations (Simmons et al. 1983; Swanson 2000, 2001; Kosaka et al. 2009). The variation of background flow could also affect the generation of Rossby wave source,

as manifested in the second term on the right-hand side of Eq. (6).

The use of the PV equation here instead of the vorticity equation is because the Rossby wave could induce divergence over the subtropical region, which could result in vorticity sources that may have larger amplitudes than those induced by the advection effect [similar to the second term on the right-hand side of Eq. (6)], therefore complicating the interpretation of how the MJO's convection excites the teleconnections. This complication rises from the fact that the vorticity equation [i.e. Eq. (2)] is not conserved under adiabatic motion. With the conservation property, the PV equation here unambiguously disentangles the direct and indirect effects of the tropical convection, making it powerful for studying the origins of the MJO teleconnection.

TABLE 1. Pattern correlation coefficients of the composited 200-hPa normalized daily geopotential height anomalies between the canonical MJO and the four MJO groups over different phases (pentads). The first, second, and third numbers separated by the slashes are pattern correlation coefficients over the global area, the Northern Hemisphere, and the Southern Hemisphere, respectively.

	Fast	Slow	Jumping	Standing
Phase 8 (pentad 1)	0.36/0.23/0.57	0.61/0.63/0.58	0.34/0.36/0.32	0.16/0.17/0.14
Phase 1 (pentad 2)	0.64/0.65/0.63	0.42/0.33/0.63	0.24/0.08/0.45	0.51/0.54/0.50
Phase 2 (pentad 3)	0.77/0.70/0.86	0.56/0.61/0.56	0.61/0.63/0.63	0.53/0.62/0.49
Phase 3 (pentad 4)	0.73/0.64/0.86	0.61/0.67/0.56	0.44/0.41/0.52	0.31/0.48/0.18
Phase 4 (pentad 5)	0.56/0.68/0.38	0.56/0.56/0.56	0.20/0.11/0.35	0.40/0.47/0.35
Phase 5 (pentad 6)	0.46/0.63/0.29	0.68/0.71/0.65	0.15/0.11/0.19	0.38/0.31/0.45
Phase 6 (pentad 7)	0.56/0.55/0.58	0.59/0.53/0.66	0.21/0.38/0.09	0.18/0.07/0.24
Phase 7 (pentad 8)	0.55/0.61/0.47	0.51/0.46/0.59	0.28/0.26/0.29	0.17/0.11/0.23

b. The effect of the MJO's diabatic heating

As shown by Figs. 1 and 3–6, each MJO group corresponds to distinct tropical heating patterns. To see whether the diverse heating patterns could directly lead to diverse Rossby wave trains, Fig. 7 (left column) shows the direct effect of diabatic heating [first term on the right-hand side of Eq. (6)] for the four MJO groups on pentad 4. The direct effect of diabatic heating (shadings) is negligibly small over the equatorial regions, although the convection anomalies of the MJO are largest there (contours of Fig. 7). This is because the planetary vorticity vanishes over the equator, making the direct effect of diabatic heating insignificant. Note that even if the absolute vorticity is used instead of planetary vorticity, the direct effect of diabatic heating over tropics is still negligible. On the other hand, it shows that the direct effect of diabatic heating is relatively large over the subtropics, which is due to the increased planetary vorticity there. These PV sources over the subtropics are results of convection induced by the Rossby waves that are forced by the MJO tropical heating. These secondary heat sources in the subtropics (as well as in midlatitudes) can modify the Rossby wave train patterns in response to the MJO, explaining a portion of the nonlinear part of the MJO-related circulation responses.

What about the indirect effect of the MJO's tropical diabatic heating? As shown by Fig. 1, there is coherence between the MJO's tropical convection anomalies and the upper-level velocity potential anomalies. Consequently, different MJO groups correspond to distinct anomalous velocity potential and divergent wind patterns, which is manifested in Fig. 7 (contours and vectors). The divergent wind patterns in the fast and slow MJO are similar. Both have southerly anomalies over the northern IO and northerly anomalies over East Asia, due to similar dipole heating patterns over the IO and WP. But differences exist due to discrepancies in the details of the heating patterns (e.g., differences in the zonal scale and meridional scale of the dipole heating). The divergent flows in the jumping and standing MJO are considerably different from those in the fast and slow MJO, as there are no significant northerly anomalies over the East Asia in these two MJO groups, due to lack of suppressed convection over the WP. Discrepancies are also found between the jumping and standing MJO; for example, the position of southerly anomalies over the northern

IO is shifted westward in the standing MJO, which is attributed to the westward shifted IO enhanced convection in the standing MJO.

To study the indirect effect of the MJO diabatic heating [i.e., the second term on the right-hand side of Eq. (6)] and to focus on the effect of the diverse divergent flow, the boreal winter average (i.e., NDJFMA average) of climatological monthly mean PV is used as background PV for calculation. The results are presented in Fig. 7 (right column). It shows that the indirect effect of MJO diabatic heating dominates the PV generation and is the main mechanism for the MJO's tropical convection to excite teleconnections, consistent with previous studies (Seo and Lee 2017; Tseng et al. 2019). As a consequence of diverse heating patterns and the associated divergent flow, each MJO group corresponds to distinct PV source patterns. The various PV sources could generate assorted PV anomalies, which propagate on the background flow, forming diverse Rossby wave trains. Therefore, the diverse MJO tropical convection patterns are sources for the teleconnection diversity.

As the MJO's tropical diabatic heating is the source for exciting the MJO teleconnection, it is interesting to ask to what extent the MJO teleconnections can be considered as linear circulation responses to the MJO's diabatic heating. To answer this question, numerical investigation is performed by using the LBM. Again, to focus on the effect of the MJO diabatic heating, the boreal winter averages of climatological monthly mean data are used as background states for the model. For all four types of MJO, the integration starts from day –12 and the integration length is 30 days (i.e., from pentad 2 to pentad 7), and the observed time-dependent intraseasonal heating rate anomalies are added into the model as external forcing. These experiments are defined as control experiments, as opposed to the sensitivity experiments shown in the next subsection.

Figure 8 shows the pattern correlations between the observed and the simulated 200-hPa streamfunctions. The global domain is used for the pattern correlation, as the main goal of this study is to explore the global teleconnection associated with MJO. The results in Fig. 8 to some extent depict how well the MJO teleconnections can be interpreted as linear responses to the MJO's diabatic heating, despite the fact that the LBM may use overly heavy damping for removing the nonlinear contribution. It shows that the teleconnections in the fast MJO can be well delineated as linear responses to the MJO

FIG. 7. The 200-hPa PV sources associated with the four MJO groups on pentad 4 (from day -2 to day 2). Shown are (left) the diabatic heating term of PV source at 200 hPa (shading; 10^{-11} s^{-2}) and the heating rate anomalies at 400 hPa (contour with interval of $6.67 \times 10^{-6} \text{ K s}^{-1}$), and (right) the advection term of PV source at 200 hPa (shading; $1 \times 10^{-11} \text{ s}^{-2}$), the 200-hPa velocity potential anomalies (contour with interval of $1 \times 10^6 \text{ m}^2 \text{ s}^{-1}$), and divergent wind anomalies (vector; m s^{-1}). The solid contours denote positive values, the dashed contours denote negative values, and the zero contours are omitted. A 9-point smoothing has been applied to the PV sources and heating rate anomalies.

heating anomalies. The averaged pattern correlation for the fast MJO is about 0.73 and the highest pattern correlation can take up to 0.84. The teleconnections in the slow MJO can also be fairly explained by the linear dynamics, in which the highest pattern correlation can take up to 0.64 and the averaged pattern correlation is about 0.55. On the contrary, the teleconnections in the jumping and standing MJO are less well explained by the linear dynamics. The averaged pattern correlation is about 0.37 for the jumping MJO and 0.42 for the standing MJO. However, there are some particular phases in the jumping and standing MJO that the teleconnections can be somewhat explained by the linear dynamics. For example, the pattern correlation can take up to 0.60 on pentad 4 in the jumping MJO and pattern correlations are over 0.5 on pentads 3–4 in the standing MJO. As a result, the MJO teleconnections can be overall considered as

linear responses to the MJO's diabatic heating in the fast and slow MJO, while they can be delineated by linear dynamics in the jumping and standing MJO to some extent only for some particular phases.

To test the sensitivity of the pattern correlation to the domain, Table 2 shows the corresponding pattern correlation coefficients for the Northern Hemisphere and the Southern Hemisphere. It shows that although the pattern correlation is to some extent sensitive to the domain, the conclusion that the fast MJO is best simulated still holds. It is also indicated by Table 2 that the circulations in Southern Hemisphere are generally better explained by the linear dynamics than those in Northern Hemisphere.

To illustrate the horizontal structures of the simulated circulation responses, Fig. 9 shows the model simulated 200-hPa

FIG. 8. Pattern correlations over the global domain between the observed 200-hPa streamfunction anomalies and the simulated 200-hPa streamfunctions in the control experiment for (a) fast, (b) slow, (c) jumping, and (d) standing MJO. P2 represents pentad 2 (from day -12 to day -8), and so on. The zonal mean has been removed for calculating the pattern correlation.

streamfunctions on pentad 4 for the four MJO groups, as well as the corresponding observed 200-hPa streamfunctions. It shows that the circulation patterns can overall match to the observations, especially for the fast MJO and over the tropical and subtropical regions for other MJO groups. For all the MJO groups, the discrepancies between the observed and the simulated flows are relatively larger in midlatitude and polar regions than the tropical regions where the MJO convection is presented. For example, the LBM cannot simulate the wave pattern around the Antarctic region in the standing MJO, but it can well simulate the tropical and subtropical flows. The discrepancy between the observed and the simulated flows suggests that not all the observed circulation anomalies are linear

responses to the MJO's tropical convection, and the nonlinear processes may have significant roles over the regions with large simulation errors. Further examining of Fig. 9 reveals that the PNA-like pattern emerges on pentad 4 (Fig. 9a) in the fast MJO simulation. The PNA-like pattern starts to emerge on pentad 5 in the slow MJO simulation (not shown). In the standing and jumping MJO simulations, there are no apparent PNA-like patterns.

c. The effect of the background flow

If the MJO events are evenly distributed throughout the boreal winter, the mean background states for the MJO can be approximated by the boreal winter averages of the climatological

TABLE 2. Pattern correlation coefficients between the observed 200-hPa streamfunction anomalies and the simulated 200-hPa streamfunction anomalies in the control experiments for different MJO groups. The first and second numbers separated by the slash are pattern correlation coefficients over the Northern Hemisphere and the Southern Hemisphere, respectively. The zonal mean has been removed for calculating the pattern correlation.

	Fast	Slow	Jumping	Standing
Pentad 2	0.51/0.78	0.38/0.65	0.22/0.32	0.51/0.46
Pentad 3	0.68/0.81	0.33/0.59	0.48/0.55	0.41/0.60
Pentad 4	0.81/0.87	0.50/0.65	0.52/0.72	0.40/0.64
Pentad 5	0.71/0.83	0.52/0.67	0.42/0.58	0.39/0.58
Pentad 6	0.59/0.72	0.59/0.71	0.13/0.33	0.41/0.28
Pentad 7	0.53/0.74	0.52/0.61	0.13/0.22	0.22/0.20

monthly mean. However, this is not the case. Figure 10 shows the frequency distribution of the four MJO groups during the boreal winter. The frequency distribution for a particular month is calculated as number of days when the MJO events occur in that month. For an MJO event, only the period from day -10 to day 15 of that event is counted. It is shown in Fig. 10 that each MJO group has some sort of seasonal dependence. The fast MJO occurs more frequently in March–April, whereas the slow MJO occurs more frequently in November–February. The standing MJO occurs more frequently in transitional season (i.e., November and April), while the jumping MJO has double peaks in January and March.

Various seasonal dependences for different MJO groups imply diversity in the background states. The mean background states for the four MJO groups are then calculated as weighted boreal winter averages of climatological monthly mean, with weights being the frequencies shown in Fig. 10. Figure 11 shows the boreal winter average of climatological monthly mean zonal wind and the deviations from this average when the weighted mean is used as background state. The variations of background zonal wind are mainly manifested in the region of the jet streams in all MJO groups. The deviations in the Asian jet region are relatively larger in the standing and slow MJO than the fast and jumping MJO, but the amplitudes of the deviation are small compared to the magnitudes of the climatological mean.

According to Eq. (6), the variation of background state could affect the propagation of Rossby waves and the growth of the waves. The question is whether these small variations of background flow could result in significant changes of teleconnections. To answer this question, sensitivity experiments are performed using the LBM. The settings of the sensitivity experiments are the same as the control experiments described in last subsection, except that the background states are the weighted averages of the climatological monthly mean.

Figure 12 shows the root-mean-square differences (RMSDs) of the 200-hPa streamfunctions between the control and sensitivity experiments for the last 20 days of integration, which measure the effect of the variations of the background states. Also shown is the root-mean-square (RMS) of the 200-hPa streamfunctions in the control experiment, which measures the

FIG. 9. Horizontal patterns of observed 200-hPa streamfunction anomalies (shading; $1 \times 10^6 \text{ m}^2 \text{ s}^{-1}$) and the simulated 200-hPa streamfunctions (contour with interval of $1 \times 10^6 \text{ m}^2 \text{ s}^{-1}$) in the control experiment on pentad 4 (from day -2 to day 2) for the four MJO groups. The zonal mean has been removed for both the observation and simulation. The pattern correlations over the global domain between the observation and simulation are shown in the top-right corner of each panel.

Frequency Distribution

FIG. 10. Frequency distribution of the MJO events during the boreal winter for (a) fast MJO, (b) slow MJO, (c) jumping MJO, and (d) standing MJO. See text for how to calculate the frequency distribution.

signal strength of the simulated circulation responses. It shows that the RMSDs are larger in the slow and fast MJO than the jumping and standing MJO. Compared to the RMS, the RMSDs are overall negligible in the standing and jumping MJO, while the RMSDs are significant over the northern Pacific region in the slow and fast MJO. Therefore, the variations of the Asian jet stream can significantly affect the teleconnections in the slow and fast MJO over the northern Pacific region in the simulation.

Given that the variation of Asian jet stream is largest in the standing MJO, it is interesting to ask why the variations of Asian jet have more profound impacts on the slow and fast MJO. Note that the most significant impact region of the background flow is the jet exit region over the northern Pacific. This is because the zonal gradient of the background zonal

wind over that region can destabilize the eddies through barotropic energy conversion (Simmons et al. 1983; Swanson 2000, 2002), favoring the growth of a PNA-like internal mode. When the strength of the Asian jet varies, the zonal gradient of the background zonal wind over the Pacific jet exit region changes, leading to changes in the barotropic energy conversion process. Compared to the standing and jumping MJO, the simulated circulation responses in the slow and fast MJO are stronger over the jet exit region (i.e., subtropical central North Pacific) where large zonal gradients of the background zonal wind occur, as manifested by the RMS in Fig. 12. Thus, the simulated teleconnection in the slow and fast MJO could extract energy from the background flow more effectively over the Pacific jet exit region,

FIG. 11. The boreal winter average of the climatological monthly mean zonal wind (contour; m s^{-1}) and the deviations from this average (shading; m s^{-1}) when the weighted mean is used as background state (see text for details) for the four MJO groups. The contour interval is 10 m s^{-1} , and the thick solid contours denote zero contours.

given certain amplitudes of background flow. Consequently, the simulated teleconnections over the northern Pacific region in the slow and fast MJO are more sensitive to the variation of background flow.

Note that the LBM has low skill in simulating the teleconnections in the jumping and standing MJO, as indicated by Fig. 8. In fact, the observed upper-level streamfunction anomalies are large over the Pacific jet exit region in all four MJO groups

FIG. 12. The RMSDs of the 200-hPa streamfunctions between the control and sensitivity experiments (contour with interval of $0.3 \times 10^6 \text{ m}^2 \text{ s}^{-1}$) during the last 20 days of integration (i.e., pentads 4–7) for the four MJO groups. Also shown are the RMS of the 200-hPa streamfunctions in the control experiment (shading; $1 \times 10^6 \text{ m}^2 \text{ s}^{-1}$).

(not shown). Therefore, it implies that the variation of Asian jet could also significantly affect the teleconnections of the jumping and standing MJO over the Pacific jet exit region, even though this effect is not seen in the LBM.

It should be noted that including this background state effect almost does not change the pattern correlations between the simulated and the observed flow in the global domain, because this effect is only significant over a small region and some of circulation changes are manifested in the changes of circulation amplitudes rather than the circulation patterns. Thus, for the global domain, the effect of background flow variation plays an insignificant role in causing the MJO teleconnection diversity.

Another effect of the background state is that it can potentially affect the Rossby wave sources, as indicated by second term on the right-hand side of Eq. (6). It can be demonstrated that this effect is negligible.

5. Conclusions and discussion

a. Conclusions

The diversity of the global teleconnections associated with the MJO is investigated through classifying the MJO into four archetypes: standing MJO, jumping MJO, slow eastward propagating MJO, and fast eastward propagating MJO. The results indicate that each type of MJO corresponds to distinct global teleconnections, manifested as various upper-tropospheric Rossby wave train patterns. The teleconnections of the four MJO groups are further compared to those of the canonical MJO defined by the RMM indices. Overall, the teleconnections of the fast and slow MJO are similar to those of the canonical MJO, while the teleconnections of the standing and jumping MJO are generally distinct from those of the canonical MJO. This suggests that conventional view of MJO teleconnections by focusing on the canonical MJO has limitations, as the canonical MJO cannot describe the diverse propagation patterns of the tropical convection and the associated global teleconnections.

The causes of the MJO teleconnection diversity are investigated in terms of the linear dynamics. The linearized PV equation indicates that the diversity could come from two sources: the diversity of MJO tropical heating patterns and the variation of background flow. It is found that the diversity of the MJO tropical heating pattern is the main cause of the teleconnection diversity. The diverse MJO tropical heating anomalies induce various upper-level divergent flows, generating assorted Rossby wave sources through advecting the background PV. The numerical investigation with the LBM further shows that the teleconnections in the fast and slow MJO can be largely interpreted as linear responses to the MJO's diabatic heating, and the pattern correlation between the observed and the simulated flows can take up to about 0.84 for the fast MJO. The teleconnections in the jumping and standing MJO are overall poorly interpreted by the linear dynamics, but the linear dynamics could still explain the circulation features for some certain phases. On the other hand, the numerical investigation with the LBM indicates that the variation of the Asian jet stream can affect the MJO teleconnections at the Pacific jet exit region, but this effect plays an insignificant role in causing the diversity of MJO global teleconnection.

b. Discussion

The teleconnections considered in this study are represented by upper-tropospheric circulation anomalies. It can be shown that in tropics the circulation anomalies at the lower troposphere are out of phase with those at the upper troposphere, signifying first baroclinic structures in the tropics, whereas in the extratropics the circulation anomalies exhibit equivalent barotropic structures in the troposphere, which are evidences of horizontal propagation of external Rossby waves. Besides horizontal propagation of Rossby wave trains, there are also signals of vertical wave propagation into the lower stratosphere over the high latitudes in both hemispheres (not shown), implying connections between the MJO's tropical convection activity and the polar regions. Therefore, it will be interesting to ask whether different MJO groups have distinct interactions with the polar regions.

As the MJO can affect the global weather and climate systems through teleconnections, the assorted teleconnection patterns associated with different MJO groups imply that there exist diversities in the MJO-related tropical–extratropical interactions and different MJO groups could have distinct impacts on the global weather and climate. For example, different MJO groups could have distinct impacts on the global precipitation anomalies and surface temperature anomalies. Moreover, as the MJO teleconnection could interact with other extratropical climate variabilities (e.g., the PNA and the NAO), the results here imply that different MJO groups could have different interactions with these climate variabilities. Therefore, further studies are needed to explore the diverse relations between different MJO groups and the global weather and climate systems.

The results of this study also suggest that the teleconnections in the fast and slow MJO may have higher predictability than those in the jumping and standing MJO, as the teleconnections in the fast and slow MJO can be largely considered as linear circulation responses to the MJO's tropical convection anomalies. Therefore, it is interesting to ask how the climate model forecasts the teleconnections of the four MJO groups, whether the predictabilities and the prediction skills of different MJO groups and their associated teleconnections are significantly different, and how these differences affect the prediction of the global weather and climate systems.

Acknowledgments. This work is jointly supported by the National Key R&D Program of China (Grant 2018YFC1505905), the National Natural Science Foundation of China (Grant 2081011900501), the Nature Science Foundation of the Jiangsu Higher Education Institutions of China (Grant 1421011901005), and the Startup Foundation for Introducing Talent of NUIST (Grant 1441012001018). This is ESMC Publication No. 338.

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