Energetic processes regulating the strength of MJO circulation over the Maritime Continent during two types of El Niño

HSU Pang-Chia, FU Zhen, and XIAO Ting

ABSTRACT
The zonal shift of SST warming patterns associated with the eastern Pacific (EP) and central Pacific (CP) El Niño leads to a significant contrast in MJO strength over the Maritime Continent. The MJO circulation tends to be stronger over the Maritime Continent during the mature phase (autumn-winter) of CP El Niño than of EP El Niño. Based on a new MJO kinetic energy (KE) budget equation, in which the effects of mean flow and high-frequency disturbances on the MJO are separated, we found that the low-level MJO gains more KE from the background mean flow during CP El Niño events, although at the same time the enhanced MJO transfers more KE to high-frequency eddies. Among the three-dimensional circulation anomalies, the low-level convergence and cyclonic anomalies associated with upward anomalies of the Walker circulation over the Maritime Continent play leading roles in inducing the enhanced barotropic energy conversion from mean flow to MJO during CP El Niño events relative to EP El Niño events. The more vigorous MJO with strengthened vertical motion and heating anomalies at the upper troposphere can maintain its amplitude through the baroclinic energy conversion from the MJO available potential energy to KE. Both the low-to-mid tropospheric barotropic energy conversion from mean flow to MJO and upper-level baroclinic energy conversion contribute positively to the enhanced MJO over the Maritime Continent during CP El Niño years compared to during EP El Niño years.

1. Introduction
The MJO (Madden and Julian 1971) is the dominant mode of intraseasonal variability over the tropics. Its convection-circulation coupled signals are of a planetary scale and propagate eastward along the equator. During its journey, the MJO interacts with different weather and climate systems, such as tropical cyclones (Camargo, Wheeler, and Sobel 2009; Maloney and Dickinson 2003), extreme rainfall events (Mao, Sun, and Wu 2010; Yang 2010; Hsu, Lee, and Ha 2016), monsoon activity (Lee et al. 2013), and ENSO (Slingo et al. 1999; Kessler 2001; Hendon, Wheeler, and Zhang 2007), influencing the evolution and amplitude of these weather and climate systems. Advancing our understanding of MJO variation at different timescales and mean flow-MJO-eddies scale interactions can bridge the gap between weather forecasting and climate prediction (Waliser 2006), which is key to developing a seamless prediction system (Palmer et al. 2008).

The interannual variation of MJO activity is generally linked to the changes in equatorial SST at the interannual
timescale. Earlier studies (Slingo et al. 1999; Kessler 2001; Hendon, Wheeler, and Zhang 2007) focused on the interaction between the MJO and conventional ENSO, which has the maximum SST warming over the eastern equatorial Pacific (referred to as eastern Pacific El Niño, or EP El Niño). Accompanied by the eastward shift of anomalous SST warming, the strengthened MJO signals tend to extend farther east toward the eastern Pacific, while weakened MJO activity appears over the western Pacific, during EP El Niño years (Hendon, Zhang, and Glick 1999; Kessler 2001). Since the beginning of the twenty-first century, a new type of El Niño with a significant SST warming over the central Pacific (referred to as CP El Niño) has been observed frequently. CP El Niño induces a different modulating effect on MJO activity compared to EP El Niño (Gushchina and Dewitte 2012; Feng et al. 2015; Yuan, Li, and Ling 2015; Chen, Ling, and Li 2016; Hsu and Xiao 2017). The suppressed MJO over the western Pacific and Maritime Continent during CP El Niño events is of less significance than that during EP El Niño years. Some studies have suggested that the difference in the MJO over the western Pacific/Maritime Continent could be related to the suppressed effect of the Walker circulation and the anticyclonic circulation anomaly near the Philippine Sea during different types of El Niño events (Feng et al. 2015; Yuan, Li, and Ling 2015; Chen, Ling, and Li 2016).

Although possible relationships between the anomalous mean flow and MJO associated with each type of El Niño have been indicated (Feng et al. 2015; Yuan, Li, and Ling 2015; Chen, Ling, and Li 2016), the detailed processes and relative contributions of these anomalous circulations to the changes in the MJO need to be investigated. In addition to large-scale circulations, synoptic-scale variability is also vigorous over the Maritime Continent (Chang, Harr, and Chen 2005) and may have influences on MJO activity through upscaled feedback. In this study, we examine the main source of increased MJO kinetic energy (KE) during CP El Niño events based on a newly proposed MJO KE budget equation derivation. We also quantitatively discuss how scale interactions among low-frequency background flow, the MJO, and high-frequency disturbances modulate the MJO strength during different types of El Niño.

2. Methodology

To identify the deep convection associated with MJO and high-frequency disturbances, we use daily OLR on a 2.5° × 2.5° grid from NOAA (Liebmann 1996). The changes in dynamic and thermodynamic conditions and their influences on the MJO are examined using daily-averaged fields of horizontal wind (u, v), vertical p-velocity (ω), temperature (T), and geopotential (ϕ) from ERA-Interim (Dee et al. 2011). These fields have a resolution of 1.5 × 1.5 and 19 levels from 1000 to 100 hPa with 50-hPa intervals. All data cover the period 1979–2014.

To reduce data uncertainty, the average of monthly SST data derived from HadISST1 (Rayner et al. 2003) and ERSST. v3 (Smith et al. 2008) are used to categorize the two different types of El Niño. Using the method proposed by Yeh et al. (2009) and others (e.g. McPhaden, Lee, and McClurg 2011; Ren and Jin 2011), the CP and EP cases are classified based on the amplitude of SST anomalies over the Niño3 (5°S–5°N, 90°–150°W) region and the Niño4 (5°S–5°N, 160°E–150°W) region. Those El Niño events with a larger Niño3 than Niño4 (larger Niño4 than Niño3) warming during boreal winter are considered as EP El Niño (CP El Niño) events. Four EP El Niño events (1982/83, 1986/87, 1991/92, and 1997/98) and five CP El Niño events (1994/95, 2002/03, 2004/05, 2006/07, and 2009/10) are selected for the study period.

To quantitatively examine the physical processes modulating the MJO activity during the two types of El Niño, the MJO KE budget is derived and then diagnosed. The conventional energy budget equation is derived by partitioning the meteorological variable into two parts — background mean flow and perturbation — to diagnose the energy conversion between the two (Oort 1964; Lau and Lau 1992; Maloney and Dickinson 2003; Hsu and Chih-Hua 2009). To understand the scale interactions of MJO with both the mean flow and high-frequency disturbances, we decompose a variable into three parts in the time domain, including the low-frequency mean flow (> 90 days), MJO (20–90 days), and high-frequency disturbances (< 20 days), as follows:

\[ A = \bar{A} + A' + A^\ast, \]

where the overbar denotes the low-frequency component; the prime and asterisk denote the 20–90-day MJO and the high-frequency disturbances of shorter than 20 days, respectively. Here, we apply Lanczos band-pass filtering (Duchon 1979), 90-day low-pass and 20-day high-pass filtering to extract the MJO, low-frequency mean flow and high-frequency disturbances, respectively. This derivation strategy is similar to that used in Hsu, Li, and Tson (2011) and Tsou, Hsu, and Hsu (2014), although these studies focused on the KE sources of synoptic-scale eddies rather than the MJO.

By multiplying u' and v' on both sides of the MJO-filtered horizontal momentum equations, respectively, the MJO KE budget equation is obtained as

\[
\frac{\partial K'}{\partial t} = -\nabla' \cdot [(\nabla')^3 \cdot \nabla'] V' - (\nabla' \cdot (v' + w'))_3 \cdot \nabla_3 V' + \frac{R}{\rho} \frac{T' \cdot \omega}{\omega_0} - \nabla_3 \cdot (\nabla' \phi') + D \]

where

- \( A = \bar{A} + A' + A^\ast \)
- \( \bar{A} \), \( A' \), and \( A^\ast \) denote the low-frequency component, the 20–90-day MJO, and the high-frequency disturbances, respectively.
- \( \bar{A} \) is the background mean flow.
- \( A' \) is the MJO component.
- \( A^\ast \) is the high-frequency disturbances.
- \( R \) is the Coriolis parameter.
- \( \rho \) is the density.
- \( T' \) is the temperature perturbation.
- \( \omega \) is the vertical velocity.
- \( \phi \) is the geopotential.
- \( D \) is the diabatic heating.

The above equation describes the evolution of MJO KE, with terms representing the advection, dissipation, and forcing by mean flow and high-frequency disturbances.

This equation provides a framework for analyzing the physical processes modulating the MJO activity during different types of El Niño, allowing for a detailed examination of how these processes affect the MJO KE budget.
where \( K' = \frac{1}{2} (u''^2 + v''^2) \) is the MJO KE, and \( t \) is time. \( \mathbf{V} \) indicates the horizontal wind vector. \( \nabla \) and \( \nabla_3 \) indicate the two- and three-dimensional gradient operators, respectively. \( R \) is the gas constant. \( P \) is pressure. \( D \) includes dissipation and subgrid-scale effects. The terms on the rhs of Equation (2) represent the processes that modulate the tendency of MJO KE. The first two terms, \( CK_{L-M} \) and \( CK_{H-M} \), indicate the barotropic energy conversion from the low-frequency mean flow and high-frequency disturbances to MJO, respectively. Term CE, the baroclinic conversion from the MJO available potential energy to MJO KE, is related to the interaction between MJO circulation and convection. When the MJO upward (downward) motion occurs over the convectively heating (cooling) area, the MJO gains KE through the baroclinic energy conversion. The advection of MJO induced by the three-dimensional wind fields is denoted by BK. The convergence of MJO geopotential flux (B\( \phi \)) can also induce MJO KE. Note that only terms \( CK \) (\( CK_{L-M} \) and \( CK_{H-M} \)) and CE are related to the major sources of MJO KE via generation and conversion processes, while the other terms (BK and B\( \phi \)) represent redistributions of MJO KE.

### 3. Results

Figures 1 and 2 show the changes in subseasonal variability (including 20–90-day MJO and high-frequency disturbances of less than 20 days), large-scale circulations, and SST patterns during the mature phase (autumn-winter) of the two types of El Niño events relative to their climatological conditions. When the SST warming maximizes at the eastern equatorial Pacific (Figure 1(a)), the ascending motion of the Walker circulation and trade winds are reduced significantly. A low-level divergence (Figure 1(a)) associated with a downward anomaly of the Walker circulation (Figure 2(a)) can be observed over the Maritime Continent. An anticyclonic anomaly appears near the Philippine Sea (Wang, Wu, and Fu 2000). Along with the changes in background dynamic and thermodynamic conditions, both the atmospheric MJO (Figure 1(a)) and high-frequency eddies (Figure 2(a)) are weakened over the western Pacific and Maritime Continent during the EP El Niño events.

As the warm SST anomaly shifts westward during CP El Niño events, the low-level divergence and anticyclonic anomalies associated with the descending anomaly of

![Figure 1](image_url). Kinetic energy of 20–90-day MJO (shading; units: m² s⁻²), monthly SST (contours; units: °C), and monthly 850-hPa wind (vectors; units: m s⁻¹) anomalies during autumn-winter (September-February) of (a) EP and (b) CP El Niño events relative to their climatological states. The differences in these fields between CP and EP El Niño events (CP minus EP) are shown in (c). Stippling marks the regions with the changes in MJO KE exceeding the 90% confidence level.
during CP El Niño appears over the Maritime Continent from mid-September of the El Niño developing year to the following February. This confirms our composite analysis for the period of autumn-winter (September-February) is reasonable.

To compare the amplitude and life cycle of MJO KE over the Maritime Continent between the two types of El Niño, enhanced MJO circulation events occurring over the region (10°S–10°N, 90°–150°E) with significant changes in MJO KE between the CP and EP El Niño events (CP minus EP) are shown in (c). Stippling marks the regions with the changes in eddy KE exceeding the 90% confidence level. The thick solid and dashed contours denote the anomalies of 500-hPa vertical p-velocity at 0.2 and −0.2 Pa s⁻¹, respectively.

Figure 2. Kinetic energy of less than 20-day eddies (shading; units: m² s⁻²) and 500-hPa monthly vertical p-velocity (contours; units: Pa s⁻¹) of (a) EP and (b) CP El Niño events relative to their climatological states. The differences in these fields between CP and EP El Niño events (CP minus EP) are shown in (c). Stippling marks the regions with the changes in eddy KE exceeding the 90% confidence level. The thick solid and dashed contours denote the anomalies of 500-hPa vertical p-velocity at 0.2 and −0.2 Pa s⁻¹, respectively.

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To compare the amplitude and life cycle of MJO KE over the Maritime Continent between the two types of El Niño, enhanced MJO circulation events occurring over the region (10°S–10°N, 90°–150°E) with significant changes in MJO KE between the CP and EP El Niño events (Figure 1(c)) are selected and composited. An enhanced MJO circulation event is identified by the MJO KE over the key region of (10°S–10°N, 90°–150°E) exceeding one standard deviation. The amplitude of transient eddies at the intraseasonal and synoptic timescales vary obviously over the Maritime Continent during the two types of El Niño. The MJO has higher KE over the Maritime Continent during CP El Niño than during EP El Niño (Figure 1(b) and (c)), consistent with the findings of Chen, Ling, and Li (2016). Although the high-frequency variability tends to weaken over the Maritime Continent during both CP and EP El Niño events relative to the climatology (Figure 2(a) and (b)), the reduction in KE of high-frequency disturbances is less during CP El Niño events compared to that during EP El Niño events (Figure 2(c)).

The results of Figures 1 and 2 are based on the seasonal average. To ensure the timing when the two types of El Niño exert differential influences on the MJO circulation, we analyze the temporal evolution of equatorial MJO KE (not shown). The significant increase in MJO KE during CP El Niño appears over the Maritime Continent from mid-September of the El Niño developing year to the following February. This confirms our composite analysis for the period of autumn-winter (September-February) is reasonable.

To compare the amplitude and life cycle of MJO KE over the Maritime Continent between the two types of El Niño, enhanced MJO circulation events occurring over the region (10°S–10°N, 90°–150°E) with significant changes in MJO KE between the CP and EP El Niño events (Figure 1(c)) are selected and composited. An enhanced MJO circulation event is identified by the MJO KE over the key region of (10°S–10°N, 90°–150°E) exceeding one standard deviation. The date with maximum KE for each enhanced MJO event is defined as Day 0. Figure 3(a) compares the KE evolution of composited active MJO events in CP and EP El Niño years. The enhanced MJO KE is obvious over the Maritime Continent during CP El Niño and larger than that during EP El Niño, in agreement with the result in Figure 1(c). From nine days before the MJO KE reaches its maximum, a positive tendency of MJO KE can be found for both CP and EP El Niño (not shown). The growth rate of MJO KE is larger during CP El Niño than during EP El Niño,
accounting for the enhanced MJO KE over the Maritime Continent during CP El Niño (Figure 3(a)).

To understand the key processes modulating the sources of MJO KE associated with the two types of El Niño, the column (1000–200 hPa) MJO KE budget (Equation (2)) is diagnosed during Day −9 to 0 (Figure 3(b)). The larger growth rate of MJO KE during CP El Niño is mainly from the barotropic energy conversion from mean flow to MJO (CK\_L\_M) and the baroclinic energy conversion from the MJO available potential energy to KE (CE). The positive contribution of CK\_L\_M via scale interaction between anomalous mean flow and MJO appears in the mid-to-lower troposphere (Figure 4(a)). However, the CE associated with the MJO circulation-convection coupled feedback plays an important role in maintaining the increased MJO KE during CP El Niño at the upper troposphere (Figure 4(b)). Although the MJO obtains more KE during CP El Niño, it provides more KE to high-frequency eddies through CK\_H\_M (Figure 3(b)) in the meantime, supporting the enhanced high-frequency variability over the Maritime Continent (Figure 2(c)). The redistributions of MJO KE associated with the advection process and geopotential flux contribute negatively to the increased MJO KE during CP El Niño (Figure 3(b)).

The individual terms of CK\_L\_M are then compared to identify the major contributors (Figure 3(c)). Although relatively small, the background vertical wind shear also plays a role in increased MJO KE (−u′ω′\partial\bar{u}/\partial p). The first two terms related to zonal wind convergence and cyclonic anomalies show a large contribution at the lower troposphere, while the
third term associated with vertical wind shear maximizes around 400 hPa where the zonal wind changes its sign (not shown). During CP El Niño, the descending anomaly of the Walker circulation and low-level divergence anomaly over the Maritime Continent are weaker compared to those during EP El Niño (Figure 2(a) and (b)). Meanwhile, the Philippine Sea anticyclonic anomaly tends to be weakened during CP El Niño (Figure 1(c)), similar to the findings of Yuan, Yang, and Zhang (2012). These large-scale anomalies associated with the westward shift of the equatorial SST warming pattern (i.e. CP El Niño) generate enhanced barotropic energy conversion from the mean flow to MJO KE as they work with MJO eddy momentum fluxes.

4. Summary

The distinct impacts of CP and EP El Niño events on western Pacific MJO activity have been documented previously (Gushchina and Dewitte 2012; Feng et al. 2015; Yuan, Li, and Ling 2015; Chen, Ling, and Li 2016; Hsu and Xiao 2017). However, the physical mechanisms responsible for the differences in MJO associated with the two types of El Niño have not been fully understood. Particularly, the western Pacific/Maritime Continent is the region that undergoes vigorous multi-scale variability. How and to what extent the changes in background mean flow and high-frequency disturbances influence the MJO during the CP and EP El Niño need further elucidation.

In this study, we derive a new MJO KE budget equation, in which the low-frequency background mean flow-MJO interaction and high-frequency disturbances-MJO interaction are formulated, to quantitatively examine the physical processes modulating the MJO activity during different El Niño events. The results show that both the barotropic energy conversion from background mean flow to MJO KE (CKLM) and baroclinic energy conversion from MJO available potential energy to KE (CE) contribute positively to the enhanced MJO KE over the Maritime Continent during the mature phase of CP El Niño. Among the three-dimensional large-scale circulation anomalies during CP El Niño, the low-level convergence and cyclonic anomalies related to a weakened descending branch (or an upward anomaly) of the Walker circulation over the Maritime Continent and the reduced Philippine anticyclonic anomaly play crucial roles in favoring the KE conversion from mean flow to MJO. Different from the positive contribution of CKLM occurring at the mid-to-lower troposphere, the enhanced CE is the major contributor to the strengthened MJO KE at the upper troposphere during CP El Niño. Based on the diagnosis of interaction between MJO and high-frequency disturbances (CKH,M), we find that the high-frequency variability over the Maritime Continent is enhanced during CP El Niño because it obtains more KE from the MJO.

Understanding the multi-scale interaction is a key step for developing seamless prediction (Waliser 2006; Palmer et al. 2008), while the quantitative diagnosis of scale interactions is still challenging. The new MJO KE budget equation proposed in this study can help to diagnose how and to what extent the MJO interacts with the mean flow and with the high-frequency disturbances. The energy source of the MJO is also examined quantitatively using the MJO KE budget equation. Specifically, we use this diagnostic approach to explain the modulation of the MJO by different types of El Niño. We plan to carry out more studies related to MJO dynamics and scale interactions based on the diagnosis of the MJO KE budget equation.

Acknowledgments

The authors would like to thank the anonymous reviewers for their help in improving the manuscript.
Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study was supported by the National Natural Science Foundation of China [grant number 41375100]; the National Basic Research Program of China [973 Program, grant number 2015CB453200]; and the Natural Science Foundation of Jiangsu Province [grant number BK20140046].

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