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Revisiting the intraseasonal, interannual and interdecadal variability of tropical cyclones in the western North Pacific

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ABSTRACT
This paper reviews the recent progress and research on the variability of tropical cyclones (TCs) at different time scales. Specific focus is placed on how different types of external forcings or climatic oscillations contribute to TC variability in the western North Pacific (WNP). At the intraseasonal scale, recent advances on the distinctive impacts of the Madden–Julian Oscillation (MJO), the Quasi-biweekly Oscillation, and the asymmetric MJO modulation under different El Niño–Southern Oscillation (ENSO) states, as well as the influences of the Pacific–Japan teleconnection, are highlighted. Interannually, recent progress on the influences of the ENSO cycle, different flavors of ENSO, and impacts of Indian Ocean warming is presented. In addition, the uncertainty concerning interdecadal TC variations is discussed, along with the recently proposed modulation mechanisms related to the zonal sea surface temperature gradient, the North Pacific Gyre Oscillation, and the Pacific Decadal Oscillation (PDO). It is hoped that this study can deepen our understanding and provide information that the scientific community can use to improve the seasonal forecasting of TCs in the WNP.

1. Introduction
Tropical cyclones (TCs) are one of the most destructive and threatening natural disasters and can cause heavy casualties worldwide. The distributions and impacts of TCs are widespread (Figure 1(a)), with major activity centers spanning the tropical oceans. Each year, the intensification and subsequent landfall of TCs, together with the associated strong wind gusts, torrential rains, and storm surges, cause severe damage to many coastal countries and result in tremendous loss of life and property. For example, during 6–13 August 2009, Typhoon Marakot brought more than 3000 mm of rainfall and caused more than 400 deaths in Taiwan. And in September 2013, Typhoon Usagi caused widespread destruction in the Philippines, China, and Hong Kong (CEDD 2014).

Among different ocean basins, the western North Pacific (WNP) is the most active region of cyclogenesis, accounting for approximately one-third of the global TC frequency (Gray 1968) and about 40% of the global accumulated cyclone energy (Maue 2011). Because it is a highly active region of cyclogenesis, understanding and accurately predicting TC behavior in the WNP becomes particularly important and has been of primary concern for many Asian countries (Wang 1988; Li and Wang 1994; Li et al. 2012; Wang et al. 2012; Wang and Huang 2013). Yet, changes in different TC metrics, including frequency, intensity, track, and landfall, are complex and involve multi-scale interactions of different phenomena, such as the El Niño–Southern Oscillation (ENSO) (Chan 1985; Wang and Chan 2002; Li and Zhou 2012) and the intraseasonal oscillation (ISO) (Liebmann, Hendon, and Glick 1994; Li and Zhou 2013a, 2013b). Other climatic variabilities, such as the Pacific–Japan (PJ) teleconnection pattern and Indian Ocean warming, have also recently been identified as having a significant influence on WNP TCs as well (Du, Yang, and Xie 2011; Zhan, Wang, and Lei 2011; Zhan, Wang, and Wu 2011; Zhang, Leung, and Min 2013; Li, Zhou, and Li 2014). In other words, variations of TCs in the WNP are actually shaped and controlled by a combination of climatic phenomena at different time scales. A recent study by Zhan, Wang, and Ying (2012) noted a pronounced increase in the forecasting error of existing TC prediction schemes in the WNP, which are operated by various meteorological agencies/institutes (City University of Hong Kong, Tropical Storm Risk, and the Shanghai Typhoon Institute of the China Meteorological Administration). They found that the
Before looking into what controls WNP TC variability, this section first provides a brief summary of the climatology of TC genesis in the WNP. Figure 1(b) shows the monthly TC distribution together with the associated dynamic (850 hPa relative vorticity and vertical wind shear) and thermodynamic (sea surface temperature (SST) and 600 hPa relative humidity) parameters in the WNP. The active TC season in the WNP spans from June to November in boreal summer, when the dynamic and thermodynamic parameters both favor cyclogenesis. Climatologically, several unique features in the WNP make it the most active TC region. First, the WNP has the world’s largest warm pool, with a mean SST greater than 29 °C in boreal summer (Figure 2(c)). The warm SST and rich moisture supply provide excellent thermodynamic conditions for the growth of synoptic disturbances as well as TCs. Apart from the thermodynamic parameters, low-level circulation in the WNP is characterized by a confluence of monsoon westerlies and trade easterlies in boreal summer (Figure 2(a)), forming the WNP monsoon trough (Briegel 2002; Chan and Evans 2002). The cyclonic vorticity, enhanced convergence, and rising motion associated with the monsoon trough are favorable for zonal wave energy accumulation (Maloney and Hartmann 2001; Chen and Huang 2008), and thus beneficial for TC development. The western North Pacific

2. Climatology of cyclogenesis in the WNP

Before looking into what controls WNP TC variability, this section first provides a brief summary of the climatology of TC genesis in the WNP. Figure 1(b) shows the monthly TC distribution together with the associated dynamic (850 hPa relative vorticity and vertical wind shear) and thermodynamic (sea surface temperature (SST) and 600 hPa relative humidity) parameters in the WNP. The active TC season in the WNP spans from June to November in boreal summer, when the dynamic and thermodynamic parameters both favor cyclogenesis. Climatologically, several unique features in the WNP make it the most active TC region. First, the WNP has the world’s largest warm pool, with a mean SST greater than 29 °C in boreal summer (Figure 2(c)). The warm SST and rich moisture supply provide excellent thermodynamic conditions for the growth of synoptic disturbances as well as TCs. Apart from the thermodynamic parameters, low-level circulation in the WNP is characterized by a confluence of monsoon westerlies and trade easterlies in boreal summer (Figure 2(a)), forming the WNP monsoon trough (Briegel 2002; Chan and Evans 2002). The cyclonic vorticity, enhanced convergence, and rising motion associated with the monsoon trough are favorable for zonal wave energy accumulation (Maloney and Hartmann 2001; Chen and Huang 2008), and thus beneficial for TC development. The western North Pacific
subtropical high (WNPSH), which manifests as an anticyclone in the northeast of the monsoon trough, primarily controls the movement of TCs. With such a favorable dynamic and thermodynamic background, the majority of TCs form along the axis of the monsoon trough at 10°–20°N with maximum SST, moisture supply, and cyclonic vorticity during boreal summer (Figure 2(e)). As for boreal winter, both dynamic and thermodynamic conditions in the WNP become less favorable (Figure 2(b) and (d)). The monsoon trough degenerates, with a southward shift of the convective center and the WNPSH, as well as a reduction in SST and relative humidity. This results in the concomitant southward shift in TC genesis positions and a reduction in TC number in boreal winter (Figure 2(f)). Nevertheless, the total number of TCs arising in the WNP during this period is still higher than that in any other ocean basin. The intraseasonal, interannual, and interdecadal variability of WNP TCs will be reviewed in the next three sections.

3. Intraseasonal variability of TCs

Intraseasonal TC variation in the WNP is found to be controlled by a combination of factors, including the Madden–Julian Oscillation (MJO; Madden and Julian 1971), Quasi-biweekly Oscillation (QBWO), and PJ teleconnection, as summarized by the schematic diagram in Figure 3. The MJO primarily controls the intraseasonal basin-wide TC frequency, while the smaller-scale QBWO exerts localized
accumulation (Maloney and Hartmann 2000; Sobel and Maloney 2000; Hall, Matthews, and Karoly 2001; Bessafi and Wheeler 2006; Chand and Walsh 2010). Some studies have also emphasized the important role of ENSO, the monsoon trough, and the subtropical high in the MJO–TC relationship (Kim et al. 2008; Wang and Zhou 2008; Chen et al. 2009; Mao and Wu 2010).

Recent advances regarding the MJO–TC relationship include a better understanding of the differences in MJO modulation under different ENSO states (Li et al. 2012). The MJO–TC relationship over the WNP is significantly strengthened during El Niño years, when the enhancement-to-suppression ratio of TCs is double during El Niño compared to neutral years and La Niña years (Zhou and Li 2010; Hsu and Li 2011; Hsu, Li, and Tsou 2011). The asymmetric background modification by ENSO was found to

Figure 4. Schematic diagram illustrating the differences in Madden–Julian Oscillation (MJO) modulation under different ENSO conditions. EN, El Niño; LN, La Niña; TC, tropical cyclone.

Figure 5. Composite differences of 850 hPa eddy kinetic energy (units: m^2 s^-2) between the convective and nonconvective Madden–Julian Oscillation phase during (a) El Niño (EN) and (b) La Niña (LN) years. (c, d) As in (a, b) but for the differences of 850 hPa eddy kinetic energy tendency (units: 10^{-6} m^2 s^{-3}). Shading denotes statistically significant values exceeding the 95% confidence level, based on the Student’s t-test.
play an important role in affecting the MJO modulation on TCs, which is summarized in the schematic diagram in Figure 4. The background El Niño-induced westerlies favor the eastward propagation of the MJO. The MJO activity is intensified and extends further eastward to the dateline during El Niño years, instead of being confined west of 150°E in neutral and La Niña periods, which in turn exerts stronger influences on TCs during El Niño years. From a synoptic perspective, there is also a larger contrast in eddy kinetic energy and perturbation activity between convective and nonconvective MJO phases during El Niño years compared to La Niña years (Figure 5), thus contributing to greater TC discrepancies and stronger TC modulation during El Niño years. Conversely, Zhou and Li (2010) discovered that the synoptic scale variability can also exert an upscale feedback to the ISO through the nonlinear rectification of the surface latent heat flux, while Hsu, Li, and Tsou (2011) and Hsu and Li (2011) further confirmed this by analyzing the barotropic energy conversion and the nonlinear rectification of the apparent heat and moisture sources.

Note that the ISO does not consist solely of the MJO. The kinetic energy of the 10–20-day QBWO can be stronger than that of the 30–60-day mode (Li and Zhou 1995). This 10–20-day QBWO has been observed in the Asian monsoons (Krishnamurti and Bhalme 1976; Krishnamurti and Ardanuy 1980; Chen and Chen 1993, 1995; Mao and Chan 2005; Zhou and Chan 2005, 2007; Kikuchi and Wang 2009; Wen et al. 2010) and originates from the WNP through an equatorial Rossby wave (Chen and Sui 2010). The results of Li and Zhou (2013a, 2013b) highlighted the distinctive role of both the 30–60-day and the 10–20-day ISO modes in intraseasonal TC prediction. Specifically, the MJO accounts for about 23% of the total TC formation in the WNP and predominantly controls the basin-wide TC frequency in the WNP as well as the northeastward shift in TC genesis locations. There is a significant enhancement (suppression) in cyclogenesis during the convective (nonconvective) MJO phases, associated with the concomitant strengthening (weakening) of the monsoon trough. Such a large contrast in TC frequency also results in a significant difference in daily accumulated cyclone energy between the convective and nonconvective phases, even though the variation in intensity is small. Apart from the genesis frequency and intensity, the MJO also exerts significant impacts on TC activity and landfalls through alternations of the genesis positions and the environmental steering flows, influencing a wide area including the Philippines, Vietnam, China, and Japan. The QBWO, on the other hand, is characterized by alternating positive and negative convection anomalies associated with the QBWO result in opposite TC modulations mainly in the WNP and result in a northwestward shift in TC genesis positions. The prominent change in genesis locations in turn leads to substantial differences in intensity distribution and daily accumulated cyclone energy for different QBWO phases. Besides, the tracks and landfalls of TCs also possess quasi-biweekly variations that are closely associated with the QBWO. The characteristics of the MJO and QBWO and their respective impacts on TCs are summarized in Table 1.

Apart from the ISO, recent studies have also identified other factors that can exert significant influence on the synoptic scale, as well as on TC activity in the WNP. Li, Zhou, and Li (2014) found that the PJ teleconnection, which manifests as a dominant tropical–extratropical wave train in boreal summer (Nitta 1987, 1989), exhibits salient intraseasonal features with a period of 10–50 days and can significantly modulate the synoptic scale variability in the WNP. As shown in Figure 6, the growth of synoptic disturbances, as well as TC frequency, are significantly strengthened (suppressed) in the positive (negative) PJ phases, and there is a higher (lower) tendency for TCs to take a recurving track during positive (negative) PJ phases,
interannual changes in the Atlantic, and on the frequency of TCs in the WNP. Later, Wang and Chan (2002) found that cyclogenesis positions in the WNP tend to shift southeastward (northwestward) during El Niño (La Niña) events, which in turn may favor (suppress) the development of intense TCs. Their findings are further supported by a number of subsequent studies (such as Chia and Ropelewski 2002; Camargo and Sobel 2005; Camargo, Emanuel, and Sobel 2007; Camargo et al. 2007), which have similarly identified such a shift during ENSO events. Emanuel and Nolan (2004) proposed a genesis potential and emphasized the important role of vorticity and relative humidity in the eastward shift of the mean genesis location of TCs in the WNP. Chan (2007) also suggested that changes in dynamics (vorticity and wind shear) and thermodynamic structure (moist static energy) associated with an El Niño event are more important than local SST in controlling the interannual variations in TC intensity in the WNP. But the frequency distribution of WNP TCs might be controlled by the interannual variability of the thermal state of the warm pool during ENSO years (Chen and Huang 2008).

Many of the aforementioned studies focused primarily on the effect of ENSO on intense TCs or considered all TCs as a whole regardless of their intensity. As an extension,
in the WNP, as well as in the SCS, as summarized in Table 2. The heat source and sink are found to have a meridional dipole structure during canonical El Niño years, leading to insignificant changes in basin-wide TC frequency due to mutual cancellation in TC number between the southeast and northwest quadrant (Chen and Tam 2010).

Kim, Webster, and Curry (2011) examined the change in TC activity over the WNP in association with changes in dynamic and thermodynamic parameters during different ENSO conditions. Compared to canonical El Niño, TC activity during El Niño Modoki years shifts to the west, with a broad suppressed area over the eastern Pacific, favoring more TCs making landfall over East Asia. Wang et al. (2014) showed that the frequency of TCs in the SCS during fall (September–November) is negatively related to El Niño Modoki, instead of canonical ENSO. They suggested that the large-scale circulation anomalies associated with El Niño Modoki enlarge the low-level northerlies over the SCS, which in turn enhances the vertical wind shear and suppresses local TC formation. The results of these studies have similarly highlighted the growing importance of El Niño Modoki in TC activity over the WNP.

Another research area that has received increasing attention in recent years is the different impacts of canonical ENSO and ENSO Modoki (Ashok et al. 2007; Yu and Kao 2007). In contrast to canonical El Niño, with persistent warming in the eastern Pacific, El Niño Modoki is characterized by central Pacific warming flanked by below-average SST on its eastern and western side. A number of recent studies (Chen and Tam 2010; Kim, Webster, and Curry 2011; Wang et al. 2014) have elucidated the distinctive impacts of these two flavors of ENSO on TC activity in the WNP, as well as in the SCS, as summarized in Table 2. The heat source and sink are found to have a meridional dipole structure during canonical El Niño years, leading to insignificant changes in basin-wide TC frequency due to mutual cancellation in TC number between the southeast and northwest quadrant (Chen and Tam 2010). Kim, Webster, and Curry (2011) examined the change in TC activity over the WNP in association with changes in dynamic and thermodynamic parameters during different ENSO conditions. Compared to canonical El Niño, TC activity during El Niño Modoki years shifts to the west, with a broad suppressed area over the eastern Pacific, favoring more TCs making landfall over East Asia. Wang et al. (2014) showed that the frequency of TCs in the SCS during fall (September–November) is negatively related to El Niño Modoki, instead of canonical ENSO. They suggested that the large-scale circulation anomalies associated with El Niño Modoki enlarge the low-level northerlies over the SCS, which in turn enhances the vertical wind shear and suppresses local TC formation. The results of these studies have similarly highlighted the growing importance of El Niño Modoki in TC activity over the WNP.

Apart from ENSO, several recent studies have also emphasized the critical forcing from the East Indian Ocean on WNP TC activity (Du, Yang, and Xie 2011). According to

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**Figure 7.** Schematic diagram illustrating the relationship between different types of tropical cyclone (TC) and the ENSO cycle. (Annotation: EN, El Niño; LN, La Niña; WNP, western North Pacific; TY, typhoon; STY, super typhoon; TSTD, Tropical storm and depression ↑, increase; ↓, decrease).

**Table 2.** Summary of the distinctive impacts of El Niño and El Niño Modoki on tropical cyclones (TCs).

<table>
<thead>
<tr>
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<th>El Niño</th>
<th>El Niño Modoki</th>
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<tr>
<td>Western North Pacific (WNP) TC genesis activity</td>
<td>Insignificant change in basin-wide TC frequency increase in TC activity in central and eastern Pacific</td>
<td>Increase in basin-wide TC frequency increase in TC activity shifts westward, leading to enhanced landfalls over East Asia</td>
</tr>
<tr>
<td>South China Sea TC genesis</td>
<td>No significant change during fall</td>
<td>Reduction in TC frequency during fall</td>
</tr>
</tbody>
</table>

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both observational analyses and numerical studies, Zhan, Wang, and Lei (2011), and Zhan, Wang, and Wu (2011) suggested that SST warming in the East Indian Ocean can induce positive pressure anomalies accompanied by divergent circulations over the WNP as a warm Kelvin wave response (Xie et al. 2009), thereby suppressing the basin-wide TC frequency. Du, Yang, and Xie (2011) revealed that vertical wind shear over the WNP increases through the development of a warm Kelvin wave from the tropical Indian Ocean in the summer following strong El Niño events, which then suppresses WNP TC formation. The increase in vertical wind shear was also noted by Li and Zhou (2012), who also found that changes in vertical wind shear and relative vorticity during the transition phase of ENSO play a decisive role in controlling typhoon frequency in the WNP.

5. Interdecadal TC variability

Compared to the large number of studies on interannual and intraseasonal TC variability, TC studies at interdecadal scales are relatively fewer, and the exact mechanisms are yet to be determined. TCs in both the WNP and SCS exhibit significant interdecadal variability, with distinct active and inactive periods, and several external forcings have been proposed to be associated with the interdecadal changes in TC activity in the WNP and SCS, including the Pacific Decadal Oscillation (PDO; Leung, Wu, and Chang 2005; Chan 2008; Liu and Chan 2008, 2013; Goh and Chan 2009), the North Pacific Gyre Oscillation (Zhang, Leung, and Min 2013), the Indian Ocean SST (Wang and Huang 2013), and the zonal SST gradient (Li and Zhou 2014).

Ho et al. (2004) suggested that the westward expansion of the WNP SH might be a reason for more frequent typhoon passages over the SCS but less frequent ones over East China after the 1980s, while Liu and Chan (2013) attributed the recent inactive TC period (1998–2011) in the WNP to interdecadal change in the vertical wind shear and WNP SH. It was further noted by Liu and Chan (2013) that the modulation of cyclogenesis by the PDO mainly appears in the southeast WNP, whereas its relationship with cyclogenesis over the entire region is insignificant. In contrast to the weak relationship between the PDO and WNP TC occurrence, Zhang, Leung, and Min (2013) pointed out that the North Pacific Gyre Oscillation has a significant negative relationship with WNP TC frequency on the interdecadal time scale. Results from Zhang, Leung, and Min (2013) showed that more WNP TCs might be related to positive low-level relative vorticity and weaker zonal shear under negative North Pacific Gyre Oscillation phases, especially on the decadal time scale.

Focusing on the SCS, Wang et al. (2012) identified two high-frequency periods (1965–1974 and 1995–2004) and one low-frequency period (1979–1993) during 1965–2004 and attributed the interdecadal TC variations to changes in the intensity of the East Asian jet stream. They showed that a weaker East Asian jet stream can induce anomalous divergence of wave activity fluxes over the SCS, which in turn reduces the shear and is favorable for TC genesis there. On the other hand, Wang et al. (2014) related the significant reduction in May–November SCS TC frequency after the mid-1970s to an increase in SST over the tropical Indian Ocean. Recently, Li and Zhou (2014) further discovered that interdecadal changes in SCS TC frequency are strongly related to the zonal SST gradient between the north Indian Ocean and the WNP. Associated with a positive zonal SST gradient (warmer north Indian Ocean and cooler WNP), anomalous easterlies were observed to develop over the tropics, which in turn induce an anomalous subsidence and boundary-layer divergence over the SCS, further suppressing the moisture as well as TC development over the SCS at interdecadal time scales.

6. Conclusions and discussion

In this review article, recent progress and research on TC variability has been summarized and discussed. Though it is impossible to cover every aspect and report on all the available studies, we attempt to provide a comprehensive overview of TC variability at different time scales. At the intraseasonal scale, recent advances on the distinctive impacts of the MJO and QBWO, the asymmetric modulation of the MJO under different ENSO conditions, and the influence of the PJ teleconnection are highlighted. Interannually, recent progress on the influence of the ENSO cycle, the different flavors of ENSO, and the impacts of Indian Ocean SST are discussed. In addition, the uncertainty concerning interdecadal TC variations is discussed along with the recently proposed possible modulation mechanisms related to the East Asian jet stream intensity, zonal SST gradient, North Pacific Gyre Oscillation, and PDO. All these studies have advanced our understanding and, more importantly, laid a strong foundation for improving the predictability of TCs at different time scales. Therefore, with respect to the increasing forecasting error mentioned in Section 1, future studies should definitely consider including some of the aforementioned newly identified TC-related factors, such as the Pacific teleconnection index, the East Asian jet stream intensity, the zonal SST gradient, and so forth, in updating TC prediction schemes at different time scales.

With the major TC-related factors being identified, the next crucial, yet challenging, task is to try to incorporate these factors into actual TC forecasting. Since most previous studies have focused only on a certain parameter, much more effort needs to go into studying the interactions
between these various factors, in order to improve the accuracy of TC forecasting and predict the future changes of TCs against the background of global warming. The interaction processes are obviously not simple, as they might involve tropical–extratropical interactions as well as wave interactions at different time scales (Tam and Li 2006; Wang, Yamazaki, and Fujiyoshi 2007; Hsu, Li, and Tsou 2011). Inconsistency in the results of TC projection often emerge from modeling studies due to different downscaling methodologies and warming scenarios, inconsistencies in projected changes of large-scale conditions, differences in model physics and tracking algorithms, and incomplete understanding of the underlying mechanisms (Knutson et al. 2010; Walsh et al. 2016). As a result, continued monitoring and further understanding of the couplings of these various factors at different time scales are a must. Numerical studies are also desirable to further verify the proposed mechanisms. Because of their intimate relationship with TCs, these factors might also serve as indirect indicators for future TC projections under different global warming scenarios. With the availability of the CMIP5 datasets, changes in TC activity in association with these different environmental factors can be assessed. It is expected that the predictability of TCs can be further improved through successful completion of the aforementioned research.

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