The Roles of Westward-Propagating Waves and the QBO in Limiting MJO Propagation

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Abstract: A recent study categorized the Madden-Julian Oscillation (MJO) during boreal winter season into four types including stand, jump, slow and fast MJO. This study focuses on the stand and jump MJO. Based on whether their convection penetrates the Maritime Continent (MC), stand and jump MJO are seen as non-penetrating (NP) MJO, while the rest two are seen as eastward-penetrating (EP) MJO. Results reveal the relative roles of the westward-propagating wave (WPW), as well as the QBO and ENSO, in limiting MJO propagation. Lack of the pre-moistening over the southern sea surface of the MC stops NP MJO from penetrating the MC. The active convection of the WPWs hinders the descending branch of the NP MJO circulation and therefore leads to the insufficient meridional advective moistening over the southern sea surface of the MC. The independent convection over the Pacific for jump MJO is influenced by a combined effect of the QBO and ENSO. The tropopause instability induced by MJO is found to significantly decouple from its convection over the Pacific in the QBOW winters than in the QBOE winters. For jump MJO, the independent convection over the central Pacific comes from local WPWs whose amplification and further development into deep convection are correlated to jump MJO’s decoupled tropopause instability. For stand MJO, however, the seasonal-mean La Nina-like cool SST anomalies weaken the WPW activity over the central Pacific and confine WPWs within the western Pacific. Therefore, the decoupled tropopause instability of stand MJO is out phase of WPWs and fails to induce an independent convection over the central Pacific.
1. Introduction

The Madden-Julian Oscillation, named after its discoverers (Madden and Julian 1971, 1972), refers to a large-scale organized convective envelope coupled with a baroclinic circulation. Statistically, MJO is characterized by an intraseasonal timescale (20-100 days), and a planetary scale with zonal wavenumber of 1-3 (Kiladis et al. 2009). MJO is typically initiated over the Indian Ocean, propagating eastward with a relatively slow phase speed (5 m/s). After crossing the dateline, MJO convection dies while its higher-troposphere circulation keeps propagating eastward around the global tropical belt at a faster speed (Lau and Waliser 2011; Zhang 2005). As the dominant tropical intraseasonal signal in the atmosphere, the MJO provides predictability for the Subseasonal to Seasonal (S2S) timescale (Zhang 2013). It also affects the weather and climate systems around the globe, such as the outbreak and withdraw of Asian monsoon system (Lau and Waliser 2011), the initiation of El Niño events (Zhang 2013), the genesis of tropical cyclones (Kim and Seo 2016), and the evolution of extratropical circulations through teleconnections (Adames and Wallace 2014; Weickmann 1983).

There is a growing body of theoretical work to understand the core dynamics of MJO propagation. Among this, four main schools of MJO theory are summarized in Zhang et al. (2020), including the skeleton and multiscale theory (Majda and Biello 2004; Majda and Stechmann 2009; Thual and Majda 2016; Thual et al. 2014), the moisture mode theory (Adames and Kim 2016; Sobel and Maloney 2012, 2013), the convective-dynamic-moisture trio-interaction theory (Wang et al. 2016), and the gravity wave theory (Yang 2020; Yang and Ingersoll 2011, 2013, 2014). The gravity wave theory views MJO as a dry wave where its eastward propagation is a result of the gravity wave’s faster eastward phase speed compared with its westward phase speed (Yang and Seidel 2020), while the other three theories all emphasize the essential role of moisture in the MJO dynamics. In the other three theories, the so-called pre-moistening in the lower troposphere leading the MJO deep convection system is fundamental for its eastward propagation (Majda and Stechmann 2009; Adames and Kim 2016; Wang et al. 2016). However, they consider different physics responsible for this leading pre-moistening. The skeleton and multiscale theory argues that the pre-moistening is a result of the leading small-scale convection organized by equatorial wave activities. By contrast, in the moisture mode theory, both the horizontal and vertical moisture advections above the planetary boundary layer (PBL) induced by the MJO anomalous winds provides the dominant contribution.
to the leading pre-moistening. In the convective-dynamic-moisture trio-interaction theory, the frictional moisture convergence within the PBL caused by the Kelvin wave component ahead of the MJO deep convection is essential for the pre-moistening in the lower troposphere.

Recent studies demonstrate the impacts of the Maritime Continent (MC) on MJO propagation. MJO convection always decays and sometimes is even terminated while crossing the MC, referred to as the MC barrier effect (Feng et al. 2015; Zhang 2005; Zhang and Ling 2017). Some studies argue that the unique topography of the MC such as the high mountains blocks the moisture advection and causes the MC barrier effect (Hsu and Lee 2005; Wu and Hsu 2009; Inness and Slingo 2006). The strong diurnal cycle of precipitation over the MC is found to compete with MJO for moisture and it is considered part of the reason for the MC barrier effect (Neale and Slingo 2003; Oh et al. 2012, 2013; Wang and Li 1994; Zhang and Hendon 1997). Recently, DeMott et al. (2018) demonstrate that some westward-propagating dry precursors may interact with the MJO over the MC and cause the demise of the MJO convection. Gonzalez and Jiang (2019) also found a competition over the Pacific Ocean between the eastward propagation of the MJO and the westward propagation of a West Pacific Intraseasonal Mode (WPIM). Moreover, scale analysis using a simple model by Adames et al. (2019) suggests that the westward-propagating large-scale intraseasonal wave component in the tropics is probably a moisture mode like the MJO. Although it is not clear whether the westward-propagating dry precursors in DeMott et al. (2018) and the WPIM in Gonzalez and Jiang (2019) refer to the same phenomenon, both DeMott et al. (2018) and Gonzalez and Jiang (2019) argued that the amplitude of these westward-propagating waves (WPWs) are related to the seasonal mean background changes due to the El Niño Southern Oscillation (ENSO). However, changes in the seasonal mean background also leave a direct impact on MJO propagation as described in the next paragraph. Therefore, it is unknown which influence is more important for MJO propagation, the direct impacts from the seasonal mean background, or the interaction with these WPWs.

MJO propagation also exhibits year-to-year variations due to the influences of interannual variability like ENSO and the Quasi Biennial Oscillation (QBO). The interannual variation of MJO was initially attributed to ENSO influences (Hendon et al. 1999, 2007; Marshall et al. 2016). The MJO is found to propagate farther eastward across the dateline during El Niño winters than during neutral or La Nina winters. The probability of a MJO crossing the MC, however, does not change...
significantly in different ENSO phases (Hendon et al. 1999; Son et al. 2017). More recent studies found that less than 10% of the variance in MJO interannual activity can be attributed to ENSO (Hendon and Abhik 2018; Son et al. 2017). In contrast, 40-50% of the interannual variability of boreal winter MJO activity can be attributed to the QBO (Marshall et al. 2017; Son et al. 2017). During the QBO Westerly (QBOW) phase, MJO activity is decreased while during the QBO Easterly (QBOE) phase, it is enhanced (Densmore et al. 2019; Marshall et al. 2017; Nishimoto and Yoden 2017; Son et al. 2017; Yoo and Son 2016). Moreover, MJO shows a more continuous eastward propagation across the MC during QBOE while it is more confined west of the MC during QBOW (Nishimoto and Yoden 2017; Son et al. 2017; Wang et al. 2019; Zhang and Zhang 2018). However, the argument that MJO events are stronger during QBOE than QBOW remains controversial. Zhang and Zhang (2018) demonstrate that the stronger MJO during QBOE is due to more MJO days as a result of more frequently initiated events with longer duration, rather than due to stronger individual MJO events. The physical mechanisms for the QBO-MJO connection are not completely understood. It is generally thought to be through the QBO-related changes in the upper tropospheric static stability and the vertical zonal wind shear across the tropopause (Nishimoto and Yoden 2017; Son et al. 2017; Yoo and Son 2016). Hendon and Abhik (2018) suggested that the positive temperature anomalies in the upper troposphere and cold anomalies near the tropopause at 100hPa are stronger and more in-phase with the MJO convection during QBOE, leading to reduced tropopause instability which enhances the MJO convection and extends MJO propagation farther eastward across MC. The strong wind shear of the QBO could also disrupt the coherent structure of deep convective plumes, thus influencing MJO activity (Collimore et al. 2003; Gray et al. 1992; Nie and Sobel 2015). Also, like ENSO, the QBO could lead to seasonal mean state changes (Zhang and Zhang 2018; Collimore et al. 2003; Liess and Geller 2012). Sun et al. (2019) found a combined effect of ENSO and QBO on MJO propagation due to changes in the zonal gradients of the seasonal mean background. The possible combined effects of QBO and ENSO on MJO propagation needs further investigation. It is noteworthy that both the interannual variability and the intraseasonal WPWs could have impacts on MJO propagation over the MC, but it is unknown which impacts are more important.

The categorization of the MJOs into propagating and nonpropagating types was first proposed by Kim et al. (2014) where the nonpropagating MJO refers to the ones failing to propagate from the
Indian Ocean across the MC and into the western Pacific. Kim et al. (2014) suggest that the strongly suppressed convection to the east of MJO active convection is the key for the MJO’s eastward propagation. The negative heating anomaly associated with the strongly suppressed phase of outgoing longwave radiation (OLR) would induce a local low-level anticyclonic Rossby gyre, which advects the moisture to the east of MJO convection. This moisture advection promotes the eastward propagation of the MJO. However, Wang et al. (2017) argue that such positive moisture tendency to the east of MJO convection comes from the vertical advection of the mean moisture induced by an anomalous intraseasonal ascending motion instead of the horizontal moisture advection. Such vertical moisture advection is disrupted by a dry Rossby-wave-like signal for nonpropagating MJO. Recently, Wang et al. (2019) further categorizes boreal-winter MJO cases into four types according to their propagation. By applying a k-means cluster analysis on their OLR Hovmöller diagrams,
four types of MJO propagation are found, including stand, jump, slow, and fast MJO (Fig.1). The slow and fast MJO cases propagate eastward continuously from the Indian Ocean into the Pacific with different phase speeds. They are similar to the propagating MJO in Kim et al. (2014) and Wang et al. (2017). The stand and jump MJO are more like nonpropagating MJO with standing convection over the Indian Ocean. Jump cases have an independent convection that initiates and develops over the Pacific while the convection over the Indian Ocean decays. Therefore, the jump MJO propagates in a jumping-like behavior. Wang and Li (2021) investigated the diversity in MJO intensity and phase speed and found that the Sea Surface Temperature anomaly (SSTA) may influence the MJO diversity through tuning the background seasonal-mean moisture as well as the leading boundary layer moistening processes for MJO. Xiang et al. (2021) also investigated MJO diversity in a subseasonal-to-seasonal prediction system and found different QBO phase background as well as different predictability for four MJO types. Chen (2020) demonstrate the four types of MJO found in Wang et al. (2019) can excite significantly different extratropical teleconnections, and thus result in diverse global responses. Different extratropical teleconnections induced by slow and fast MJO are also noted in Yadav and Straus (2017).

Based on the four types of MJO propagation identified in Wang et al. (2019), this paper will attempt to understand the physical processes involved in limiting the propagation of the MJO from the perspective of the moisture mode theory by investigating the relative role of the intraseasonal WPWs in MJO propagation. Also, the potential QBO and ENSO phase preference among these four MJO types as well as their influences will be investigated. This work will also address the debate whether the horizontal or vertical moisture advection is more important for the propagation of the MJO through the MC.

2. Data

Three datasets are used in this work. The daily averaged OLR data with a resolution of $2.5^\circ \times 2.5^\circ$ from National Centers for Environmental Prediction /National Oceanic and Atmospheric Administration-interpolated OLR dataset (Liebmann and Smith 1996) is used to identify and categorize MJO cases. The daily wind components, temperature, geopotential, and specific humidity on 37 vertical levels (10-1000hPa) from the Era-Interim reanalysis dataset (Dee et al. 2011) provide the insight on MJO horizontal and vertical structure. Also, the monthly Sea Sur-
face Temperature (SST) data from the Extended Reconstructed Sea Surface Temperature version 5 (ERSSTv5) dataset (Huang et al. 2017) is used to diagnose the seasonal SST background. The temporal range of the three datasets are the same, covering 1979 to 2013. The original resolution of the Era-Interim dataset is 0.75° × 0.75°. The original resolution of the ERSSTv5 dataset is 1.0° × 1.0°. They are both interpolated onto the same spatial grids as OLR before the analysis.

3. Methodology

a. MJO identification and categorization

Methods for MJO identification and categorization in this work follow that in Wang et al. (2019). They are briefly illustrated here. Details can be found in Wang et al. (2019).

To identify MJO events, the daily OLR anomalies are obtained by subtracting the daily climatology and its first three harmonics. Then, a 20-70-day band-pass Lanczos filtering is applied on OLR anomalies to extract its intraseasonal variations. A MJO event is identified when the box-mean band-pass-filtered OLR time series over the Indian Ocean (10°S – 10°N, 75°E – 95°E) is below its -1 standard deviation for at least 5 successive days. The reference day, or day 0, for each MJO event is defined as the date when the time series reaches its local minimum. 104 MJO events are identified within the boreal winter seasons (November to April) of 1979-2013.

A k-means cluster analysis (Kaufman and Rousseeuw 2009) is applied to 104 Hovmöller diagrams of the intraseasonal OLR anomalies (10°S – 10°N) to categorize them into four types. Four clusters are chosen because these MJO events can be optimally fitted into four clusters (Wang et al. 2019). The cluster analysis domain in the Hovmöller diagram covers 30 days from day -10 to day 20 and a zonal range of 60°E to 180°E after applying a zonal three-point running mean and setting OLR > −5W/m² to zero on diagrams. To determine how well each MJO event fits into its assigned cluster, a silhouette test (Kaufman and Rousseeuw 2009) is applied to each cluster member of the k-means cluster analysis. The silhouette score for each member ranges from -1 to 1. With a higher silhouette score, the member is more similar to the centroid of its assigned cluster than the other cluster centroids (Kaufman and Rousseeuw 2009). MJO events with silhouette score lower than 0.06 are identified as "outliers" not clearly belonging to any of the four clusters and excluded from the corresponding clusters after the k-means cluster analysis. 90 MJO events remain in the four clusters after removing 14 "outliers" as shown in Fig.1.
To address the robustness of the k-means cluster analysis, a series of sensitivity experiments are conducted by changing the defined cluster number for k-means cluster analysis and the threshold for the silhouette test after the analysis, respectively (shown in Appendix). Results show that the cluster number of 4 is the best fit for this method, and the threshold for silhouette test set as 0.06 is reasonable.

The four types of MJO propagation, namely stand, jump, fast, and slow, are also seen in visual inspection of individual MJO events (not shown).

b. QBO and ENSO indices

The monthly global mean of the equatorial \((5^\circ S - 5^\circ N)\) zonal wind at 50hPa from Era-Interim reanalysis is used as the QBO index to diagnose the QBO phase. Following Son et al. (2017), the easterly and westerly phase of the QBO are defined when the monthly global mean of the zonal wind is below and above one half of its standard deviation, respectively.

The widely used Nino3.4 index is used to diagnose the ENSO phase, which is computed by averaging the monthly sea surface temperature (SST) anomalies from ERSSTv5 within the central-eastern Pacific \((5^\circ S - 5^\circ N, 170^\circ W - 60^\circ W)\).

c. Composite analysis

Composite analysis is used to diagnose the MJO vertical structure and the seasonal mean background state of the four types of MJO with the reference day defined in Sec.2a. The composite analysis of MJO-related structures is performed using 20-70-day band-pass-filtered variables. Composite analysis of the seasonal mean background states uses monthly, three-month running mean and seasonal mean (April to November) variables. A Student-t test is conducted to validate these composite results are significantly different from zero.

4. Results

a. Horizontal evolution

By definition, the four types of MJO exhibit distinctly different propagating features during their lifespans as illustrated in Fig.1. More detailed evolution of their convection and the coupled lower-tropospheric horizontal circulations are given in Fig.2. For EP (slow and fast) MJO events, their
convection and circulation highly resemble that of the canonical MJO with a continuous eastward propagation (Zhang 2005, 2013; Yadav and Straus 2017). At day -10, weak convection can already be seen over the central-western Indian Ocean with leading lower-troposphere easterlies. The organized convection gets amplified from day -10 to day 0. At day 0, the strong MJO convective envelope over the Indian Ocean is accompanied by suppressed convection over the MC. The leading equatorial easterlies and lagging westerlies are well organized. The off-equatorial cyclones in both hemispheres are also evident in the coupled circulation pattern, indicating the well-developed Rossby wave gyres of the MJO. With the help of leading easterlies as well as the off-equatorial meridional winds, EP MJO events penetrate the MC with a southward detouring over the sea surface between the MC and Australia, consistent with previous studies on MJO propagation (e.g., Kim et al. 2017). During their propagation through the MC, the convection over the Indian Ocean turns from an active to a suppressed phase at day 10.

For NP MJO events, the convection and circulation evolution are different than that of EP MJO events. At day -5 to day 5, when the MJO convection is over the Eastern Indian Ocean, the suppressed convection over the MC is very weak or even missing (Fig.2). The leading easterlies of NP MJO are disrupted. For stand MJO events, such disruption can be seen over the middle-eastern MC in the southern hemisphere at day 0, and it is coupled with a smaller-scale convective dipole mode over the same region. Also, the lower-troposphere leading easterlies vanish from day 5, while the extremely strong equatorial westerlies related to the off-equatorial Rossby gyres in the west of stand MJO convection are evident. Such a circulation pattern indicates a strong Rossby wave component and weak Kelvin wave component for stand MJO events. For jump MJO, the circulation is much less organized. Both the equatorial Kelvin wave component and off-equatorial Rossby wave component are not evident. The leading easterlies almost vanish over the MC and western Pacific. It is unique for jump MJO that an independent convection develops over the central western Pacific from day 0 when its stalled convection over the Indian Ocean decays. The independent convection over the Pacific Ocean also shows a westward propagation, similar to the convective dipole mode for stand MJO events. From day 5, the independent convection reaches the MC with lower-troposphere westerlies over the western Pacific. The convection over the Indian Ocean decays from day 0 and turns to a suppressed phase at day 10. The independent convection
over the western Pacific also starts to decay from day 10 and turns to the suppressed phase at day 20.

Although the convective envelope of NP MJO events highly resembles that of EP MJO events at day 0, their disrupted leading easterlies at the lower troposphere over the MC indicate a different coupled circulation than that for EP MJO events. Also, the convective dipole mode over the western Pacific for stand MJO events and the independent convection over the central Pacific for jump MJO events both show a westward propagation, suggesting a potential role of WPWs in limiting the NP MJO propagation over the MC.
b. Westward-propagating waves for NP MJO

As suggested in DeMott et al. (2018) and Feng et al. (2015), the WPWs over the western Pacific are more clearly evident in the longitude-height cross section of intraseasonal moisture anomalies. To confirm the potential WPWs during the NP MJO lifespan, the vertical structure of MJO convection and circulation is diagnosed.

The composited height-longitude section of equatorial specific humidity and wind circulation of the four MJO types are shown in Fig.3. For EP MJO, its westward-tilted convection is coupled by a well-constructed baroclinic circulation with a lower-troposphere convergence and a higher-troposphere divergence. The descending motion ahead of EP MJO convection and the dry anomalies in the middle troposphere are strong and broad in the zonal range. The convection-circulation-coupled structure of the EP MJO events propagate eastward with a slow phase speed. NP MJO events, however, show a smaller zonal scale in their convection and circulation. Their dry anomalies and descending motions are relatively weak. For stand MJO events, the convection and circulation becomes almost vertically stacked from day 0, consistent with previous studies indicating that the westward-tilted convection is important to the eastward propagation of the MJO (Majda and Stechmann 2009; Adames and Kim 2016; Wang et al. 2016). The leading lower-troposphere easterlies for NP MJO events are also disrupted from day 5.

The WPWs during NP MJO lifespans are confirmed in Fig.3 with their potential existence indicated by thick arrow lines. Dry anomalies are evident over the western and central Pacific for stand and jump MJO events, respectively. These dry anomalies are considered different than those for EP MJO which occupies almost the whole central-western Pacific and are the result of the descending branch of EP MJO circulation. The dry anomalies for NP MJO over the Pacific, however, are not induced by the descents of NP MJO circulation. At day -10, the descending branch of the NP MJO circulation is still over the Indian Ocean centered around 90°E and these descents already induce some dry anomalies there. The dry anomalies marked by the red arrows over the Pacific at day -10 are separated from those induced by the NP MJO descending branch. At day -5, the dry anomalies over the Pacific for NP MJO propagate westward and intercept NP MJO convection over the MC. At day 0, the westward-propagating suppressed convection is replaced by organized shallow convection, indicated by wet anomalies in the lower troposphere over the Pacific for NP MJO. The shallow convection also propagates westward from the Pacific to the MC. For
jump MJO, the new shallow convection over the central Pacific gets amplified from day 0. It is noteworthy that the descending motions to the east of NP MJO convection are still evident at day -5, but they are replaced by shallow ascents at day 0.

The WPWs for NP MJO can be more clearly seen in Fig.4, where they are represented by equatorial specific humidity anomalies propagating westward from the central-western Pacific to the MC. They are independent from the NP MJO since some westward-propagating dry anomalies
are evident as early as from day -10 over the Pacific, separated from the suppressed-convection MJO phase over the Indian Ocean. The WPWs for stand MJO are weaker than that for jump MJO. Also, the WPWs are mainly over the western Pacific for stand MJO while those for jump MJO occupy the whole central-western Pacific during their propagation.

The lower-tropospheric wind and the column-integrated specific humidity related to the WPWs for NP MJO are shown by Fig. 5. These WPW horizontal structures are obtained by applying the westward-filtering on the intraseasonal anomalies. Noted that such filtering may also include the signals from any standing mode. The WPWs for NP MJO have a dipole mode with wet anomalies over the equatorial Pacific and dry anomalies to the west in the southern (northern) hemisphere for stand (jump) MJO at day -5. The westward propagation of the dipole mode is led by lower-tropospheric westerlies to the west of wet anomalies, which is the equatorial part of the coupled cyclonic gyres in both hemispheres symmetric about the equator. These westerlies induced by WPWs over the eastern MC disrupt the leading easterlies there for stand and jump MJO (Fig. 2). As the WPWs reach the MC, they propagate to higher latitude as shown by the wet anomalies in
the southern hemisphere at day 5 for stand MJO and the dry anomalies over the northeastern MC at day 0 to day 5 for jump MJO, respectively.

c. **Moisture budget analysis of MJO propagation**

The lower-troposphere pre-moistening to the east of the MJO convection is considered as the key for the MJO propagation through the MC (Majda and Stechmann 2009; Adames and Kim 2016; Wang et al. 2016). It is still controversial whether the horizontal moisture advection or the vertical advection is responsible for such leading moistening. As suggested in Kim et al. (2014), the strong descending motion of the MJO to the east of the MC excites dry Rossby waves over the MC. The lower-troposphere off-equatorial meridional wind anomalies of the Rossby wave, in turn, generate positive moisture tendencies by advecting the moisture from the equatorial region to the southern sea surface of the MC. However, Feng et al. (2015) emphasize that the vertical motion induced by
Fig. 6. Composited MJO OLR (lines) and column-integrated (100-1000hPa, shadings) moisture tendency over the Eastern Indian Ocean and MC region at day 0 for (a) NP MJO and (b) EP MJO. OLR intervals are 10W/m² from -40W/m² to 40W/m² with positive OLR represented by dashed yellow lines while negative OLR represented by solid green lines. Only the composited OLR exceeding 95% confidence level are drawn, and the composited moisture tendency exceeding 95% confidence level are stippled.

the shallow convection over the MC generates vertical moisture advection and leads to the positive moisture tendencies there.

The WPWs have potential impacts on both the horizontal and vertical moisture advection over the MC. The descending motion induced by the suppressed convection of the WPWs could directly weaken the shallow convection over the MC, and the local vertical moisture advection will be weakened as a result. The ascending motion of the WPWs may weaken the MJO descending motion to the east of the MC, so that the dry Rossby wave over the MC is also weakened. As a result, the horizontal moisture advection over the MC induced by the Rossby wave wind anomalies would be insufficient.

Therefore, to address the question how MJO propagation over the MC is influenced by the intraseasonal WPWs, it is essential to investigate how the moisture tendencies vary over the MC among NP and EP MJO and the roles of the horizontal and vertical moisture advection play in that variability. The moisture budget analysis (Yanai et al. 1973) is conducted over the eastern Indian Ocean and the MC to answer these questions. The moisture budget equation is,

\[
\frac{\partial q}{\partial t} = \left\langle -u \frac{\partial q}{\partial x} \right\rangle + \left\langle -v \frac{\partial q}{\partial y} \right\rangle + \left\langle -\omega \frac{\partial q}{\partial p} - \bar{F} \right\rangle + \bar{E}
\]

(1)
The left-hand term in Eq.1 is the moisture tendency term. The four terms on the right-hand side of Eq.1 are the zonal advection, meridional advection, column process, and the surface evaporation term, respectively. We combine the vertical advection and precipitation together as the column process term here because the vertical moisture advection naturally has greater amplitude due to the great background vertical moisture gradient. And the vertical moisture advection is largely canceled out by the condensation induced by precipitation within the atmosphere column. The tilde represents the 20-70-day band-pass-filtering and the bracket symbol represents the column integration from the surface to 100hPa.

The moisture tendencies over the MC for NP MJO events are different from that for EP MJO events. Fig.6 shows the composited maps of the intraseasonal OLR and column-integrated moisture tendency over the eastern Indian Ocean and MC at day 0. For EP MJO events, the MJO convection over the Eastern Indian Ocean is led by a large-scale moistening centered over the southern sea surface of MC, which allows the MJO convection to penetrate the MC through a southward detouring as in Fig.2. For NP MJO, the moisture tendencies are characterized by negative anomalies lagging the MJO convection over the Indian Ocean, and the leading moistening is almost missing over the southern sea surface of the MC. Although there is some moistening over the equatorial eastern MC, the anomalies are weak and disconnected from the MJO convection. Also, these leading moistening anomalies are mainly over the eastern islands of the MC. Moistening anomalies around 90°E in both hemispheres symmetric about the equator are evident for NP MJO, possibly related to the strong Rossby gyres as noted in Fig.2.

The meridional moisture advection is responsible for EP MJO’s successful propagation across the MC. Fig.7 shows the maps of the right-hand-side terms at day 0. For both NP and EP MJO, the drying anomalies to the west of the MJO convection over the Indian Ocean are induced by the zonal advection term. For EP MJO, the leading moistening tendencies over the southern sea surface of the MC mainly come from the meridional advection term. The moisture tendency caused by the vertical motion is largely canceled out by the drying induced by the water phase change term. As a result, the column process term (Vertical adv - Precip) is out phase of the moisture tendency term over the MC. The contributions of right-hand-side terms over the southern sea surface of the MC are quantified by the box-mean of these terms over that region (20°S – 10°S, 100°E – 140°E). The box-mean values are given in Fig.8. For EP MJO events which penetrate the MC, the meridional
moisture advection is the main contributor to the leading pre-moistening processes. For NP MJO events, the missing pre-moistening is represented by the small value of the moisture tendency term, and it is due to the sharp decrease in the meridional moisture advection term. The contribution from the column term is even slightly negative for both EP and NP MJO over the southern sea surface of the MC. Therefore, it is the meridional moisture advection that mainly influences MJO’s propagation across the MC.

d. Roles of the WPWs in limiting MJO propagation

To investigate how the WPWs influence the NP MJO’s propagation across the MC, the meridional wind component and specific humidity in the meridional moisture advection terms of Eq.1 are decomposed into three different timescales including the seasonal (>70 days), intraseasonal (20–70 days), and higher frequency (2–20 days) timescales. The seasonal variations are indicated by the subscript of m such as $v_m$ and $q_m$. They are obtained by applying a low-pass-filtering on the raw data which includes the annual cycle and its first three harmonics. The intraseasonal variations are indicated by the variables with primes such as $v'$ and $q'$. They are obtained by applying a band-pass-filtering on the anomalies excluding the annual cycle and its first three harmonics. The higher frequency variables are indicated by the subscript of h such as $v_h$ and $q_h$. They are obtained by applying a high-pass-filtering on the anomalies excluding the annual cycle and its first
three harmonics. Since the temporal resolution of the dataset is daily, the timescale of 2-20 days is retained after the high-pass-filtering. The horizontal advection term is therefore decomposed into nine terms, including \(-v_m \cdot \partial q_m / \partial y, -v' \cdot \partial q_m / \partial y, -v_h \cdot \partial q_m / \partial y, -v_m \cdot \partial q'/ \partial y, -v' \cdot \partial q' / \partial y, -v_h \cdot \partial q'/ \partial y, -v_m \cdot \partial q_h / \partial y, -v' \cdot \partial q_h / \partial y, -v_h \cdot \partial q_h / \partial y\). These nine terms are then vertically integrated and band-pass-filtered to extract their intraseasonal variation.

To quantify the contribution of each decomposed term to the leading pre-moistening processes over the southern sea surface of the MC, the box-mean values of these nine terms over that region (20\(^\circ\)S – 10\(^\circ\)S, 100\(^\circ\)E – 140\(^\circ\)E) at day 0 are calculated for EP and NP MJO, respectively (Fig.9). For EP MJO events, the meridional moisture advection responsible for the pre-moistening over the southern sea surface of the MC is mainly contributed by the seasonal mean moisture advection induced by the intraseasonal meridional wind anomalies. For NP MJO events, this term is largely reduced as shown in Fig.9b. It is found that such reduction for NP MJO is due to the missing intraseasonal off-equatorial meridional wind anomalies over that region as displayed in Fig.10.
This indicates that the dry Rossby wave induced by the MJO descending motion to the east of MC is not well developed. This is probably related to the active convection of the WPWs as it disrupts the MJO descending motions starting from day 0 (Fig.3a and Fig.3b). The lower-tropospheric leading easterlies over the eastern MC for NP MJO are also disrupted as displayed in Fig.10b. This is probably due to the involvement of the lower-tropospheric westerlies induced by WPWs over the same region as shown in Fig.5. As for the seasonal-mean moisture background, there are not much difference between NP and EP MJO. They both show some weak dry anomalies over northern Australia. For NP MJO, there are also some broad wetting over the northern hemisphere and some drying over the Indian Ocean in the southern hemisphere. But again, the amplitude of such biases from the reference state is very small.
e. **QBO and ENSO phase preferences**

Apart from the intraseasonal WPWs presented above, the MJO propagation over the MC is also influenced by ENSO and QBO phases. Wang et al. (2019) already found that the composited seasonal mean SST anomalies for stand MJO events show a La Nina-like pattern, while that for fast MJO events show an El Niño-like pattern. The QBO’s influence on MJO propagation is found to be more dominant than that of ENSO (e.g., Son et al. 2017). Xiang et al. (2021) found that stand MJO shows a QBOW phase background while slow MJO shows a QBOE phase background. However, it is meaningful to investigate whether different QBO phase preferences still stand in our analysis since we focus on a different and longer time period from 1979 to 2013 which provides more MJO cases for study.

There are indeed certain phase preferences among MJO types as shown by the QBO-ENSO phase diagram for MJO events (Fig.11). NP MJO including stand and jump MJO events show a QBOW preference. Among all the NP MJO events, 19 of them occur during the QBOW phase, while only 6 of them happen during the QBOE phase. Such QBOW phase preference is not seen for EP MJO events, consistent with the conclusions of previous studies that during the QBOW
Fig. 11. Phase diagram of QBO and ENSO for MJO events. X axis refers to the QBO index defined as global mean of equatorial (5°S – 5°N) monthly zonal wind. Y axis refers to the ENSO index using monthly Nino3.4 index. Solid lines represent the climatology mean of two indices. Dashed gray lines parallel to X axis represent 1°C below and above the climatology mean of monthly Nino3.4. Dashed gray lines parallel to Y axis represent 1/2 standard deviation above and below the climatology mean of monthly QBO index. Each dot represents one MJO event with different colors indicating the corresponding MJO type. Four stars tell the mean values of QBO and ENSO indice for four types of MJO. Also, numbers of MJO events lying in each quadruplet of the phase diagram are labeled, respectively.

phase, MJO is less active over the Pacific with more events failing to penetrate the MC (Nishimoto and Yoden 2017; Son et al. 2017; Wang et al. 2019; Zhang and Zhang 2018). For the ENSO phase preference, which is already revealed in Wang et al. (2019), stand MJO shows a La Nina phase preference while fast MJO shows an El Niño phase preference. It is worth noting that the ENSO phase preferences are statistically significant as the composited 3-month running mean of monthly SST anomalies over the central-eastern Pacific exceed the 95% confidence level (shown by Fig.5 in Wang et al. (2019)). However, the composited 3-month running mean of monthly zonal wind at 50hPa fails to pass the 95% confidence level (not shown). This is probably due to both the limited number of cases for NP MJO and the fact that a few NP MJO events happen when the stratospheric zonal wind anomalies at 50hPa are extremely strong easterlies (6 NP MJO in the QBOE phase indicated in Fig.11). Both factors increase the standard deviation for the samples and make the composited background stratospheric zonal wind not significant. Therefore, the possible QBOW phase preference for MJO propagation is not entirely clear.

Our findings of the QBO phase preferences among MJO types are different from that in Xiang et al. (2021) where they found a QBOW background state for stand MJO and a QBOE background
state for slow MJO. This is possibly due to the decadal variability of the MJO-QBO connection since we use different time period for our analysis. We find that there are changes of the MJO case distribution among four types before and after the 1990s. In the 1980s, the case number for EP MJO is more than the twice of that for NP MJO. However, beginning with the 1990s, the case number of NP MJO increases so that it is almost about the same as that for EP MJO (not shown here). The time period of our analysis is not long enough to confirm that the decadal variability is robust. Therefore, possible decadal variation needs further investigation.

f. A combined effect of the QBO and ENSO on MJO propagation

The jump MJO events are also characterized by an independent convection developing over the central Pacific from day 0 (Fig.2b). Both the longitude-height cross section (Fig.2b) and the Hovmöller diagrams of the jump MJO convection (Fig.4b) indicate that the independent convection over the Pacific shows a westward propagation. Does this independent convection for jump MJO events develop from the WPW? Hendon and Abhik (2018) demonstrate that during the QBOW phase, the tropopause instability induced by the MJO is less in phase with its convection over the Pacific. Is it possible that the less-coupled tropopause instability tends to enhance other convective systems over the Pacific during the QBOW phase? Also, the phase diagram of the QBO and ENSO for MJO events (Fig.11) show that besides the QBOW phase preference shared by both stand and jump MJO events, stand MJO events also have a La Nina phase preference which is not seen for jump MJO events. Does this particular La Nina phase preference prevent the development of an independent convection over the Pacific for stand MJO?

The temperature anomalies induced by the MJO convection vary among MJO types. Fig.12 shows the longitude-height section of MJO-induced heating and circulation. For EP MJO, the MJO-induced heating is well confined around the MJO convection with the maximum heating centered in the middle troposphere and a westward-tilted vertical structure in the middle-lower troposphere. In the middle-higher troposphere, MJO-induced heating exhibits an eastward-tilted vertical structure. Such heating is overlain by an anomalous cooling at around 100hPa, which is a result of adiabatic adjustment to maintain hydrostatic balance in response to the diabatic warming of the troposphere induced by enhanced convection (Holloway and Neelin 2007). The anomalous heating below anomalous cooling around the tropopause leads to the tropopause instability (Hendon
and Abhik 2018), which is in favor of the development for convective systems. For EP MJO events, the tropopause instability is coupled with MJO convection and propagates eastward coherently with it. For NP MJO events, the tropopause instability is still evident but with reduced heating anomalies below the level of 200hPa. It is noteworthy that although the NP MJO convection does not propagate over the Indian Ocean, its corresponding tropopause instability shows an eastward propagation. For jump MJO events, the propagating tropopause instability becomes in phase with the shallow convection over the central Pacific, as indicated by the shallow ascending motions in the lower troposphere at day 0. The shallow convection then develops into a deep convective system with the help of the tropopause instability at day 5. The decoupling between the MJO convection and its induced tropopause instability is probably due to the preferred QBO phase for stand and jump MJO.

To better investigate the possible changes in the tropopause instability and MJO convection coupling during different QBO phases, we composited the equatorial OLR and the tropopause stability Hovmöller diagrams during QBOE and QBOW boreal winters for MJO cases in Fig.13. During QBOE boreal winters, MJO tends to propagate further east into the Pacific Ocean while during QBOW winters, MJO OLR is very weak over the Pacific. Also, the tropopause instability generated by the MJO in QBOW boreal winter is decoupled with its convection over the Pacific as it maintains a continuous eastward propagation but the MJO convection stalls over the MC. Such
Fig. 13. Compositied Hovmöller diagrams of the intraseasonal equatorial (10°S – 10°N) OLR (shading) and tropopause stability (T100 minus T200, lines) for MJO events in Fig.11 lying in (a) QBOE and (b) QBOW phases. (c) The covariance between OLR and tropopause stability as a function of the longitude in (a) and (b). Noted that the covariances are normalized by the variance of the box-mean 20-70-day-band-pass-filtered OLR timeseries over the Indian Ocean (10°S – 10°N, 75°E – 95°E) from day -25 to day 25 for MJO events in QBOE and QBOW phases, respectively.

decoupling is then quantified by the covariance between the OLR and tropopause stability. The covariance is then normalized by the variance of the box-mean intraseasonal band-pass-filtered OLR timeseries over the Indian Ocean (10°S – 10°N, 75°E – 95°E) from day -25 to day 25 for MJO events in QBOE and QBOW phases, respectively. The normalization is applied to remove the influence of the stronger MJO magnitude in QBOE phase than in QBOW phase. As shown by Fig.13c, the normalized covariance between MJO convection and its tropopause instability is very strong over the Indian Ocean in both QBOE and QBOW boreal winters. During QBOE phases, such normalized covariance remains strong over the Pacific Ocean although with slight decreases over the MC, and it gradually decreases with longitude, reaching to zero at the dateline. However, during the QBOW phase, the normalized covariance shows a rapid drop to below zero over the MC and remains weak over the whole Pacific. Such contrast in the normalized covariance over the Pacific between the QBOE and QBOW phases again indicates that the coupling between the MJO tropopause instability and its convection is highly related to and possibly influenced by the QBO phase.

The lack of independent convection over the central Pacific for stand MJO events can be attributed to their La Nina phase preference. As displayed in Fig.14, the WPW activity is largely influenced by the ENSO while the QBO has very slight influence. In the boreal winters with El Ninõ conditions,
the WPW is stronger over the equatorial central-western Pacific than in the boreal winter season with La Nina condition. With a preferred La Nina conditions, the WPWs for stand MJO are more confined over the western Pacific and the MC as shown in Fig.15. For stand MJO events, the corresponding WPWs are mainly over the western Pacific while the WPW activities for jump MJO occupy the whole central-western Pacific. Therefore, the eastward-propagating tropopause instability of stand MJO fails to induce an independent convection due to the weak WPWs over the central Pacific which is a result of the preferred La Nina phase. It is noteworthy that the WPWs over the western Pacific encounter with the decoupled tropopause instability around day 0 as indicated by Fig.15a, which amplify the shallow convection of the WPW around the MC. Such amplification can be seen from the deepening of the ascents over the MC for stand MJO as in Fig.3a at day 0 to day 5 as well as the accumulation of the wet anomalies in the lower troposphere there. However, as the moisture tendency over the MC soon turns to drying anomalies after day 5 as in Fig.15a for
stand MJO, such amplification of WPW convection over the MC is disrupted and the wet anomalies over the MC vanish after day 10 (Fig. 3a).

5. Summary and Discussions

Inspired by the four types of MJO propagation identified in Wang et al. (2019), this paper investigates what limits the propagation of MJO events across the MC. We diagnose the roles of WPWs on the failure of NP MJO events to propagate across the MC. Results show that these events are accompanied by intraseasonal WPWs over the central-western Pacific which interfere with MJO convection and propagation. Different QBO and ENSO phase preferences are also found to contribute to the diverse evolution of the convective systems over the Pacific among four MJO types through the tropopause instability structure and the WPW activity, respectively. This work...
suggests that both the low-level pre-moistening processes and the high-level tropopause instability structure are important for the diversity in MJO propagation.

The moisture budget analysis reveals that the intraseasonal WPWs are able to influence the MJO propagation across the MC mainly through suppressing the meridional moisture advection over the southern sea surface of the MC, which is responsible for the insufficient pre-moistening there. For EP MJO events, the meridional moisture advection over the southern sea surface of the MC is related to local off-equatorial meridional winds which are part of the dry Rossby gyre over the MC induced by the descending motion of the MJO circulation (Kim et al. 2014). For NP events, the active convection of the WPWs weakens this descending motion and the meridional moisture advection is therefore insufficient for them to propagate. While this mechanism is identified in composite analysis, it is also evident in individual events (see supplementary information for details). Note that although the column process term differences between EP and NP MJO are small over the southern sea surface of the MC, they are large over the equatorial MC (Fig.7). For EP MJO, the column process term contributes to the moistening tendencies around the equator (Fig.6b) and helps parts of the EP MJO convection to penetrate MC over the islands (Fig.2). We also found that for jump MJO events, the WPWs induce intraseasonal dry anomalies over the northeastern MC and these dry anomalies are advected by local seasonal-mean northeasterlies into the MC, responsible for the overall drying tendencies over the MC for jump MJO (see supplementary information for details). Some differences in the seasonal-mean moisture background among four MJO types are also found and this is probably related to the background ENSO state as presented in the supplementary information.

The different evolutions of convection over the central Pacific for stand and jump MJO events can be explained by the combined influence of the QBO and ENSO. The tropopause instability induced by the MJO is less coupled with its convection during QBOW than QBOE (Hendon and Abhik 2018). The NP MJO events, which have a QBOW phase preference, induce the eastward-propagating tropopause instability decoupled from the stalled convection. The WPWs over the central Pacific are amplified by the tropopause instability and develop into an independent convective envelope for jump MJO events. This independent convection does not develop for stand MJO events because of the La Nina-like cool seasonal mean SST anomalies over the central Pacific.
These cool anomalies confine the WPWs over the western Pacific which are out phase with the tropopause instability.

The influences of the WPWs on NP MJO are supported by the findings of them in previous studies on MJO propagation like DeMott et al. (2018) and Gonzalez and Jiang (2019). It demonstrates the essential role of the pre-moistening for MJO propagation, as supported by four schools of MJO theory (Zhang et al. 2020). This paper links the physical mechanism for the influences of WPWs on horizontal moisture advection to their active convection through hindering the vertical descending motion of MJO circulation, rather than focusing on the role of the intraseasonal dry anomalies of WPWs such as dry precursors in DeMott et al. (2018).

Previous studies have emphasized the tropopause instability as the potential mechanism by which the QBO impacts MJO (Hendon and Abhik 2018). In this study, we confirmed the decoupling of the tropopause instability with MJO convection during the QBOW phase from an event-based view. We also quantified such decoupling by the normalized covariance between the tropopause instability and the MJO OLR (Fig.13). We found that the decoupled tropopause instability for NP MJO will enhance the intraseasonal WPWs over the central Pacific, complicating the local intraseasonal variability. The combined effects of QBO and ENSO were also proposed by Sun et al. (2019). However, they explain such effects solely as a result of changes in the seasonal zonal mean gradients of moisture and vertical velocity in the equatorial region. We identify another mechanism for the combined effects through the changes in the tropopause instability influenced by the QBO as well as the WPW activity influenced by the ENSO-related SST anomalies (Fig.14).

The QBO phase preferences found in this paper are somewhat different from that found in Xiang et al. (2021). This is probably due to the different time periods used (1979-2013 for our study and 2000-2019 in Xiang et al. (2021)). This indicates a possible decadal variation for the MJO-QBO connection. We investigated the case number distribution of these four MJO types as a function of decade and found an apparent change in the ratio of NP to EP MJO case number before and after the 1990s (not shown). During the 1980s, the number of EP MJO is more than twice of that for NP MJO. However, from the 1990s, the EP MJO case number is about the same as that for NP MJO. Due to the limited time period of 35 years in our study, robust conclusions about this decadal variability will require further investigation.
A complete understanding of the relationship between the QBO and MJO remains elusive from the results of this study. The tropopause instability occurs at a very high level of the atmosphere. How such high-level instability amplifies the shallow convection, such as for jump MJO over the central Pacific and for stand MJO around the MC, remains a open question. However, our study suggests that these two processes are highly correlated. The cloud-radiative feedback is another very potential mechanism for the QBO-MJO connection (Son et al. 2017; Zhang and Zhang 2018). We investigated this mechanism through the linear regression coefficients between the net radiative heating rate and precipitation rate over the Indo-Pacific (not shown). But the result does not show much differences among four MJO types. Due to limited sample size available in the reanalysis dataset used, the proposed mechanism for the QBO-MJO connection remains elusive. In particular, there are only 14 jump MJO events and whether the QBOW phase preference is robust for these types of events is not clear. Future work will explore this relationship in model simulations and sensitivity experiments.

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**Data availability statement.** The data generated by the identification and classification of MJO events is available at https://github.com/KaiHuang94/MJO_Diversity/tree/master/outputs and from the corresponding author.
APPENDIX

Robustness of the k-means Cluster Analysis

The robustness of the k-means cluster analysis is examined in sensitivity experiments by varying the pre-defined number of clusters, as well as the threshold value ($\sigma$) of the silhouette score. A higher silhouette score indicates an MJO event is well-matched to its assigned cluster. The goal is to find optimal value such that the number of clusters is robust when varied and the threshold chosen allows the most MJO events to be successfully classified into a cluster. Fig. A1 demonstrates that the MJO cases can be best fit into 4 clusters using the k-means cluster analysis. The number of cases passing the silhouette test is always the highest for 4 clusters with a threshold from 0.05 to 0.07.

Fig. A1. Number of MJO cases passing the Silhouette test with different cluster numbers defined for the K-means cluster analysis. Dot-lines with different colors represents results with different thresholds ($\sigma$) for the Silhouette test ranging from 0.04 to 0.08 with an increment of 0.01.
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