Influence of Intraseasonal–Interannual Oscillations on Tropical Cyclone Genesis in the Western North Pacific

JAU-MING CHEN

Department of Maritime Information and Technology, National Kaohsiung Marine University, Kaohsiung, Taiwan

CHING-HSUAN WU

Department of Atmospheric Science, National Taiwan University, Taipei, Taiwan

PEI-HSUAN CHUNG

Department of History and Geography, University of Taipei, Taipei, Taiwan

CHUNG-HSIUNG SUI

Department of Atmospheric Science, National Taiwan University, Taipei, Taiwan

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ABSTRACT

Influences of intraseasonal–interannual oscillations on tropical cyclone (TC) genesis are evaluated by productivity of TC genesis (P_{TCG}) from the developing (TC_d) and nondeveloping (TC_n) precursory tropical disturbances (PTDs). A PTD is identified by a cyclonic tropical disturbance with a strong-enough intensity, a large-enough maximum center, and a long-enough lifespan. The percentage value of PTDs evolving into TC_d is defined as P_{TCG} . The analysis is performed over the western North Pacific (WNP) basin during the 1990–2014 warm season (May–September). The climatological P_{TCG} in the WNP basin is 0.35. Counted in a common period, mean numbers of PTDs in the favorable and unfavorable conditions of climate oscillations for TC genesis [such as equatorial Rossby waves (ERWs), the Madden–Julian oscillation (MJO), and El Niño–Southern Oscillation (ENSO)], all exhibit a stable value close to the climatological mean [~ 31 (100 days) $^{-1}$]. However, P_{TCG} increases (decreases) during the phases of positive-vorticity (negative-vorticity) ERWs, the active (inactive) MJO, and El Niño (La Niña) years. P_{TCG} varies from 0.17 in the most unfavorable environment (La Niña, inactive MJO, and negative-vorticity ERW) to 0.56 in the most favorable environment (El Niño, active MJO, and positive-vorticity ERW). ERWs are most effective in modulating TC genesis, especially in the negative-vorticity phases. Overall, increased P_{TCG} is facilitated with strong and elongated 850-hPa relative vorticity overlapping a cyclonic shear line pattern, while decreased P_{TCG} is related to weak relative vorticity. Relative vorticity acts as the most important factor to modulate P_{TCG} , when compared with vertical wind shear and 700-hPa relative humidity.

1. Introduction

Statistics of tropical cyclones (TC) reveals that the western North Pacific (WNP) hosts the largest TC genesis numbers (about 36% of the total number) among the global ocean basins (e.g., Gray 1968). During the warm season (May–September), the WNP features warm seawater and a monsoon trough, jointly providing excellent thermodynamic and dynamic conditions for TC genesis (e.g., Gray 1968; McBride 1995). Most TC

genesis in the WNP occurs within a monsoon trough in company with several types of environmental flow patterns, such as a shear line pattern and a confluence region (Ritchie and Holland 1999; Yoshida and Ishikawa 2013; Molinari and Vollaro 2013). Mechanisms able to modulate intensity and locations of the monsoon trough and associated low-level dynamic variables have been found to modulate TC genesis in the WNP (e.g., Chen et al. 2006), such as the circulation changes associated with dynamics of El Niño–Southern Oscillation (ENSO; e.g., Rasmusson and Carpenter 1982; Rasmusson and Wallace 1983; Philander 1990) and the 30–60-day and

Corresponding author: Chung-Hsiung Sui, sui@as.ntu.edu.tw

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10–20-day intraseasonal oscillations (ISOs) (e.g., Masunaga 2007). The 30–60-day ISO is dominated by the Madden–Julian oscillation (MJO) that was first identified by Madden and Julian (1971, 1972). The 10–20-day ISO (or quasi-biweekly oscillation) is essentially the equatorial Rossby wave (ERW) as shown in previous studies (e.g., Kikuchi and Wang 2009; Chen and Sui 2010). ENSO, the MJO, and ERWs all exert important impacts on TC genesis in the WNP.

During an El Niño event, the emergence of equatorial westerlies causes a monsoon trough to extend eastward, leading to more TC genesis in the southeast quadrant of the WNP and less TC genesis in the western section and the northwestern quadrant (e.g., Wu and Lau 1992; Lander 1994; Dong 1988; Wang and Chan 2002; Tao et al. 2012; Wang et al. 2013; Kim et al. 2013). Reduced TC genesis in the South China Sea (SCS) and the western section of the WNP is affected by anomalous suppressed convections following variability of the Walker circulation (e.g., Chan 1985; Li 1988). The favorable conditions for the above TC genesis include warmer ocean surface, enhanced convection, increased relative humidity in the lower and middle troposphere, reduced vertical wind shear, increased upper-level divergence, and low-level cyclonic vorticity (e.g., Camargo et al. 2007; Wu et al. 2012). For a La Niña year, the westward-retreated monsoon trough concurs with more TC genesis in the northwestern quadrant of the WNP but suppressed TC activity in the entire WNP from August to November (e.g., Chan 2000; Camargo et al. 2007; Chung and Li 2015).

For the influence of 30–60-day ISOs, the MJO may propagate eastward from the Indian Ocean across the WNP into the eastern Pacific (e.g., Madden and Julian 1994). Huang et al. (2011) found that the intraseasonal modulation on TC genesis in the subtropical WNP is mainly via variability of low-level vorticity that represents the major effect from a monsoon trough over there. A convectively enhanced (suppressed) phase of ISOs tends to be associated with more (less) TC genesis in the WNP and other TC basins (e.g., Kim et al. 2008; Barrett and Leslie 2009; Klotzbach 2014).

Many studies have recognized that ERWs are highly related to TC genesis (e.g., Frank and Roundy 2006; Schreck and Molinari 2009; Ching et al. 2010; Chen and Chou 2014). TC genesis associated with ERWs tends to occur in a strong enough ERW interacting with a favorable flow environment resembling a monsoon trough via a wave breaking of ERWs by which vorticity is organized on the scale of a TC (e.g., Gall and Frank 2010). When easterly vertical wind shear is present, the available potential energy is trapped in the lower troposphere. This acts to enhance wave amplitude and the

possibility of TC genesis within the wave (e.g., Xie and Wang 1996).

The combined contributions of multiple tropical climate oscillations to TC genesis have also been analyzed. Chen and Chou (2014) examined the mixture of the MJO and tropical waves that causes a deeper monsoon trough that acts to intensify local circulation by increasing upward motion and low-level vorticity at the genesis location, and by modulating vertical wind shear. By examining the abundant TC genesis in June 2004, Ching et al. (2010) and Ching et al. (2015) demonstrated that both the MJO and ERWs have important modulation effects on TC genesis.

The precursory tropical disturbance (PTD) is commonly recognized as a synoptic-scale system featuring continuously developing deep convection or a strong cyclonic vortex. Using satellite data, Hennon et al. (2011) constructed a global climatology of tropical cloud clusters (TCCs) defined as the synoptic-scale areas with deep convection. A TCC can develop into a TC under favorable conditions. Hennon et al. (2013) examined the genesis productivity of TCCs into TCs for global ocean basins and found the highest productivity occurring over the WNP basin (about 12%). During El Niño years, TCC frequency increases (decreases) in the eastern (western) Pacific. However, TC genesis productivity shows no evident interannual variability associated with ENSO. Teng et al. (2014) further employed satellite data to investigate ENSO effects on TCC activity in the WNP basin. In their analysis, the overall genesis productivity of TCCs into TCs is about 27.3%, while productivity in El Niño (25.9%) and La Niña (28.6%) years are relatively close, showing no noticeable ENSO impacts. Their analyses also showed that more TCs in the eastern (western) WNP during El Niño (La Niña) years mainly result from changes in TCC number, rather than changes in genesis productivity. In a different approach, Fu et al. (2012) employed reanalysis data to compare PTDs that are developing or not developing into TCs in the WNP and associated determining mechanisms. The PTD is represented by a strong-enough ($\geq 10^{-5} \text{ s}^{-1}$ of 850-hPa relative vorticity) and long-lasting ($\geq 72 \text{ h}$) cyclonic vortex. They concluded that dynamic variables are more important than thermodynamic variables in facilitating the developments of PTDs into TCs in the WNP. This conclusion is consistent with that of Hennon et al. (2013) using TCC analysis. Their analyses indicate that the major dynamic parameters appear as large-scale vorticity and vertical wind shear.

The past studies mainly focused on the characteristics of resultant TC numbers in the WNP, while genesis productivity and associated modulations of background

climate oscillations are less studied. TC genesis productivity in the WNP has been examined via TCC analysis by [Hennon et al. \(2013\)](#) and [Teng et al. \(2014\)](#). However, it has not been systematically examined via the approach of a vortex analysis. Moreover, impacts of the MJO and ERWs on TC genesis productivity in the WNP remain unexplored so far. The major purposes of this study are to analyze productivity of TC genesis (P_{TCG}) in the WNP via a vortex analysis using the reanalysis data; to use P_{TCG} as a more appropriate variable to show the influence on TC activity by ENSO, the MJO, ERWs, and their combined phases; and to reveal key environmental factors affecting TC genesis in the WNP on interannual and intraseasonal time scales. Results obtained from this study should advance our understanding for the developing processes and probability for TC genesis in the WNP on various time scales (e.g., climatological, intraseasonal, and interannual). This knowledge should help to improve short-term climate prediction tasks for TC activity in the WNP.

2. Methodology and data

A synoptic-scale tropical disturbance with a strong and persistent cyclonic vortex is a potential PTD to TC genesis (e.g., [Lau and Lau 1990](#); [Fu et al. 2007](#)). A PTD is identified from the reanalysis data with three criteria modified from [Fu et al. \(2012\)](#) and [Peng et al. \(2012\)](#). The criteria are as follows: 1) a cyclonic vortex inferred from the 3–8-day filtered 850-hPa relative vorticity (VOR850) has to reach the intensity of 10^{-5} s^{-1} , 2) its vortex center stronger than 10^{-5} s^{-1} has to exceed $16\,000 \text{ km}^2$, and 3) the above two criteria remain satisfied for 72 consecutive hours. Note that this study uses the size of maximum vorticity center instead of the circulation size. This change allows us to identify a vortex by only one variable (vorticity), rather than two variables (wind and vorticity) used previously. Our detected PTDs have a mean radius greater than 5° (not shown), which satisfies the circulation size criterion with a radius greater than 400 km used by [Fu et al. \(2012\)](#) and [Peng et al. \(2012\)](#).

The identified PTDs are further separated into two categories: developing and nondeveloping TCs. The developing TCs (TC_d) have to match named TCs ($\geq 34 \text{ kt}$) in the best-track data of the Joint Typhoon Warning Center (JTWC). The remaining TCs are classified as the nondeveloping TCs (TC_n). A rapidly growing TC is possibly to develop from a tropical disturbance into a named TC within 72 h. It is counted as a developing TC, instead of a nondeveloping TC. The location of a developing TC is defined at that revealed by the first record of that named TC in the

JTWC best-track data, while the location with the maximum intensity of the 3–8-day-filtered VOR850 is for a nondeveloping TC. The European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim) data (e.g., [Dee et al. 2011](#)) with a $0.75^\circ \times 0.75^\circ$ grid are used in the vortex analyses for TC genesis productivity over the WNP (0° – 35°N , 100°E – 170°W). The analysis periods include TC-active warm seasons (May–September) during 1990–2014. This season is also the southwest monsoon season in the SCS and the western WNP.

3. TC genesis productivity in the WNP

To evaluate the relative importance of different climate oscillations on TC genesis, we need to count total TC_d and TC_n numbers in the period 1990–2014 and illustrate their spatial distributions in a specific spatial domain, say a $5^\circ \times 5^\circ$ box. In this study, we normalize TC_d and TC_n counts as numbers per 100 days (e.g., [Liebmann et al. 1994](#)). For the period of this study (1990–2014), there were 3825 warm-season days in which 420 TC_d and 769 TC_n were detected over the whole WNP basin. This gives 11.0 TC_d , 20.1 TC_n , and a total of 31.1 PTDs per 100 days. The climatological value of productivity of TC genesis, $P_{TCG} = TC_d / (TC_d + TC_n)$, is 0.35. It is larger than the 0.27 obtained from [Teng et al.'s \(2014\)](#) TCC analysis. This is probably due to a longer-lasting time being selected in this study (72 h) than in [Teng et al. \(24 h\)](#). Our analyses also show that P_{TCG} decreases into 22.6% and 14.2% with a shorter lasting time of 48 h and 24 h, respectively. In other words, a longer-lasting time results in a higher chance for a PTD developing into a named TC and thus a higher genesis productivity.

Spatial features associated with TC genesis productivity are depicted by numbers of TC_d , TC_n , and P_{TCG} averaged for each $5^\circ \times 5^\circ$ box. Spatial patterns of TC_d cases ([Fig. 1a](#)) exhibit maximum centers (larger than 0.35) extending southeastward from the eastern SCS across the Philippine Sea into the tropical WNP. This southeastward extension largely overlaps with climatological locations of a monsoon trough (e.g., [Lander 1996](#); [Chen et al. 2006](#)). Total PTDs ($TC_d + TC_n$) show a pattern similar to that of TC_d , except at larger numbers ([Fig. 1b](#)). P_{TCG} patterns ([Fig. 1c](#)) reveal that the development of a PTD into a TC is evidently facilitated in the western WNP over 10° – 20°N , 120° – 160°E with a P_{TCG} value of 0.4–0.65, followed by the regions east of 160°E with a P_{TCG} value about 0.35–0.5. P_{TCG} values in boxes having fewer than two TC_d cases are not shown because of an insufficient representation of TC genesis.

FIG. 1. Climatological values every 100 days for (a) developing cases, (b) total precursor tropical disturbances, and (c) productivity of TC genesis (P_{TCG}) for each $5^\circ \times 5^\circ$ box in the WNP.

4. TC genesis productivity and ENSO

Impacts from the large-scale environment variability associated with ENSO and the MJO on TC genesis productivity are studied in a spatial domain covering the entire WNP basin. The oceanic Niño index (ONI; e.g., Xue et al. 2003) represented by the Niño-3.4 sea surface temperature (SST) anomalies (5°S – 5°N , 120° – 170°W) from the Climate Prediction Center at the National Oceanic and Atmospheric Administration (NOAA) is used to separate ENSO cases into the warm, cold, and normal years. An El Niño (a La Niña) year that represents a warm (cold) ENSO case needs to have an averaged ONI value larger (smaller) than 0.3°C (-0.3°C) during May–September and 0.5°C (-0.5°C) in the succeeding winter. The remaining cases are classified as the normal years. These definitions result in to six El Niño years (1991, 1994, 1997, 2002, 2004, and 2009), seven La Niña years (1998, 1999, 2000, 2007, 2008, 2010, and 2011), and 12 normal years. As shown in Table 1,

TABLE 1. Normalized numbers of TC_d and TC_n per 100 days and P_{TCG} in the WNP basin for climatology, interannual oscillations (El Niño, La Niña, normal) years, the MJO (active, inactive) phases, and ERWs (positive vorticity, negative vorticity). P_{TCG} values significant at the 0.1, 0.05, and 0.01 levels of a Student's t test are marked with +, ++, +++, respectively. TC_d and TC_n numbers significant at the 0.1, 0.05, 0.01 levels of a Z test are marked with *, **, ***, respectively.

Type	(TC_d, TC_n)		$(TC_d + TC_n)$	P_{TCG}
Climatology	(11.0, 20.1)		31.1	0.35
El Niño years	(12.4, 18.6)		31.0	0.40 ⁺
La Niña years	(9.3, 21.7)		31.0	0.30 ⁺⁺⁺
Normal years	(11.2, 19.9)		31.1	0.36
Active MJO	(13.7 ^{***} , 18.7)		32.4	0.42
Inactive MJO	(9.6 ^{**} , 20.8)		30.4	0.32
Positive vorticity ERW	(16.3, 22.1)		38.4	0.43
Negative vorticity ERW	(6.1, 18.3)		24.4	0.25

TC_d and TC_n numbers per 100 days during the normal years are 11.2 and 19.9, respectively. The P_{TCG} is 0.36, close to the climatological value (0.35). Both El Niño and La Niña years have the same total disturbance number of 31 per 100 days. Nevertheless, TC_d cases are 12.4 in El Niño years and 9.3 in La Niña years. P_{TCG} increases in El Niño years (0.40) and decreases in La Niña years (0.30). Both P_{TCG} values are statistically significant at the 0.1 level of a Student's t test. It appears that ENSO has significant impacts on P_{TCG} in the WNP, but not on the total number of PTDs.

A box difference index (BDI) proposed by Peng et al. (2012) and Fu et al. (2012) is adopted to quantitatively measure the relative importance of environmental variables in differentiating TC_d and TC_n cases, as well as effects on the P_{TCG} . The BDI is computed as $(M_{TCd} - M_{TCn}) / (\text{STD}_{TCd} + \text{STD}_{TCn})$, where M and STD represent the variable mean and standard deviation of TC_d or TC_n cases, respectively. Environmental variables affecting the potential of TC genesis are evaluated from their 30-day low-pass-filtered components averaged from a $3^\circ \times 3^\circ$ box within 1.5° from the center of each TC_d or TC_n case. The above low-pass components include both intraseasonal and interannual signals and allow us to measure the modulations of ENSO, the MJO, and their combined phases on TC genesis with a unified variable. A variable with greater BDI amplitudes indicates its more important role in affecting TC genesis. The analyzed environmental variables important to TC genesis include VOR850, 700-hPa relative humidity (RH700), and vertical wind shear of total winds between 200 and 850 hPa (VWS) (e.g., Chia and Ropelewski 2002; Wang and Chan 2002; Frank and Roundy 2006; Camargo et al. 2007). As shown in Table 2, BDI amplitudes of VOR850 for El Niño and La Niña

TABLE 2. Composite statistics associated with the box difference index (BDI) analysis (see the texts) for 850-hPa relative vorticity (VOR850), 700-hPa relative humidity (RH700), and vertical shear of total winds (VWS). The difference values ($M_{TCd} - M_{TCn}$) significant at the 0.1, 0.05, and 0.01 levels of a Student's t test are marked with *, **, and ***, respectively.

Type	VOR850			RH700			VWS		
	(M_{TCd} , M_{TCn})	$M_{TCd} - M_{TCn}$	BDI	(M_{TCd} , M_{TCn})	$M_{TCd} - M_{TCn}$	BDI	(M_{TCd} , M_{TCn})	$M_{TCd} - M_{TCn}$	BDI
El Niño	(9.85, 4.40)	5.45***	0.43	(71.1, 65.1)	6.0***	0.41	(12.5, 13.2)	−0.7	−0.09
La Niña	(7.20, 1.94)	5.26***	0.40	(69.8, 67.1)	2.7***	0.19	(12.6, 13.2)	−0.6	−0.09
Active MJO	(8.95, 4.52)	4.03***	0.31	(71.5, 67.9)	3.6***	0.25	(12.5, 13.6)	−1.1***	−0.15
Inactive MJO	(7.20, 2.08)	5.12***	0.42	(69.0, 65.4)	3.6***	0.25	(11.8, 12.6)	−0.8***	−0.11

years (0.43–0.44) are larger than those of RH700 (0.19–0.41) and VWS (−0.09). Differences of VOR850 and RH700 between M_{TCd} and M_{TCn} are statistically significant for both El Niño and La Niña years. Overall, VOR850 plays a more important role than RH700 and VWS in affecting P_{TCG} during ENSO years in the WNP.

The spatial patterns of P_{TCG} and the associated environmental variables are shown in Fig. 2. Composite P_{TCG} patterns in El Niño years (Fig. 2a) elongate southeastward from the SCS into the tropical eastern WNP with a maximum center over 5°–15°N, 130°–155°E. In La Niña years, P_{TCG} concentrates westward with a maximum center over 10°–20°N, 125°–145°E (Fig. 2b). The environmental variables are illustrated by composite differences between El Niño and La Niña years (El Niño–La Niña). The differences of VOR850 and 850-hPa wind (V850) reveal that the elongated P_{TCG} patterns in El Niño years are associated with cyclonic shear and positive VOR850 anomalies across the tropical WNP (Fig. 2c). These features concur with the eastward displacement of a monsoon trough and TC genesis locations (e.g., Lander 1994; Wang and Chan 2002), yielding increased P_{TCG} in the southeastern WNP over 5°–15°N, 145°–175°E. In this southeastern region, increased P_{TCG} during El Niño years is also associated with positive RH700 anomalies (Fig. 2d) and negative VWS anomalies (Fig. 2e). Increased humidity and weakened vertical wind shear provide positive contributions to the southeastward shift of TC genesis locations (e.g., Wang and Chan 2002; Camargo et al. 2007; Kim et al. 2013), as well as an increase in P_{TCG} .

5. TC genesis productivity and the MJO

The MJO's influence on P_{TCG} is evaluated by contrasting their differences in the active and inactive phases of the MJOs. To categorize these phases, a convective MJO index is constructed from the NOAA daily outgoing longwave radiation (OLR) data with a $2.5^\circ \times 2.5^\circ$ resolution (e.g., Liebmann and Smith 1996). The daily OLR data in May–September of each year are filtered to reserve temporal components of 30–90 days

and spatial components of wavenumbers 0–5. A MJO index is measured as the filtered OLR value averaged from the tropical WNP domain of 0°–15°N, 110°–170°E. The active MJO phases with enhanced convection are defined as the period of the negative phases of the MJO index except the first three and last three days of the period. The remaining period is categorized as the inactive MJO phases with suppressed convection. A comparison of our MJO index with the real-time multivariate MJO (RMM) index constructed by Wheeler and Hendon (2004) reveals that our active MJO phases correspond to phases 4, 5, and 6 of RMM, featuring major convective activity over the Maritime Continents and the WNP. The active MJO phases in this study spatially correspond well with the major TC-genesis region in the WNP. In case a burst of TCs occurs in a fraction of the intraseasonal time scale falling in one of the MJO active phases, it can be reasonably regarded as TC genesis in a favorable environment under the MJO influence. The MJO phases from our index are thus suitable for analyzing impacts of the MJO on TC genesis productivity in the WNP basin.

Table 1 shows that 13.7 TC_d and 18.7 TC_n cases occur in the active MJO phases every 100 days, while there are 9.6 TC_d and 20.8 TC_n cases for the inactive MJO phases. The averaged total disturbance number for the active (32.4) and inactive (30.4) phases is 31.4, comparable to the climatological value (31.1). A Z test (Hall et al. 2001; Li et al. 2012) discloses that increased (decreased) TC_d cases during the active (inactive) MJO phases are statistically significant at the 0.05 level, leading to an increased (a decreased) P_{TCG} value of 0.42 (0.32). BDI analyses in Table 2 reveal that $M_{TCd} - M_{TCn}$ values of VOR850, RH700, and VWS are statistically significant for both active and inactive MJO phases. However, BDI amplitudes are the largest for VOR850 (0.31–0.42), followed by RH700 (0.25) and VWS (about −0.15). VOR850 appears as the dominant variable in affecting P_{TCG} during the MJO phases.

Composite P_{TCG} patterns for the active (Fig. 3a) and inactive (Fig. 3b) MJO phases both exhibit an elongated distribution across the tropical WNP, except a generally

FIG. 2. Composite P_{TCG} patterns for (a) El Niño and (b) La Niña years. Composite differences (El Niño–La Niña) of (c) 850-hPa relative vorticity and flow, (d) 700-hPa relative humidity, and (e) vertical wind shear of total winds. Units are s^{-1} in (c), % in (d), and $m s^{-1}$ in (e).

larger value in the active phases than the inactive phases. The MJO phases selected in this study correspond to an eastward propagation of enhanced or suppressed convection across the WNP. This propagation feature tends to affect TC genesis productivity across the entire WNP basin. To the east of $150^{\circ}E$, the major center stretches southeastward to the south of $15^{\circ}N$ in the active phases, but northeastward to the north of $15^{\circ}N$ in the inactive phases. This is consistent with the MJO modulation effects on TC genesis found by Kim et al. (2008). For the environmental variables, composite differences (active–inactive) of VOR850 and V850 (Fig. 3c) show that a cyclonic circulation and positive VOR850 anomalies result in larger P_{TCG} to the west of $150^{\circ}E$ in the active phases. To the east of $150^{\circ}E$, decreased (increased) humidity as indicated by negative (positive) RH700 anomalies (Fig. 3d) causes reduced (enhanced) P_{TCG} to the north (south) of $15^{\circ}N$. The VWS differences (Fig. 3e) show positive anomalies to the east of $150^{\circ}E$, revealing its generally suppressing (enhancing) effects on P_{TCG} during the active (inactive) MJO phases. It is clear that favorable impacts on TC genesis productivity by the MJO are given by VOR850 in the western WNP to the west of $150^{\circ}E$, while unfavorable impacts given by VWS are strong to the east of $150^{\circ}E$ (Fig. 3e). Humidity also provides regional impacts on P_{TCG} , favorable in the regions north of $15^{\circ}N$ and unfavorable in the regions south of $15^{\circ}N$ during the active phases.

6. Combined effects of ENSO and the MJO

Both the MJO and ENSO affect the WNP TC activity in a basin scale. Their joint effects on P_{TCG} patterns are examined via four combined phases: El Niño–active MJO (EN-aM), El Niño–inactive MJO (EN-iM), La Niña–active MJO (LN-aM), and La Niña–inactive MJO (LN-iM). As shown in Table 3, $TC_d(100 \text{ days})^{-1}$ is 16.3 for an EN-aM phase and only 8.3 for a LN-iM phase. The value becomes 10.0 for an EN-iM phase and 11.1 for a LN-aM phase, with no significant difference from the climatological value of 11.0. Consequently, an evident increase (decrease) in P_{TCG} from the climatological mean (0.35 in Table 1) results in a value of 0.47 (0.26) in an EN-aM (a LN-iM) phase, while a value closer to climatological value in the EN-iM (0.35) and LN-aM (0.38) phases. As analyzed previously, El Niño and the active MJO phases tend to enhance P_{TCG} , while La Niña and the inactive MJO phases act to suppress P_{TCG} . The combination effects in the EN-aM (LN-iM) phases thus provide double positive (negative) impacts for TC genesis productivity. Similarly, effects of ENSO and the MJO compensate each other in the EN-iM and LN-aM phases, leading to a P_{TCG} value close to the climatological mean.

FIG. 3. Composite P_{TCG} patterns for the (a) active and (b) inactive MJO phases. Composite differences (active–inactive) of (c) 850-hPa relative vorticity and flow, (d) 700-hPa relative humidity, and (e) vertical wind shear of total winds. Units are s^{-1} in (c), % in (d), and $m s^{-1}$ in (e).

With the highest and lowest P_{TCG} values, doubly strengthened effects from ENSO and the MJO on TC genesis productivity are examined via a comparison between the EN-aM and LN-iM phases. Their composite P_{TCG} patterns exhibit an elongated pattern across the tropical WNP in the EN-aM phases (Fig. 4a), but a confined pattern in the western WNP in the LN-iM phases (Fig. 4b). The above zonal contrasts resemble those between El Niño and La Niña in Fig. 2, rather than between the active and inactive MJO phases in Fig. 3. This pattern contrast reveals that ENSO seems to have more influence on P_{TCG} patterns than the MJO in the combined phases. Composite differences of VOR850 and V850 for the EN-aM and LN-iM phases (EN-aM–LN-iM) (Fig. 4c) possess a cyclonic shear overlapping elongated positive VOR850 anomalies extending from the SCS eastward up to 180° , similar to the composite difference patterns of ENSO in Fig. 2c. In this eastward-extending region east of $150^\circ E$, there are positive difference anomalies of RH700 (Fig. 4d) to the south of $15^\circ N$ that accompany negative VWS anomalies (Fig. 4e). The above differences of RH700 and VWS between the EN-aM and LN-iM phases resemble the differences between El Niño and La Niña years (see Figs. 2d and 2e), but are evidently different from the differences between the active and inactive MJO phases (see Figs. 3d and 3e). In the region west of $150^\circ E$, RH700 difference anomalies shows positive patterns to provide favorable conditions for TC genesis productivity, while positive VWS anomalies provide negative effects for genesis productivity. The above difference analyses of P_{TCG} and environmental variables reveal that VOR850 and RH700 provide positive contributions to modulate P_{TCG} in the WNP during the combined ENSO–MJO phases. Moreover, ENSO plays a more important role than the MJO in the modulation processes of the combined phases.

7. TC genesis productivity and ERW

In this study, an ERW is extracted from space–time-filtered (Wheeler and Kiladis 1999) ERA-Interim reanalysis data. It contains temporal components of 10–30 days and spatial components of the westward-moving wavenumbers 1–10. We separated TC_d and TC_n into two ERW types: positive-vorticity ERW (pvERW) and negative-vorticity ERW (nvERW). The separation is determined by the sign of a $5^\circ \times 5^\circ$ mean background VOR850 at a TC's center. A domain mean statistics of TC numbers and P_{TCG} is shown in Table 1. There are 295 TC_d and 398 TC_n in the pvERW type and 114 TC_d and 338 TC_n in the nvERW type. Unlike the MJO or ENSO oscillations that influence the entire WNP

TABLE 3. TC_d/TC_n numbers per 100 days and P_{TCG} in the WNP basin corresponding to different combinations of favorable and unfavorable phases of climate oscillations [i.e., (El Niño, La Niña, normal) $\times$ (active MJO, inactive MJO) $\times$ (positive-vorticity ERW, negative-vorticity ERW)]. P_{TCG} values in favorable (unfavorable) phases are in bold (italic). The most favorable and unfavorable phases are in both bold and italic.

		El Niño		La Niña		Normal	
		aMJO	iMJO	aMJO	iMJO	aMJO	iMJO
ENSO–MJO–ERW combination	Positive vorticity ERW	23.1/17.9 0.56	15.1/20.1 0.44	17.2/18.2 0.49	11.9/24.5 <i>0.33</i>	21.2/21.2 0.50	13.8/24.1 0.36
	Negative vorticity ERW	9.6/19.2 0.33	4.9/17.0 <i>0.23</i>	5.0/17.6 <i>0.22</i>	4.7/23.1 0.17	7.5/17.6 0.30	6.3/16.1 <i>0.28</i>
ENSO–MJO combination		16.3/18.9 0.47	10.0/18.5 0.35	11.1/17.4 0.38	8.3/24.2 0.26	14.1/19.4 0.43	10.0/20.0 0.33

domain uniformly at any given day because of their planetary spatial scales, the wavelength of ERWs is smaller than the WNP's zonal width. We cannot assume the entire WNP is in a pvERW or nvERW condition like in ENSO conditions or the MJO phases. To compare TC statistics in ERWs with that of ENSO and the MJO properly, we calculate occurrence frequency of daily mean vorticity averaged over each $5^\circ \times 5^\circ$ box to normalize TC numbers for the pvERW and nvERW types in the WNP. The normalized TC_d (TC_n) over the whole WNP domain per 100 days is 16.3 (22.1) in the pvERW type and 6.1 (18.3) in the nvERW type. The corresponding P_{TCG} for the pvERW type is 0.43, compatible with El Niño and the active MJO. However, P_{TCG} for the nvERW type is only 0.25, notably lower than that of La Niña (0.30) and the inactive MJO (0.32). This suggests that the inhibition effect on TC genesis by negative vorticity of ERWs is stronger than that by La Niña and the inactive MJO. Spatial patterns of P_{TCG} of the pvERW and nvERW types are shown in Fig. 5. In general, the degree of enhanced P_{TCG} above climatology by the pvERW type is comparable to that by ENSO and the active MJO, but the area of influence by the pvERW type in the WNP extends north of 20°N , clearly broader than the influence area of the other climate oscillations considered here. On the other hand, P_{TCG} distribution in the nvERW type shows a dipole pattern, higher (lower) P_{TCG} in the eastern (western) part of the WNP separated by 150°E .

Composite ERW flows relative to all TC_d centers are shown in Fig. 6. For the pvERW type, the composite TC_d center is located near the center of cyclonic vorticity at 850 hPa (Fig. 6b) and anticyclonic divergent flows at 150 hPa (Fig. 6a). The center of low-level cyclonic flow and upper-level divergent flow coincides with enhanced convection (Fig. 6c). Figures 6a–c show that the development of TC_d in ERWs produces a strong convection-coupled vertical structure of the first baroclinic mode and twin cyclone (anticyclonic) wave trains

with the northern portion (north of 10°N) stronger than the southern portion of the wave train. For the nvERW type, the composite TC_d center is located in the southwesterly flows between a cyclonic circulation and an anticyclonic circulation of ERWs at 850 hPa (Fig. 6e) and a reversed circulation pattern at 150 hPa (Fig. 6d). The composite ERW circulation is SW–NE oriented and convection appears to shift 1/4 wavelength eastward of the low-level cyclonic center (Fig. 6f). The composite wavelength of both pvERW and nvERW types is about 50° – 60° . The overall composite structure of the nvERW type is similar to the Rossby wave destabilized by easterly shear and convective heating (Xie and Wang 1996; Chatterjee and Goswami 2004).

The composite structure of the pvERW type relative to TC_n (figures not shown) is similar to the structure shown in Figs. 6a–c but weaker in magnitude. The composite structure of the nvERW type relative to TC_n shows a reversed pattern of Figs. 6a–c. The composite result of the ERW structure discussed above leads us to propose the following arguments that deserve further investigations. First, there exists an unstable ERW mode with a northeast–southwest horizontal tilt in the nvERW type that may provide energy for TC genesis (TC_d). Second, the degree of coupling between TCs and ERWs decides the chance of TC genesis as suggested from the pvERW structure relative to TC_d and TC_n . Third, low-level anticyclonic vorticity of ERWs effectively inhibits TC genesis.

Composite ERW structures relative to TCs have been discussed in previous studies (e.g., Frank and Roundy 2006; Chen and Chou 2014). Their composite studies are formed for all ERWs corresponding to TCs (TC_d in this study) without separation into the pvERW and nvERW types. Their composite TC center is located southeast of a low-level cyclonic circulation where strong southwesterly flows prevail, which can be reproduced by forming a weighted mean of the composite structure of the pvERW and nvERW types in Fig. 6.

FIG. 4. Composite P_{TCG} patterns for (a) El Niño-active MJO phases and (b) La Niña-inactive MJO phases. Composite differences (EN-aM-LN-iM) of (c) 850-hPa relative vorticity and flow, (d) 700-hPa relative humidity, and (e) vertical wind shear of total winds. Units are s^{-1} in (c), % in (d), and $m s^{-1}$ in (e).

FIG. 5. Composite P_{TCG} patterns for (a) the positive-vorticity ERW and (b) the negative-vorticity ERW.

8. Relative influence of ENSO, MJO, and ERW on TC genesis and their combined effects

Summarizing the results discussed in previous sections, we compare the relative influence of climate oscillations on TC genesis by comparing occurrence of TC_d and TC_n in favorable and unfavorable environment caused by interannual and intraseasonal oscillations. To compare their relative influences, the TC_d and TC_n numbers are all normalized to show the values per 100 days over the whole WNP domain as shown in Fig. 7. The numbers of TC_d and TC_n in the figure can be summed to show the respective mean number of PTD ($TC_d + TC_n$) for El Niño and La Niña, the active and inactive MJO, and the pvERW and nvERW types that are about the same, ~ 31 per 100 days per whole WNP domain. ERWs appear to be more effective on the influence of TC genesis as shown by the P_{TCG} that is 0.43/0.25 for the pvERW/nvERW type as compared with the P_{TCG} for El Niño/La Niña and the active/inactive MJO that is about 0.4/0.3 and 0.42/0.32, respectively. This result indicates that negative vorticity of ERWs has stronger inhibition effects on TC genesis than La Niña and the inactive MJO do. Negative vorticity of ERWs is particularly effective in lowering P_{TCG} in the western WNP west of 150°E as shown in Fig. 5, while positive vorticity of ERWs promotes P_{TCG} to be higher than the climatology over most parts of the WNP relative to the spatial distribution of P_{TCG} for El Niño (Fig. 2a) and the active MJO (Fig. 3a). This is likely due to a stronger vorticity in the pvERW type than that in El Niño and the

FIG. 6. Composite structure for ERWs relative to all TC_d centers: (a) divergence and streamline at 150 hPa, (b) vorticity and streamline at 850 hPa, and (c) OLR and 850-hPa streamline, all for the positive-vorticity ERW. (d)–(f) As in (a)–(c), but for the negative-vorticity ERW.

active MJO because a domain of influence by ERWs is a fraction of the western Pacific warming pool while that of ENSO and the MJO is the whole warm pool.

The combined effect of interannual and intraseasonal oscillations on TC genesis is shown by P_{TCG} in Table 3 under different combined environments. Based on eight combinations of the two phases of each of the three oscillations (ENSO, the MJO, ERWs), we divide the large-scale environments into four groups: most favorable environment (El Niño, the active MJO, pvERW), most unfavorable environment (La Niña, the inactive MJO, nvERW), favorable environment (two favorable phases, one unfavorable phase), and unfavorable environment (one favorable phase, two unfavorable phases). The favorable environment can also include the group of the active MJO, pvERW in the normal years and the unfavorable environment can include the group of the inactive MJO, nvERW in the normal years. The two groups of the active MJO, nvERW and the inactive MJO, pvERW in the normal years are regarded as the

normal environments. The most favorable and unfavorable environments produce the highest (0.56) and lowest (0.17) P_{TCG} (values in bold and italic in Table 3), respectively. P_{TCG} for the favorable environments ranges from 0.33, 0.44, 0.49, to 0.50 (bold values in Table 3) that

FIG. 7. TC_d and TC_n number per 100 days over the whole WNP domain for ENSO (warm plus cold), the MJO (active plus inactive), and ERWs (positive vorticity plus negative vorticity). The corresponding values of P_{TCG} are also shown.

are generally higher than the climatology value of 0.36. P_{TCG} for the unfavorable conditions ranges from 0.33, 0.28, 0.23, to 0.22 (values in italic in Table 3) that are all below climatology. As mentioned already, the P_{TCG} value for the nvERW type (0.25) is notably lower than that for La Niña (0.30) and the inactive MJO (0.32).

9. Conclusions

The main purpose of this study is to better understand the influence of interannual (ENSO) and intraseasonal oscillations (the MJO, ERWs) on TC genesis based on the probability of a precursory tropical disturbance (PTD) developing into a TC in the WNP basin (0° – 35° N, 100° E– 170° W) during 1990–2014 warm seasons (May–September). PTDs are identified by a vortex analysis of 3–8-day-filtered 850-hPa relative vorticity to search for PTDs with the following three criteria: 1) its maximum cyclonic relative vorticity at 850 hPa reaches 10^{-5} s^{-1} , 2) the maximum center reaching 10^{-5} s^{-1} has to exceed 16000 km^2 , and 3) the above two criteria have to be satisfied for 72 consecutive hours. Identified PTDs are further divided into two types: developing (TC_d) and nondeveloping (TC_n) cases into TCs. Productivity of TC genesis (P_{TCG}) is estimated by a value of $TC_d / (TC_d + TC_n)$. Climatologically, there are 11.0 TC_d cases and 20.1 TC_n cases over the entire WNP basin in every 100 days during the warm seasons. The total PTD number ($TC_d + TC_n$) is 31.1 and the climatological P_{TCG} value is 0.35 over the entire WNP basin.

The composite analyses for the warm and cold phases of ENSO and the active and inactive phases of the MJO all show a PTD number close to the climatological value. However, more TC_d cases occur in El Niño and the active MJO phases than La Niña and the inactive MJO phases, resulting in a larger P_{TCG} in El Niño (0.40) and the active MJO phases (0.42) than La Niña (0.30) and the inactive MJO phases (0.32). P_{TCG} patterns elongate southeastward from the SCS into the tropical WNP during El Niño years, but are confined to the western WNP during La Niña years. VOR850 anomaly is the key variable affecting the above P_{TCG} patterns. P_{TCG} patterns elongate eastward to the south of 15° N toward the eastern WNP in the active MJO phases, but to the north of 15° N in the inactive MJO phases. VOR850 causes higher P_{TCG} in the western WNP during the active phases, while reduced VWS enhances P_{TCG} in the northeastern parts of the WNP during the inactive phases. Combined ENSO–MJO conditions result in significantly increased (decreased) P_{TCG} in the EN-aM (LN-iM) phases as a result of them producing doubly positive (negative) effects. P_{TCG} is 0.46 for the EN-aM phases and only 0.26 for the LN-iM phases.

The contrasting P_{TCG} patterns indicates that ENSO is more effective than the MJO in modulating P_{TCG} over the WNP basin. VOR850 and RH700 are the two leading variables affecting P_{TCG} patterns in these two phases.

The effect of ERWs on TC genesis is analyzed for TC_d and TC_n in two ERW types with positive vorticity (pvERW) or negative vorticity (nvERW) at 850 hPa over a TC's center. Considering regions of cyclonic and anticyclonic flows in the WNP in any given day, numbers of TC_d , TC_n normalized by fractional areas of the ERW types in the WNP per 100 days are 16.3, 22.1 for the pvERW type and 6.1, 18.3 for the nvERW type. Consequently, the P_{TCG} value is 0.43 in the pvERW type and 0.25 in the nvERW type. Spatial distributions of P_{TCG} show enhanced P_{TCG} above climatology by the pvERW type over a broader area in the WNP than that of ENSO and the active MJO phases, and a significantly lower (higher) P_{TCG} in the western (eastern) part of the WNP separated by 150° E. Composited ERW flows relative to TC_d and TC_n centers reveal two types of ERW flows with first baroclinic vertical structure: an asymmetric twin cyclone (anticyclonic) wave train with the northern portion (north of 10° N) stronger than the southern portion of the wave train; a SW–NE-oriented cyclonic and anticyclonic circulation. In the pvERW flow, PTDs tend to develop into TC_d in the center of a low-level cyclonic circulation if convection-wave coupling is strong, while those PTDs in the center of a low-level anticyclonic circulation are more likely to decay as TC_n . In the nvERW flow, a TC center (convection) appears to shift 1/4 wavelength eastward of the low-level cyclonic center.

The combined ENSO–MJO–ERW impacts on TC genesis and P_{TCG} are shown in four different environments based on the 12 combinations of El Niño, La Niña $\times$ aMJO, iMJO $\times$ pvERW, nvERW and aMJO, iMJO $\times$ pvERW, nvERW in the normal years. The most favorable and unfavorable environments correspond to triple positive (El Niño, aMJO, pvERW) and triple negative (La Niña, iMJO, nvERW) phases. The P_{TCG} value is 0.56 and 0.17, respectively. Favorable and unfavorable environments are further defined for more positive and more negative phases of the remaining combinations, except two normal combinations of aMJO, nvERW and iMJO, pvERW in the normal years. The P_{TCG} values range from 0.33 to 0.50 for favorable environments and from 0.22 to 0.33 for unfavorable environments. The result also suggests that ENSO is more effective than the MJO in modulating spatial patterns of P_{TCG} over the WNP basin, yet ERWs are the most effective in regulating TC genesis, especially in the negative vorticity type.

For the entire WNP basin, TC genesis productivity appears to be primarily modulated by dynamic variable such as 850-hPa relative vorticity. This is consistent with the previous findings of Fu et al. (2012) and Hennon et al. (2013). TC genesis productivity in the WNP analyzed with a vortex analysis in this study show some different features from Teng et al. (2014) using a TCC analysis. Their P_{TCG} does not vary closely with ENSO. Our analysis shows a higher productivity during El Niño years and a lower productivity during La Niña years. Both Teng et al. (2014) and the present study show that total disturbance numbers between El Niño and La Niña years are comparable. Different P_{TCG} values are mainly due to a difference in detected TC numbers. The disturbance has to last for 72 h in our study, but only 24 h in Teng et al. (2014). This may lead to a better chance for TC genesis in our study, yielding a different ratio in genesis productivity under ENSO environments between these two studies.

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