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CHARACTERISTICS OF TROPICAL CYCLONE GENESIS IN THE WESTERN NORTH PACIFIC DURING THE DEVELOPING AND DECAYING PHASES OF TWO TYPES OF EL NIÑO

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Abstract: During the developing phase of central Pacific El Niño (CPEN), more frequent TC genesis over the northwest quadrant of the western North Pacific (WNP) is attributed to the horizontal shift of environmental vorticity field. Such a northwestward shift resembles the La Niña composite, even though factors that cause the shift differ (in the La Niña case the relative humidity effect is crucial). Greater reduction of TC frequency over WNP happened during the decaying phase of eastern Pacific El Niño (EPEN) than CPEN, due to the difference of the anomalous Philippine Sea anticyclone strength. The TC genesis exhibits an upward (downward) trend over the northern (southern) part of the WNP, which is linked to SST and associated circulation changes through local and remote effects.

Key words: tropical cyclone genesis; western North Pacific; two types of El Niño; growing and decaying phases; genesis trends

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1 INTRODUCTION

Tropical cyclone activity over the western North Pacific (WNP) exhibits a pronounced annual cycle with a peak phase in July-October (JASO). It also exhibits a robust interannual variability influenced by El Niño/Southern Oscillation (ENSO) (See Chan [1]; Chen and Huang [2]; Wang and Song [3]; Du et al.[4]). It was found that during El Niño, the genesis of TC number increases over the southeastern part of WNP; accordingly TCs tend to have longer duration and larger intensity. During La Niña, however, TCs occur more frequently over the northwestern part with shorter life span and weaker intensity. The contrast of TC genesis location between the warm and cold phases of ENSO is primarily caused by regional circulation changes in response to anomalous heating in the equatorial central Pacific (Camargo et al.[5]; Lander[6]).

Different from the canonical El Niño that has a maximum SST warming over the eastern Pacific (EP El Niño, EPEN) (See Rasmusson and Carpenter[7]), a new type of El Niño emerged, with a maximum SST anomaly (SSTA) appearing in the equatorial central Pacific (CP El Niño, CPEN) (See Ashok et al.[8]; Kao and Yu[9]; Kug et al.[10]). Chen and Tam [11] found that TC occurrence frequency over the WNP is positively correlated with the Modoki index. Kim et al.[12] indicated that during CPEN, TC activity was extended westward due to the westward shift of anomalous diabatic heating.

TC frequency over the WNP also exhibits an interdecadal variability. It is likely that the interdecadal TC variability arises from the change of local circulation associated with the interdecadal change of the equatorial central Pacific SST (Matsuura et al.[13]). TC tracks also show an interdecadal change in association with the longitudinal variation of WNP subtropical high on the interdecadal timescale (Ho et al.[14]; Wu et al.[15]).

The objective of the present study is two folds. Firstly we intend to reveal TC genesis characteristics during the developing and decaying phases of CPEN and EPEN. Note that most of previous studies were based on simultaneous TC-SSTA (Niño3.4 or Modoki index) relationship. As shown by Li[16], the simultaneous correlation between the Niño3.4 index and WNP TC frequency is not statistically significant (for the period of 1970-2010), while the TC frequency is significantly negatively (positively) correlated with the Nin3.4 index in the preceding (succeeding) winter. This indicates that it is necessary to separate El Niño developing and decaying phases. In addition, we will identify specific environmental factors that contribute to genesis pattern difference between EPEN and CPEN. Secondly, we will investigate the regional character of WNP TC trend in the past 30 years. It was shown that a La-Niña like trend pattern appeared in the tropical Pacific during 1980-2010 and such a pattern is responsible for more frequent occurrence of CPEN in the last decade (McPhaden et al.[17]; Chung and Li[18]). This motivates us to examine how such a SST trend and associated

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large-scale circulation changes affect regional TC be havior through local and remote effects.

2 DATA AND METHODOLOGY

TC genesis information is from best-track dataset (including TC location and intensity at a 6-h interval) produced by Joint Typhoon Warning Center (JTWC) from 1980-2010. Here, a TC is defined when a storm has a sustained wind of 34 knots or above. The analysis is focused on the WNP region during its most active TC season from July to October (JASO). Annual TC genesis density was calculated by counting the number of TC on the genesis date (first warning position) at each of 2.5°×2.5° latitude and longitude square box. To examine the shift of TC genesis location, we separate the WNP into four sub-regions as northeast (NE), northwest (NW), southwest (SW) and southeast (SE) quadrants.

The monthly atmospheric variables are from National Centers for Environmental Prediction (NCEP) /National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay[19]) at 2.5°×2.5° horizontal resolution during 1980-2010. The monthly SST dataset used in this study is from the Extended Reconstructed Sea Surface Temperature version 3b (ERSSTv3b) (See Smith et al.[20]).

To assess the impact of environmental parameters on TC genesis, the following four variables associated with genesis potential index (GPI) (See Camargo et al.[5]; Emanuel and Nolan [21]) are examined; they are absolute vorticity (AVOR hereafter) at 850 hPa, magnitude of vertical wind shear between 200 hPa and 850 hPa (VWS hereafter, the 200 hPa value minus the 850 hPa value), potential intensity (PI hereafter, Emanuel[22]), and relative humidity at 700 hPa (RH hereafter). Although the interannual relationship between the GPI and TC frequency in the WNP is relatively weak during JASO[5], it is still useful to examine the contributions from each of the individual variables.

The CPEN (EPEN) events are defined when the Ni ño4 (Niño3) SST index averaged from July to December is greater than one standard deviation. Five CPEN events (i.e., 1994/95, 2002/03, 2004/05, 2006/07, 2009/10) and two EPEN events (1982/83, 1997/98) were selected. A composite analysis was made based on these CPEN and EPEN events. Here the year before the slash denotes the developing phase, and the year after it represents the decaying phase. Although the 1987 El Ni ño amplitude exceeded one standard deviation, it was not chosen as an EPEN event because its peak phase is in boreal summer so that it cannot be divided into a developing and decaying phase. Besides, the 1987 event was regarded as a mixed episode because its maximum SSTA center is somewhere between EP and CP [10]. For comparison, three strong La Niña events (1985, 1988 and 1999) were selected for composite. Other three (1998, 2007, 2010) La Niña events were also strong, but we did not select these cases simply because they are associated with the decaying of preceding El Niño episodes, which have already been selected in the EPEN or CPEN decaying phase composite.

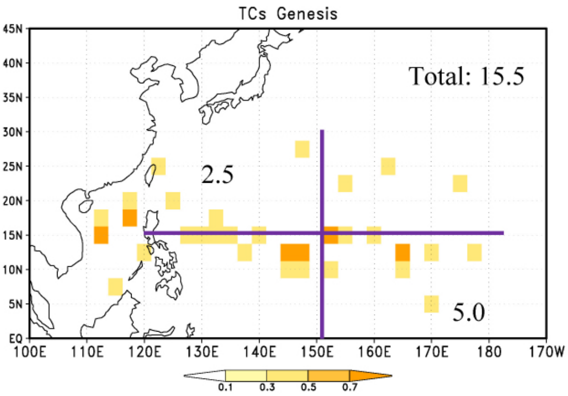
For the long-term trend analysis, we assume the time series of TC numbers (at each box) and large-scale variables (at each grid point) during 1980-2010 are linear growing or decaying. The values in the trend patterns denote the slope (in the unit of year) of the trend line estimated via a simple regression in which Y is the dependent variable and X is the independent year.

3 TC GENESIS CHARACTERISTICS DURING THE DEVELOPING PHASE OF CPEN AND EPEN

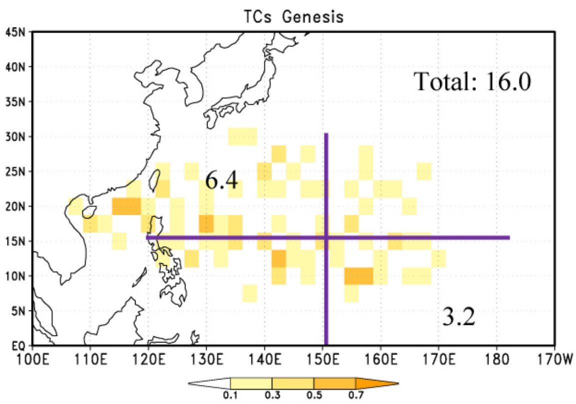
TC genesis number in the SE quadrant is about 2 times greater than that in the NW quadrant during the developing phase of EPEN (Fig. 1a). On the contrary, TC genesis frequency in the NW quadrant is about 2 times larger than that in the SE quadrant during the developing phase of CPEN (Fig. 1b). The total TC genesis number in CPEN (16.0) is larger than that of EPEN (15.5), and the latter is the same as the climatological mean (15.5). The contrast of TC genesis location between the two types of El Niño calls for further physical interpretation.

In EPEN, two broad Rossby gyre circulation anomalies occupy the entire tropical Pacific in response to El Niño related central Pacific diabatic heating (Fig. 2a). Maximum westerly anomalies in the central equatorial Pacific induce stronger low-level cyclonic shear in the SE quadrant than in the NW quadrant. As a result, the absolute vorticity parameter favors cyclogenesis in the SE quadrant (Table 1). Meanwhile, the greater cyclonic shear in the SE quadrant strengthens boundary layer moisture convergence (through Ekman pumping process) and increases the lower-tropospheric relative humidity. Table 1 shows that the two parameters above are major environmental factors responsible for more frequent TC genesis in the SE quadrant during EPEN developing phase. This result is consistent with Camargo et al. [5] and Wu et al. [23], who used more El Niño events in their composite analysis

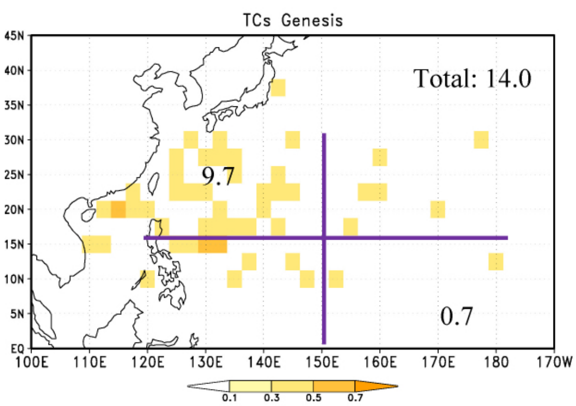
In CPEN, maximum anomalous vorticity center shifts northwestward, owing to the westward shift of the heating anomaly at the equator (Fig. 2b). This feature is similar to Chen and Tam [11] and Kim et al.[12]. Table 1 indicates that the vorticity and vertical shear are two environmental factors that contribute to more frequent cyclogenesis in the NW quadrant during CPEN developing phase. A statistical significance test shows that only the AVOR factor in the NW quadrant exceeds 95% confidence level. Given that the climatological value of the AVOR in the NW quadrant is more than two times larger than that in the SE quadrant, the significantly enhanced AVOR in the NW quadrant may be regarded as the primary factor.



(a)EPEN developing



(b)CPEN developing



(c) La Niña

Figure 1. Composites of TC genesis density (year-1) in JASO during the developing phases of (a) eastern Pacific and (b) central Pacific El Niño, and (c) during La Niña years. The purple crosses in the left panels indicate 4 sub-regions over WNP, northeastern, northwestern (NW), southwestern and southeastern (SE) quadrants. Averaged total TC genesis numbers in JASO over (0°-30°N, 120°-180°E) are shown on the upper-right corner, and averaged TC numbers in NW (15°-30°N, 120°-150°E) and SE (0°-15°N, 150°-180°E) quadrants are shown in the corresponding quadrants.

It is worth noting that the northwestward shift of TC genesis location associated with CPEN is similar to that of the La Niña composite (Fig. 1c). Thus the contrast of cyclogenesis between EPEN and CPEN is analogous to the contrast between the conventional El Niño and La Niña. However, the physical interpretation of the genesis location shift differs between CPEN and La Niña. The cause of more frequent TC formation in the NW quadrant during La Niña is attributed to the following two processes. Firstly, a greater anticyclonic circulation anomaly in the SE quadrant suppresses local TC formation (Table 1). Secondly, anomalous low-level moisture advection increases the relative humidity in the NW quadrant (figure not shown, but can be interpreted by Fig. 2c). The comparison of four environmental parameters shows that the greatest contrast between the NW and SE quadrant arises from the RH parameter (Table 1), and the difference exceeds 95% confidence level (according to a student *t*-test).

4 TC GENESIS CHARACTERISTICS DURING THE DECAYING PHASE OF CPEN AND EPEN

The most pronounced circulation feature during the El Niño decaying summer and early fall is an anomalous anticyclone over the WNP (Chang et al.[24]; Wang et al.[25]; Chung et al.[26]). This anomalous circulation causes a weakening of the WNP monsoon trough and intraseasonal variability (Lin and Li[27]), as well as the decrease of TC frequency[16]. Will the conventional El Niño characteristics occur in the decaying phase of both EPEN and CPEN. Fig. 3 (left panel) shows that the decrease of total TC number over the WNP is mostly pronounced in EPEN, and is less so in CPEN. The averaged number is 10.0 (12.8) for EPEN (CPEN), whereas the climatological TC number during JASO is 15.5. Most of TCs during EPEN and CPEN decaying phase occur to the west of 150°E and between 10°N and 25°N.

The contributions of four environmental parameters averaged over the area of (120°-150°E, 10°-25°N) during the decaying phase of EPEN and CPEN are shown in Fig. 4. The difference of TC genesis number between the EPEN and CPEN is primarily attributed to the environmental vorticity and RH factors (difference exceeds 95% confidence level). It is seen that the anomalous anticyclone is much stronger in the EPEN composite than in the CPEN composite (Fig. 3, right panel). The stronger anticyclone in EPEN induces greater boundary layer divergence and lower-tropospheric subsidence, which further leads to a larger decrease of local relative humidity. The effect of the other two environmental parameters is relatively small.

5 TC TREND PATTERN DURING 1980–2010

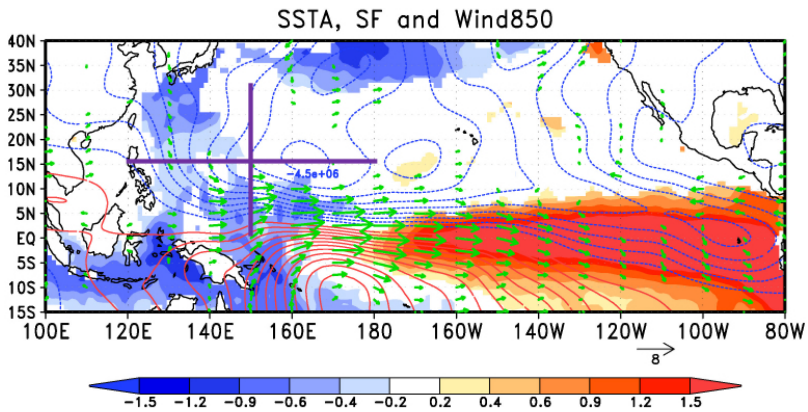
The linear trend patterns of TC genesis density and large-scale circulation during JASO over the WNP were presented in Figs. 5 and 6. During the last 31-year period (1980-2010), the trend of TC genesis density experiences a north-south dipole pattern, with more TC occurrence appearing over the region of (17°-25°N, 105°-135°E) and less TC occurrence over (7°-17°N, 110°-160°E). The difference of TC genesis number between the two regions (northern minus southern region) shows

Table 1. Environmental parameters averaged in JASO (subtracted by their climatologic values) over NW and SE quadrants of the WNP during the developing phase of EPEN and CPEN and during La Niña years. Here AVOR denotes 850-hPa absolute vorticity (unit: 10^{-7} s^{-1}), VWS denotes a vertical wind shear from 200 hPa to 850 hPa (unit: m s^{-1}), PI denotes the potential intensity (unit: m s^{-1}), and RH denotes 700-hPa relative humidity (unit: %).

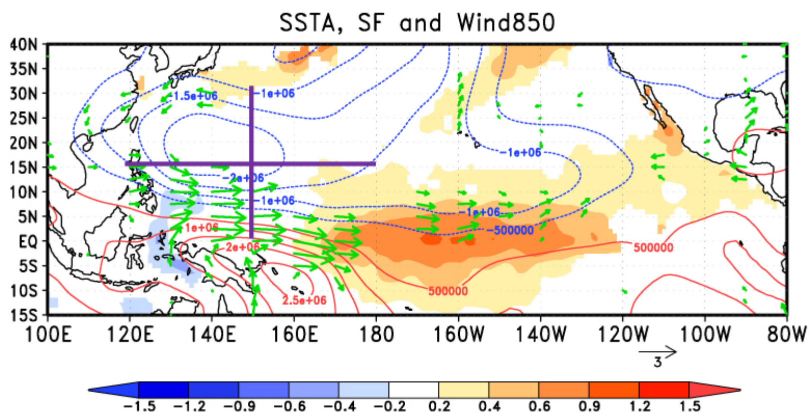
	EPEN Developing				CPEN Developing				La Niña			
	AVOR**	VWS	PI	RH**	AVOR	VWS	PI	RH	AVOR	VWS	PI	RH**
NW	-0.3	0.1	-2.1	-0.7	15.6*	-0.2	0.8	-0.2	-6.9	0.3	0.0	1.8
SE	31.9*	4.4	-2.5	3.0*	12.3	0.2	0.9	5.3	-10.8	-0.6	0.6	-4.7

*Values exceeding the 95% confidence level.

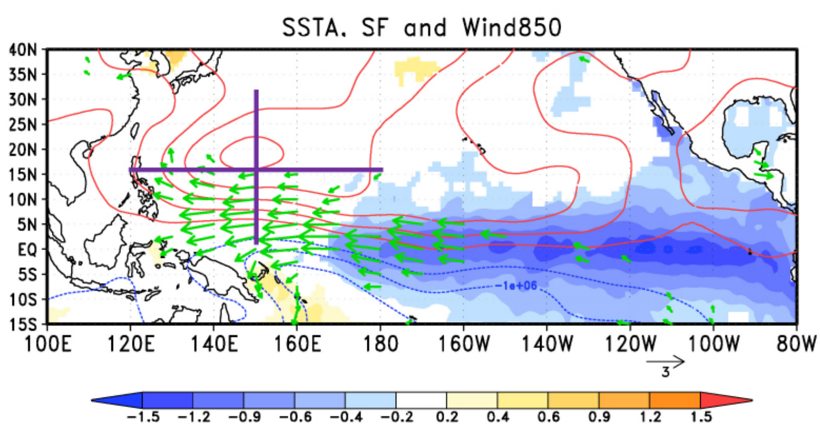
** NW and SE difference exceeding the 95% confidence level.



(a) EPEN developing

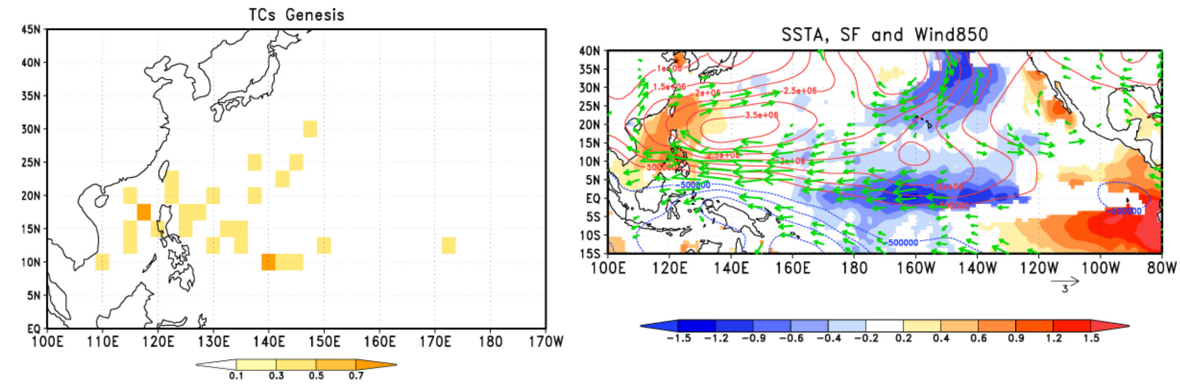


(b) CPEN developing

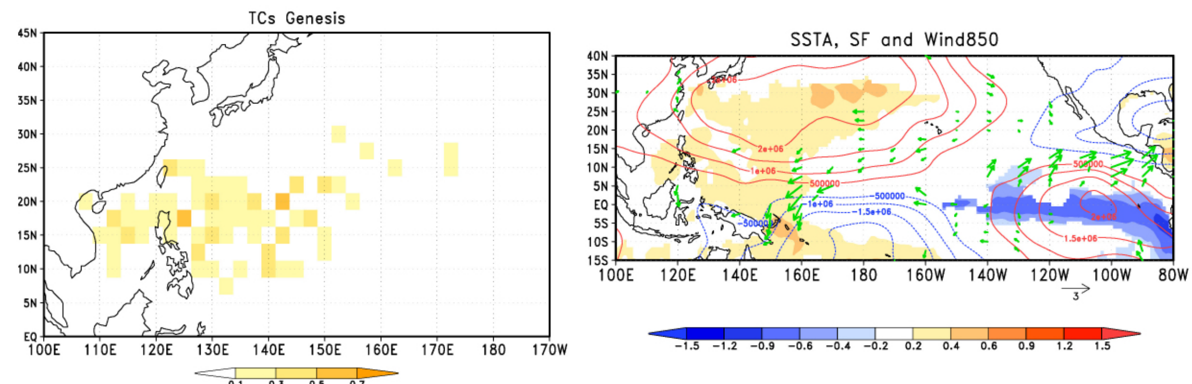


(c) La Niña

Figure 2. As in Fig. 1 but for the anomalous SST (shading, ℃), 850-hPa stream function (contour, m^2 s^{-1}) and 850-hPa wind fields (vector, m s^{-1})



(a) EPEN decaying



(b) CPEN decaying

Figure 3. As in Fig. 1 and Fig. 2 except for the (a) EPEN decaying and (b) CPEN decaying phases.

Figure 4. Composites of the environmental climate factors averaged over (120°-150°E, 10°-25°N) (subtracted by their climatologic values) for EPEN (blue bar) and CPEN (red bar) decaying phases. The magnitude is normalized based on following values (AVOR: 3.0×10^{-6} s^{-1}, VWS: 0.7 m s^{-1}, PI: 2.4 m s^{-1}, RH: 0.7 %). The asterisk denotes that the difference between EPEN and CPEN passes the 95% confidence level for the particular environmental factor.

a significant (exceeding 95% confidence level) upward trend (Fig. 5, lower panel). To reveal the cause of this dipole pattern, we examined the trend of large-scale circulation and SST in Fig. 6. Note that a negative mean sea level pressure (MSLP) trend appears to the south and north of the Philippine Sea, and correspondingly there is a ridge in the 850-hPa streamline over the Philippine Sea, which extends eastward toward the subtropical high center (Fig. 6a). The resembling of a meridional contrast pattern between anomalously high pressure south of 17°N and anomalously low pressure north of 17°N to the TC trend pattern implies that the low-level circulation change is responsible for the TC long-term trend.

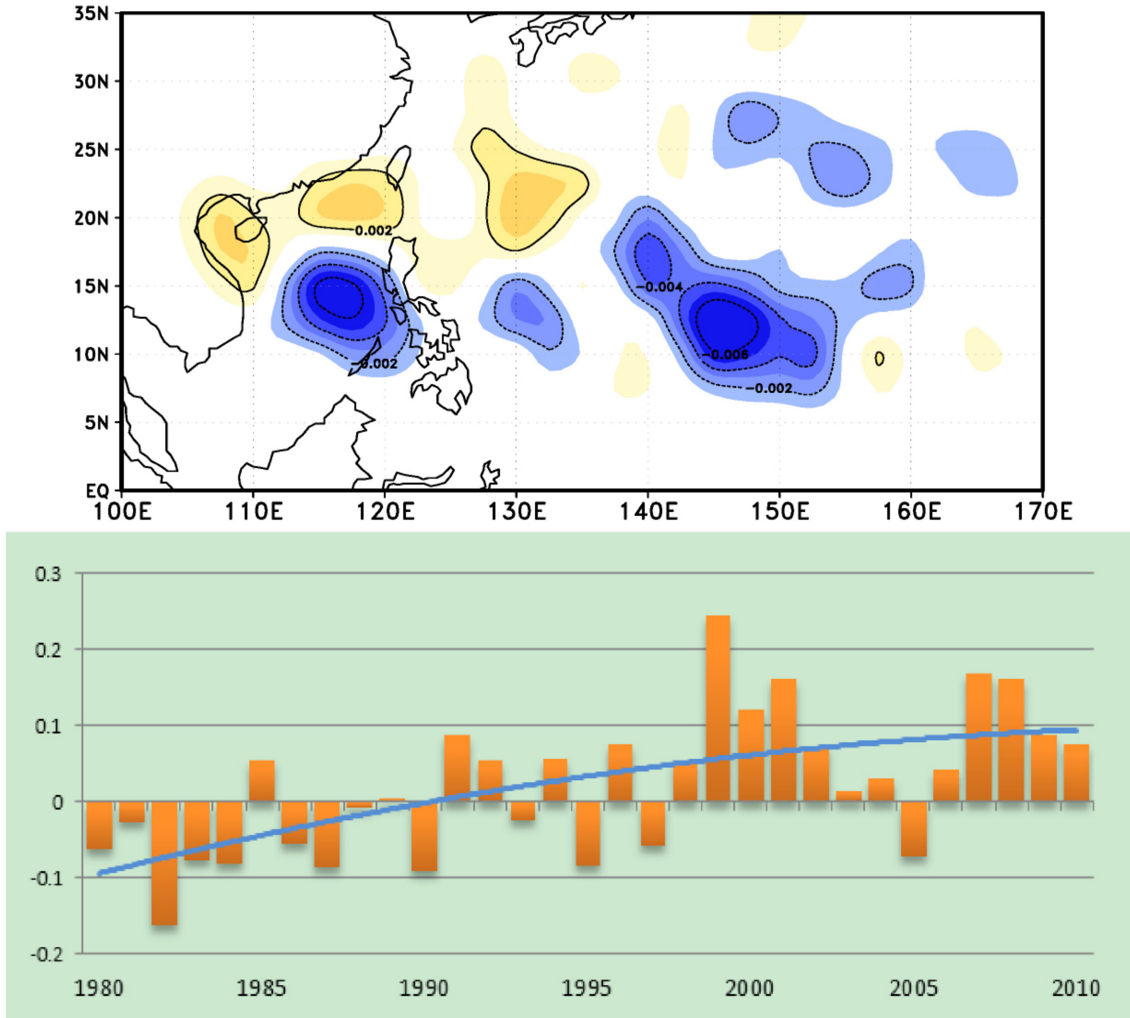


Figure 5. Linear trends of JASO TC genesis density (year^{-1}, upper) and time series of JASO TC genesis number difference between northern and southern WNP regions (lower, blue line is its trend, which passes 95% Mann-Kendall trend test).

The change of the low-level circulation is possibly caused by the SST trend. As one can see from Fig. 6b, maximum SST warming appears in the equatorial western Pacific and the region north of 20°N. Such a SST pattern promotes two anomalous local Hadley cells with rising branches over the maritime continent (5°S-5°N) and southeast Asia (20°-27°N) and a descending branch over the Philippine Sea (5°-15°N) (Fig. 6c). The northern ascending motion induces low-level convergence and cyclonic vorticity, leading to the increase of TC occurrence. The descending motion to its south tends to weaken the WNP monsoon trough and reduce the TC formation in situ.

In addition to local SST forcing, a La Niña like SST trend pattern (figure not shown, similar to Fig. 6b) in the central equatorial Pacific may also contribute to the anticyclonic circulation near the Philippine Sea through a Rossby wave response to a negative heating anomaly in the central equatorial Pacific. Thus both the local and remote SST trends play a role in modulating the TC characteristics over the WNP.

The overall argument above suggests that the long-term SST trend plays a critical role in modulating the TC characteristics in the WNP. One may argue that more frequent occurrence of TCs may produce anoma lous rising motion. To clarify the cause-effect relationship between the anomalous vertical motion and TC activity, the trend patterns of vertical p-velocity and SST in May-June (MJ) (when TC is less active) were examined. A similar trend pattern is found in MJ vertical motion and SST fields (figure not shown), implying that the background SST trend plays an active role in affecting the TC characteristics.

6 CONCLUSION AND DISCUSSION

Using the NCEP-NCAR reanalysis and JTWC best track data, we examined TC genesis characteristics and environmental factors that contribute to cyclogenesis. Different from previous studies such as Chen and Tam[11] and Kim et al.[12], we separated EPEN and CPEN into developing and decaying phases. In contrast to the southeastward shift of TC genesis location during the

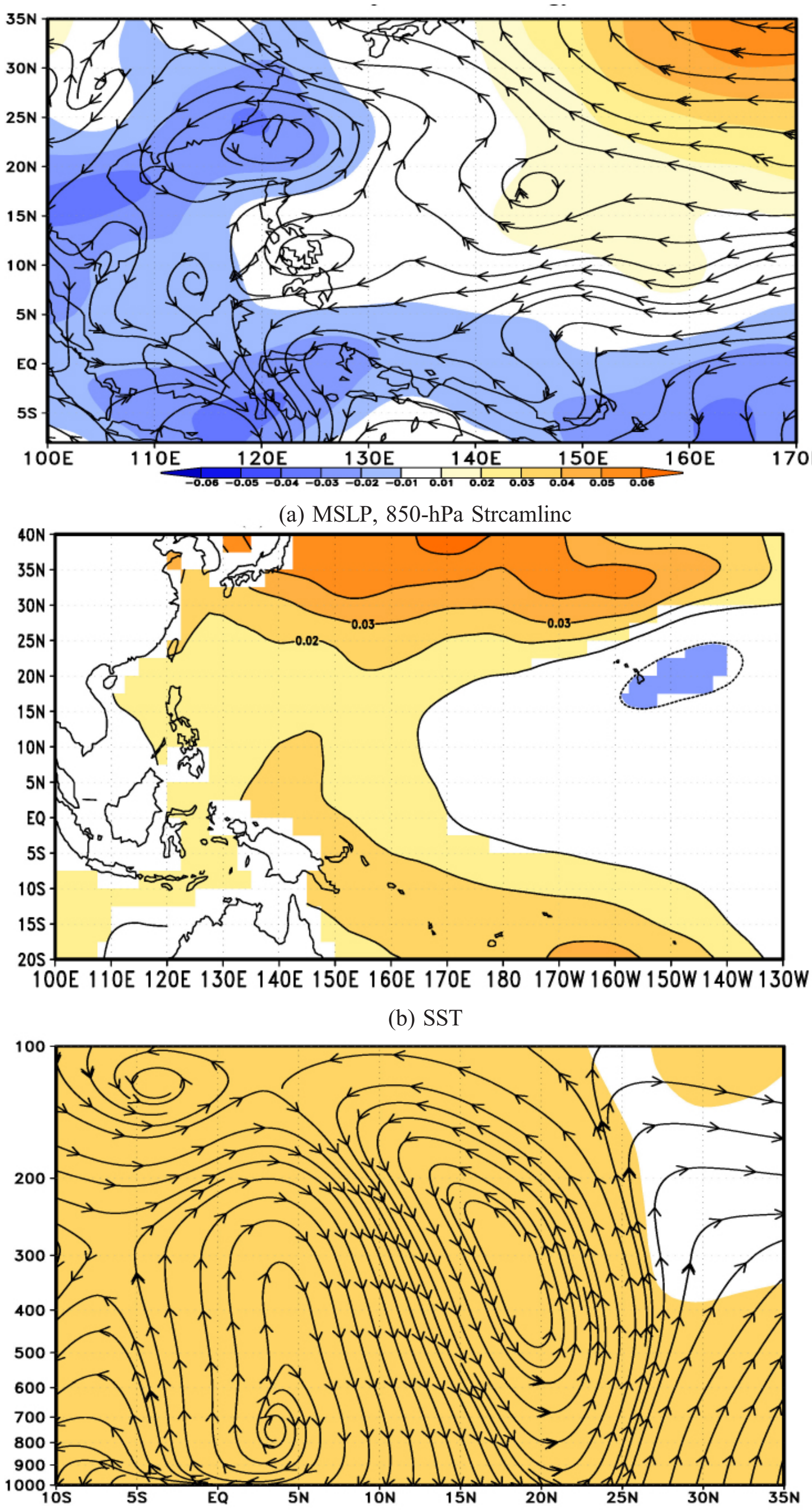


Figure 6. JASO trends of (a) 850-hPa streamline and sea level pressure (areas passing 90% confidence level are shaded), (b) sea surface temperature, and (c) vertical-meridional streamline averaged over 110°E-140°E. In (b) and (c), areas exceeding 90% confidence level are shaded.

EPEN developing phase, TCs occur more frequently in the northwest quadrant during the CPEN developing phase. A diagnosis of environmental controlling parameters indicates that the southeastward shift in EPEN is attributed to both the vorticity and relative humidity changes, whereas the northwestward shift in CPEN is mainly contributed by the vorticity change. The northwest-southeast contrasting feature in CPEN resembles that of the La Niña composite, even though the environmental factor contributing to the pattern differs. During the La Niña , more frequent TC occurrence over the northwest quadrant is primarily attributed to higher relative humidity caused by anomalous horizontal moisture advection.

In the EPEN decaying phase, TC genesis frequency experienced a significant decrease over the WNP. Such a decrease is attributed to the occurrence and persistence of an anomalous anticyclone over the Philippine Sea from the El Niño mature winter to the succeeding summer (Wang et al.[25]; Chung et al.[26]). The decrease of TC frequency is less significant during the decaying phase of CPEN, due to a weaker, less robust anomalous anticyclone response over WNP. The comparison of environmental factors shows that the difference between EPEN and CPEN is attributed to the vorticity and relative humidity fields.

TC genesis frequency in northern (southern) WNP experienced an increasing (decreasing) trend during 1980-2010. Such a dipole pattern is consistent with the trend of regional circulation and SST changes. An increasing (decreasing) of TC genesis number over the northern (southern) WNP coincides with the trend of low-level cyclonic (anticyclonic) circulation, negative (positive) sea-level pressure, and enhanced large-scale ascending (descending) motion. It was further noted that the aforementioned circulation changes are closely related to the trend of the local SST pattern. Greater SST warming near the equator and north of the Philippine Sea induces two anomalous local Hadley cells with a descending branch over the Philippine Sea and rising branches over the maritime continent (5°S-5°N) and along 20°-27°N. Such background dynamic and thermodynamic conditions favor less frequent TC genesis over the Philippine Sea but more frequent TC formation to its north.

The local SST trend over the WNP was accompanied by a significant La Niña trend in the central equatorial Pacific during the same period (Fig. 6a). It was also accompanied by the trend of more frequent occurrence of CPEN [17, 18]. As a result, the observed WNP TC trend may be influenced by both the long-term SST trend and the accumulated effect of interannual perturbations. The former is related to SST induced circulation changes, whereas the latter is associated with the remote influence of CPEN due to its interdecadal variation. A further study is needed to understand their relative roles.

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