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Key Points:

- Madden-Julian Oscillation (MJO) activities are stronger in easterly phases of the quasi-biennial oscillation (QBO) because of more MJO days, not larger amplitudes of individual MJO events
- More MJO days in easterly phases of QBO come from more MJO events formed over the Indian Ocean and a weaker barrier effect of the Maritime Continent
- Responses of the MJO and total precipitation to QBO are not zonally uniform, which remains to be explained

Correspondence to:
B. Zhang,
bxz125@miami.edu

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QBO-MJO Connection

Chidong Zhang[1] and **Bosong Zhang**[2]

[1]NOAA Pacific Marine Environmental Laboratory, Seattle, WA, USA, [2]Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL, USA

Abstract Activities of the Madden-Julian Oscillation (MJO) in boreal winter has recently been found to be stronger in easterly phases of the stratospheric quasi-biennial oscillation (QBO) than its westerly phases. This QBO-MJO connection was investigated in this study using a method that identifies individual MJO events by tracking their eastward propagating signals in precipitation. Stronger MJO activities in QBO easterly phases are a consequence of more MJO days, not larger amplitudes of individual MJO events as previously thought. More MJO days come from more MJO events initiated over the Indian Ocean and their longer duration because of a weaker barrier effect of the Maritime Continent on MJO propagation. Zonal heterogeneity exists in the connection between QBO, MJO, and tropical total precipitation in general. This poses a challenge to our current understanding of the MJO dynamics, which has yet to fully include upper-tropospheric and stratospheric processes.

1. Introduction

A very intriguing connection between the stratospheric quasi-biennial oscillation (QBO) and Madden-Julian Oscillation (MJO) has recently been found (Liu et al., 2014; Yoo & Son, 2016). MJO activities are significantly stronger in QBO easterly phases (QBOE) than westerly phases (QBOW) but only in boreal winter. This observed QBO-MJO connection is prominent evidence of troposphere-stratosphere interaction. It connects two sources of predictability on subseasonal-to-seasonal (S2S) timescales (Board et al., 2016). And it presents a challenge in understanding the dynamics of the MJO, which serves to bridge weather and climate (Zhang, 2013).

Several studies have been conducted to describe and explain this connection (Hood, 2017; Nishimoto & Yoden, 2017; Son et al., 2017) and to explore its implication to MJO prediction (Marshall et al., 2017). Up to 40% of the interannual variation in boreal winter MJO activities is related to QBO (Son et al., 2017). MJO propagation appears to be slower and its period longer in QBOE than QBOW (Nishimoto & Yoden, 2017). The exact reason for the QBO-MJO connection is, however, still unclear.

During QBOE (QBOW), associated with ascending (descending) motions, the tropopause is higher (lower) and colder (warmer), the vertical zonal wind shear across the tropopause is weaker (stronger), and upper-tropospheric static stability is lower (higher) (Baldwin & Dunkerton, 2001). These contrasts between the two QBO phases in the tropopause height, temperature, wind shear, and static stability are thought to be the reasons for observed stronger tropospheric deep convection in QBOE than QBOW (Collimore et al., 2003). These alternations in conditions for tropical deep convection between the two QBO phases have also been used to explain the observed QBO-MJO connection (Nishimoto & Yoden, 2017; Son et al., 2017; Yoo & Son, 2016). In addition, the fluctuation in MJO strength between the two QBO phases appears to be amplified by the minimum and maximum of the 11 year solar cycle (Hood, 2017).

Differences in MJO activities between the two QBO phases were observed over both the Pacific and Indian Oceans (Nishimoto & Yoden, 2017; Son et al., 2017; Yoo & Son, 2016). Differences in tropical total (including MJO and non-MJO) convection between the two QBO phases were observed mainly over the Pacific, but not over the Indian Ocean and the western part of the Maritime Continent (MC) (Liess & Geller, 2012). There are thus intriguing contrasting behaviors of MJO and total precipitation over the two sectors of the Indo-Pacific warm pool. Over the western Pacific, where differences in precipitation between the two QBO phases exist in both MJO and total precipitation, the QBO-MJO connection might simply be an intraseasonal manifestation of the differential conditions for precipitation in general. The previously suggested possible mechanisms in terms of static stability, tropopause height, and wind shear would equally apply to MJO as well as total precipitation. It is very different over the Indian Ocean, where differences between the two QBO phases exist in

MJO precipitation but not in total precipitation. Explanations are needed for the different behaviors of MJO and total precipitation over the Indian and Pacific Oceans between the two QBO phases.

Motivated by this unsettled issue, we in this study revisited the QBO-MJO connection using a recently developed method of identifying individual MJO events. The application of this method distinguishes this study from the previous ones (Liu et al., 2014; Marshall et al., 2017; Nishimoto & Yoden, 2017; Son et al., 2017; Yoo & Son, 2016) on the same subject that used Empirical Orthogonal Function (EOF) based global MJO indices to represent the MJO. The objective of this study is to see what new insight this new method may provide relative to the existing knowledge on this subject. We shall in this article illustrate the new perspectives provided by this method.

Section 2 describes the new method along with the data used. Results are presented in section 3. A summarizing discussion is given in section 4.

2. Method and Data

The method used to identify individual MJO events was developed by (Ling et al., 2014) and described in detail by (Zhang & Ling, 2017). In essence, this method first tracks all eastward propagating large-scale anomalies in equatorial (15°S–15°N) precipitation, then it identifies MJO events based on certain criteria, such as propagation range (>50° longitude), propagation speed (3–7 m s^{-1}), and timescale (>20 days). Statistics of all identified MJO events remain the same with small perturbations in these criteria. One major advantage of this tracking method is that it provides more quantitative information of the MJO than what available from other measures of the MJO. Such quantitative information includes strength, starting and ending longitudes, and dates, which yield propagation ranges and durations, of individual MJO events.

The tracking method was developed using the daily Tropical Rainfall Measuring Mission (TRMM) 3B42 version 7 (3B42v7) Multisatellite Precipitation Analysis (Huffman et al., 2007) that covers a period of 1998–2015 on 0.25° × 0.25° grids. In this study, the method was applied to the Pentad mean Climate Prediction Center Merged Analysis of Precipitation (CMAP) rainfall (Xie & Arkin, 1997) for a period of 1979–2016. The CMAP data were interpolated to daily data on 0.25° horizontal grids before the tracking method was applied. MJO statistics based on the TRMM and CMAP data are comparable (Zhang & Ling, 2017). The CMAP data provide a longer record for more robust results.

We first focused on the QBO-MJO connection during extended boreal winter (November to March, or NDJFM), following (Yoo & Son, 2016), for larger sample sizes than those from the traditional definition of the season (December to February, or DJF). For the analysis period of 1979–2016, totally 86 MJO events were identified during NDJFM. We compare results based on the two definitions of boreal winter for their consistency in section 3.5.

Phases of the QBO were defined using an index based on 50 hPa zonal wind from the National Oceanic and Atmospheric Administration Climate Prediction Center, smoothed by a 3 month running mean. Following (Hamilton, 1984) and (Marshall et al., 2017), we first defined QBOE when the smoothed index is negative and QBOW when the index is positive. By these definitions, there are totally 83 (107) months of QBOE (QBOW) in NDJFM during 1979–2016. Results based on this definition of the QBO phases are qualitatively the same as those based on a more restrictive definition that requires the index to be greater or less than 0.5 standard deviations (Yoo & Son, 2016). Their comparisons are discussed in section 3.5.

We grouped all identified MJO events into QBOE and QBOW. A given MJO event is considered to be in QBOE (QBOW) if its middate, defined as the midpoint between its starting and ending dates, is in a month of QBOE (QBOW). Using starting or ending dates in place of the middate yielded the same results.

We also revisited the results from the previous studies (Marshall et al., 2017; Nishimoto & Yoden, 2017; Son et al., 2017; Yoo & Son, 2016) using the Real-time Multivariate MJO (RMM) index (Wheeler & Hendon, 2004) and the Outgoing Longwave Radiation (OLR) MJO Index (OMI) (Kiladis et al., 2014). An index of Niño-3.4 (5°N–5°S, 170°W–120°W) sea surface temperature (SST) smoothed by a 5 month running average was used to investigate the possible role of El Niño–Southern Oscillation (ENSO) in the QBO-MJO connection. El Niño and La Niña events were defined when the Niño-3.4 SST exceeds ±0.4°C for a period of 6 months or more (Trenberth, 1997).

Results presented in section 3 include comparisons of mean states in low-level zonal wind, tropopause height, SST, high-cloud coverage, and lower-tropospheric humidity between the two QBO phases. This was

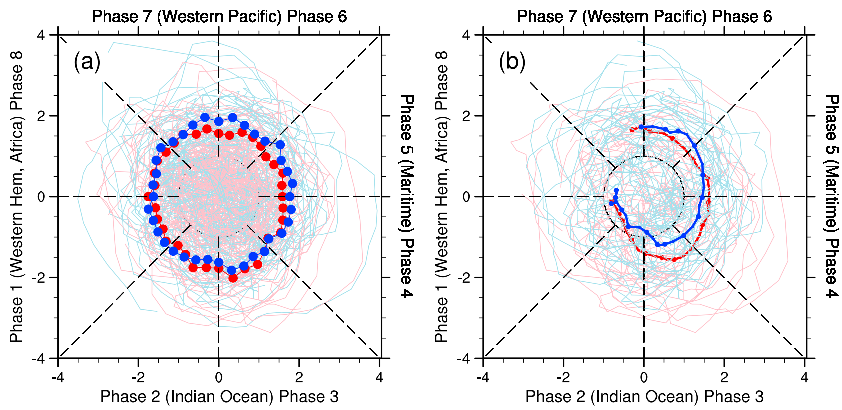

Figure 1. Phase diagrams of the Real-time Multivariate Madden-Julian Oscillation (MJO) (RMM) index for (a) all days (thin lines) and their averages when |RMM| > 1 (thick), and (b) tracked MJO events formed west of the Maritime Continent (40°W–100°E) and their averages (thick) in quasi-biennial oscillation easterly phases (blue) and quasi-biennial oscillation westerly phases (red). Averages were made for every 10° angle in the phase diagram in (a) and over each 5° longitude in (b). Dots in (b) mark longitudes of every 10°.

done using daily data from the European Centre for Medium-Range Weather Forecasts interim reanalysis (ERA-I; Dee et al., 2011). The horizontal resolution of this data set is 2.5° × 2.5°. Its vertical resolutions are 25 hPa between 1,000 and 750 hPa, 50 hPa between 750 and 250 hPa, and 25 hPa between 250 and 100 hPa. The tropopause is defined as the lowest level at which the lapse rate decreases to 2 K/km or less, provided also the average lapse rate between this level and all higher levels within 2 km does not exceed 2 K (Tuck et al., 1985).

Seasonal means of high-cloud coverage in the two QBO phases and their difference from ERA-I are validated against those from the International Satellite Cloud Climatology Project H series (Rossow & Schiffer, 1991) at 1° × 1° spatial grids. The two compare reasonably well against each other with detailed differences, especially in significance of their results because of the different record lengths (not shown).

Statistical results (means, differences, and correlation) are subject to significance tests. We consider a result statistically significant when the *p* value of its test is equal to or less than 0.05, which is equivalent to the confidence level of 95% or higher.

3. Results

In sections 3.1–3.4, results are for NDJFM and based on the QBO definition of the QBO index greater or smaller than 0 for all years during the analysis period (1979–2016). In section 3.5, we discuss the sensitivity of the results to the definitions of the season and QBO, and to ENSO.

3.1. MJO Amplitude Versus MJO Days

In the previous studies on the QBO-MJO connection (Marshall et al., 2017; Nishimoto & Yoden, 2017; Son et al., 2017; Yoo & Son, 2016), the MJO was measured by amplitudes of EOF-based indices (RMM and OMI). Amplitudes of these MJO indices are defined as the root square of the two leading EOFs. For the RMM index, for example, its amplitude is $|RMM| = (RMM1^2 + RMM2^2)^{1/2}$. Averaged MJO amplitudes thus defined are found to be larger in QBOE than QBOW when all days in the two QBO phases are included in the averages (e.g., Figure 3 in Yoo & Son, 2016, and Figure 5 in Nishimoto & Yoden, 2017).

It is a common practice that when an EOF-based MJO index is used to describe the MJO, an MJO event is considered to exist only if the amplitude of the index is greater than one (or its one standard deviation if not normalized). When we applied this common practice to calculate mean amplitudes of RMM for QBOW and QBOE, we could not find any significant difference between them (Figure 1a). We also calculated their amplitudes averaged over days of MJO events identified by our tracking method; we could not find any significant difference between QBOW and QBOE either (Figure 1b). Same results were obtained when we used OMI (not

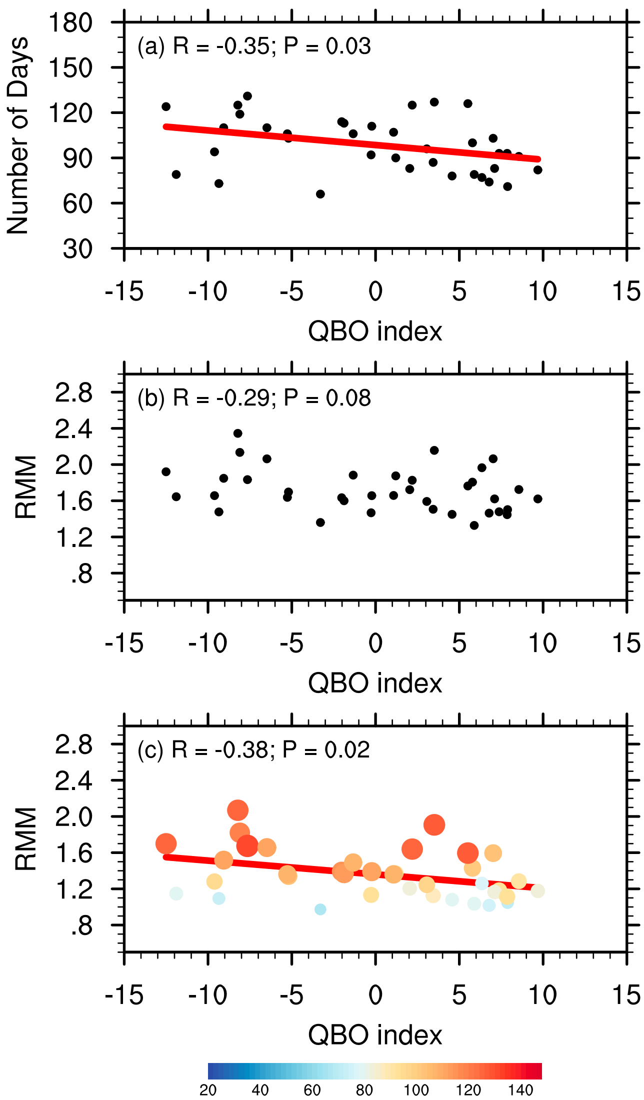

Figure 2. Scatter diagrams for the mean quasi-biennial oscillation (QBO) index versus (a) the number of days of |RMM| > 1; (b) averaged Real-time Multivariate Madden-Julian Oscillation (RMM) amplitude for days of |RMM| > 1; (c) averaged RMM amplitude for all days with colors and sizes marking the number of days of |RMM| > 1. Each dot represents an average for a season of November to March. The *p* values are for statistical significance of the linear correlation coefficients. Red solid lines in (a) and (c) indicate significant correlation at the 95% confidence level.

shown). It is clear that MJO amplitude or strength, measured by the EOF-based MJO indices but only for MJO events however defined, is of no difference between the two QBO phases.

Prompted by this unexpected result, we calculated the statistical significance for the differences in RMM amplitudes between the two QBO phases using all days for the eight RMM phases, as done in the previous studies. The degree of freedom used in the significance test is the total number of MJO events in each phase. We found no significance at the 95% confidence level in any of the phases. This result persists when we used all combinations of the definitions of QBO and boreal winter and the MJO indices (RMM and OMI). While the differences in mean amplitudes of RMM and OMI between the two QBO phases might be visually obvious in certain MJO phases (e.g., Figure 3d in Yoo & Son, 2016, and Figure 5 in Nishimoto & Yoden, 2017), they are much smaller than the standard deviation of the amplitude in each MJO phase. We also compared probability distribution functions (PDFs) of the strength of individual MJO events (defined as precipitation averaged between the starting and ending dates) in the two QBO phases. There are very strong MJO events in QBOE that are absent in QBOW. But the two PDFs are not significantly different based on a Kolmogorov-Smirnov two-sample test (K-S test) against a null hypothesis that the two PDFs are from the same data population. These results lead to a conclusion that there is no significant difference in the amplitude of the MJO between the two QBO phases.

Does this conclusion invalidate all previous results on the QBO-MJO connection? No. It turns out that the number of days when MJO events exist is greater in QBOE than QBOW. Correlation between the QBO index and the number of days of |RMM| > 1 in a season (Figure 2a) is significantly different from zero based on a student's *t* test and a bootstrapping test. But it is not significant between the QBO index and seasonally averaged amplitude of |RMM| > 1 (Figure 2b). The correlation between the QBO index and MJO amplitude found in the previous studies (Marshall et al., 2017; Son et al., 2017; Yoo & Son, 2016) is due to MJO days of |RMM| > 1, not amplitudes of MJO events (Figure 2c).

3.2. Barrier Effect of the Maritime Continent

More MJO days suggest two possibilities: longer durations of MJO events and more MJO events. The most prominent factor determining MJO duration is the barrier effect of the Maritime Continent (MC) on MJO propagation (Inness & Slingo, 2006; H-M. Kim et al., 2016). In addition to the MJO being weakened over the MC, a large portion of MJO events formed over the Indian Ocean fail to propagate through the MC (Zhang & Ling, 2017). These MJO events that are blocked by the MC (hereafter referred to as MJO-B), defined as those with their ending longitudes between 100 and 160°E (see (Zhang & Ling, 2017) for details), have shorter life span (duration) than those that propagate through.

Time-longitude diagrams of composite anomalies in precipitation of MJO events formed west of the MC (40°W–100°E) show stronger MJO signals over the western Pacific in QBOE than QBOW (Figures 3a–3c). Similar results can be found in composites of OLR in previous studies (e.g., Figure 8 in Liu et al., 2014, Figure 4 in Son et al., 2017, and Figure 6 in Nishimoto & Yoden, 2017). This suggests a stronger barrier effect of the MC in QBOW. This stronger barrier effect of the MC on MJO propagation is confirmed by comparing the number of MJO events that terminate over the MC without reaching the western Pacific (MJO-B) in the two QBO phases. The percentage of MJO-B versus total MJO events formed west of the MC is doubled from 28%

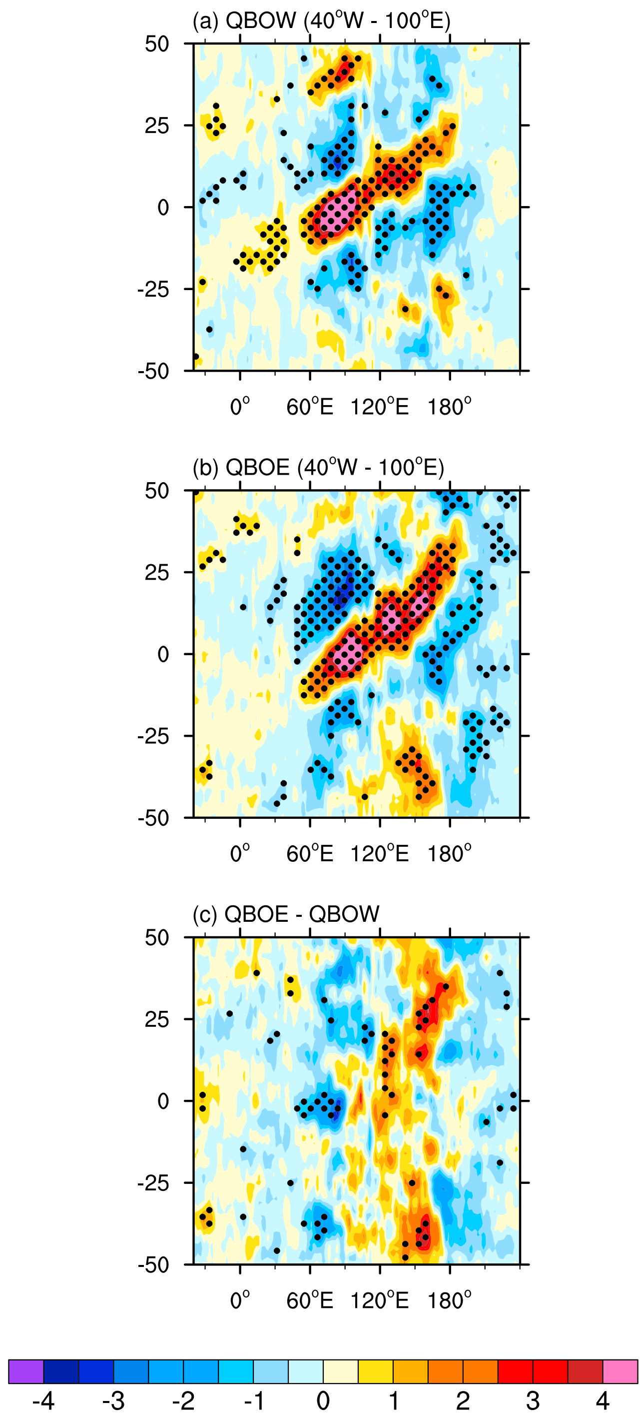

Figure 3. Composites of precipitation anomalies (mm day^{-1}) for tracked Madden-Julian Oscillation events formed west of the Maritime Continent (40°W–100°E) during (a) quasi-biennial oscillation westerly phases (QBOW) and (b) quasi-biennial oscillation easterly phases (QBOE); (c) their difference (QBOE − QBOW). Stipples mark significant results at the 95% confidence level.

in QBOE to 59% in QBOW; the monthly probability of MJO-B (total number of MJO-B events divided by total number of months) is also nearly doubled from 10% in QBOE to 19% in QBOW (Table 1).

The result from the simple counting of MJO-B events in the two QBO phases is further supported by comparing PDFs of ending longitudes of MJO events formed west of the MC in the two QBO phases. As shown in Zhang and Ling (2017), there are two peaks for all MJO events (Figure 4a). One is over the MC (around 140°E) and the other over the central Pacific. These two peaks manifest the MC barrier effects: precipitation signals of the MJO formed west of the MC either terminate over the MC or propagate through and cease to exist over cold water of the central Pacific. There is no other dominant mechanism other than the MC barrier effect to end propagation of MJO precipitation, and MJO events simply do not terminate themselves randomly over the broad longitudinal range of the Indo-Pacific warm pool. These two peaks remain in both QBO phases. While the peaks over the MC are about the same in both phases, that over the Pacific is much larger for QBOE than QBOW, indicating a much higher chance for MJO events to survive the MC barrier effect and propagate through to reach the Pacific in QBOE than QBOW. The two distributions in Figure 4b are significantly different based on a K-S test.

We noticed from Figure 3c that signals in MJO precipitation over the Indian Ocean are weaker in QBOE than QBOW, in contrast to those over the Pacific. We shall discuss this in section 3.5.

3.3. MJO Formation Over the Indian Ocean

We now turn to initiation of MJO events over the Indian Ocean (30°E–100°E), where the majority of MJO events start (Zhang & Ling, 2017). During the analysis period (1979–2016), there are 40 identified MJO events formed over the Indian Ocean. Of which, 19 are in QBOW and 21 in QBOE. The occurrence frequency (the total number of MJO events in a QBO phase divided by the total number of months of that phase) increases from 18% in QBOW to 25% in QBOE (Table 1). This increase is one third of the MJO mean occurrence frequency (21%) for all years. This result implies that there are more MJO events initiated over the Indian Ocean in QBOE than QBOW given the same lengths of the two QBO phases. Occurrence frequency of MJO events outside the Indian Ocean differs insignificantly between the two QBO phases.

Results from section 3.2 and this section demonstrate that from QBOE to QBOW, the chance for MJO events to form over the Indian Ocean increases by 50% and the chance for these MJO events to be blocked by the barrier effect of the MC is reduced by 50%. A consequence of these results is that there are more MJO days in QBOE (48% of NDJFM) than QBOW (33%). This supports the results from section 3.1. It is this difference in the MJO days, not strength of individual MJO events, that makes MJO activities greater in QBOE than QBOW, as suggested by the previous studies.

3.4. Zonal Heterogeneity

Figure 3c indicates that mean MJO signals in precipitation is weaker over the Indian Ocean, albeit more events initiated there, but stronger over the western Pacific in QBOE than QBOW. This zonal heterogeneity in the difference of MJO precipitation between the two QBO phases is puzzling because QBO is a zonally

Table 1
Statistics of the MJO Events During NDJFM (DJF) in QBOW and QBOE Defined as the QBO Index Greater or Less Than 0 (±0.5 Standard Deviation)

	QBOW	QBOE	Total
Number of months	107 (47)	83 (33)	190 (80)
Number of MJO events formed west of the MC	34 (10)	29 (15)	63 (25)
Number of MJO-B events	20 (6)	8 (3)	28 (9)
Percentage of MJO-B versus total	59% (60%)	28% (20%)	44% (36%)
Monthly probability of MJO-B	19% (13%)	10% (9%)	15% (11%)
Number of MJO events formed over the Indian Ocean	19 (8)	21 (11)	40 (19)
Monthly frequency of MJO events formed over the Indian Ocean	18% (17%)	25% (33%)	21% (24%)
Total MJO days	1054 (358)	1202 (659)	2256 (1017)
Percentage of MJO days	33% (25%)	48% (67%)	30% (42%)

Note. MJO = Madden-Julian Oscillation; QBO = quasi-biennial oscillation; QBOE = QBO easterly phases; QBOW = QBO westerly phases; NDJFM = November to March; DJF = December to February; MC = Maritime Continent.

symmetric phenomenon. This is further complicated by the zonal heterogeneity in the difference of total precipitation between the two QBO phases.

It is known (Collimore et al., 2003; Liess & Geller, 2012) that total precipitation (as opposed to MJO precipitation) over the western Pacific and the eastern part of the MC is significantly stronger in QBOE than QBOW during boreal winter (Figure 5a). The difference becomes much greater when a more restrictive QBO phase definition (QBO index $>$0.5 standard deviation (Yoo & Son, 2016) is used. But when MJO days (from starting to ending dates) are excluded from the calculation of mean precipitation, the difference pattern changes substantially. Now the significantly stronger precipitation in QBOE disappears from the western Pacific but emerges over the eastern Indian Ocean (Figure 5c). This drastic change in the difference pattern suggests two possibilities: First, stronger total precipitation in QBOE over the western Pacific is mostly contributed by the MJO; and second, over the Indian Ocean, increases in precipitation not related to the MJO from QBOW to QBOE are compensated by decreases in MJO precipitation seen in Figure 3c.

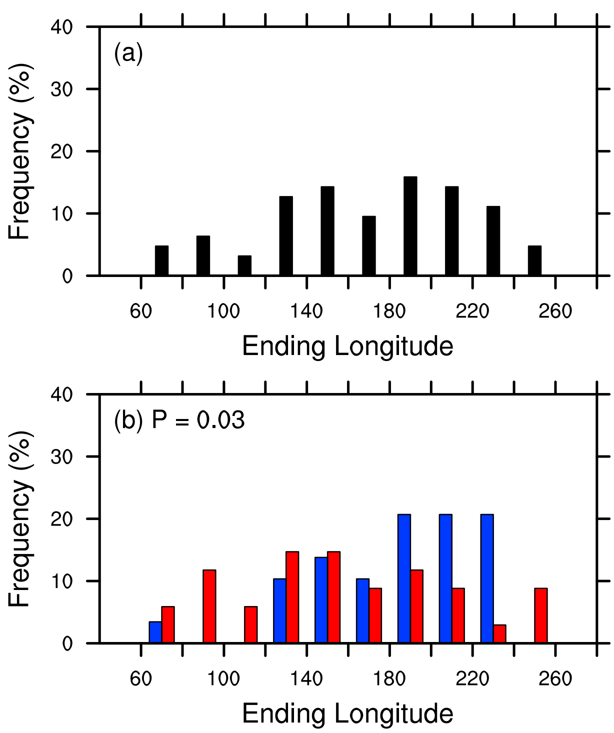

Figure 4. Frequency distributions of ending longitudes for tracked MJO events that are formed west of the Maritime Continent (40°W–100°E) during November to March for (a) both quasi-biennial oscillation easterly phases and quasi-biennial oscillation westerly phases together; (b) quasi-biennial oscillation easterly phases (blue) and quasi-biennial oscillation westerly phases (red). The *p* value in (b) is for a K-S test.

The zonal heterogeneity in responses of precipitation to QBO can be summarized as the following. Precipitation of the MJO increases from QBOW to QBOE over the Pacific but decreases over the Indian Ocean (Figure 3). Total precipitation significantly increases from QBOW to QBOE only in the Pacific (Liess & Geller, 2012). Over the western and central Pacific, the increase in total precipitation comes mainly from the MJO. Over the Indian Ocean, responses of MJO and non-MJO precipitation to QBO are opposite to each other, resulting in nonsignificant change in the total.

One possible explanation for this zonal heterogeneity is that the MJO response to QBO depends upon the mean background state which is not zonally uniform. To explore this possibility, we calculated NDJFM means of several variables deemed relevant to the MJO. We found that influences of the MJO on the background state exist not only in precipitation (Figures 5a and 5c) but also in other variables. Low-level (850 hPa) westerly anomalies increase significantly from QBOW to QBOE over the southeastern tropical Indian Ocean and the Timor Sea (Figure 5b), which is a pathway of MJO propagation through the MC (H-M. Kim et al., 2016; Zhang & Ling, 2017). This increase in 850 hPa zonal wind is completely from the MJO and disappears when the mean is recalculated with MJO days removed (Figure 5d). In calculating the NDJFM mean state of other variables for the two QBO phases, we thus excluded all MJO days to minimize possible effects from the MJO on the mean state. Results are similar with or without removing the seasonal cycle.

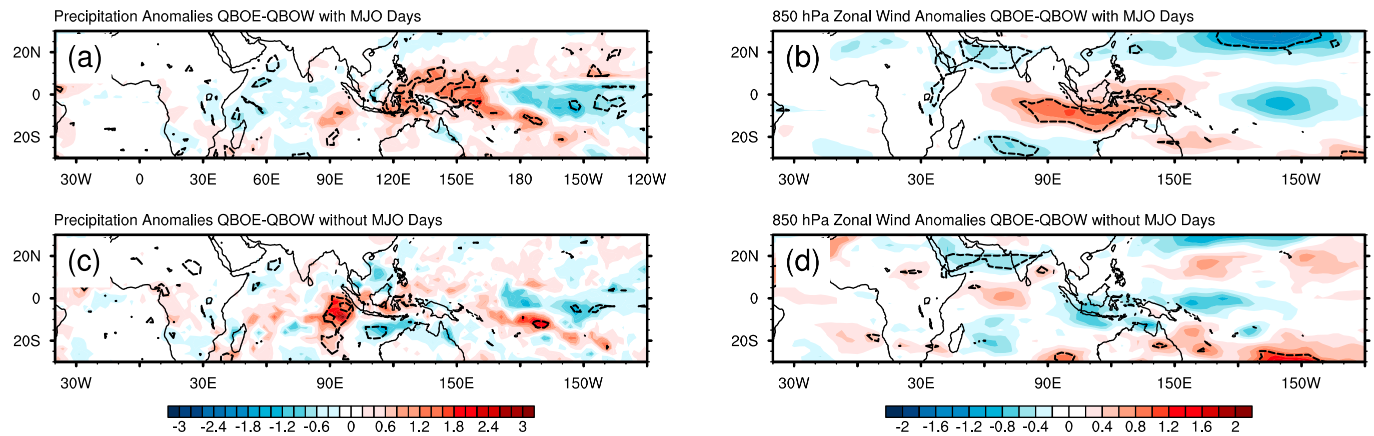

Figure 5. Differences in seasonal (November to March) means of (a) precipitation (mm d^{-1}) and (b) 850 hPa zonal wind between the two quasi-biennial oscillation (QBO) phases (QBO easterly phases (QBOE) − QBO westerly phases (QBOW)); (c and d) are the same as (a) and (b) but with Madden-Julian Oscillation (MJO) days excluded. Significance at the 95% confidence level is highlighted by dashed lines.

The mean high-cloud coverage is significantly large in QBOE than QBOW over the MC (Figure 6a). This might be a reason for far fewer MJO-B events in QBOE than QBOW. A modeling study has suggested that reduction in insolation due to large cloud coverage would damp the amplitude of the diurnal cycle in land convection, which creates a favorable condition for MJO propagation through the MC (Hagos et al., 2016). The larger high-cloud coverage in QBOE might be a result of deeper mesoscale convective systems due to a higher tropopause over the MC (Figure 6d).

Mean SST exhibit very interesting patterns in its difference between the two QBO phases (Figure 6b) that is similar to the pattern of the negative phase of the Indian Ocean Dipole (Saji et al., 1999; Webster et al., 1999). SST has been thought to be important to explain the general response of deep convection to QBO (Nie & Sobel, 2015). But its significant differences between the two QBO phases are outside the areas of significant differences in precipitation and high clouds.

There is no significant difference in sea level pressure between the two QBO phases (not shown). Changes in lower-tropospheric (900–500 hPa) specific humidity between the two QBO phases are not indicative either (Figure 6c).

3.5. Sensitivity to Analysis Parameters

We have two main parameters in our analysis. One is the length of boreal winter. All results presented so far are based on extended boreal winter (NDJFM), which was used by Hood (2017) and Yoo and Son (2016). Most

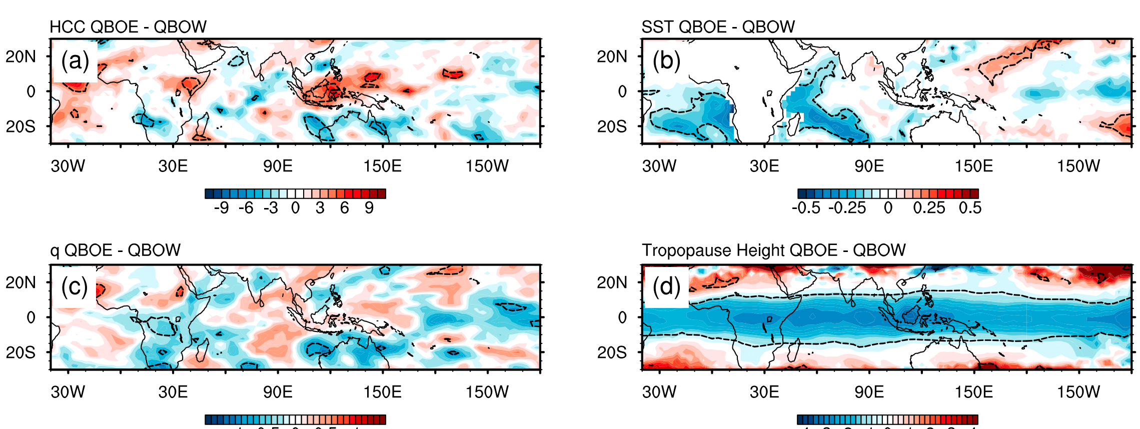

Figure 6. Difference between the two quasi-biennial oscillation (QBO) phases (QBO easterly phases (QBOE) − QBO westerly phases (QBOW)) during November to March for (a) high-cloud coverage (HCC) (%), (b) sea surface temperature (SST) (°C), (c) specific humidity integrated over 900–500 hPa (g kg^{-1}), and (d) tropopause height (hPa) with November to March days excluded. Significance at the 95% confidence level is highlighted by dashed lines.

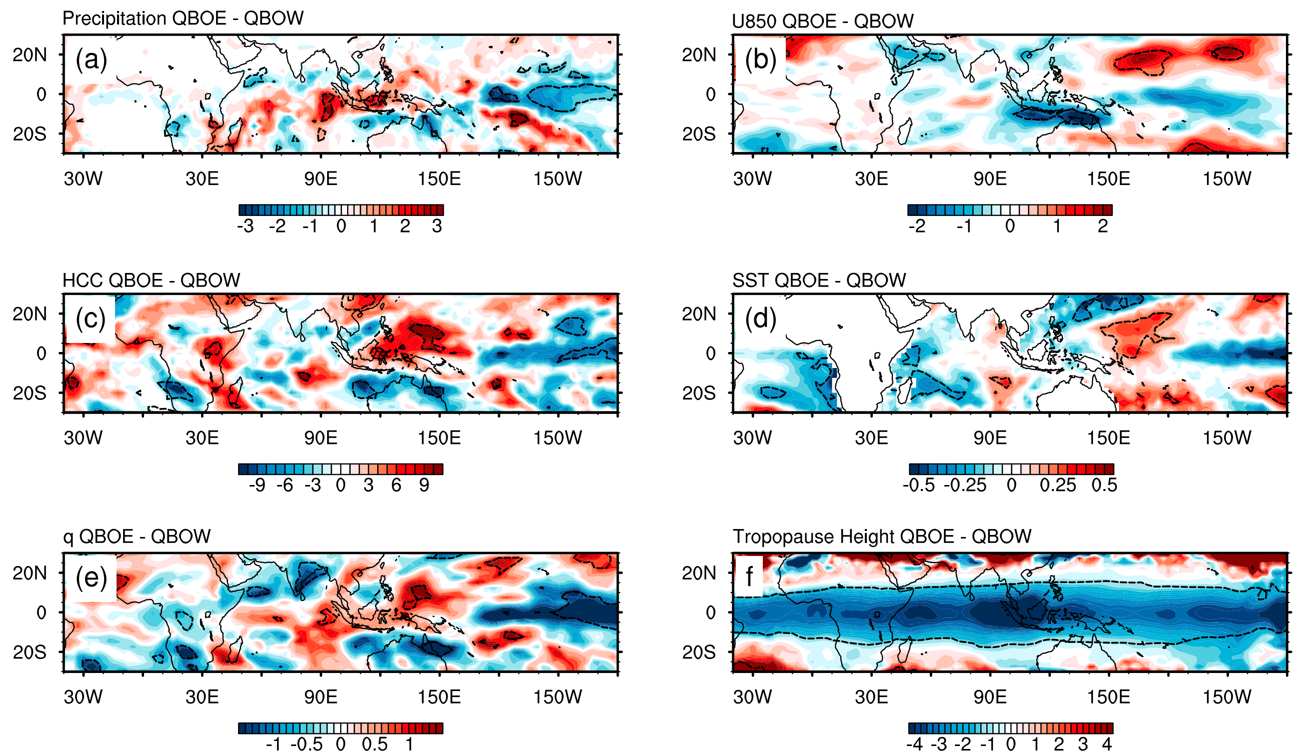

Figure 7. Difference between the two quasi-biennial oscillation (QBO) phases (QBO easterly phases (QBOE) − QBO westerly phases (QBOW)) defined by QBO index greater or smaller than 0.5 standard deviation during Dcember to February with Madden-Julian Oscillation days excluded for (a) precipitation (mm d^{-1}), (b) 850-hPa zonal wind (m s^{-1}), (c) high-cloud coverage (HCC) (%), (d) sea surface temperature (SST) (°C), (e) specific humidity integrated over 900–500 hPa (g kg^{-1}), and (f) tropopause height (hPa). Significance at the 95% confidence level is marked by dashed lines.

other previous studies on the same subjects (Marshall et al., 2017; Nishimoto & Yoden, 2017; Son et al., 2017) used the traditional boreal winter definition of DJF. The second main parameter in our analysis is the definition of westerly and easterly phases of QBO. We used a less restrictive one that requires the QBO index to be positive or negative. This definition of QBO phases (hereafter briefly referred to as the definition by the sign) has been used before (Hamilton, 1984; Marshall et al., 2017). Other studies on the same subject (Nishimoto & Yoden, 2017; Son et al., 2017; Yoo & Son, 2016) used a more restrictive definition of QBO phases that requires the positive/negative QBO index to be greater than 0.5 standard deviation (briefly as the definition by the standard deviation). Of all the combinations of the definitions of boreal winter and QBO, NDJFM with the QBO definition by the sign yielded largest sample sizes and weakest yet significant signals, which are what we have presented in this study so far. DJF with the QBO definition by the standard deviation yielded smallest sample sizes and strongest signals which, however, may not be statistically significant because of the small sample sizes. Next, we compare the results shown so far based on the most relaxed definitions of the season and QBO to those based on the most restrictive definitions.

For DJF and using the QBO definition by the standard deviation, we reproduced the results shown in Figures 1–3. The PDFs of ending longitudes for the MJO in the two QBO phases (Figure 4) are no longer statistically distinct because of the small sample sizes. The contrast between the two QBO phases in the percentage of MJO-B versus total MJO events, monthly probability of MJO-B events, monthly frequency of MJO events formed over the Indian Ocean, and percentage of MJO days all remain the same and, in most cases, become stronger (Table 1 in parentheses).

Differences in the mean state between the two QBO phases remain qualitatively the same when the most relaxed and restrictive definitions of the season and QBO are used, although the strength and spatial coverage of significant signals may vary (Figures 5–7). One exception is 850 hPa zonal wind. While its difference between the two QBO phases are insignificant over the Indo-Pacific warm pool for NDJFM and the QBO definition by the sign (Figure 5d), significantly easterly anomalies emerge south of the MC in QBOE in comparison

Table 2
Statistics of the MJO Events During NDJFM and the Two QBO Phases Defined by the Sign of the QBO Index and Months of the Two QBO Phases in El Niño and La Niña Events

	QBOW	QBOE	Total
Number of all MJO events	48	38	86
Number of MJO events in El Niño	16	8	24
Number of MJO events in La Niña	15	10	25
Percentage of MJO events in El Niño versus all	33%	21%	25%
Percentage of MJO events in La Niña versus all	31%	26%	29%
Number of months in El Niño	35	17	52
Number of months in La Niña	32	25	57
Percentage of months in El Niño versus all	32%	20%	27%
Percentage of months in La Niña versus all	30%	30%	30%

Note. MJO = Madden-Julian Oscillation; QBO = quasi-biennial oscillation; QBOE = QBO easterly phases; QBOW = QBO westerly phases; NDJFM = November to March.

to QBOW for DJF and the QBO definition by the standard deviation (Figure 7b). This is a consequence of a northward shift of the climatological mean low-level westerly in the region from QBOW to QBOE in DJF (not shown).

Previous studies have found that ENSO does not significantly alter the observed connection between QBO and tropical convection in general (Liess & Geller, 2012) and between QBO and the MJO in specific (Son et al., 2017). It is also known that ENSO and the MJO do not exhibit any simultaneous relationship in boreal winter (Hendon et al., 2007; Hendon et al., 1999). They are significantly related with MJO leading El Niño by 6–12 months (Zhang & Gottschalck, 2002). Possible influences of ENSO on the QBO-MJO connection are, however, still a concern (Nishimoto & Yoden, 2017). One may wonder, for instance, if the stronger barrier effect of the MC on MJO propagation in QBOW than QBOE might be a consequence of ENSO influences. Slightly more MJO-B events were found during El Niño than other years (Kerns & Chen, 2016).

We found that numbers of MJO events in QBOW and QBOE differ only slightly for the two ENSO phases (Table 2). Thus, the contrast in MJO behaviors in the two QBO phases cannot be explained in term of ENSO, as previously pointed out (Son et al., 2017). We also noticed, however, that La Niña events are more likely than El Niño events to occur in QBOE, and El Niño events are more likely to occur in QBOW than QBOE (Table 2). The possibility that such a skewed distribution of ENSO events in the two QBO phases may lead to biases in our results cannot be ruled out without scrutiny. For this, we reproduced our results without El Niño or La Niña years and found they are consistent to those based on all years. This indicates that ENSO does not significantly affect the way QBO modulates tropical convection, the MJO, and their mean states, confirming the previous results from Liess and Geller (2012) and Son et al. (2017).

4. Summary and Discussion

The recently found QBO-MJO connection was investigated using a method of identifying individual MJO events by tracking their eastward propagation signals in precipitation anomalies. This new method of identifying MJO events yielded new interpretations for stronger MJO activities in QBOE than QBOW that were suggested by previous studies using EOF-based global MJO indices, such as the RMM index (Wheeler & Hendon, 2004) and OMI (Kiladis et al., 2014). Stronger MJO activities in QBOE than QBOW (Marshall et al., 2017; Nishimoto & Yoden, 2017; Son et al., 2017; Yoo & Son, 2016) are due to a greater number of MJO days during QBOE than QBOW, not greater amplitudes of individual MJO events as previously thought. The greater number of MJO days in QBOE are consequences of both more MJO events initiated over the Indian Ocean and their longer durations. This longer MJO duration, previously documented (Nishimoto & Yoden, 2017), results from a weaker barrier effect of the MC on MJO propagation.

A possible reason for the weaker barrier effect of the MC is greater coverage of high cloud during QBOE than QBOW. A previous study has found that reduced insolation by high cloud weakens the diurnal cycle in land convection, which is an important factor of the barrier effect of the MC (Hagos et al., 2016). The greater coverage of high cloud over the MC during QBOE is consistent to the largest QBOW-to-QBOE increase in the tropopause height there in comparison to the rest of the tropics. This possible role of high cloud needs to be confirmed or refuted.

The results from this study highlight the zonal heterogeneity of tropospheric response to QBO and contrast between responses in MJO and total precipitation. Our results suggest that the observed increase in total precipitation over the western Pacific is mainly due to increased MJO activities. In contrast, insignificant responses to QBO in total precipitation over the Indian Ocean is likely due to compensation between increases in non-MJO precipitation and reduction in net MJO precipitation.

The main results from this study are sensitive to neither the definitions of boreal winter (December–February versus November–March) and QBO phases (QBO index greater/less than 0 versus 0.5 standard deviation) nor whether ENSO years are included. A by-product of this study is its finding of considerable contributions to the mean state by the MJO. This suggests that the previously advocated possible roles of the mean state in the MJO (D. Kim et al., 2011; Ray et al., 2011) need to be reevaluated with MJO days removed from the calculation of the mean state.

Reasons for the zonal heterogeneity and contrast between MJO and total precipitation in their responses to the two QBO phases are still unclear. While all previously suggested mechanisms (e.g., changes in the tropopause height and temperature, wind shear across the tropopause, and static stability in the upper troposphere) are plausible, they alone cannot explain the zonal heterogeneity and contrast between the responses of MJO and total precipitation to QBO. We too failed to find an obvious and convincing explanation for the zonal heterogeneity in the differences of MJO and total precipitation between the two QBO phases and for the QBO-MJO connection in general. Tentative and speculative explanations offered in this study need to be substantiated. It is likely that an understanding of this problem would not be reached from conventional data analysis or numerical modeling. Innovative approaches are needed. Our results suggest that to understand the observed QBO-MJO connection, we need to pay special attention to MJO initiation over the Indian Ocean and to the barrier effect of the MC on MJO propagation.

Results from this and previous studies on the different behaviors of the MJO between the two QBO phases may have substantial implications to our general understanding of MJO dynamics. Current MJO theories mostly emphasize processes in the lower to mid troposphere and boundary layer (Adames & Kim, 2016; Majda & Stechmann, 2009; Wang et al., 2016; Yang & Ingersoll, 2013). A possible effect of cloud-radiation on the MJO is the only upper-tropospheric factor considered in an MJO theory (Adames & Kim, 2016). A recent study (Powell & Houze, 2015) suggested a possible role of upper-tropospheric motions in MJO initiation over the Indian Ocean. A full explanation of the observed different behaviors of MJO activities between the two QBO phases is possible perhaps only when potential roles of upper-tropospheric or even stratospheric processes are fully considered in MJO theories.

The observed QBO-MJO connection may also have substantial implications to subseasonal-to-seasonal prediction. The MJO and QBO are two potential sources of S2S predictability. The degree to which their connection would affect overall S2S predictability and prediction skill is an extremely important issue to advance S2S prediction. Increased MJO prediction skill in QBOE in an operational model (Marshall et al., 2017) is very encouraging. It would be interesting to explore whether the overall S2S prediction skill is higher in QBOE than QBOW and if so, to what degree it is related to the MJO.

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