Forecasting tropical cyclone (TC) intensity is challenging, particularly at the subseasonal scale. In this study, we found that compared to the 30–90-day Madden–Julian oscillation (MJO), the activity of 10–30-day quasi-biweekly oscillation (QBWO) has a closer connection with the intensity change of TCs over the tropical western North Pacific. Both the TC growth rate (24-hr increases in maximum sustained wind speed) and the probability of TC intensification during the active phases of QBWO increase significantly compared to those during the inactive QBWO phases. The effects of QBWO on TC intensification take place mainly through alteration of the large-scale dynamic conditions. During the active convection phase of QBWO, the 10–30-day cyclonic vorticity and convergence in the lower troposphere, divergence in the upper troposphere, and the circulation-induced moistening anomalies provide a favorable environment for TC growth. The thermodynamic conditions of atmospheric instability, sea surface temperature (SST), and ocean heat potential show negative but insignificant contributions to TC intensification at the quasi-biweekly time scale. These results not only aid our understanding of the influences of QBWO-related environmental conditions on TC intensification, but also suggest the potential predictability of TC intensity at an extended range (10–30 days) once the QBWO has been successfully predicted.

**KEYWORDS**

dynamic and thermodynamic conditions, quasi-biweekly oscillation, tropical cyclone intensification

**1 | INTRODUCTION**

Intense tropical cyclones (TCs) with strong winds and heavy rainfall can cause severe damage to infrastructure and human life. Because TC intensity change is controlled by both internal dynamics and environmental conditions (Wang and Wu, 2004; Hendricks et al., 2010), forecasting TC intensity change is much more challenging than that of TC track changes (McAdie and Lawrence, 2000; DeMaria et al., 2007). Although improvements in forecasting methods and models have led to progress in TC intensity predictions at short-term and seasonal timescales (DeMaria et al., 2014; Murakami et al., 2016), the ability to forecast TC intensity at extended ranges (e.g., 10–30 days) remains limited (Vitart et al., 2012; Elsberry et al., 2014). It is well-accepted that intra-seasonal oscillation (ISO) represents the source of predictability on subseasonal or extended-range timescales (Waliser, 2006). The key to improving extended-range TC intensity forecasts involves a deep understanding of the relationship between ISO and TC intensification, as well as the related controlling factors through which the intra-seasonal background environment interacts with TCs and results in changes in TC intensity.
The influences of ISO on TC genesis and track over the western North Pacific (WNP) have been discussed in the past (Liebmann et al., 1994; Kim et al., 2008; Hsu et al., 2011; Li and Zhou, 2013a; 2013b; Zhao et al., 2015). Through modulating the large-scale circulation and moisture distributions, the genesis count and trajectory of TCs are positively (negatively) correlated with the active (inactive) phase of ISO. How ISO affects WNP TC intensity, however, has received relatively less attention. Liebmann et al. (1994) analyzed the occurrence of different TC intensity categories, such as tropical depression, tropical storm, and typhoon, during the active and inactive phases of ISO and found that the ratio of typhoons to weak TCs (tropical depressions and tropical storms) does not vary significantly with the life cycle of ISO. Li and Zhou (2013a) documented that TCs forming over the eastern (western) parts of the WNP, when quasi-biweekly oscillation (QBWO) convection prevails in those areas, tend to reach a stronger (weaker) lifetime maximum intensity because they persist for a longer (shorter) duration over the ocean. These studies, however, did not examine how ISO-related environmental conditions influence the intensity change (such as the growth rate and probability to intensify) of TCs.

Over the WNP and Asian monsoon regions, boreal summer ISO has two prominent modes: the 30–90-day Madden–Julian oscillation (MJO) and the 10–30-day QBWO. These two modes have distinct spatial structures and propagation features (Lee et al., 2013). The 30–90-day MJO is characterized by a northwest–southeast tilted structure that moves northwards and northeastwards over the Indian and East Asian monsoon regions (Yasunari, 1979; Lau and Chan, 1986; Wang and Rui, 1990). QBWO convection, however, tends to possess a northeast–southwest elongated structure, propagating westwards and northwestwards from the tropical central-western Pacific towards East Asia (Chen and Sui, 2010). In the present reported study, we compared the connection between these two different ISO modes with TC intensity changes over the WNP. Statistical analysis shows that the QBWO (rather than the MJO) is closely linked with WNP TC intensification. Armed with this knowledge, the key factors controlling TC intensification at the 10–30-day timescale are discussed.

2 METHODS

The data used in this study were (a) WNP TC best-track data from the Joint Typhoon Warning Center (JTWC, 2016) at 6-hr intervals; (b) daily mean outgoing longwave radiation (OLR) from the NOAA polar-orbiting satellites (Liebmann and Smith, 1996), with a horizontal resolution of 2.5°; (c) daily mean large-scale atmospheric variables of wind, moisture, sea surface temperature (SST), air temperature, and precipitation from the European Centre for Medium-Range Weather Forecasts interim reanalysis (ERA-Interim; Dee et al., 2011), with a horizontal resolution of 1.5°; and (d) TC heat potential (TCHP), defined as the vertically integrated ocean heat potential from the surface to the depth of the 26 °C isotherm, from the National Centers for Environmental Prediction Coupled Forecast System Reanalysis (CFSR), at a resolution of 0.5° (Saha et al., 2010). All data covered the period 1981–2012, except the CFSR data, which were from 1979 to 2010. We focused on boreal summer (May–October), when both ISO and TC activity are vigorous over the WNP.

Only TC events with a lifetime maximum sustained wind speed \( V_{\text{max}} \) greater than or equal to 34 knots (i.e., tropical storm) were considered in this study. Typhoons with a lifetime \( V_{\text{max}} \) greater than or equal to 64 knots were classified into categories 1–3 (lifetime \( V_{\text{max}} \) between 64 and 112 knots) and categories 4–5 (lifetime \( V_{\text{max}} \) greater than 113 knots) according to the Saffir–Simpson hurricane wind scale. To efficiently examine the TC intensity changes (including the growth rate and probability of intensification) modulated by the states of QBWO and MJO, which were defined by the daily convection and large-scale fields, we converted the 6-hourly TC best-track data into daily-averaged values. Then, the TC growth rate was defined as the 24-hr increase in \( V_{\text{max}} \) (i.e., \( \partial V_{\text{max}} / \partial t \) derived from the forwards difference, similar to the definitions of Hendricks et al. (2010). To estimate the probability of TC intensification for each ISO phase, we calculated the ratio of TC counts with a positive TC intensification rate \( (\partial V_{\text{max}} / \partial t > 0) \) to the total TC count occurring in a specific phase of ISO.

The dynamic and thermodynamic fields associated with the 30–90-day MJO and 10–30-day QBWO were extracted by Lanczos band-pass filtering (Duchon, 1979). To identify the dominant patterns of the two ISO modes over the WNP, the empirical orthogonal function (EOF) analysis was applied to the filtered OLR over the WNP TC active area (0°–35°N, 110°–170°E). The amplitude and phase of the MJO and QBWO can be defined by the two leading principal components (PC1 and PC2) of their EOF analyses, respectively—similar to the approach in Wheeler andendon (2004). To separate the effects of the MJO and QBWO, an active MJO event was selected on dates when the amplitude of the MJO was greater than or equal to

\[ \sqrt{PC_{1\text{MJO}}^2 + PC_{2\text{MJO}}^2} \geq 1, \]

while at the same time the QBWO signal was weak

\[ \sqrt{PC_{1\text{QBWO}}^2 + PC_{2\text{QBWO}}^2} < 1. \]

Similarly, an active QBWO event was selected on dates when the amplitude of the QBWO was greater than or equal to

\[ \sqrt{PC_{1\text{QBWO}}^2 + PC_{2\text{QBWO}}^2} \geq 1, \]

while the MJO signal was weak

\[ \sqrt{PC_{1\text{MJO}}^2 + PC_{2\text{MJO}}^2} < 1. \]

The eight phases of the MJO (QBWO) life cycle were defined as

\[ \tan^{-1}(PC_{2\text{MJO}}/PC_{1\text{MJO}}) \text{ and } \tan^{-1}(PC_{2\text{QBWO}}/PC_{1\text{QBWO}}). \]
3 | CONNECTION BETWEEN TC INTENSITY CHANGE AND EACH INTRA-SEASONAL MODE

During boreal summer, the WNP is a region with active synoptic-scale and subseasonal variability (Figure 1a–c). Vigorous TC activity with increased frequency of occurrence (Figure 1a) and strong intensity (Figure 1d) occurs consistently with regions of enhanced QBWO (Figure 1b) and MJO (Figure 1c). The respective modulation of TC frequency by the two ISO modes has been discussed previously (Liebmann et al., 1994; Kim et al., 2008; Hsu et al., 2011; Li and Zhou, 2013a; Zhao et al., 2015). Nonetheless, how and to what extent the QBWO and MJO affect TC intensification still needs to be clarified. Climatologically, TCs show a high growth rate (Figure 1e) and increased probability to intensify (Figure 1f) when they are located over the tropical WNP, including the South China Sea (SCS) (5°–25°N, 105°–180°E), where the QBWO and MJO are also active. This suggests a potential linkage between ISO activity and TC intensification.

To understand the influence of ISO evolution on TC intensification, we compared the changes in TC intensity, growth rate and probability to intensify during the different QBWO and MJO phases (Figures 2 and 3). Notable from Figure 1 is that TCs tend to weaken quickly near coastal areas. To avoid the effects of land on TC intensity changes, which may contaminate our discussion on ISO-induced TC intensity changes, in the following analysis we only consider TC cases whose centers were located beyond 500 km of the coast. The choice of a 500-km radius as the criterion for TC extent was based on previous work (e.g., Frank, 1977; Lonfat et al., 2004; Dare, 2013). Frank (1977) documented that strong upwards TC motion appears within a 4° radius.
FIGURE 2  (left) Evolution of 10–30-day OLR anomalies (shading, units: W/m²) from phases 1–8 of QBWO. The daily-averaged location and intensity (dots, TS; asterisks, C1–C3; circles, C4–C5) of TCs occurring during each phase of QBWO are marked. (right) As in the left-hand panels but with the shading representing the 30–90-day OLR anomalies. Only convection anomalies exceeding the 95% significance level, based on the Student’s t-test, are shaded.
approximately, whereas relatively weaker ascending motion tends to be observed beyond a radius of 6°. Lonfat et al. (2004) used a 500-km radius to delineate the area affected by TC precipitation. Dare (2013) also suggested that locations lying within 500 km of a TC’s center are more affected by the TC relative to locations outside that radius.

In Figure 2, the convection associated with QBWO (left-hand panels) and the MJO (right-hand panels) show pronounced northwards propagation from the equatorial region into the subtropical WNP. Different from the MJO with an eastwards propagating component combined with northwards propagation (Wang and Rui, 1990; Madden and Julian, 1994), the QBWO tends to propagate north/northwestwards (Chen and Sui, 2010; Lee et al., 2013). During phase 6, a weak instance of QBWO-related convection appears over the tropical WNP. It then strengthens and propagates north/northwestwards towards the Philippine Sea and south of Taiwan during phases 7–8 and phase 1. An opposite phase evolution of QBWO convection is apparent during phases 2–5 (Figure 2, left). The MJO-related convection shows a zonally elongated structure. A convective anomaly across the eastern Indian Ocean, SCS and WNP between the equator and 10°N shows up during phase 7. This convective signal intensifies while moving eastwards/northeastwards.
towards the Philippine Sea and northern SCS during phases 8 and 1–2. An opposite phase cycle shows during phases 3–6 (Figure 2, right). The daily-averaged location and intensity of TCs occurring during different phases of QBWO and the MJO are also displayed in Figure 2. We can see that intense TCs (C1–C3 and C4–C5 typhoons) do not always seem to occur during the active phases of QBWO and the MJO; thus, the percentage of intense TCs does not show an obvious change during the life cycle of ISO (Liebmann et al., 1994; Li and Zhou, 2013a).

Instead of calculating the ratio of strong to weak TCs (Liebmann et al., 1994; Li and Zhou, 2013a), we compared the TC intensity changes during the different phases of QBWO (Figure 3a–c) and the MJO (Figure 3d–f). Over the key region (5°–25°N, 105°–180°E) with vigorous TC intensification (Figure 1e,f), the growth rate of TCs (Figure 3b) and the probability of TC intensification (Figure 3c) vary systematically with the life cycle of QBWO (Figure 3a). During the active phases of QBWO, when the QBWO-related OLR shows negative anomalies (phases 6 + 7 and 8 + 1), TCs tend to have a higher growth rate and probability to intensify. In contrast, TCs possess lower growth rates and lower probability of enhancement during the inactive QBWO phases (2 + 3 and 4 + 5) when the anomalous OLR shows positive anomalies (Figure 3a–c). The linkage between TC intensity changes and the MJO life cycle is relatively insignificant (Figure 3d–f). As seen in Figure 3e, TCs have an increased (decreased) growth rate even during the inactive (active) phases of MJO convection, such as phase 3 + 4 (phase 1 + 2). The changes in probability of TC intensification are of small amplitude during the entire life cycle of the MJO (Figure 3f). To ensure the results in Figure 3 are not sensitive to the domain for area averaging, we repeated the same analysis over a smaller domain (5°–25°N, 105°–160°E), where ISO shows maximum variability, and found that the results (Figure S1, Supporting Information) were nearly identical to those presented in Figure 3.

These results suggest that the connection between QBWO and TC intensification is more significant than that between the MJO and TC intensification. In other words, the rate and probability of TC growth/weakening may be more closely related to the evolution of the environmental conditions associated with QBWO than those associated with the MJO.

### 4 CONTROLLING EFFECTS OF QBWO ON TC INTENSIFICATION

To identify the key processes by which QBWO modulates TC intensification, the QBWO-related atmospheric and oceanic conditions that are known to significantly affect TC intensity change (Wang and Wu, 2004) were compared between the two phases with pronounced changes in TC intensification rate—namely, phases 8 + 1 and 2 + 3, shown in Figure 3b. During phase 8 + 1 of QBWO, the enhanced 10–30-day precipitation over the tropical WNP induces an atmospheric heating anomaly that further influences the circulation and temperature fields (Table 1 and Figure S2). The cyclonic vorticity and enhanced convergence anomalies in the lower troposphere, coupled with upper-level divergence, appear over the active TC region of the tropical WNP, providing a large-scale condition favorable for the growth of disturbances. The low-level convergence is also conducive to moisture convergence, which results in moistening in the lower to middle troposphere (Table 1 and Figure S2). In contrast, the low-level anticyclonic vorticity and upper-level convergence anomalies are unfavorable for moisture convergence in the atmosphere during phase 2 + 3 of QBWO (Table 1 and Figure S2). These large-scale conditions are less favorable for embedded development of synoptic disturbances and TCs. All the changes in QBWO-related flows between phase 8 + 1 and phase 2 + 3 are statistically significant (Table 1), indicating that the dynamic conditions associated with QBWO-related circulation anomalies play an important role in governing the differences in TC growth rate and the probability of TC intensification between the active and inactive phases of QBWO. Note that the change in vertical shear associated with QBWO is not the key factor contributing to the enhanced TC intensification, as the vertical wind shear increases during phase 8 + 1 (Table 1).

| 10–30-day filtered variable | Phase 2 + 3 | Phase 8 + 1 | Phase 8 + 1 minus phase 2 + 3 |
|----------------------------|-------------|-------------|-----------------------------|
| Precipitation              | 0.67        | 1.36        | 2.03                        |
| 850 hPa vorticity          | −5.21       | 8.64        | 13.85                       |
| 850 hPa divergence         | 1.24        | −3.50       | −4.74                       |
| 850 hPa RH                 | −7.07       | 8.97        | 16.04                       |
| 500 hPa RH                 | −0.96       | 2.80        | 3.76                        |
| 850 hPa RH                 | −0.37       | 0.94        | 1.31                        |
| [U200-U850]                | −0.84       | 0.89        | 1.73                        |
| \(\partial \omega /\partial p\) | 4.17        | −9.92       | −14.09                      |
| SST                        | −1.65       | −1.90       | −0.25                       |
| TCHP                       | −23.54      | −6.08       | 17.46                       |
examined and compared between the active and inactive phases of QBWO. Owing to the mid-tropospheric heating induced by enhanced precipitation anomaly during phase $8 + 1$ of QBWO, the atmosphere tends to be convectively stable compared to that during phase $2 + 3$ of QBWO (Table 1 and Figure S2). The oceanic conditions associated with QBWO variations contribute insignificantly to the TC growth. The TCHP and SST both show negative values during the active and inactive phases over the tropical WNP (Table 1). Their changes between the two phases of QBWO are statistically insignificant.

These results indicate that the dynamic (circulation-related) conditions associated with QBWO activity play the dominant role in modulating TC intensification. The thermodynamic parameters, however, contribute insignificantly to TC intensity changes at the 10–30-day timescale. We also compared the large-scale conditions between all active phases ($6 + 7$ and $8 + 1$) and inactive phases ($2 + 3$ and $4 + 5$), as revealed in Table S1. The results are consistent with those presented in Table 1.

To confirm these changes in large-scale atmospheric and oceanic conditions do not derive from the feedback of TCs themselves, we repeated the same analysis using data in which the TCs had been removed, based on the TC removal procedures outlined in Kurita et al. (1995). The patterns of 10–30-day environmental conditions show little change following removal of the TCs from the reanalysis (Figure S3). The differences in these large-scale fields between active and inactive phases of QBWO (Table S2) are nearly identical to the results presented in Table 1. Therefore, the large-scale environmental anomalies shown in this section are induced by QBWO activity, which in turn influences on TC development and intensification.

5 | CONCLUSION

During boreal summer, both ISO variability and TC activity are vigorous over the tropical WNP. The modulation of TC genesis and track by ISO has been well documented (Liebmann et al., 1994; Kim et al., 2008; Hsu et al., 2011; Li and Zhou, 2013a; 2013b; Zhao et al., 2015). Building upon that knowledge base, the present study reveals a connection between TC intensity change and ISO evolution. The two different modes of ISO, that is, the MJO and QBWO, show distinct contributions to the TC growth rate and probability of TC intensification. Both the TC growth rate and probability to intensify increase (decrease) significantly during active (inactive) phases of QBWO. However, a relatively weak linkage was found between TC intensity change and the MJO life cycle.

The changes in dynamic conditions associated with QBWO activity play a major role in modulating TC intensification. Through inducing large-scale low-level cyclonic vorticity and moisture convergence, as well as upper-level divergence, the active phase of QBWO provides a favorable environment for TC growth and intensification. In contrast, these environmental flows in the inactive phase of QBWO are unfavorable for the development of synoptic disturbances, including TCs. The thermodynamic conditions associated with 10–30-day convective instability and oceanic conditions (SST and TCHP) show negative but insignificant contributions to TC intensification. The close connection between QBWO evolution and TC intensification provides a potential predictability of TC intensity at the extended range of 10–30 days, once QBWO-related circulations in models have been successfully predicted (Vitart, 2009).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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