Monsoon trough influences on multiple tropical cyclones events in the western North Pacific

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In this study, the influences of the monsoon trough (MT) on the multiple tropical cyclones (MTCs) events over the western North Pacific are examined. The results suggest that both thermodynamical and dynamical conditions modulate the frequency of the MTCs events. During the active years, the enhanced MT extends eastwards, leading to a strong low-level relative vorticity, upwards motion, and moist environment that are favourable for the occurrence of the MTCs events. The barotropic kinetic energy conversion diagnosis suggests that in the active years, the synoptic-scale disturbances will develop through gaining the energy from the mean flow with the eastwards extending MT. The percentage contributions to the genesis potential index (GPI) change are from moisture field (75.9%), relative vorticity (18.5%), vertical shear (~24.2%), and vertical motion at 500 hPa (37.3%), suggesting the moisture field is the most important factor in the MTCs event. The enhanced moisture and convection processes likely contribute to more MTCs events through a positive convection–circulation–moisture feedback. Possible linkages between MT and MTCs events are proposed.

KEYWORDS
environmental conditions, monsoon trough, multiple tropical cyclones event

1 INTRODUCTION

Tropical cyclone (TC) genesis involves multiple-scales interactions, including ambient conditions and synoptic-scale precursor perturbations. For instance, the TC frequency in the western North Pacific (WNP) basin is largely controlled by the low-frequency systems such as the Madden–Julian Oscillation (MJO) (Liebmann et al., 1994; Sobel and Maloney, 2000; Maloney and Dickinson, 2003) and the El Niño–Southern Oscillation (ENSO; Lander, 1994; Wang and Chan, 2002; Wu et al., 2002; Camargo and Sobel, 2005). The occurrence TC is an unevenly distributed. That is, in a certain active period, multiple tropical cyclones (MTCs) develop successively. Gao and Li (2012) termed it as a MTCs event in which two or more TCs form within a relatively short period compared to their statistical value. In the summer season, the large-scale low-level circulation over the WNP features a monsoon trough (MT). Numerous studies (Briegel and Frank, 1997; Chan and Evans, 2002; Tomita et al., 2003; Ritchie and Holland, 2010; Molinari and Volllaro, 2013; Wu et al., 2015) suggested an important linkage between MT variability and TC genesis over the WNP. An eastwards extension of the MT enhances mid-tropospheric relative humidity (RH), upper-level divergence, and low-level anomalous cyclonic vorticity. These conditions are favourable for TC genesis. The diagnoses of barotropic energy conversion by Wu et al. (2015) revealed that synoptic-scale disturbances likely develop through extracting the energy from the mean flow with the eastwards extending MT.

Generally, the interactions among multiple TCs will lead to a larger forecasting error and thus a great challenge to the operational centre. Prediction of multiple TCs activity is essential to better prepare for and mitigate TC-induced...
disasters. Hence, the purpose of this study is to investigate the possible roles of large-scale environmental conditions on the MTCs events.

2 | DATA AND METHODOLOGY

In this study, the best track data set from Joint Typhoon Warning Center (JTWC) is used to identify the TC genesis location and timing. The definition of a MTCs event follows Gao and Li (2012). That is, a MTCs event is defined when two or more successive TCs occurred at a time interval shorter than 3 days, and the distance in between was less than 3,000 km. The MTCs events are examined during the period from 1979 to 2016. The primary data set used is the ERA-Interim reanalysis data sets from European Centre for Medium-Range Weather Forecasts (ECMWF). A composite analysis method is utilized to reveal the difference of large-scale circulations between the active and inactive MTCs years.

3 | PRELIMINARY RESULTS

Figure 1 presents the time evolution of the frequency of MTCs events in WNP during 1979–2016. It clearly shows a marked inter-annual variation. The mean value of the annual frequency is 4.0, and the standard deviation (SD) is about 1.6. In this study, the years with the number of MTCs events above (below) positive (negative) one SD are selected to be active (inactive) years, respectively. Specially, the active years include 1979, 1984, 1985, 1989, 1990, 1994, and 2011. The inactive years are 1981, 1983, 1987, 1995, 1998, 2005, and 2010. Since the majority of MTCs events in the WNP occur during June–September (Gao et al., 2010), we mainly focus on this period in this study.

3.1 | Mean circulations

Figure 2 compares the composited mean circulation during the period of interest (June–September). During the active
years, the enhanced MT extends eastwards to near 150°E, and its meridional width is about 20° from 5°N to 25°N. Furthermore, at the eastern portion of the MT, there is a strong convergence associated with southwesterly monsoonal flow and southeasterly wind from the southwest flank of subtropical high (Figure 2a). During the inactive years, the MT greatly weakens and retreats westwards significantly. The easternmost tip of the MT is located near 135°E (Figure 2b). These features agree with previous studies (Gao and Li, 2012; Cao and Wu, 2018). Figure 2c displays the difference of low-level circulation between active and inactive years. An elongated anomalous cyclonic circulation is centred on 20°N, indicating a stronger lower-level relative vorticity during the active years.

Climatologically, there is a tropical upper-tropospheric trough (TUTT) over the North Pacific. Sadler (1978) suggested that the TUTTs might assist TC genesis and intensification by enhancing an efficient upper outflow channel. Nevertheless, the TUTT can result in a large vertical wind shear (VWS) that may inhibit TCs strengthening. Wang and Wu (2016) found that the TC frequency is enhanced (suppressed) in the eastern portion of the WNP, accompanying with the eastwards (westwards) shifting of TUTT. In the active years, the TUTT shifts eastwards along with the eastwards extension of the MT. As shown in Figure 2f, an anomalous anticyclonic circulation is centred near 160°E, enhancing the upper divergence. The results indicate salient differences in the large-scale circulations between active and inactive years. Specifically, the enhanced MT extends eastwards, leading to a greater low-level relative vorticity, upwards motion, and moist environment that are favourable for the TC development. In the following sections, we will examine these underlying dynamical and thermodynamical processes.

3.2 | Box difference index

To illustrate the differences in the environmental conditions, the box difference index (BDI; Fu et al., 2012; Peng et al., 2012) is applied. Four environmental variables are selected including 850 hPa relative vorticity, 500 hPa vertical pressure–velocity, VWS, and 700 hPa RH. Figure 3a presents the BDIs of these large-scale environmental factors. It is worth mentioning that the sign of vertical pressure–velocity is reversed so that the positive value represents an ascending motion. All of the BDIs are positive, indicating that these variables are greater during the active years. Physically, a greater vorticity promotes moisture via the Ekman pumping. The positive feedback via the convection–circulation–moisture is favourable for TC development. Nonetheless, the difference in the VS is positive, indicating a greater magnitude in the active years. This seems conflict with the claim that a weaker VS benefits a single TC development. In this study, we propose that this factor likely plays an important role in trigger MTCs event, which is different from the single TC events. It is speculated that the TC energy dispersion (TCED) induced cyclogenesis is one of the mechanisms responsible for the MTCs. Previous studies (Li et al., 2006; Ge et al., 2007) revealed that the TCED-induced Rossby wave train is largely determined by the environmental flows (i.e., VS). Namely, the easterly (westerly) VWS favours a robust low (upper) level wave train. In the active years, there is a strong easterly shear, implying that the maximum amplitude of wave train occurs at low level. This type of synoptic-scale wave train acts as a precursor of TC genesis. Under favourable ambient conditions, this system favours to develop into a second TC in its wake and thus a MTCs event occurs. To test this possibility, Figure 4 compares the spatial patterns of vertical shear of the zonal wind in active and inactive years, respectively. It indicates that there is indeed strong easterly shear in the main genesis region (i.e., south
of 20°N), which is largely due to the eastwards shift of the enhanced MT in the active years. As a result, it promotes the development of low-level synoptic wave train and thus MTCs event eventually.

3.3 | Genesis potential index

The genesis potential index (GPI; Murakami and Wang, 2010) is widely to measure the environmental factors contributing to TC genesis. A modified GPI includes five terms: Term1 = \(10^5 \zeta^{3/2}\), Term2 = \((1 + 0.1V_{\text{shear}})^{-2}\), Term3 = \((H/80)^3\), Term4 = \((V_{\text{pot}}/70)^3\), and Term5 = \((-\omega+0.1/1.1)\), respectively. The \(\zeta\) is 850 hPa absolute vorticity, \(V_{\text{shear}}\) is the magnitude of the VWS between 850 and 200 hPa, \(H\) is the RH at 600 hPa, and \(V_{\text{pot}}\) is the maximum TC potential intensity (PI), \(\omega\) is 500 hPa vertical pressure–velocity. To assess their relative contribution, the percentage contribution of each term to the GPI change is applied (Li et al., 2013).

Figure 3b presents the calculated total difference and relative contributions of five terms, respectively. These terms are averaged in a box area (120°E–160°E, 5°–25°N), which covers the main TC development zone. The value of \(\delta\text{GPI}\) equals 0.75, which is approximated by the combined contribution by the RH (0.57), vorticity (+0.14), atmospheric VWS (−0.18), PI (−0.01), and the vertical motion (+0.28).

In this study, the atmospheric moisture field is the dominant factor in controlling the MTC events, which is consistent with Cao et al. (2014). The authors also found that the thermodynamic (moisture) impact is about twice as large as the dynamic at intra-seasonal timescale. Physically, a larger background vertical motion and relative vorticity favours a moist air column through the circulation–convection–moisture feedback. The higher ambient RH is crucial for TC
development. Of a particular interest is that the enhanced VS has a negative effect, but its contribution is relatively smaller. As mentioned above, the large VS is unfavourable for a single TC event, but probably enhances synoptic-scale wave train and thus a MTCs event. This is different from the conventional viewpoint in single TC events.

3.4 Barotropic kinetic energy conversion

To explore the dynamical processes of the MT in modulating the MTCs events, the barotropic kinetic energy (BKE) equation is derived as follows:

\[
\frac{\partial K'}{\partial t} = -\langle u'\rangle \frac{\partial}{\partial x} \overline{u} - \langle u'\rangle \frac{\partial}{\partial y} \overline{v} - \langle v'\rangle \frac{\partial}{\partial x} \overline{u} - \langle v'\rangle \frac{\partial}{\partial y} \overline{v} - (\langle v'\rangle)^2 \frac{\partial}{\partial y} \overline{v},
\]

where \( u' \) and \( v' \) are the 850 hPa zonal and meridional wind of transient disturbances, which is obtained by applying 3–8 days bandpass filter. \( \overline{u} \) and \( \overline{v} \) are the averaged zonal and meridional wind during June–September, respectively. \( K' \) is the kinetic energy of transient disturbances. Figure 5 suggests that the contributions by \( -\langle u'\rangle^2 \frac{\partial}{\partial x} \overline{u} \) and \( -\langle u'\rangle \frac{\partial}{\partial y} \overline{v} \) are dominated. The other two terms are insignificant and neglected here. The term \( -\langle u'\rangle^2 \frac{\partial}{\partial x} \overline{u} \) is attributed to the disturbances due to the longitudinal zonal wind convergences, and \( -\langle u'\rangle \frac{\partial}{\partial y} \overline{v} \) is due to the latitudinal zonal wind gradients over the WNP. Figure 5d–e shows the effect of the monsoon confluent flows remarkably impacts the barotropic energy conversion, which is consistent with Maloney and Dickinson (2003). A zonal convergence of the monsoon flow promotes wave accumulation, which leads to a reduced wave-length (Webster, 1988; Kuo et al., 2001). Meanwhile, this horizontal convergence favours vertical motions and thus convection therein. Furthermore, during the active years, along with the MT extends eastwards (Figure 2a), \( -\frac{\partial}{\partial y} \overline{v} \) increases and thus supports the barotropic instability and possible wave breaking (Ferreira and Schubert, 1997). In short, the results suggest that the large-scale dynamical processes play important roles in triggering the MTCs events. Admittedly, the mean state is time-invariant, by which we neglect the influences of the intra-seasonal variability on the synoptic-scale disturbance (Hsu et al., 2011). This issue awaits further study.

4 RESULT AND DISCUSSION

In this study, the MT influences on the MTCs events in the WNP are examined. During the active years, the enhanced MT extends eastwards, leading to a strong low-level relative vorticity, upwards motion, and moist environment that are favourable for the occurrence of the MTCs events. In the active years, due to strong low-level convergence and upper-level divergence, it favours strong updrafts. For the role of background vertical motion, it is likely that the strong ascending motion favours a moist air column through the circulation–convection–moisture feedback. The BKE conversion diagnosis suggests that during the active years, the enhanced zonal convergence of the monsoon flow favours wave accumulation and provides a favourable environment for the TC development. The percentage contribution to the GPI change shows that the moisture field is the most important factor in the MTCs event.

The synoptic wave train in the WNP is an unstable mode of the summer mean flow in the presence of convection–circulation–moisture feedback (Li, 2006). A Rossby wave train can be induced by TCED as well (Ge et al., 2007). These synoptic-scale wave trains act as a precursor of TC genesis. In the active years, there is a strong easterly shear, implying that the maximum amplitude of wave train occurs at low level. Given a higher background moisture field, the wave train becomes stronger and thus has a great potential to trigger MTCs events. In short, both thermodynamical and dynamical conditions over MT region will work together to promote a MTCs event. The study suggests a possible linkage between MT and MTCs events in the WNP. However, the detailed underlying processes are not yet understood completely, and this topic merits further studies.

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REFERENCES

Briegel, L.M. and Frank, W. M. (1997) Large-scale influences on tropical cyclogenesis in the western North Pacific. Monthly Weather Review, 125, 1397–1413.
Camargo, S.J. and Sobel, A.H. (2005) Western North Pacific tropical cyclone intensity and ENSO, Journal of Climate, 18, 2996–3006.
Cao, X., Li, T., Peng, M., Chen, W. and Chen, G.H. (2014) Effects of monsoon trough intraseasonal oscillation on tropical cyclogenesis in the western North Pacific. Journal of the Atmospheric Sciences, 71, 4639–4660.
Cao, X. and Wu, R.G. (2018) Simulations of development of tropical disturbances associated with the monsoon trough over the western North Pacific. Atmospheric Science Letters, 19, e801. https://doi.org/10.1002/asl.801.
Chan, S.C. and Evans, J.L. (2002) Comparison of the structure of the ITCZ in the West Pacific during the boreal summers of 1989–93 using AMIP simulations and ECMWF reanalysis, Journal of Climate, 15, 3549–3568.
Ferreira, R.N. and Schubert, W.H. (1997) Barotropic aspects of ITCZ breakdown. Journal of the Atmospheric Sciences, 54, 261–285.
Fu, B., Peng, M.S., Li, T. and Stevens, D. (2012) Developing versus nondeveloping disturbances for tropical cyclone formation. Part II: western North Pacific. Monthly Weather Review, 140, 1067–1080.
Gao, J.Y., Lv, X.Y., Bao, R.J. and Zhang, X.Z. (2010) Research on the cluster of tropical cyclogenesis in the South China Sea–western North Pacific monsoon trough. Part I: major features about the cluster of tropical cyclogenesis. Acta Oceanologica Sinica, 32, 64–71 (in Chinese).

Gao, J.Y. and Li, T. (2012) Interannual variation of multiple tropical cyclone events in the western North Pacific. Advances in Atmospheric Sciences, 29, 1279–1291.

Ge, X.Y., Li, T. and Zhou, X.Q. (2007) Tropical cyclone energy dispersion under vertical shears. Geophysical Research Letters, 34, L23807. https://doi.org/10.1029/2007GL031867.

Hsu, P.C., Li, T. and Tsou, C.H. (2011) Interactions between boreal summer intraseasonal oscillations and synoptic-scale disturbances over the western North Pacific. Part I: energetics diagnosis. Journal of Climate, 24, 927–941.

Kuo, H.C., Chen, J.H., Williams, R.T. and Chang, C.P. (2001) Rossby waves in zonally opposing mean flow: behavior in Northwest Pacific summer monsoon. Journal of the Atmospheric Sciences, 58, 1035–1050.

Lander, M.A. (1994) An exploratory analysis of the relationship between tropical storm formation in the western North Pacific and ENSO. Monthly Weather Review, 122, 333–360.

Li, T. (2006) Origin of the summertime synoptic-scale wave train in the western North Pacific. Journal of the Atmospheric Sciences, 63, 1093–1102.

Li, Z., Yu, W.D. and Li, T. (2013) Bimodal character of cyclone climatology in the Bay of Bengal modulated by monsoon seasonal cycle. Journal of Climate, 26, 1033–1046.

Liebmann, B., Hendon, H.H. and Glick, J.D. (1994) The relationship between tropical cyclones of the western Pacific and Indian Oceans and the Madden–Julian Oscillation. Journal of the Meteorological Society of Japan, 72, 3948–3970.

Maloney, E.D. and Dickinson, M.J. (2003) The intraseasonal oscillation and the energetics of summertime tropical North Pacific synoptic-scale disturbances. Journal of the Atmospheric Sciences, 60, 2153–2168.

Molinari, J. and Vollaro, D. (2013) What percentage of western North Pacific tropical cyclones form within the monsoon trough? Monthly Weather Review, 141, 499–505.

Murakami, H. and Wang, B. (2010) Future change of North Atlantic tropical cyclone tracks: projection by a 20-km-mesh global atmospheric model. Journal of Climate, 23, 2699–2721.

Peng, M., Fu, B., Li, T. and Stevens, D. (2012) Developing versus non-developing disturbances for tropical cyclone formation. Part I: North Atlantic. Monthly Weather Review, 140, 1047–1066.

Ritchie, E.A. and Holland, G.J. (2010) Large-scale patterns associated with tropical cyclogenesis in the western Pacific. Monthly Weather Review, 127, 2027–2043.

Sadler, J.C. (1978) Mid-season typhoon development and intensity changes and the tropical upper tropospheric trough. Monthly Weather Review, 106, 1137–1152.

Sobel, A.H. and Maloney, E.D. (2000) Effect of ENSO and the MJO on western North Pacific tropical cyclones. Geophysical Research Letters, 27, 1739–1742.

Tomita, T., Yoshikane, T. and Yasunari, T. (2003) Biennial and lower-frequency variability observed in the early summer climate in the western North Pacific. Journal of Climate, 17, 4254–4266.

Wang, B. and Chan, J.C.L. (2002) How strong ENSO events affect tropical storm activity over the western North Pacific. Journal of Climate, 15, 1643–1658.

Wang, C. and Wu, L. (2016) Interannual shift of the tropical upper tropospheric trough and its influence on tropical cyclone formation over the western North Pacific. Journal of Climate, 29, 4203–4211.

Webster, P.J. (1988) Equatorial energy accumulation and emanation regions: impacts of a zonally varying basic state. Journal of the Atmospheric Sciences, 45, 803–829.

Wu, L., Wen, Z.P. and Wu, R.G. (2015) Influence of the monsoon trough on westward-propagating tropical waves over the western North Pacific. Part II: energetics and numerical experiments. Journal of Climate, 28, 9332–9349.

Wu, M.C., Chang, W.L. and Leung, W.M. (2002) Impacts of El Niño–Southern Oscillation events on tropical cyclone landfalling activity in the western North Pacific. Journal of Climate, 17, 1419–1428.

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