Effect of the westward-propagating zonal wind anomaly on the initial development of quasi-biweekly oscillation over the South China Sea during early summer

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ABSTRACT
The characteristics of quasi-biweekly oscillation (QBWO) over the South China Sea during early summer are investigated. Composite results demonstrate that QBWO convection and the meridional wind anomaly exhibit local variation, while the zonal wind anomaly displays zonal propagation. Besides, emergence of the zonal wind anomaly precedes the enhancement of QBWO convection, suggesting the zonally propagating zonal wind anomaly may play a key role in initiating the development of QBWO convection. Diagnostics of the convergence of moisture flux and divergence tendency indicate that QBWO convection is primarily modulated by eddy divergence. Among the contributing factors in the divergence tendency, the $\beta$ effect associated with the zonally-propagating zonal wind anomaly makes an appropriate phase difference with the eddy divergence, which can contribute to the convergence tendency in the initial stage of QBWO. As a result, QBWO convection and the meridional wind anomaly are enhanced, thus facilitating the initial development of QBWO convection over the SCS during early summer.

1. Introduction
Intraseasonal oscillations are a key ingredient of monsoon variability over the South China Sea (SCS) during boreal summer, and can significantly affect the onset and breakup of the SCS summer monsoon (e.g. Chen and Chen 1995; Chen, Yen, and Weng 2000; Mao and Chan 2005). Among the intraseasonal modes, the 10–20-d quasi-biweekly oscillation (QBWO), with a significant peak in the power spectrum, is one of the major systems influencing tropical and subtropical weather and seasonal mean climate. As reviewed by Wang et al. (2009), the QBWO over the SCS is more active than that in the Indian summer monsoon region. In some years, QBWO energy is much stronger even than that of the MJO (Madden and Julian 1994); and moreover, the QBWO displays a distinct structure from that of the MJO in terms of dynamic and thermodynamic processes (e.g. Li and Zhou 1995; Chan, Ai, and Xu 2002; Kikuchi and Wang 2009). The QBWO signal has also been documented to play an essential role in modulating the rainfall of, and even deflecting, tropical cyclone tracks (e.g. Yang et al. 2010; Wu, Liang, and Wu 2011; Qiao, Zhang, and Jian 2015).

In terms of QBWO characteristics, most previous studies have pointed out that the QBWO is closely associated with a wave train propagation with alternating cyclonic and anticyclonic disturbances. Using OLR data over the SCS as an index, Fukutomi and Yasunari (2002) found a two-way tropical–extratropical interaction on a 10–25-d timescale. After examining the link between tropical convection over the SCS and large-scale circulation, they displayed a barotropic wave train with a zonal number of five to six arcing into the North Pacific. Chen and Sui (2010) investigated the structure, energetics, and origin of the QBWO over the western North Pacific. They pointed out that the QBWO is characterized by alternating positive and negative
vorticity originating from the equatorial region, and whose structure bears a resemblance to the equatorially trapped Rossby wave mode. From the global perspective, Kikuchi and Wang (2009) suggested that the behavior of the QBWO convection mode can be understood in terms of convectively coupled equatorial Rossby waves in the presence of monsoon mean flow in some areas, while extratropical Rossby waves can also play an important role in maintaining QBWO convection in some regions. Therefore, previous literature tends to connect QBWO convection with equatorial and extratropical Rossby waves.

Previous attention has tended to be on the QBWO associated with propagating wave trains with closed circulation, whereas less emphasis has been placed upon local development of QBWO convection. Recently, Wang, Chen, and Huang (2015) documented different QBWO characteristics and structures over the SCS during early and late summers. Specifically, different from the 10–20-d convection over the SCS during late summer, which is characterized by the westward-propagating vorticity wave train originating from the east, the 10–20-d convection during early summer is mainly characterized by local oscillation without the link to the propagating vorticity wave train from the equatorial or extratropical regions. So far, the issue as to what factors are responsible for this local development of 10–20-d convection is not yet fully understood. This work is devoted to revealing the possible underlying mechanism of the initial development of 10–20-d convection over the SCS during early summer.

The remainder of the paper is organized as follows: The data-set and methodology used in this study are introduced in Section 2. Section 3 describes the 10–20-d convection features over the SCS during early summer. A possible interpretation of the initial development of 10–20-d convection is presented in Section 4. Finally, the conclusions are summarized in Section 5.

2. Data and methodology

Daily NCEP–DOE Reanalysis-2 data are used in this study (Kanamitsu et al. 2002). The data span from 1 May to 30 June 1991–2010 and have a horizontal resolution of 2.5° × 2.5°. Daily OLR NOAA satellite data for the same period are used as a proxy for deep tropical convection (Liebmann 1996).

The 10–20-d filtered fields are obtained using Lanczos filtering with 53 daily weights that provide a very sharp cutoff (Duchon 1979). Prior to filtering, the linear trend and annual cycle, based on 20-yr daily data, are removed from the time series. Wang, Chen, and Huang (2015) revealed that the region over the SCS (12.5°–22.5°N, 110°–120°E) exhibits a spectrum peak at the 95% confidence level for 10–20-d filtered OLR during early summer (May–June). Therefore, the 10–20-d filtered OLR averaged over this region is defined as an index to choose the typical QBWO events in this study. In order to achieve a robust QBWO cycle and, moreover, study its initial development, the criteria for the selection of QBWO events are as follows: the minimum standardized index (day 0) in a QBWO cycle corresponding to the strongest convection anomaly must be less than one negative standard deviation; the following maximum standardized index (day 6) corresponding to the weakest convection anomaly must be larger than one positive standard deviation. No criterion is imposed prior to day 0 in such a way that the stage before day 0 can be approximately regarded as the initial development of a strong QBWO convection event. As such, a total of 45 typical QBWO cases are chosen in this study.

3. Characteristics of QBWO over the SCS during early summer

Based on the time series of OLR index, the evolution of QBWO convection during the stage from initiation to maturity can be demonstrated by compositing the QBWO events with respect to day 0 at which the strongest convection anomaly occurs. Figure 1 displays the evolution of 10–20-d filtered OLR and the 850-hPa wind field from day −4 to day 1. At day −4, anomalous northerly flows are predominant over the SCS, and anomalous westerly winds centered at 10°N exist over the Philippines and to its east. At that time, there are no discernible OLR anomalies over the SCS (Figure 1(a)). The following day (day −3), the westerlies are shifted westward together with a weakening and westward migration of northerly flows over the SCS (Figure 1(b)). At day −2, as depicted in Figure 1(c), the southern part of the SCS is occupied by westerly anomalies that extend continuously westward. Meanwhile, the convection anomaly starts to become active, centered at (15°N, 117.5°E). One day later (Figure 1(d)), accompanied by enhancement of the zonal wind anomaly, an evident closed cyclonic circulation forms with vigorous convection in its center. The magnitudes of 10–20-d filtered wind and OLR peak at day 0 (Figure 1(e)), which is followed by the zonal wind anomaly shifting progressively westward and the convection weakening at day +1 (Figure 1(f)).

Of interest in Figure 1 is that the zonal wind anomalies feature westward propagation from the east of the Philippines, whereas the 10–20-d filtered OLR takes on a local variation at about 115°E without notable zonal displacement. To straightforwardly demonstrate the evolution, Figure 2 depicts a composited longitude–time Hovmöller diagram of the associated dynamic variables averaged between 12.5°N and 22.5°N. It is evident that the variations of OLR and low-level divergence are almost coincident and, moreover, their oscillations are confined between 110°E
and 120°E in the absence of the signal of zonal propagation (Figure 2(a)). Similarly, the meridional wind anomalies alter locally with large magnitude at 120°E. In sharp contrast, the zonal wind anomalies exhibit apparently westward displacement with time (Figure 2(b)). The above-mentioned features are quite different from those in previous studies.

**Figure 1.** Evolution of 10–20-d filtered OLR (color-shaded; units: W m$^{-2}$) and the 850-hPa wind field (vectors; units: m s$^{-1}$) from day –4 to day 1. The domain indicated by the box at day 0 denotes the region used to define the index. Wind anomalies are plotted when exceeding the 95% confidence level based on the student-t test.

**Figure 2.** Longitude–time Hovmöller diagram of (a) 10–20-d filtered OLR (color-shaded; W m$^{-2}$) and 925-hPa divergence averaged between 12.5°N and 22.5°N (contours; units: $\times 10^{-6}$ s$^{-1}$), and (b) 10–20-d filtered zonal (color-shaded) and meridional (contours) winds (units: m s$^{-1}$) averaged from 1000 to 850 hPa between 12.5°N and 22.5°N.
in which the propagation of a wave train with alternating cyclonic and anticyclonic circulation accompanied by a convection anomaly was identified (e.g. Kikuchi and Wang 2009; Chen and Sui 2010). According to the evolution of the variables shown in Figure 2, the signal of the zonal wind anomaly appears first to the east of 140°E at day −6, and then moves westward and intensifies with time, which precedes the enhancement of OLR and meridional wind anomalies. Until day −2, the anomalous convection along with the meridional wind anomaly starts to strengthen in the region of interest. This implies that, serving as a precursor signal, the westward-propagating zonal wind anomalies may play an essential role in triggering the initial development of QBWO convection. This notion is discussed in the next section.

4. Interpretation of the initial development of QBWO

It is well known that lower-level moisture convergence (divergence) can enhance (suppress) the intraseasonal oscillation of convection. The convergence of moisture flux is defined as

\[ \nabla \cdot (qV) = \bar{q} \nabla \cdot \dot{V} + \dot{q} \nabla \bar{V} + \nabla \bar{q} \cdot \dot{V} + \nabla \cdot (q \dot{V}) + \nabla \cdot (q \dot{V})', \]

in which \( q \) and \( V \) represent specific humidity and horizontal wind, respectively. The variables with an overbar denote those averaged over a QBWO cycle, while those with a prime are 10–20-d filtered anomalies. The term on the left-hand side in Equation (1) (black solid curve in Figure 3) stands for the 10–20-d filtered divergence of moisture flux that is almost in phase with the OLR anomaly; that is, the strong convergence (divergence) anomaly of moisture flux at day 0 (+6) corresponds well to the enhanced (suppressed) convection anomaly. The first term on the right-hand side of Equation (1) (red dashed curve in Figure 3) is the product of mean vapor and eddy divergence whose phase and magnitude are nearly identical to the divergence anomaly of moisture flux on the left-hand side. In contrast, the sum of the residual terms on the right-hand side (blue dashed curve in Figure 3) is almost negligible, accounting for a small fraction of the divergence anomaly of moisture flux. It signifies that the 10–20-d filtered divergence anomaly is a primary contributor to QBWO convection over the SCS during early summer.

Naturally, in order to further elucidate the initial development of QBWO convection associated with eddy divergence, we solved the divergence tendency equation, which is formulated as

\[ \frac{\partial D}{\partial t} = -V \cdot \nabla D - \omega \frac{\partial D}{\partial p} - \nabla^2 \phi - \nabla \omega \cdot \frac{\partial V}{\partial p} - D^2 + 2J + \mathbf{f} \zeta - \beta u, \]

where \( D, V, \omega, \phi, \zeta, t, p, \beta, \) and \( u \) are divergence, horizontal wind, vertical pressure velocity, geopotential height, relative vorticity, time, pressure, meridional gradient of earth planetary vorticity, and zonal wind, respectively. The individual terms on the right-hand side of Equation (2) denote the contribution to the eddy divergence tendency associated with horizontal advection, vertical advection, Laplacian geopotential vertical wind shear, square of the divergence, flow deformation

\[ \left( J = \frac{\partial u}{\partial x} \frac{\partial v}{\partial y} - \frac{\partial v}{\partial x} \frac{\partial u}{\partial y} \right) \] vorticity, and the \( \beta \) effect. The 10–20-d bandpass filtering is employed for each term derived from the total fields. For a large-scale system, the geostrophic balance is a reasonable approximation in that \(-\nabla^2 \phi\) is almost offset by \( \mathbf{f} \zeta \). Besides, the calculation shows that the contribution of \( \omega \frac{\partial D}{\partial p} \) and \( \nabla \omega \cdot \frac{\partial V}{\partial p} \) is negligible, and at least an order of magnitude smaller than the other terms.

Figure 4 displays the composited time series of the divergence anomaly and major contributors to the divergence tendency. It is clear that the evolution related to the square of divergence is almost in phase with that of the divergence anomaly (Figure 4(b)), while those related to the horizontal advection and deformation effect are out of phase with the divergence anomaly (Figure 4(a) and (c)). The phase relationship implies that the square of divergence (horizontal advection or deformation term) makes a positive (negative) contribution to the divergence anomaly after the eddy divergence occurs. Namely, for a pre-existing divergence anomaly, these terms can further increase or decrease its amplitude.
with the zonal wind anomaly perturbs the divergence anomaly in the node and thus serves to initiate the QBWO convergence anomaly. Hence, it is the phase difference between the divergence anomaly and the $-\beta u$ term that contributes to the initial development of QBWO convection.

Recall that there is distinct westward propagation of the zonal wind anomaly prior to the establishment of a robust QBWO cycle, as displayed in Figure 2(b). This implies that the zonally propagating zonal wind anomaly may act as a key contributor to trigger the initial development of local QBWO convection over the SCS through the $\beta$ effect. This kind of QBWO evolution is quite different from cases demonstrated previously (e.g. Fukutomi and Yasunari 2002; Chen and Sui 2010), in which both QBWO convection and the alternating cyclonic and anticyclonic vorticity exhibit spatial

Figure 4. Time series of divergence (solid curve) and the major contributor to divergence tendency (dashed curve) associated with (a) horizontal advection, (b) squared divergence, (c) deformation, and (d) the $\beta$ effect. The scales of divergence and the major contributor to divergence tendency refer to the left and right y-axes, respectively.
propagating characteristics, rather than local variation as documented in this study.

In addition, the vorticity budget is calculated in this study. The vorticity budget can be expressed as

$$\frac{\partial \zeta'}{\partial t} = (-\nabla \cdot \mathbf{v}) + \left( -\frac{\partial \zeta'}{\partial p} \right) + \left[ -(\zeta + f) \cdot D' \right] + T' + (-\beta v'),$$

(3)

in which \( \mathbf{v} \) represents horizontal wind. The terms on the right-hand side of Equation (3) represent those related to horizontal advection, vertical advection, divergence, the tilting effect \( T' = \left( \frac{\partial \omega}{\partial y} - \frac{\partial u}{\partial p} - \frac{\partial v}{\partial x} \right) \), and \( \beta \) effect.

The first four terms have a phase evolution approximately in or out of phase with that of 10–20-d filtered vorticity. Similar to the abovementioned interpretation in divergence diagnostics, these terms barely account for the initial development of the QBWO. By comparison, the \( \beta \) effect term associated with the meridional wind anomaly leads the vorticity anomaly at the low level, indicative of the contribution to the initial development of the QBWO. Note that, as shown in Figure 2, the enhancement of the meridional wind anomaly is preceded by the westward propagating zonal wind anomaly, implying that the westward-propagating zonal wind anomaly prompts the strengthening of the local meridional wind anomaly over the SCS, favorable for the increase in convergence and cyclonic vorticity at the low level, and thus QBWO convection development.

5. Conclusion

Based on the 10–20-d filtered OLR index, the initial development of QBWO convection over the SCS during early summer is studied. Composite results for robust QBWO events show that the 10–20-d filtered convection anomaly displays local variation. Further examination reveals that the meridional wind and divergence anomalies also vary locally over the SCS, while the zonal wind anomaly has an evident characteristic of westward propagation before the QBWO life cycle is mature. The features are quite distinct from previous findings (e.g. Fukutomi and Yasunari 2002; Chen and Sui 2010), in which QBWO convection, in association with alternating cyclonic and anticyclonic anomalous circulations, is generally characterized by spatial propagation. Besides, the emergence of the zonal wind anomaly precedes the enhancement of QBWO convection and the meridional wind anomaly, implying that the zonally-propagating zonal wind anomaly may play an important role in triggering the initial development of the QBWO over the SCS during early summer.

The evolution of QBWO convection is closely related to the convergence of moisture flux. Compared with other contributing terms, the term associated with eddy divergence is a dominant contributor to the convergence of moisture flux. To shed further light on the possible mechanism behind the initial development of QBWO convection, the divergence tendency equation is diagnosed. Among the major contributing terms, the temporal evolution of the square of divergence is in phase with that of the divergence anomaly, while the terms associated with horizontal advection or flow deformation are out of phase with the divergence anomaly. However, these terms contribute mainly to increasing or decreasing the magnitude of pre-existing eddy divergence, but cannot be responsible for the initial development of eddy divergence. Considering the phase relationship, the \( \beta \) effect associated with the zonal wind anomaly can act to generate the convergence tendency in the initial stage of QBWO convection. Consequently, the 10–20-d filtered convection and meridional wind anomaly are enhanced further and thus favor the initial development of the QBWO over the SCS during early summer.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study was supported financially by the National Basic Research Program of China [grant number 2014CB953902] and the National Natural Science Foundation of China [grant numbers 41275001 and 41475074].

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