Quasi-biweekly oscillation of the Asian monsoon rainfall in late summer and autumn: different types of structure and propagation

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Abstract

This study contrasts two types of quasi-biweekly oscillations (QBWOs) over tropical Asia in late-summer and autumn (from August to October). Using a tracking method to calculate the frequency of QBWO events over the Asian monsoon region, two types of QBWOs in monsoon rainfall are revealed. One originates from 110° to 140°E and propagates westward to southern China with a notable impact on the regional rainfall, while the other initiates from 160°E to the dateline and does not affect southern China rainfall significantly. Analysis of the vertical structure of moisture flux shows that the moisture source for type 1 events is dominated by the zonal flux component and that for type 2 the meridional flux component. The nature of the moisture flux determines whether the oscillation can propagate across 120°E and affect rainfall over southern China. Results also show that the strength of the South Asian high and the western Pacific subtropical high differently modulate the generation of the two types of QBWOs. Specifically, mutually stronger (weaker) highs favor the first (second) type of the oscillation. A close relationship also exists between the QBWOs and western Pacific sea surface temperature (SST) anomalies, suggesting that the SST anomalies can potentially trigger the QBWOs.

Keywords Quasi-biweekly oscillation · Intraseasonal variability · Boreal summer intraseasonal oscillation · Asian monsoon

1 Introduction

Two dominant intraseasonal oscillation (ISO) modes exist in the Asian summer monsoon system: a 10–20-day oscillation, which is also called the quasi-biweekly oscillation (QBWO), and a 30–60-day oscillation. The QBWO was perhaps first discovered over the Indian Ocean region (Keshavam 1971; Keshavamurty 1972). It propagates westward and is closely linked to activity (e.g., active and inactive periods) of the

monsoon. Previous studies have compared the QBWO with the 30–60-day oscillation and found many differences between the two modes (Chen and Chen 1993, 1995; Chen et al. 2000; Annamalai and Slingo 2001; Yokoi et al. 2007; Yang et al. 2008; Li et al. 2015). Wang et al. (2009) revealed that the quasi-biweekly and 30–60-day modes of intraseasonal variation are characterized by different source regions and life cycles. However, compared to the Madden–Julian Oscillation (MJO) and other 30–60-day oscillations (Zhang et al. 2013; Ling et al. 2017a, b), the characteristics of QBWOs are much less understood, especially when considering the maintenance mechanisms and the effects of the QBWO on weather and climate outside the tropics.

Figure 1 exhibits the variance of quasi-biweekly filtered GPCP rainfall (contours) and the ratio of quasi-biweekly variance to 30–60-day variance (shading) during late-summer and autumn (August to October, or ASO) for 1997–2014. As the shading shows, in most parts of the Asian monsoon region, QBWO variance is much larger than that of 30–60-day variability. The maximum variance of QBWOs (contours) appears in regions of active Asian monsoon convection. Large centers are located in the Bay of Bengal, the South China Sea, and the western Pacific Ocean. Especially

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Fig. 1 Variance of quasi-biweekly rainfall (contour; interval $20 \text{ mm}^2/\text{day}^2$) and ratio of QBWO variance to 30–60-day variance (shading) during late-summer and autumn (from August to October)

noteworthy is that the ratio of variance is about 3 (grey shading) in the active QBWO center, indicating that the variance of QBWOs is dominant over the Asian monsoon region. Similar behavior can also be found in the spring season [see Fig. 4 in Wen and Zhang (2008)]. Although QBWO variance is larger than variance associated with the 30–60-day oscillation in the tropics, it may not be as spatially coherent. Many studies, especially those based on empirical orthogonal function (EOF), do not show a 10–20-day oscillation as the leading EOF mode. For example, Lin (2012) found that the first two modes of outgoing longwave radiation (OLR) and winds represented the 30–60-day oscillation and the next two modes were related to QBWOs. Lee et al. (2013) also found that the first two EOF modes in the boreal summer intraseasonal oscillation index were consistent with the 30–60 day mode and the fourth mode was has timescale of the QBWO (the third mode was dominated by 20–30 day variability). Due to the orthogonality of EOF modes, the physical meaning of the third and fourth modes was limited. Therefore, EOF methods may not be the most suitable tool for studying QBWOs. In addition to the EOF analysis, tracking methods are often used to study intraseasonal oscillations. For MJO events, Kerns and Chen (2016) used a two-dimensional (2D) method that could track convective centers in both longitude and latitude. Zhang and Ling (2017) defined a one-dimensional (1D) method that only focuses on zonal propagation in longitude. For QBWO events, Kikuchi and Wang (2009) used a 2D method to track QBWOs from a global perspective. There are relatively fewer studies using tracking methods to investigate QBWOs than 30–60 day variability. Since QBWO events are more irregular, and propagate both eastward and westward (Kikuchi and Wang 2009), it is more difficult to track and monitor the QBWO than longer timescale intraseasonal disturbances such as the MJO, including the development of EOF-based indices to monitor such events. Tracking methods provide advantages over EOF-based methods for detection and monitoring of ISO events. For example, tracking methods currently used in MJO studies can better capture quantitative information about the MJO compared to the traditional EOF analysis. In

particular, tracking methods provide a more detailed analysis of the source, frequency, intensity, and propagation distance of these oscillations (Ling et al. 2017a, b). Following Zhang and Ling (2017), we applied a 1-D tracking method to analyze QBWO events that tracks these events in longitude, complementing the 2D tracking method of Kikuchi and Wang (2009).

QBWO activity is clearly seasonal and regional, much like for the 30–60 day boreal summer ISO where the climatological propagation characteristics of convective anomalies in the Indian Ocean to western Pacific are quite different from May to June (MJ) that during ASO (Kemball-Cook and Wang 2001). In the Asian monsoon region, the summer QBWO propagates westward, and the main genesis region for disturbances is the western Pacific Ocean (Kikuchi and Wang 2009; Jia and Yang 2013). Fukutomi and Yasunari (1999) noted that on the time scale of 10–25 days, convection was associated with well-organized low-level cyclonic circulation anomalies over the South China Sea. Annamalai and Slingo (2001) showed that QBWO is more regional than 30–60 day variability, and the QBWO is mainly generated in the western Pacific with prominent zonal propagation. The propagation characteristics of the QBWO vary substantially with month of the year given its diverse origins in different seasons (Wen and Zhang 2008; Chen and Sui 2010; Wen et al. 2010). Although extra-tropical processes over land can affect the intraseasonal variability of monsoon rainband (Wang et al. 2017b), Wang et al. (2017a) showed that the boreal summer QBWO in the Asian monsoon region has its primary origins in the western equatorial Pacific and it propagates northwestward into the Bay of Bengal. Therefore, we focus on the QBWO in the Asian monsoon region in this study. While the study of Kikuchi and Wang (2009) emphasized global behavior of QBWOs, here we focus on regional QBWO events that begin in the western Pacific and propagate westward.

The paper is organized as follows. In Sect. 2, we describe the data sets and methodology. We modify the MJO tracking method of Zhang and Ling (2017) for use in tracking QBWO events. In Sect. 3, the propagation characteristics and

vertical structures of two types of QBWOs are discussed. In Sect. 4, the large-scale circulation anomalies associated with QBWOs are investigated. Summary and discussion are given in Sect. 5.

2 Data and methodology

2.1 Data

To represent QBWO events in Asian monsoon rainfall, we use daily rainfall data from 1996 to 2015 from the Global Precipitation Climatology Project, version 1.2 (Huffman et al. 2001, 2016), with a horizontal resolution of $1^\circ \times 1^\circ$. ERA-Interim data from the European Centre for Medium-range Weather Forecasts (Simmons et al. 2007) with a resolution of $0.75^\circ \times 0.75^\circ$ are used to study dynamic and thermodynamic atmospheric fields during QBWO events. We also use daily sea surface temperature (SST) derived from the NOAA high-resolution ($0.25^\circ \times 0.25^\circ$) blended analysis, OISSTV2 (National Climatic Data Center 2007; Reynolds et al. 2007; Banzon and Reynolds 2013), which includes daily SST and sea ice. The Real-time Multivariate MJO (RMM) index of Wheeler and Hendon (2004) is used to analyze the relationship between the QBWO and MJO. The RMM index is derived using a multivariate EOF analysis on equatorial wind anomalies in the upper and lower troposphere and outgoing longwave radiation anomalies.

2.2 Tracking method

As discussed earlier, EOF analysis is more suitable for MJO study (e.g. Lin 2012; Lee et al. 2013; Maloney et al. 2014) than for QBWO study, since the first two EOF modes derived from unfiltered anomalies are dominated by 30–60 day variability. Considering that QBWOs have higher variance but are less spatially-coherent, tracking methods seems to be a more effective means of analyzing the QBWO. Following the method of Zhang and Ling (2017), which objectively identified the eastward movement of positive rainfall anomalies along the equator, we track the QBWO using GPCP rainfall anomalies. This method focuses primarily on 1D motion in longitude. The method of Zhang and Ling is able to provide several characteristics of the identified events (Fig. 2 in Zhang and Ling 2017), such as the starting longitude and time, ending longitude and time, propagation speed and range, strength, life span, and zonal scale. These quantities are not provided by conventional EOF-based indices. The Zhang and Ling (2017) method could also be conceivably used in other tropical or extra-tropical wave disturbances. For example, easterly waves or convectively coupled Rossby waves could be tracked by changing the settings of

the tracking method or by preprocessing the data to preselect certain wavenumbers and frequencies.

The tracking method is introduced point by point in Zhang and Ling (2017), which we will only briefly summarize here. There are three main steps in the method: data preparation, a six-step process to track movement of the anomalies, and then a final selection step consisting of three criteria (propagation range, propagation speed, interval between events). In our study, most of them are still suitable. To apply the method to QBWOs over the Asian monsoon region, we modify the Zhang and Ling (2017) method as follows:

- In the data preparation stage, the original tracking method uses the fast Fourier transform (Gottschalk et al. 2013) to obtain eastward-propagating intraseasonal (20–100-day) precipitation signals using equatorial symmetric data. Since the strongest QBWO signals in summer are over the Asian monsoon region (not equatorially symmetric), we replace the fast Fourier transform with the Lanczos filtering (Duchon 1979) to get 10–20 day subseasonal signals.
- After filtering, rainfall anomalies are averaged between 10° – 25° N.
- For better identifying the tracking lines which show QBWO events, nine-point local smoothing is performed as the last step of data preparation.
- In the tracking stage, the analysis domain is from 40° E to 160° W.
- Only data from late summer to early autumn (from August to October) are used for 1997–2015.
- The interval between two tracked events is required to be longer than 5 days (for MJO, its interval is from 20 to 25 days), with characteristics of propagation speed and range discussed in more detail below.
- Considering that the QBWO primarily originates over the western Pacific and propagates westward (Kikuchi and Wang 2009), we set a reference longitude to 120° E for effectively identifying MJO events over the western Pacific (about 90° E in Zhang and Ling 2017) and only track westward movement. Because of this, all tracking lines will be positive.

2.3 Other analysis methods

Lanczos filtering (Duchon 1979) is applied to extract QBWO signals from OLR and atmospheric circulation fields based on a 10–20-day filtering window. For the 10–20-day oscillation, a Lanczos digital filter with 61 daily weight coefficients would provide a sharp cutoff response with negligible Gibbs oscillation. In addition, a composite analysis approach is applied to investigate the large-scale features associated with

the QBWOs. The Student's t test is used to assess the statistical significance of the results obtained.

3 Propagation and vertical structures of QBWO

3.1 Definitions of QBWO types and their propagation characteristics

Using the tracking method defined in Sect. 2, we identified a total of 88 events from the 1997–2015 rainfall data. We first obtained statistics about propagation speed, propagation range, and zonal scale, and then removed irrelevant events on this basis (see “Conclusions and discussion” below).

Most frequently the speed of tracked events (Fig. 2a) is between -5 m s^{-1} and -3 m s^{-1} with an average speed of

about -7 m s^{-1} (negative value means westward propagation), a bit faster than that of the MJO which has an average speed about $+5 \text{ m s}^{-1}$ (see Fig. 3 of Zhang and Ling 2017). Second, the most frequent propagation range of events (Fig. 2b) is about 40° . Few events have a propagation range of more than 80° . For MJO events, the propagation range can exceed 120° . This result confirms that QBWO events are more regional compared to the MJO, which has a more global character. Further, the dominant zonal scale of QBWO precipitation (Fig. 2c) is between 10° to 20° and that of MJO events is about 30° , which is about twice that of the QBWO.

Based on the aforementioned QBWO attributes, we chose QBWO events with westward propagation speed between 2 m s^{-1} and 10 m s^{-1} , which results in 21 events (23.9%) being excluded. We also choose events with propagation distance greater than 20° , which resulted in the exclusion of an additional 11 events (12.5%). A total of 59 QBWO events are thus retained in our analysis.

To further explore the characteristics of the selected QBWO events, such as the starting and ending longitudes, propagation speed, range, and strength, individual and joint frequency distributions are provided (see Fig. 3). The starting longitudes of QBWO events cluster in two different regions (Fig. 3a). One region is 110° – 140°E (the South China Sea) and the other is from 150°E to the dateline (the western Pacific). The joint frequency distributions indicate that the starting and ending longitudes are strongly correlated, with a correlation coefficient of 0.69. As mentioned above, these events propagate on average about 40° of longitude (Fig. 2b). The QBWO events that originate in the South China Sea end primarily between 60° and 90°E (the Indian Ocean), while those originating in the western Pacific end primarily between 110° and 130°E (the South China Sea). In addition, a few QBWO events generated between 170°W and 160°W disappear in the western Pacific. The average strength is defined as the rain rate averaged along a track the starting to end point. The strength of QBWO events is distributed over a range of 2–5 mm/day (Fig. 3b), regardless of whether the events originate from the South China Sea or the western Pacific. However, the ones that originate between 170°W and 160°W are weaker. Further, a clear connection exists between QBWO strength and its zonal scale (Fig. 3c), although there is no well-defined connection between the propagation range and zonal scale (Fig. 3d).

Intraseasonal oscillations such as the QBWO are closely related to the East Asian monsoon rainfall (Lau et al. 1988). Therefore, to understand how QBWO events that originate in the western Pacific affect the climate in the East Asian monsoon region, we use the starting longitude (Fig. 3a) as a criterion to define two types of QBWO events for the subsequent analysis. Among the total of 59 QBWO events, the events with a starting longitude between 110°E and 140°E

Fig. 2 Distributions of **a** propagation speed, **b** propagation range, and **c** averaged zonal scale of all tracked westward QBWO events based on GPCP data. Triangle marks the mean

Fig. 3 Individual and joint frequency distributions of **a** starting longitude (units: degree) vs ending longitude: **b** starting longitude vs mean strength (units: mm/day), **c** mean zonal scale (units: degree) vs mean strength, and **d** mean zonal scale vs propagation range of tracked QBWO events

are defined as type 1, and those with a starting longitude between 150°E and the dateline are defined as type 2. Using these definitions, 22 type-1 events and 20 type-2 events are defined. To better illustrate the westward propagation of the two types of QBWOs, longitude-time sections of 10–20-day filtered precipitation composites are shown (Fig. 4). The composite type-1 events originate at 140°E and end to the east of 90°E 12 days later (Fig. 4a). The most prominent propagation occurs in the South China Sea. The main propagation region of type-2 events occurs over the Philippine Sea and lasts for about 10 days (Fig. 4b).

3.2 Three dimensional QBWO structure

Comparing the two types of QBWO indicates several important structural differences at initiation. At day 0 for the type-1 events (Fig. 5a), a negative rainfall anomaly near Vietnam is accompanied by an anti-cyclonic circulation. A positive rainfall anomaly occurs in the western Philippine Sea, accompanied by a cyclonic circulation. For the type-2 events (Fig. 5b), the center of positive rainfall anomaly is weighted more toward the east side of the cyclonic

circulation than for the type-1 disturbances, associated with southwesterly anomalies. The northeasterly wind anomaly between the cyclonic and anti-cyclonic circulations that extends into the Philippines is associated with suppressed rainfall.

Moisture flux convergence for the two types of QBWO disturbances is examined next. The most intense centers of both types of QBWOs occur mainly over the band of 15° – 20°N (Fig. 5). Hence, Fig. 6 shows a longitude-height cross-section of the moisture flux convergence and wind anomalies averaged between 15° and 20°N at day 0. Consistent with previous observations, at the initiation of type-1 events, total moisture flux convergence (Fig. 6a) is mainly focused in the eastern Philippines (120° – 130°E) and accompanied by strong upward motion, while the corresponding sinking branch is near the Indo-China Peninsula (110°E). This moisture flux convergence anomaly is mainly provided by its zonal (Fig. 6b) and vertical (Fig. 6d) flux convergence components. However, the positive moisture convergence anomaly of type-2 disturbances (Fig. 6e) occurs over the ocean in the region of 140° – 160°E , accompanied by strong upward motion, while the corresponding sinking branch is located near 130°E . The moisture flux convergence of type-2

Fig. 4 Longitude-time section (averaged for 10°N–25°N) of 10–20-day filtered precipitation anomalies of type 1 (a) and type 2 (b). Only significant values above the 95% confidence level are highlighted

Fig. 5 Maps of 10–20-day filtered precipitation (shading; units: mm/day) and 850-hPa wind (vector; units: m s^{-1}) anomalies at day 0 for type 1 (a) and type 2 (b). Only the significant values above the 95% confidence level are highlighted

QBWOs is dominated by the meridional (Fig. 6g) and vertical (Fig. 6h) components. We note that cause and effect regarding precipitation and moisture flux convergence anomalies is difficult to determine, since the heating associated

with convection can drive tropical convergence anomalies (e.g. Neelin and Held 1987). However, dry dynamical considerations have been documented to be important for driving vertical motion that focuses convection in some disturbances (e.g. Kiladis et al. 2006; Rydbeck and Maloney 2015).

Note that significant difference in positive anomalies occurs near 120°E east of the Philippines, where the type-1 QBWO originates (Fig. 5a) and propagates to mainland China, and the type-2 QBWO weakens and disappears (Fig. 5b). We plot the 105°–115°E averaged latitude-height cross-section to present the downward branch of the type 1 QBWO, and the 120°–130°E averaged latitude-height cross-section to present the upward branch (Fig. 7). For the type 2 QBWO, we plot the 125°–135°E and 120°–130°E averages to present the downward and upward branches, respectively (Fig. 8). The leading moisture convergence is mainly provided by the zonal component for type 1 (Fig. 7f), and by the meridional component for type 2 (Fig. 8g) QBWO disturbances. It is worth noting that the source of water vapor in the middle-upper atmospheres for both type 1 and type 2 are provided by vertical moisture flux (Figs. 7h, 8h), although cause and effect relative to precipitation anomalies is difficult to determine from this analysis. In general, the structures of type-1 and type-2 QBWOs are different, and the generation mechanisms of the two types may also be different.

Fig. 6 Composite patterns of 15° – 20° N averaged longitudinal–height cross-section of moisture flux convergence (shading; units: $10^{-5} \text{ g kg}^{-1} \text{ s}^{-1}$) and wind field (vector; units: m s^{-1}) anomalies for type 1 (left) and type 2 (right) disturbances. (a, e), (b, f), (c, g), and (d, h) are for total, zonal, meridional, and vertical moisture flux convergence components, respectively. Vertical velocities are scaled by a factor of 250 for visualization. 95% significance stippling is shown

3.3 Life cycles of QBWO events

A lagged composite analysis of 10–20-day filtered precipitation and 850-hPa wind anomalies illustrates the life cycles of the two types of QBWOs. The left column of Fig. 9 presents the life cycle of the type-1 QBWOs. On day 0, the negative anomaly of rainfall occurs in the Beibu Gulf, while the positive anomaly appears to the east of the Philippines (Fig. 9a). This positive anomaly propagates westward and becomes stronger over the South China Sea with an associated cyclonic circulation (Fig. 9b–c). The positive anomaly then reaches the Indo-China Peninsula and southern China (Fig. 9d). On day 8 (Fig. 9e), the positive anomaly weakens over northern Vietnam, and a negative rainfall anomaly appears near 120°E . The evolution shown in Fig. 9e–h for days 8 to 14 is quite similar to that from day 0 to day 6 (Fig. 9a–d), but with opposite sign. The right column of Fig. 9 shows the life cycle of type 2 QBWOs. The starting longitude for type 2 (Fig. 9i) QBWO events is further eastward than that for type 1 (Fig. 9a). On

day 0 (Fig. 9i), a negative anomaly of rainfall occurs at 140° – 160°E , while a positive anomaly emerges east of the Philippines. From day 0 to day 6 (Fig. 9j–l), the positive rainfall center moves westward from the western Pacific. It strengthens and eventually reaches the South China Sea. From day 8 onward (Fig. 9m), the positive rainfall center continues to propagate westward but gradually weakens. The positive rainfall anomaly fades and disappears when the disturbance propagates to the south of Japan (Fig. 9n–p). The southwest–northeast tilted wind structure of type 2 QBWO disturbances in this study also bear some resemblance to the synoptic-scale disturbances described in Lau and Lau (1992).

Previous results using EOF-based methods have indicated that QBWOs originate mainly near 160°E and strong QBWOs can propagate to 110°E . An important finding from our study is that the QBWO events generated near 160°E are not necessarily linked to those events that initiate and propagate near 110°E . There are two kinds of QBWO events with different origins, propagation paths, and ranges of influence.

Fig. 7 Same as the left panels of Fig. 6, except for a latitudinal–height cross-section of type 1 disturbances. The left column is for terms averaged over 105°–115°E, and the right, over 120°–130°E

The positive anomaly of the type-1 QBWO propagates to East Asia where it affects precipitation before decaying. However, the positive anomaly of the type-2 QBWO decays over the topography of the Philippine Islands, and has little effect on mainland Asia. Comparing these two types of QBWO events, topography and interaction with land may be important factors in determining the propagation of QBWOs.

4 Variation of large-scale features associated with QBWO propagation

4.1 Relationships with western Pacific subtropical high and South Asia high

The western Pacific subtropical high (WPSH) and the South Asia high (SAH) are two important systems related to the Asian summer monsoon. Previous have studies suggested that variability of the WPSH and SAH can affect the Asian summer monsoon, and it is logical to expect an influence

on QBWOs since they are also an integral part of precipitation variability in this region. Yang et al. (2014) found that the SAH and the WPSH, which influence the evolution of QBWOs, move toward (away from) each other in early (late) summer. Wang et al. (2016) suggested that the intensity and extent of the WPSH might affect the evolution and propagation of QBWOs by modulating the occurrence and characteristics of convection. To further explore the interactions between the different types of QBWOs and the large-scale circulation, we now focus on WPSH and the SAH variations on both 10–20-day and climatological time scales in the context of their interactions with QBWOs.

As many tropical systems exhibit a prominent baroclinic structure, we first compare the characteristics of 10–20 day geopotential height anomalies at 200 hPa and 850 hPa. With the westward propagation of type-1 QBWO disturbances (Fig. 9a–d), the corresponding negative geopotential height anomaly at 850 hPa propagates westward with a cyclonic circulation (Fig. 10a–d). When the positive rainfall anomaly center is at the strongest on Day 6

Fig. 8 Same as Fig. 7, except for type-2 disturbances. The left column is for terms averaged over 125°–135°E, and the right, over 150°–160°E

(Fig. 9d), a distinct wave train appears with alternating positive–negative height and divergence/convergence anomalies (Fig. 10d). As the positive rainfall anomaly weakens over northern Vietnam on day 8 (Fig. 9e), the negative center of the height anomaly weakens (Fig. 10e). When the negative rainfall anomaly moves westward and weakens gradually near 120°E (Fig. 9f–h), the positive anomaly of geopotential height also moves westward and weakens (Fig. 10f–h). With the westward propagation of type-2 QBWO disturbances (Fig. 9i–n), negative height anomalies propagate westward from the western Pacific (Fig. 10i–l) and induce wave trains on both sides of the anomaly (Fig. 10n). For the type-1 QBWO, the resulting negative height anomaly center, which is coincident with QBWO rainfall, starts at more northerly latitudes and moves gradually southward as it propagates. The negative height anomaly for type 2 disturbances starts more southward and propagates to the northwest. Geopotential height anomalies at 500 hPa are similar to those at 850 hPa (not shown).

A wave train is also observed in the 200-hPa geopotential height field (Fig. 11). The most significant westward-propagating wave train for type-1 QBWO events occurs on day 6 (Fig. 11d), when the positive rainfall anomaly is strongest (Fig. 9d). For type 2 QBWO events, the wave train appears to propagate northward. The mid-latitude wave train appearing as a $(- + - +)$ pattern on day 2 (Fig. 11j) becomes a $(+ - + -)$ pattern on day 8 (Fig. 11m).

On the 10–20-day time scale, anomalies in 850-hPa and 200-hPa height fields that are associated with QBWO also appear to be associated with intraseasonal variability in the WPSH and the SAH themselves. However, we can also examine how longer-term variability in the characteristics of WPSH and SAH affect the formation of the different types of QBWO events. Figure 12 shows the extent of the SAH represented by the contour of 12,230 gpm of 200-hPa height and that of the WPSH by the contour of 5760 gpm of 500-hPa height for both types of QBWOs in day 0. For the type-1 QBWO, the longitude span of the SAH in the upper troposphere is broad, with the easternmost point of its ridgeline

Fig. 9 Life cycle of the type-1 (left) and type-2 (right) QBWO events shown by the 10–20-day filtered precipitation (shading, units: mm/day) and 850-hPa wind (vector; units: m s^{-1}). Stippling indicates significant precipitation anomalies above the 95% confidence level based on a Student's *t* test. For winds, only significant anomalies above the 95% confidence level are plotted

around 130°E (Fig. 12a). The longitude span of the WPSH in the mid-troposphere is vast as well, and the westernmost point of its ridgeline reaches the Hainan Island (Fig. 12c). The WPSH exerts a major impact on the variability of the western Pacific monsoon rainfall. Its strong westward extension is not conducive to convection over the western Pacific, but is more favorable for convection near the Philippine

Islands. It favors the propagation of the QBWO through the South China Sea to the Asian continent where it can produce rainfall anomalies (Wang et al. 2016). When type 2 QBWO events occur, the SAH (Fig. 12b) and the WPSH (Fig. 12d) are weaker. Convection is thus more active over the western Pacific, and QBWOs are generated more easily there.

Fig. 10 Composite patterns of 10–20-day filtered 850-hPa geopotential height (shading; units: gpm) and winds (vector; units: m s^{-1}) for type-1 (left) and type-2 (right) QBWO. Stippling indicates significant geopotential height anomalies above the 95% confidence level. Only the significant wind anomalies above the 95% confidence level are plotted

The results above suggest that the interactions between subtropical highs and QBWOs may be different at different time scales. On the 10–20-day time scale, the geopotential height anomalies associated with QBWOs perturb the WPSH and SAH circulations. The 10–20-day filtered height anomalies associated with the SAH at 200 hPa are characterized by a northward propagation. Longer term

variations in the SAH and WNSH can also affect the type of QBWO that is produced. Simultaneously stronger SAH and WPSH are more conducive to type-1 QBWO events, while simultaneously weaker SAH and WPSH are more beneficial for type-2 QBWO events.

Fig. 11 Same as Fig. 10, except for the 200-hPa level

4.2 Relationships with Pacific SST and the Madden-Julian Oscillation

Ocean–atmosphere interactions have been hypothesized to play an important role in supplying energy to sustain convection and atmospheric circulations during the northwestward propagation of intraseasonal oscillations over the western North Pacific (Hsu and Weng 2001). Next, we analyze the

background SST anomaly state when QBWO events occur. It is noted that a small positive SST anomaly is apparent over the South China Sea for type 1 disturbances (Fig. 13a), which should contribute to stronger convection in the region, allowing QBWO events to further develop and propagate westward after they cross the northern mountains of the Philippines. For type 2 disturbances (Fig. 13b), robust negative SST anomalies to the east of the Philippines would

Fig. 12 Composite patterns of 200-hPa geopotential height (contour of 12,230 gpm; left) and 500-hPa geopotential height (contours of 5760 gpm; right) for type 1 (top) and type 2 (bottom) disturbances. The black line represents climatological values. Only the significant anomalies above the 95% confidence level are plotted

Fig. 13 Composite anomalies of SST (shading; units: °C) for **a** type-1 and **b** type-2 QBWO events during August–October. Stippling indicates significant SST anomalies above the 95% the confidence level

inhibit convective activity, which is not conducive to the continued westward propagation and maintenance of type 2 QBWO events.

In addition to the local SST anomalies that can directly influence QBWO convection, it is worth noting that in the eastern equatorial Pacific there exist also significant positive (Fig. 13a) and negative (Fig. 13b) SST anomalies, likely reflecting El Niño–Southern Oscillation (ENSO) events. The change in monsoon ISOs with ENSO evolution has been an important research topic in recent years.

In El Niño developing summers, the 30–60-day oscillation has been suggested to be stronger than the QBWO (Wu and Cao 2017), although these results were not conclusive. Yang et al. (2008) indicated that year-to-year variations in the intensity of the QBWO and of the 30–50-day oscillation over the South China Sea were anti-correlated during June–July. Pillai and Chowdary (2015) found that the ISO characteristics such as variance, northward propagation, spatial distribution, and durations of active and break days were strongly modulated by the seasonal background anomalies over the Indo-Pacific region. El Niño phases exert a stronger impact on the 30–60-day time scale than on the 10–20-day time scale. Liu et al. (2016) found that during El Niño summers, the ISO in the western North Pacific was dominated by a higher-frequency oscillation with a period around 20–40 days, whereas during La Niña summers the ISO was dominated by lower-frequencies between 40 and 70 days. Wu and Cao (2017) argued that the feedback of surface heat flux onto the intensity of atmospheric oscillations is more prominent on the 10–20-day time scale than on the 30–60-day time scale. The 10–20-day oscillation is stronger during El Niño-developing summers, whereas the 30–60-day oscillation is stronger during La Niña decaying summers. In general, the above results suggest a role for air–sea interaction and background SST state in the occurrence of QBWO events, although the precise nature of the modulation is sometimes contradictory.

Here we address the question: During El Niño developing years, is QBWO activity in the monsoon region stronger or weaker? Given the cold tongue anomalies in the eastern Pacific Ocean in Fig. 13, we speculate that ENSO variability and associated variability in the large-scale circulation will lead to different types of QBWO events. 14 type-1 events (out of total 22 events) occur in La Niña developing summers, which are shown in Fig. 14a as blue dots. Another 11 type-2 events (out of total 20 events) occur in El Niño

Fig. 14 Occurrence dates for QBWO events in an RMM index phase diagram for type 1 (a) and type 2 (b) disturbances. Blue, red and green dots denote La Niña years, El Niño years, and neutral years, respectively

Fig. 15 Individual and joint frequency distributions of tracked QBWO events for starting longitude (units: degree) vs zonal scale (units: degree) in La Niña years (a) and El Niño years (b); and starting longitude vs mean strength (units: mm/day) in La Niña years (c) and El Niño years (d)

developing summers, which are shown in Fig. 14b as red dots. These results suggest that the QBWO events during ASO have a relationship with ENSO. During the development phase of ENSO, the SST anomaly in the western

Pacific may affect the occurrence of QBWO through oceanic feedback.

We further examine whether QBWO events are modulated by the MJO. For this, the phases of the RMM index on

the days of QBWO event initiation are shown in Fig. 14. In La Niña developing summers (Fig. 14a), the type-1 QBWO events tend to occur when the MJO is in any phase. However, in El Niño developing summers (Fig. 14b), the emergence of a QBWO event appears most likely in phases 1, 6, 7 and 8 of the MJO. This suggests that when a positive MJO convective event is present over the Indian Ocean or the Maritime Continent (in phase 2, 3, 4 and 5), it is not conducive to the occurrence of QBWOs. In general, the impact of MJO on the QBWO does not appear to be substantial based on this preliminary analysis and requires further study.

To discern the impact of ENSO on the characteristics of QBWO events, the frequency distributions of QBWO characteristics are shown in Figs. 15 and 16, in which we separate the La Niña and El Niño developing summers. The first thing of note is that more events originate at around 120°E in La Niña developing summers while a large number of events originate near 160°E in El Niño developing summers (Fig. 15a, b), providing a difference perspective on the information in Fig. 13. Second, the zonal scale does not substantially change in for different ENSO phases (Fig. 15a, b). Third, the strength in La Niña developing summers is weaker (3 mm/day) on average than in El Niño developing

summers (4 mm/day). Further, it is found that the propagation speed is between 3 and 10 m/s and it has two frequency maxima (4–6 m/s and 7 m/s) in both La Niña and El Niño developing summers (Fig. 16a, b) which also can be found in Fig. 2a. The most frequent propagation speed in La Niña developing summers is 8 m/s (Fig. 16a). In contrast, the most frequent propagation speed in El Niño developing summers is near 5 m/s (Fig. 16b). Finally, it does not seem that propagation range and ENSO are strongly related (Fig. 16c, d). These results suggest that QBWO events in La Niña developing summers have a larger strength and higher propagation speed, but that ENSO does not substantially affect the QBWO events' zonal scale and propagation range.

5 Conclusions and discussion

The QBWO and the 30–60-day oscillation are two primary modes of intraseasonal variability in the tropical and subtropical summer monsoons. While the 30–60-day oscillation has been investigated extensively, many features of the QBWO remain unclear, especially its complex generation and propagation mechanisms. The present study is focused on the

Fig. 16 Individual and joint frequency distributions for tracked QBWO events of starting longitude (units: degree) vs propagation speed (units: m/s) in La Nina years (a) and El Niño years (b); and starting longitude vs propagation range (units: degree) in La Nina years (c) and El Niño years (d)

QBWO of Asian monsoon rainfall during August–October. Building on the MJO tracking algorithm of Zhang and Ling (2017), we depict the westward propagation of QBWOs over the monsoon region using an improved tracking method.

Previous studies (Yang et al. 2014; Wang et al. 2016) have compared different paths of QBWO propagation at different stages of monsoon development. Our study shows that different types of QBWO propagation can occur in the same season. The tracked QBWO events can be divided into two categories. One originates from 110° to 140°E and exerts its influence westward to southern China. The other is characterized by initiation locations from 160°E to the dateline, and shows a weaker effect on mainland China. Our results suggest that environmental conditions over the South China Sea after disturbances pass through the northern mountains of the Philippines are important for determining whether these QBWO events can affect the Asian continent.

Analysis of the vertical structure of moisture flux convergence shows that the moisture source for type-1 QBWO disturbances is mainly the zonal flux component, and for type 2 disturbances the meridional flux component. The difference in moisture sources for the two types of QBWOs provides clues into their different generation mechanisms.

The SAH and the WPSH play an important role in the generation and propagation of QBWOs. On the 10–20-day timescale, both SAH and WPSH are modulated by wave trains associated with the QBWOs. WPSH geopotential height anomalies appear most strongly modulated by westward-propagating QBWO wave trains. However, the SAH is primarily modulated by QBWO wave trains that propagate northward. Associated with longer timescale fluctuations of the SAH and WPSH, type-1 QBWO events are more likely to occur when both SAH and WPSH are stronger, while type-2 QBWO events correspond to simultaneously weaker SAH and WPSH. Previous studies (e.g., Tao and Xu 1962; Tao and Wei 2006) have suggested that the SAH and the WPSH were closely related to each other. This coupling of the SAH and WPSH strongly modulates the meridional circulation, vertical motion, and summer monsoon rainfall that affect QBWOs, although the responsible physical mechanisms are not entirely clear. The multi-scale dynamic processes linking SAH and WPSH to the QBWO events originating in the western Pacific are an issue that deserves further investigation.

More generally, the physical mechanisms underlying QBWO dynamics and its variability are still not fully understood. It is believed that the QBWO is an intrinsic mode of the tropical atmosphere (Goswami and Mathew 1994; Chatterjee and Goswami 2006), and may be supported by an evaporation–wind feedback under conditions of mean westerly flow or convective heating induced by boundary layer convergence. However, it has also been suggested that

feedbacks among convection, Rossby wave dynamics, and the low-level circulation are crucial in maintaining observed QBWO structure (Wen and Zhang 2008). SST anomalies are important for determining convection activity and are closely related to the origin and development of intraseasonal oscillations. Our study indicates that SST anomalies in the South China Sea to the west of the Philippines may be an important factor for the occurrence of different types of QBWO events. However, the air–sea interaction processes by which the SST anomalies affect QBWO propagation needs further investigation.

A recent study by Liu et al. (2016) on differences in ISO activity over the South China Sea and the western Pacific during different stages of ENSO showed that during El Niño developing summers the ISO is dominated by a higher-frequency oscillation with a period around 20–40 days, whereas during La Niña developing summers the ISO is dominated by a lower-frequency period around 40–70 days. On shorter timescales, Wu and Cao (2017) found that the 10–20-day oscillation was enhanced during El Niño developing summers, whereas the 30–60-day oscillation was enhanced during La Niña decaying summers. Our results complement the work above and show that during August–October the type-1 QBWO events are more likely to occur in La Niña developing summers, and the type-2 QBWO events more likely in El Niño developing summers, especially during phases 1 and 6–8 of the MJO.

Based on the above results, we can confidently say that the occurrence of type-1 QBWO events affects rainfall over the Asian continent. Thus, the simultaneous enhancement of SAH and WPSH can be considered as a precursor for QBWO events that affect the Asian continent, which would be useful information for short-term forecasts. The SST in the South China Sea is also an important factor for whether QBWOs reach Asian, and how such SST variability affects QBWO characteristics deserves further investigations.

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