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Influences of the equatorial waves on multiple tropical cyclone genesis over the western North Pacific

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ABSTRACT

The statistical features of tropical cyclone (TC) genesis (TCG) related to the convectively coupled equatorial waves (CCEW), including Kelvin, Equatorial Rossby (ER), mixed Rossby-Gravity (MRG), and tropical depression (TD)-type waves, are examined during the TC season (May to October) in the western North Pacific (WNP) for the period of 1979 - 2015. The result indicates that 84.1% of TC genesis occurs within the active phase of CCEW. Among them, about 71.3% concurs with a single wave or two coexisting waves. The contribution of each tropical wave shows notable seasonal dependence. The relative roles of individual tropical waves related to multiple tropical cyclone (MTC) events are examined. The CCEW provide strong (weak) favorable environmental conditions to result in more (less) TC genesis. In the active and normal MTC phases, ER waves play a more important role to TC genesis, while in the inactive MTC phase, TC genesis is primarily affected by TD waves and secondly by MRG waves. The contribution of CCEW to the OLR variance is more significant in the active MTC phase, especially in the region east of 150°E. Among them, ER waves make the contribution. Composite analyses reveal that all types of CCEW produce consistent forcing mechanisms for TCG with positive vorticity anomalies in the lower level and divergence anomalies in the upper level. Compared to the synoptic-scale waves (TD and MRG waves), the long-lasting ER waves produces more favorable humidity and convective conditions for MTC formation.

1. INTRODUCTION

The accurate forecast of tropical cyclone (TC) genesis (TCG) is still a puzzle at present, particularly in the extended forecast with the leading time of 2 - 4 weeks. TCs appear to form irregularly with large-scale systems providing favorable environmental conditions during the warm season in the western North Pacific (WNP) (e.g., Gray 1968; Briegel and Frank 1997; You et al. 2019b; Chen et al. 2020) and the South China Sea (SCS) (e.g., Wu et al. 2020). The large-scale environmental conditions alone are not sufficient to determine the formation of TC genesis. Recent studies found that near-equatorial tropical waves extensively involve in TC genesis (Bister and Emanuel 1997; Landsea et al. 1998; Ritchie and Holland 1999) by either modulating environmental conditions or providing precursor disturbances for TC genesis. Therefore, these tropical waves have been adopted by some TC forecast models to improve TC genesis predictability (Roundy and Schreck 2009).

The tropical waves are generally separated into five types (e.g., Wheeler and Kiladis 1999; Tsai et al. 2020): Mixed Rossby-Gravity (MRG) wave, Tropical depression (TD)-type disturbance, Equatorial Rossby (ER) wave, Kelvin wave, and Madden-Julian Oscillation (MJO). The MRG wave could evolve into an off-equatorial synoptic-scale TD-type disturbance which is also known as easterly waves that may serve as seedlings of initial disturbances for TC genesis (e.g., Briegel and Frank 1997; Ritchie and Holland 1999; Dickinson and Molinari 2002; Aiyyer and Molinari 2003; Fu et al. 2007). The eastern part of the lower center of ER waves often supplies convection and cyclonic vorticity to

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facilitate TC genesis (Molinari et al. 2007). It's also been found that the MJO indirectly affect TC genesis via intraseasonal modulations on synoptic-scale MRG, TD, and Kelvin waves. Schreck et al. (2012) noted that Kelvin waves and the MJO may jointly assist TC genesis by providing favorable westerlies and cyclonic potential vorticity. Nevertheless, the impact of Kelvin waves on TC genesis remains uncertain.

Most studies investigate the impacts of the tropical waves on TC genesis are obtained from case studies. However, TC genesis events are usually inconsecutive, as being active in some time and inactive or totally unrecognizable in some other time (Gray 1979) and the percentage of TC genesis is not consistent among different case studies. Moreover, few studies investigate the contribution of these tropical waves to TC genesis. Base on the analyses of outgoing longwave radiation (OLR) data, Bessafi and Wheeler (2006) found that the MJO and ER waves could cause a large phase modulation on TC genesis in the South Indian Ocean. The majority of TC genesis, especially in the WNP can be attributed to the enhanced convections caused by tropical waves (Schreck et al. 2012). Zhao et al. (2019) re-examined association of multiple scale waves with TC genesis events in the WNP based on empirical orthogonal function (EOF) analysis and found that synoptic-scale waves are critical for many TC genesis events and these intraseasonal waves all exert significant modulation on TC genesis events. In the meanwhile, a majority of TCs (approximately 79%) are related to more than one wave types. Wu and Takahashi (2018) also found that about 83.2% of TCs form within an active phase of tropical waves, mainly in a single wave or two coexisting waves. The above relationship between tropical wave types and TC genesis mainly focused on the statistical characteristics of the entire TC season. However, such a relationship is not sufficient to be applied to the real operation of TC forecast.

Therefore, further analysis of influences of multi-scale tropical waves on subseasonal TC genesis, particularly during the active phase, could be helpful for further understanding of the physical processes for TC genesis and consequent improvements in TC genesis predictability. The objective of this study is to examine the influences of convectively coupled equatorial waves (CCEW) on subseasonal TC genesis in the WNP. The remainder of the paper is organized as follows. Section 2 describes the data and methodology used in this study. Sections 3 and 4 further investigate the impacts of CCEW on multiple tropical cyclone (MTC) events. Summary and discussion are given in section 5.

2. DATA AND METHODOLOGY

2.1 Datasets

The primary datasets used in this study are the National Ocean and Atmospheric Administration (NOAA) outgoing longwave radiation (OLR; Liebmann and Smith 1996) and the National Centers for Environmental Prediction-Department of Energy (NCEP-DOE) Atmospheric Model Intercomparison Project (AMIP-II) Reanalysis (Kanamitsu et al. 2002). Both of the datasets are daily averaged products at a 2.5° × 2.5° grid for the global domain. The best-track TC data from the Joint Typhoon Warming Center (JTWC) are used to determine TC genesis features (time and location) in the WNP. The typical warning of JTWC occurs when a TC just reaches the tropical depression intensity. The analysis period is confined in the TC season (May to October) from 1979 to 2015.

2.2 Methodology

2.2.1 Spectral Analysis and Filtering

A Lanczos filter (Duchon 1979) is applied to both the daily OLR and reanalysis data and the zonal wavenumbers are filtered by using the Kalman filter. The ER waves are extracted with a period of 6.25 - 48 days and westward wavenumbers 1 - 10. They are bounded by theoretical ER wave dispersion curves for equivalent depths of 8 and 90 m. The Kelvin waves are defined for positive zonal wavenumbers 1 - 14 and a period of 2.5 - 20 days. They are bounded by theoretical Kelvin wave dispersion curves for equivalent depths of 8 and 90 m. Those two filtering modes are similar to that used in the studies of Wheeler et al. (2000) and Frank and Roundy (2006). Base on the study of Dickinson and Molinari (2002), we defined the MRG waves with a period of 5 - 10 days and the TD waves with a period of 2.5 - 6 days.

2.2.2 Definition of MTC Genesis Events

According to previous studies multiple tropical cyclone (MTC) events can be classified into three different phases (active, normal, and inactive) based on the statistical features of TC genesis dates (Gao et al. 2010). An inactive phase is defined as a TC genesis interval (TGI) is being greater than or equal to 9 days, which means the genesis interval between two consecutive TCs being over or equal to 9 days. An active phase is defined as a TGI being less than or equal to 3 days. A normal phase is with a TGI of 3 to 9 days. If two or more active or inactive phases occur successively, they are considered as the same active or inactive phase. In this study, we only focus on the MTC events with more than 5 TC geneses in the active or normal phases and the inactive phase with a TGI being greater than or equal to 20 days.

2.2.3 Determining the TC Genesis Related to CCEW

Genesis events are referred as wave type-related events if their occurrence is associated with the active phase of certain type of tropical wave mentioned above. A wave band is considered active if its variance of filtered OLR time series with certain filter window length is locally above the predefined thresholds in every grid point within the WNP domain and is verified every day to determine if the variances of these grid points exceed given thresholds of different wave types related to TC genesis. Variances of time series in this section are extracted by smoothing the squared filtered anomaly with a running mean in time for each grid point. The filter windows length of the running mean for the ER, MRG, Kelvin, and TD-type wave bands are 21, 11, 11, and 7 days, respectively (Frank and Roundy 2006).

There are three well and widely accepted methods to determine the thresholds. Wheeler et al. (2000) applied a wave activity threshold equal to the maximum variance of wave-filtered OLR of the entire time series for all genesis events of the whole basin for each wave type which is called the max-variance method. The second method is called the area-variance method which applied a wave activity threshold equal to the area averaged variance for all grid points within the WNP domain. The third method is named as the TC-variance method, which sets the wave activity threshold equal to variance of each location of TC genesis. The major difference among these three methods is that the first two methods have the same threshold for certain type of wave for all grid points, while the third method has different thresholds at different locations. The numbers of wave-related TC genesis identified by applying three different methods are showed in Fig. 1. It shows that the number of TC genesis associated with CCEW is the largest by using the TC-variance method. Due to a reduction in the amplitude of waves, the fewest wave-related TC genesis are identified by using the area-variance method. Considering the orders of magnitude are incomparable in different latitudes and for different tropical waves (Wheeler et al. 2000), we choose the TC-variance method instead of the other two methods in later analysis. Therefore, the thresholds of all genesis events uniquely set to the variance of the base point for each type of tropical wave.

To examine the rationality of this method, the percentages of wave-related TC genesis for each wave type are shown in Table 1 and the seasonal variation of CCEW and its relationship with TCG are presented in Fig. 2. There were 558 TC genesis events over the WNP domain (0 - 20°N, 90 - 180°E) during 1979 - 2015. Table 1 indicates that about 84.1% of TC genesis events occur during the active phases of CCEW. Among them, 36.4% of TC genesis events are related to a single wave and 34.9% related to two coexisting waves. Synoptic-scale waves cause more significant modulation on TC genesis when they are associated with other large-scale waves. Figure 2 shows that TD, MRG, and ER waves exhibit annual variations with peaks in coherence with the active TC season in the WNP. These results are consistent to previous studies, which means using a new definition of the wave-related TC genesis events and discussing the respective influences of tropical waves on TC genesis are applicative in our study.

3. STATISTICAL CHARACTERISTICS OF CCEW AND MTC EVENTS

According to the definition and methodology described above, 288 TC genesis events are selected with 126 TCs in the active phase, 148 TCs in the normal phase, and 14 TCs in the inactive phase. Figure 3 shows the percentages of four tropical waves associated with TC genesis in different MTC phases. It suggests that the TC genesis has a stronger connection to ER waves, TD waves, and MRG waves, and a relatively weaker relation with Kelvin waves. The relative roles of these four types of CCEW vary noticeably in different MTC phases. In the active MTC phase, ER waves and TD waves make the largest and almost equal contribution to the TC genesis. In the normal phases, the ER waves make the most contribution, followed by TD waves. By comparison, very different scenario exists in the inactive phase with the largest contribution coming from TD waves and the secondary contribution from MRG waves. These results indicate that the synoptic-scale waves (TD waves and MRG waves) become more important to TC genesis in the inactive MTC phase in contrast to the active and normal MTC phases.

The contribution of various wave combinations to TC genesis in different MTC phases is examined in Fig. 4. TC genesis events associated with a single wave or two coexisting waves account for over 25%, while the cases associated with three or four coexisting waves decrease to less than 15 and 5%, respectively. The percentages of TC genesis associated with a single wave or two co-existing waves are comparable in the active (35.7 - 36.5%) and normal (34.5 - 35.8%) phases (Table 2). The relative contribution of the four single wave types to TC genesis exhibits a salient feature. Waves with longer timescale, like ER waves, show larger contribution than the other three tropical waves in the normal (19.6%) and active (11.1%) phases.

The contribution of the four types of waves during the inactive MTC phase is shown in Table 3. It reveals that a single wave is the dominate process to facilitate TC genesis. However, this process only works for TD waves (21.4%) and MRG waves (14.3%), but not for ER waves at all (0%). Consequently, the cases associated with two coexisting waves are more likely to be with the TD waves and MRG waves. You et al. (2019a) suggested that variability of MTC phases is closely related to the northward propagations of intraseasonal oscillation (ISO). In the inactive MTC phase, TD waves and MRG waves can provide favorable conditions to overcome the unfavorable condition provided by the ISO to assist TC genesis.

4. IMPACTS OF CCEW ON MTC EVENTS

4.1 Intensity of CCEW in Different MTC Phases

To investigate spatial distributions of the intensity of

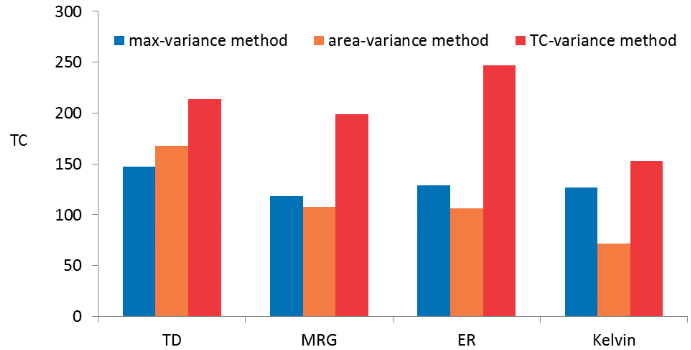

Fig. 1. Number of wave-related TCs for the different thresholds.

Table 1. Contribution of different tropical waves and their combinations to TC genesis.

Waves types		Percent (%)	Sum (%)
A single wave	T	8.2	36.4
	M	7.5	
	E	12.5	
	K	8.1	
Two coexisting waves	T-M	7.2	34.9
	T-E	8.2	
	T-K	3.9	
	M-E	8.2	
	M-K	2.9	
	E-K	4.5	
Three coexisting waves	T-M-E	4.7	11.5
	T-M-K	2.0	
	M-E-K	2.0	
	T-E-K	2.9	
Four coexisting waves	T-M-E-K	1.3	1.3
No wave		15.9	15.9

Note: TD wave is indicated as T, and M, E, K indicates for MRG wave, ER wave, and Kelvin wave.

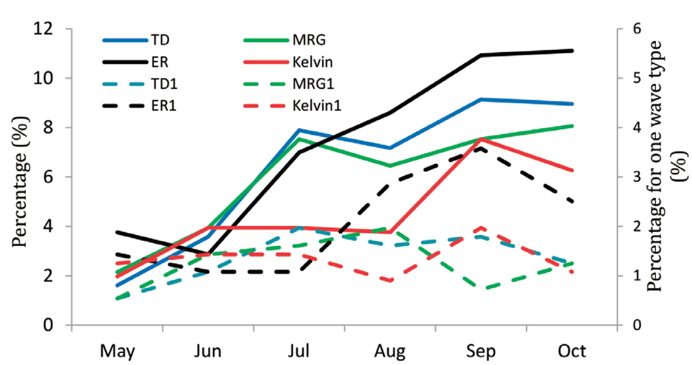

Fig. 2. Contributions of the four tropical waves associated with TC genesis in all types (solid line) and only in a single wave type (dash line) during May to October.

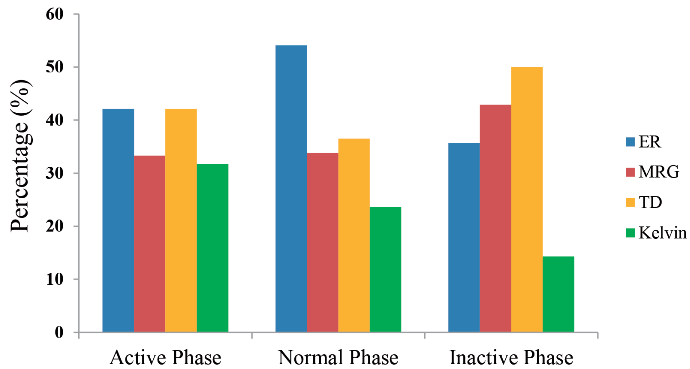

Fig. 3. Percentages of four tropical waves associated with TC genesis in three MTC phases.

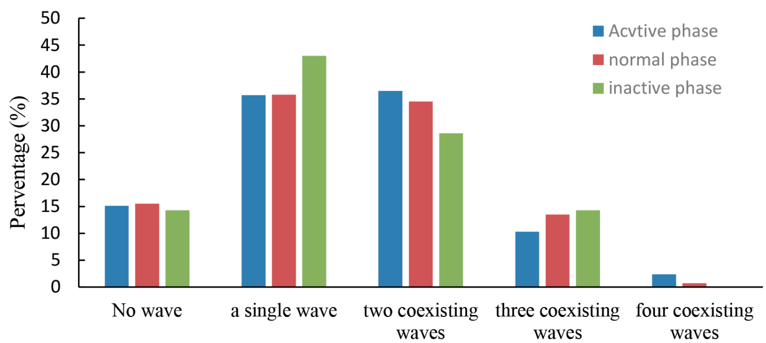

Fig. 4. Percentages of TC genesis cases associated with different tropical waves and their combinations in different MTC phases.

Table 2. Percentages of TC genesis cases associated with various tropical waves and their combinations in the active/normal phase of MTC events.

Waves types		**Percent (%)**	**Sum (%)**
A single wave	T	9.5/6.1	35.7/35.8
	M	5.6/5.4	
	E	11.1/19.6	
	K	9.5/4.7	
Two coexisting waves	T-M	7.1/6.8	36.5/34.5
	T-E	6.3/8.8	
	T-K	7.9/2.7	
	M-E	7.1/9.5	
	M-K	2.4/2.0	
	E-K	5.6/4.7	
Three coexisting waves	T-M-E	6.3/4.7	10.3/13.5
	T-M-K	0.8/2.7	
	M-E-K	1.6/2.0	
	T-E-K	1.6/4.1	
Four coexisting waves	T-M-E-K	2.4/0.7	2.4/0.7
No wave		15.1/15.5	15.1/15.5

Table 3. Percentages of TC genesis cases associated with various tropical waves and their combinations in the inactive MTC phase.

Waves types		**Percent (%)**	**Sum (%)**
A single wave	T	21.4	43
	M	14.3	
	E	0.0	
	K	7.1	
Two coexisting waves	T-M	7.1	28.6
	T-E	7.1	
	T-K	0.0	
	M-E	14.3	
	M-K	0.0	
	E-K	0.0	
Three coexisting waves	T-M-E	7.1	14.3
	T-M-K	0.0	
	M-E-K	0.0	
	T-E-K	7.1	
Four coexisting waves	T-M-E-K	0.0	0.0
No wave		14.3	14.3

four wave types of CCEW during different MTC phases, the standard deviation of the wave-filtered OLR is used to evaluate the intensity of CCEW. The active and inactive MTC phases covered 624 and 659 days, respectively. Their geographical distribution (Figs. 5a - i) exhibits highly similar patterns with the maximum centers being over SCS and the WNP, while the exception occurs in eastward-shifted Kelvin waves (Figs. 5i - l), indicating a weak correlation with the MTC evens. The intensity of CCEW changes substantially throughout different phases as the intensity is much stronger in the active MTC phase than that in the inactive phase. It suggests that TD waves, MRG waves and ER waves play more important roles in TC genesis and provide more (less) favorable environmental conditions to enhance (suppress) TC formation in the active (inactive) phase.

The occurrence of MTC events requires more persistent favorable conditions to facilitate TC genesis which is normally related to longer-time scale waves like ER waves. However, the features of the ER waves in different MTC phases vary greatly with strengthened and northward extended ER waves in the active MTC phase and weakened ER waves in the inactive MTC phase (Fig. 5i). These results suggest that long-lasting ER waves can persistently modulate environmental conditions to result in the active MTC phase whereas they are almost irrelevant to the inactive MTC phase.

4.2 Contribution of CCEW in Different MTC Phases

So far we already know that the TD waves, MRG waves and ER waves play more important roles in MTC events, but different wave types provide different favorable conditions for the TCG. Figure 6 shows the filtered OLR variance contribution of four wave types to MTC for active and inactive phases. It clearly demonstrates that the synoptic-scale waves like TD and MRG waves make less contribution to the OLR variance while the ER waves make the most contribution, particularly in the SCS and WNP in both the active and inactive phases. Compared to the inactive phase, the contribution of CCEW to the OLR variance is more significant in the active phase, especially in the region east of 150°E. In this region, an eastward extension of the enhanced monsoon trough coincides with increased tropical wave activity by accelerated wave-mean flow interaction, which is favorable to TC genesis (Wu et al. 2015a). The synoptic-scale waves could provide the dynamic conditions and longer-time scale waves like ER waves provide energy conditions. Previous studies (Briegel and Frank 1997; Ritchie and Holland 1999; Aiyyer and Molinari 2003) have shown that MRG waves could subsequently evolve into a synoptic-scale TD-type disturbance during its westward propagation to the western Pacific and that disturbance may develop into a TC later. Therefore, the MRG and TD wave trains serve as the major precursor disturbances for TC genesis (Holland 1995; Fu et al. 2007). In our study, almost all of the cases associated with a single wave or two coexisting waves are related to TD waves or MRG waves.

4.3 Composite Wave Structures at TC Genesis in the Active MTC Phase

To reveal the wave structures of the different CCEW in the active MTC phase, composite analysis is performed for several meteorological variables relative to the TCG (Figs. 7 - 10). In each of these figures the grid has been shifted zonally and meridionally for each case so that 0° longitude and 0° latitude are the longitude and latitude of the TC genesis locations. The composite analysis is performed on those cases that the intensity of CCEW exceeds the thresholds within the active phase.

In the lower-level, for the TD waves (Fig. 7a), TCs tend to form near the center of a cyclonic anomaly which belongs to a wave train propagating northwestward and within the northeasterly anomalous flow in the western part of the cyclonic gyre. For the MRG waves, TCs form in the southern part of the cyclonic anomaly (Fig. 7b). The mean TC genesis location associated with ER waves is situated to the southeast of the cyclone anomaly center (Fig. 8c), which consists with the previous findings (Wheeler et al. 2000; Frank and Roundy 2006; Chen and Chou 2014). For Kelvin waves, their composite anomalies in Fig. 7d do not exhibit a clear wave train feature. The mean genesis location of TCs associated with Kelvin waves appears in the eastern part of the cyclonic gyre and is surrounded by a strong easterly/southeasterly surge. It also shows that these formative locations are all coupled with positive vorticity anomaly which coincides with the fact that the synoptic-scale waves (with stronger vorticity) more likely provide dynamical condition than the spatial scale waves do. Increasing ambient vorticity may have been sufficient to trigger convection-circulation feedbacks that can lead to cyclogenesis (Done et al. 2011).

The upper-level composite anomalies of 200-hPa wind field associated with the four wave types are shown in Fig. 8. For the TD waves, a cyclonic anomaly lies to the east of the TCG location at 850-hPa (Fig. 7a) and an anticyclonic anomaly at 200-hPa (Fig. 8a) which depicts a reverse pattern between the lower- and upper-level circulation anomalies. TCs form within the anomalous southwesterly flow in the upper-level while within the anomalous northeasterly flow in the lower-level. In the upper atmosphere, the mean TC genesis location is sandwiched by a cyclonic anomaly to the west and an anticyclonic anomaly to the east. For the MRG waves (Fig. 8b), TC genesis is located between a cyclonic anomaly to the west and an anticyclonic anomaly to the east in the active phase. The upper-level circulation anomalies associated with the ER wave exhibit a relatively different pattern. As shown in Fig. 8c, TCs tend to form within the upper-level anticyclonic anomaly associated with the ER waves, while they are within a cyclonic anomaly in the lower level (Fig. 7c). This vertical pattern difference suggests that the wave anomalies are dominated by a baroclinic, first internal mode vertical structure for the portions of the wave near the genesis location. This result is consistent with previous studies (Wu et al. 2015b). The contribution of CCEW is more significant to the east of the enhanced monsoon trough (east of 150°E), whose baroclinic conversion process is important to produce the tilted vertical structure of ER waves, but contributes a smaller part for TD-MRG waves. For the Kelvin waves (Fig. 8d), the spatial relationship between TCG and wave pattern is not clear. TC formation seems to be facilitated by the upper-level anomalous westerly or northwesterly flow. For the four types of CCEW, TCs tend to form within the upper-level divergence areas.

The composite anomalies of 500-hPa specific humidity and OLR associated with all types of CCEW are shown in Figs. 9 and 10. It implies that the favorable mid-level humidity and convective conditions close to the TC center resulting in more latent heat releasing and consequent mid-level warm core structure which is crucial to TCG.

The above results suggest that TCs tend to form within the lower-level cyclonic anomalies and strong convective anomalies for all types of CCEW, suggesting consistent forcing mechanisms. The upper-level circulation anomalies near the TC genesis location are almost opposite to the lower-level wind with positive divergence anomalies. Comparing the four types of CCEW, the structure of ER waves is more baroclinic, with more favorable wetted anomalies and convective anomalies which can facilitate TC formation, whereas the TD waves and MRG waves are with enhanced vorticity anomalies and less humid and thermal conditions. The physical mechanism has been suggested by Done et al. (2011) and Wu et al. (2012, 2014, 2015a, b). The MRG waves and ER waves have different presents when they meet the monsoon trough, so they influence the different conditions for the TCG. For the ER waves, they amplifier along the axis of the MT and are more baroclinic, which can facilitate TC formation. For the synopticscale waves, the monsoon background flow can lead to an MRG-to-TD transition.

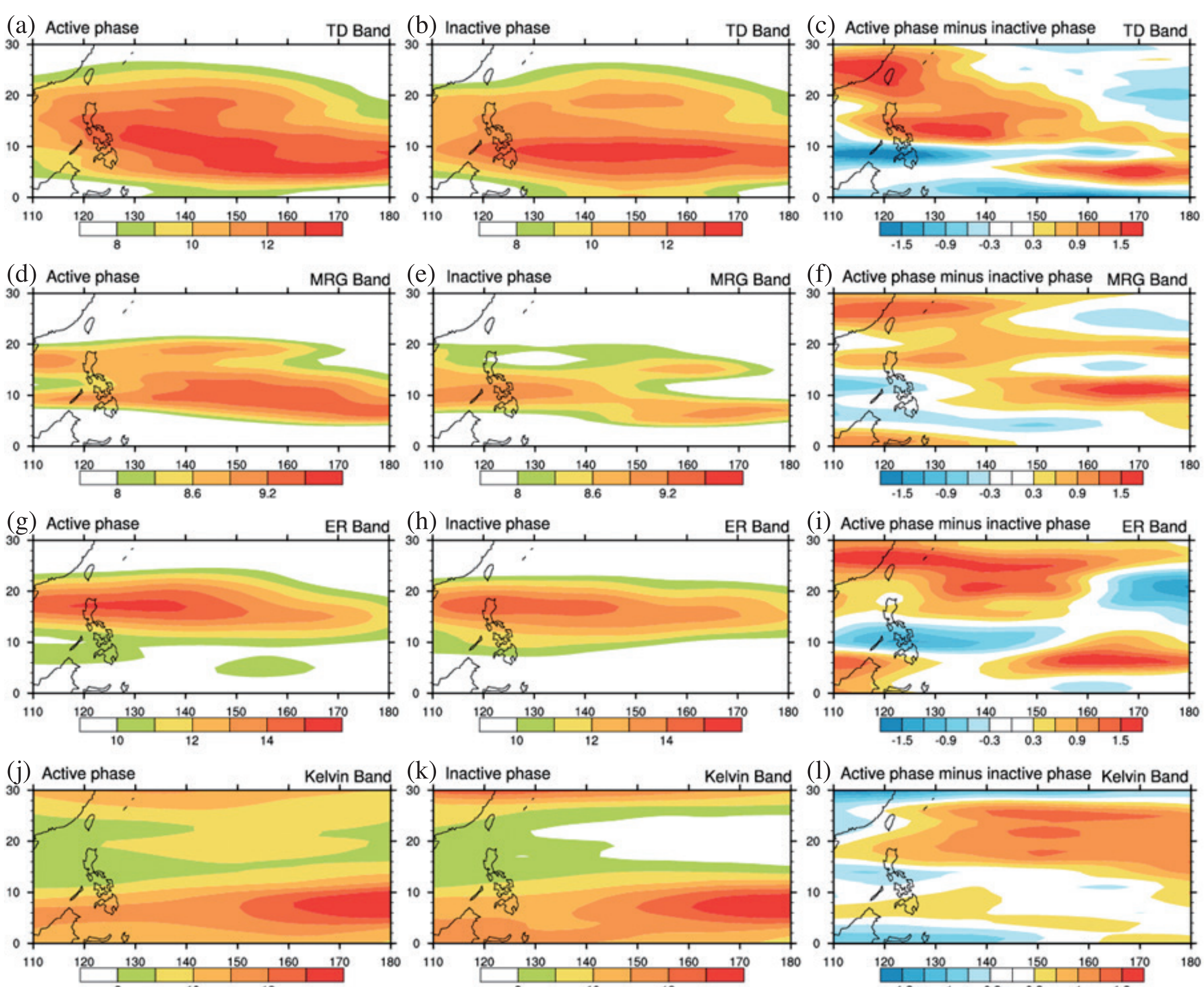

Fig. 5. Standard deviation of the filtered anomalies of 850-hPa OLR in the active/inactive phases and their difference for the (a) - (c) TD waves, (d) - (f) MRG waves, (h) - (i) ER waves, and (j) - (l) Kelvin waves.

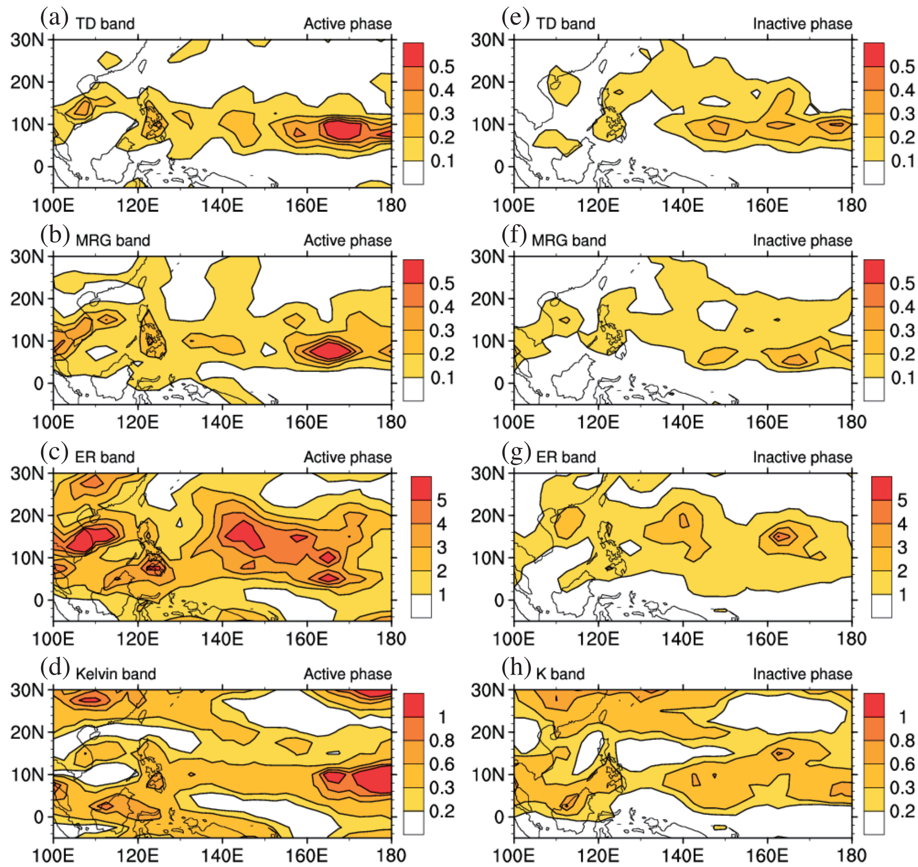

Fig. 6. The OLR filtered variance contribution of MTC active phase and inactive phase for TD waves (a) (e), MRG waves (b) (f), Kelvin waves (c) (g), and ER waves (d) (h).

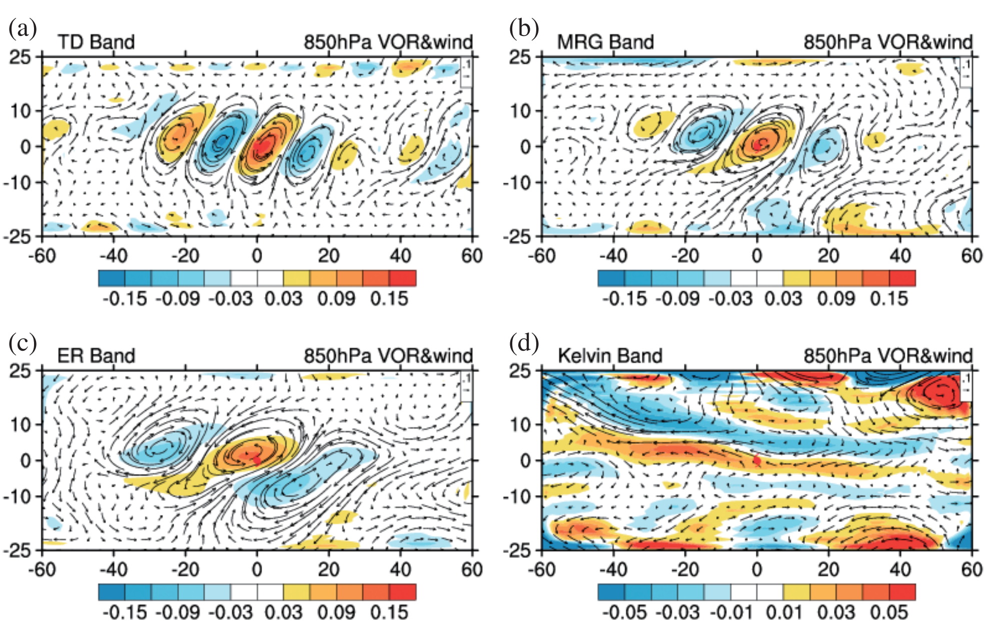

Fig. 7. Composites of the filtered anomalies of 850-hPa wind and vorticity relative to the TC genesis location and time for the TD waves (a), MRG waves (b), ER waves (c), and Kelvin waves (d) in the active MTC phase.

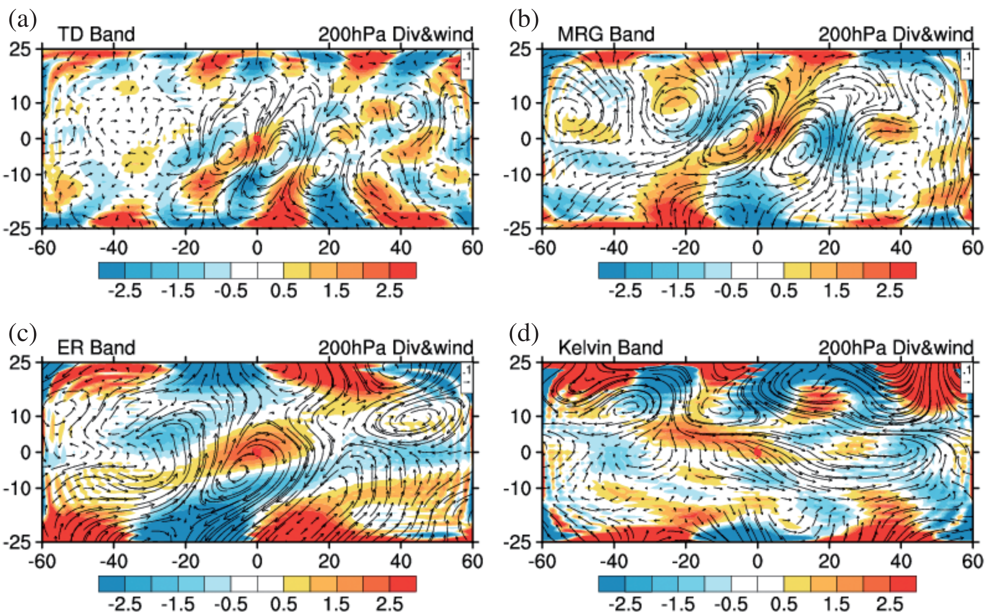

Fig. 8. Composites of the filtered anomalies of 200-hPa wind and divergence relative to the TC genesis location and time for the TD waves (a), MRG waves (b), ER waves (c), and Kelvin waves (d) in the active MTC phase.

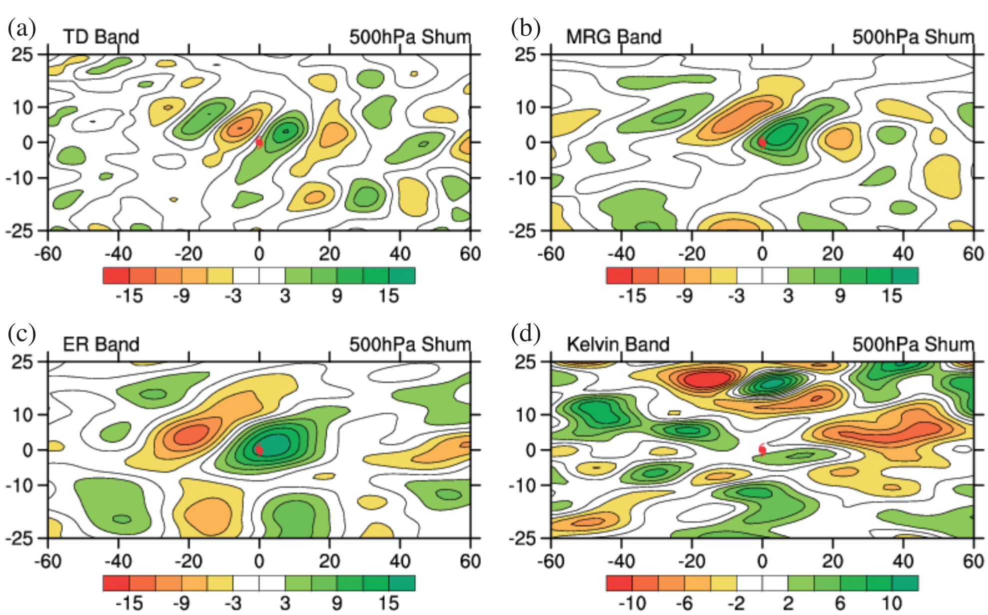

Fig. 9. Composites of the filtered anomalies of 500-hPa specific humidity relative to the TC genesis location and time for the TD waves (a), MRG waves (b), ER waves (c), and Kelvin waves (d) in the active MTC phase.

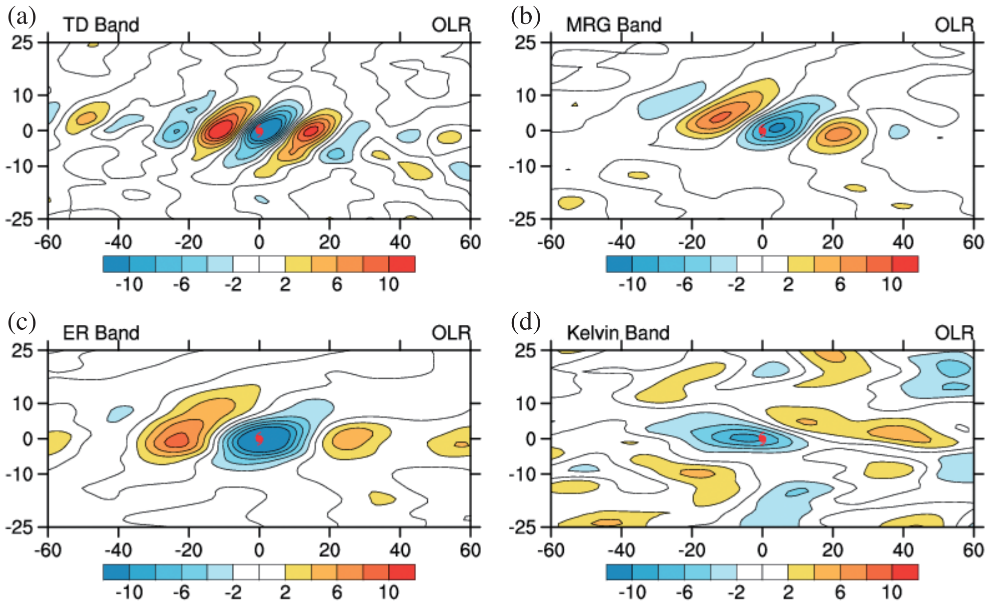

Fig. 10. Composites of the filtered anomalies of OLR relative to the TC genesis location and time for the TD waves (a), MRG waves (b), ER waves (c), and Kelvin waves (d) in the active MTC phase.

When the wave disturbances move westward from the tropical eastern Pacific, they gain energy from the mean flow if they meet with the eastward-extending monsoon trough. The energy conversion is an important mechanism for the linkage between the monsoon trough variability and the growth of the precursor synopticscale perturbations, which results in more tropical cyclogenesis in the WNP. So, the TD waves and MRG waves are with enhanced vorticity anomalies or as the major precursor disturbances for TCG.

5. SUMMARY AND DISCUSSION

In this study, a TC-variance method is employed to examine the relationships between convectively coupled equatorial waves (CCEW) and TC genesis. This method bases upon the variances of wave filtered OLR time series of four wave types at the genesis location during the formation time. Our results indicate that about 84.1% of TC genesis occurs within the active phases of CCEW. Among these TCs, the majority (71.3%) are associated with a single wave or two coexisting waves. ER waves with longer time scale allow them to interact with the synoptic-scale waves (TD waves or MRG waves) to assist TC formation. In consequence, these combinations (ER-TD and ER-MRG) account for the largest two proportions of TC genesis in the cases with two coexisting waves. The contribution of each tropical wave to TC genesis shows notable seasonal variations with peaks in coherence with the active TC season in the WNP.

In order to investigate the impacts of CCEW on multiple TC (MTC) events, which are divided into three categories: active, normal, and inactive phases. We explore the relative roles of the four types of tropical waves during three MTC phases. The result shows that the importance of CCEW varies in different MTC phases. In the active phase, the contribution of ER waves is most significant in the single wave cases, followed by TD waves and Kelvin waves which approximately make the equal contribution. In the normal phase, the waves with relatively longer time scale such as ER waves still show larger contribution than the other tropical waves for TC genesis. In the inactive phase, the largest contribution comes from TD waves and secondly from MRG waves, indicating the synoptic-scale waves play a crucial role in assisting TC formation under an unfavorable large-scale background condition during the inactive phase.

We further investigate spatial distribution of intensity and the contribution of four types of CCEW in different MTC phases. The results suggest that intensity of all CCEW are stronger in the active MTC phase than that in the inactive MTC phase. Both during the active and inactive phase, the synoptic-scale waves like TD and MRG waves make less contribution to the OLR variance while the ER waves make the most contribution, particularly in the TCG region. Compared to the inactive phase, the contribution of CCEW to the OLR variance is more significant in the active phase, especially in the region east of 150°E.

Composite analysis is performed to reveal the wave structures of the different CCEW in the active MTC phase. It suggests that TCs tend to form within the lower-level cyclonic anomalies and strong convective anomalies and with positive divergence anomalies in the upper-level for all types of CCEW, suggesting consistent forcing mechanisms. Comparing the four types of CCEW, the structure of ER waves is more baroclinic, with more favorable wetted anomalies and convective anomalies which can facilitate TC formation, whereas the TD waves and MRG waves are with enhanced vorticity anomalies and less humid and thermal conditions. That is, the intensified circulation anomalies provide more favorable environmental conditions for MTC events. The long-lasting features of ER waves, up to 48 days, can modulate environmental conditions to provide persistent favorable conditions for the occurrence of MTC events.

The above analysis demonstrates that during the TC season from June to October, the four types of CCEW can incorporate each other to modulate the subseasonal TC genesis. However, the dynamic mechanisms of how CCEW modulate the TC genesis and the joint contribution of multiple scale wave interactions still need to be studied by future studies.

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