Article ID: 1006-8775(2018) 03-0314-09

REGIONAL DISCREPANCIES OF THE IMPACT OF TROPICAL INDIAN OCEAN WARMING ON NORTHWEST PACIFIC TROPICAL CYCLONE FREQUENCY IN THE YEARS OF DECAYING EL NIÑO

JIN Shuang-long (靳双龙)[1], WU Shu-hui (武淑慧)[2], LIU Zheng-qi (刘正奇)[3], ZHANG Heng-zheng (张珩正)[3]
(1. State Key Laboratory of Operation and Control of Renewable Energy & Storage Systems, China Electric Power Research Institute, Beijing 100192 China; 2. Sanjiang University, Nanjing 210012 China; 3. Naval Ocean, Hydrology, and Meteorology Center of South China Sea Fleet, Zhanjiang, Guangdong 524000 China)

Abstract: This study investigates the influences of tropical Indian Ocean (TIO) warming on tropical cyclone (TC) genesis in different regions of the western North Pacific (WNP) from July to October (JASO) during the decaying El Niño. The results show significant negative TC frequency anomalies localized in the southeastern WNP. Correlation analysis indicates that a warm sea surface temperature anomaly (SSTA) in the TIO strongly suppresses TC genesis south of 21°N and east of 140°E in JASO. Reduced TC genesis over the southeastern WNP results from a weak monsoon trough and divergence and subsidence anomalies associated with an equatorial baroclinic Kelvin wave. Moreover, suppressed convection in response to a cold local SSTA, induced by the increased northeasterly connected by the wind-evaporation-SST positive feedback mechanism, is found unfavorable for TC genesis. Positive TC genesis anomalies are observed over higher latitudinal regions (at around 21°N, 140°E) and the western WNP because of enhanced convection along the northern flank of the WNP anomalous anticyclone and low-level convergence, respectively. Although local modulation (e.g., local SST) could have greater dominance over TC activity at higher latitudes in certain anomalous years (e.g., 1988), a warm TIO SSTA can still suppress TC genesis in lower latitudinal regions of the WNP. A better understanding of the contributions of TIO warming could help improve seasonal TC predictions over different regions of the WNP in years of decaying El Niño.

Key words: typhoon; tropical Indian Ocean; El Niño; sea surface temperature anomaly
CLC number: P444 **Document code:** A
doi: 10.16555/j.1006-8775.2018.03.005

1 INTRODUCTION

El Niño-Southern Oscillation (ENSO) is regarded as one of the most important factors that modulate tropical cyclone (TC) activities in the western North Pacific (WNP) (Chan[1]; Wang and Chan[2]; Camargo and Sobel [3]). Many previous studies focused on the impacts of ENSO's different phases on the interannual variability of TC genesis location, frequency, track, intensity, and life span in the WNP (e.g., Chan[1]; Chia and Ropelewski [4]; Wang and Chan [2]; Camargo and Sobel [3]; Chen et al.[5]; Du et al.[6]; Zhan et al.[7]; Ha et al.[8]; Jin et al.[9]). TC activities in the east (west) of the WNP have high (low) genesis frequency, strong (weak) intensity and long (short) life span during El Niño, but they exhibit the opposite features during La Niña. The influence of ENSO on TC activities is considerable not only during El Niño/La Niña but also after the warm/cold events. Moreover, evident interdecadal and decadal changes in TC activity have also been recognized over different parts of the WNP. He et al.[10] revealed that TC genesis has shown an evident decrease (increase) over the southern (northern) WNP since the late 1990s on the decadal time scale. Chan [1] first noted that TC genesis frequency over the entire WNP basin was below the climatological mean after El Niño. TC activities have close dependence on the behaviors of sea surface temperature via the supply of surface latent heat fluxes (Ma et al.[11-14]). Recent studies have revealed that a warm sea surface temperature anomaly (SSTA) in the tropical Indian Ocean (TIO) forces an equatorial baroclinic Kelvin wave to emanate toward the western Pacific after El Niño events (Yang et al.[15]; Xie et al.[16,17]), which exerts notable influence on the East Asia summer climate. Essentially, the baroclinic Kelvin wave induces both an equatorial easterly anomaly and an anomalous anticyclone, representative of the most pronounced lower-troposphere circulation anomaly over the western Pacific, which is maintained by the warm TIO and local WNP SSTAs during the decaying El Niño (Wang et al.[18]; Yang et al.[15]; Xie et al.[16]; Wu et al.[19, 20]). Therefore, significant negative correlation exists between TC

Received 2017-10-23; **Revised** 2018-06-29; **Accepted** 2018-08-15
Foundation item: Science and Technology Foundation of State Grid Corporation of China
Biography: WU Shu-hui, M.S., primarily undertaking research on numerical simulation and urban climate.
Corresponding author: WU Shu-hui, e-mail: shuhui-wu0205@163.com

frequency in the WNP and the TIO SSTA, suggesting that a warm SSTA in the TIO suppresses TC genesis over the entire WNP throughout the period of the anomalous anticyclone. In particular, suppressed TC activities appear over the WNP in summer following strong El Niño events (Du et al.[6]; Zhan et al.[7,21]; Tao et al. [22]). Du et al. [6] proposed that the equatorial baroclinic Kelvin wave in the troposphere, forced by a warm SSTA in the TIO, could induce low-level divergence off the equator and suppress convection over the WNP. Moreover, strong easterly anomalies associated with the Kelvin wave could increase the magnitude of the vertical shear over the WNP, which could be unfavorable for TC activities during July-September following a strong El Niño. Zhan et al.[7] suggested that TC genesis frequency decreases over the entire WNP during June-October in warm TIO years because of the effects of a weak western Pacific summer monsoon and the Kelvin wave activity. Tao et al.[22] further demonstrated that TC frequency decreases markedly over the WNP during warm TIO years with a more systematic method and a longer time period reanalysis data of 63 years.

Although the anomalous anticyclone suppresses TC activities and leads to decreased TC frequency over the entire WNP during the summer following El Niño, TC frequency appears higher than the climatological mean in the South China Sea (SCS) (Fig. 3b of Du et al.[6]). As the mean vertical shear in the subtropical WNP is easterly (westerly) to the west (east) of 150° E, the strong easterly anomalies associated with the Kelvin wave reduce the magnitude of the vertical shear in the SCS, which is favorable for TC genesis within the region. In addition, Wu et al. [19] proposed that the anomalous anticyclone in the WNP gradually weakened with the decay of a warm SSTA in the TIO. Thus, an increasing local warm SSTA could enhance convection and further result in positive precipitation anomalies over the SCS and western parts of the WNP in the late summer and subsequent fall in the year of a decaying El Niño. Furthermore, high moisture levels and enhanced convection might promote TC activities in these regions, implying that discrepant features of TC genesis modulated by the large-scale circulation and environmental conditions could exist in different regions of the WNP. However, hitherto, the discrepancy of TC genesis frequency over different regions of the WNP during warm TIO years following El Niño has not been revealed in detail. Therefore, the objectives of this study were to establish the discrepancies and detailed features of TC genesis frequency over different regions of the WNP during the years of decaying El Niño, and to determine how a warm SSTA in the TIO might modulate regional anomalies of TC genesis frequency over the WNP. To illustrate the mechanisms of regional TC frequency anomalies, we examined the anomalies of TC genesis frequency in different regions of the WNP, and we determined the effects of TIO warming on the large-scale circulation and environmental conditions over the WNP.

The remainder of this paper is organized as follows. The datasets and methodology used in the study are described in section 2. The detailed features of TC frequency anomalies over the WNP during warm TIO years following El Niño are presented in section 3. The mechanisms via which TC activity anomalies are modulated by TIO warming are discussed in section 4. Finally, the main conclusions are presented in section 5.

2 DATA AND METHODOLOGY

We investigated anomalies of TC genesis frequency during the season of peak TC activity (summer and subsequent fall) from July to October (JASO) during 1979–2010 over the WNP (including the SCS). The TC best-track dataset, obtained from the Regional Specialized Meteorological Center of the Japan Meteorological Agency, comprises TC positions at 6-h intervals over the WNP and the SCS. The incorporation of satellite data after the 1970s has improved the quality of TC positioning in best-track datasets considerably. In this study, TCs that reached at least tropical storm intensity based on the Japan Meteorological Agency scale were considered. To calculate TC genesis frequency, each position of TC genesis was binned into its corresponding 2.5° × 2.5° grid box. The anomalies of TC genesis frequency and the associated significance levels were calculated directly based on the warm years and the climatological mean of each grid point. Thus, the contours straightforwardly present TC genesis frequency information based on the best-track datasets. The monthly Niño-3.4 index, Merged Analysis of Precipitation (Xie and Arkin [23]), outgoing longwave radiation data, and Extended Reconstructed SST (Smith et al.[24]) were obtained from the U.S. National Oceanic and Atmospheric Administration, and the TIO SST index was extracted from the Extended Reconstructed SST reanalysis averaged within 20°S–20°N, 40°–110°E. The TIO SSTA index was extracted based on the area-weighted mean SSTA within 20°S–20°N, 40°–110°E averaged from April to October. It should be noted that this was necessary because of the significant correlation between the spring and summer TIO SSTA and the WNP TC activity (Table 1 of Zhan et al. [7]). The reanalysis data were obtained from the National Centers for Environmental Prediction/National Center for Atmospheric Research (Kalnay et al.[25]).

Correlation and composite analysis methods were applied in this study. El Niño years were defined based on a threshold of one standard deviation from the averaged Niño-3.4 index in JASO during 1979–2010, and the corresponding subsequent years were defined as El Niño decaying years. Moreover, the decaying years had to be located above the 25th percentile of the TIO

SST index to satisfy the existence of significant warming in the TIO. Thus, the six warm TIO years following El Niño events were identified in this study as 1983, 1988, 1998, 2003, 2005, and 2010 (Fig.1). A Student's *t*-test was used to examine statistical significance.

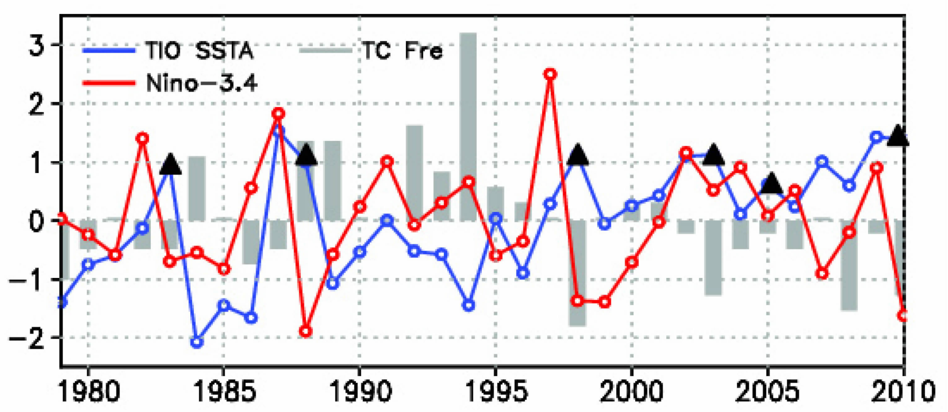


Figure 1. Interannual variations of normalized TC genesis frequency, TIO SSTA and Niño-3.4 indices during JASO. The triangle indicates the six warm TIO years following El Niño events used in this study.

3 TC FREQUENCY ANOMALIES

Suppressed TC activity in the WNP is considered the most dominant feature during the summer following El Niño events (Chan[1]; Chia and Ropelewski[4]; Wang and Chan [2]; Chen et al.[5]), as shown by the locations and anomalies of TC genesis frequency over the WNP in Fig.2. Negative anomalies of TC genesis frequency can be observed in a zonal band between 10°N and 20°N of the WNP. In particular, significant negative anomalies are located in areas south of 20°N and east of 140°E, which is generally regarded as the southeast quadrant of the WNP. Significant positive anomalies of TC genesis frequency can be observed in the region north of 20°N around 120–140°E, the SCS, and east of the Philippines in a region centered on 12°N, 135°E, with lower spatial distribution in higher latitudinal regions. It has been found that an SSTA in the TIO plays an important role in modulating the circulation over the WNP, and that it further controls the interannual variability of TC genesis, especially during the El Niño decaying years (Du et al.[6]; Zhan et al.[7]). To explore the regional features of influence of a TIO SSTA on TC genesis over the WNP, the correlation coefficients between TC genesis frequency on a 2.5°×2.5° grid and the TIO SSTA index during 1979–2010 are shown in Fig. 3a. The distribution of the correlation indicates discrepant influences of the TIO SSTA on TC genesis over different regions of the WNP. Negative correlation appears in most WNP regions, and

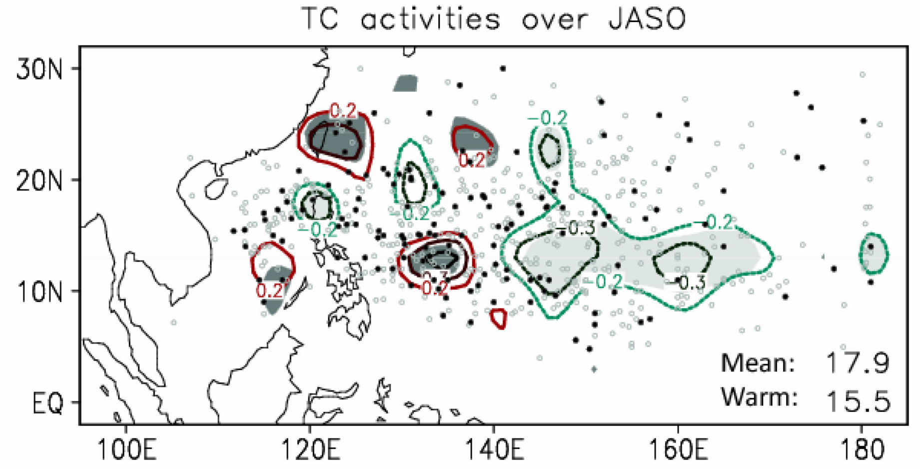


Figure 2. TC genesis in JASO. Positions of TC formation are marked as solid dots and open circles to indicate those in the 6 warm TIO years and other years during 1979–2010, respectively. The positive (negative) anomalies of TC genesis frequency are indicated by solid (dashed) contours, which start from 0.2 (–0.2) with an interval of 0.1; dark (light) shades indicate areas where the positive (negative) differences are statistically significant at the 95% confidence level by the *t*-test. The numbers in the lower-right corner indicate the TC frequencies of the composite warm TIO year and climatological means in JASO.

significantly in the region 10–20° N, 140–150° E and around 8° N, 155° E, all of which are located in the southeastern WNP. Meanwhile, positive correlation between TC frequency and the TIO SSTA index can be observed in the western WNP, although the values are below the 95% confidence level of statistical significance. To investigate the specific latitudes/longitudes of the impact of a TIO SSTA on TC genesis over the WNP, the correlation coefficients between TC frequency over regions south (east) of various latitudes (longitudes) and the TIO SSTA index were calculated and shown in Fig.3b and 3c. The most significant zonal negative correlation between TC frequency and the TIO SSTA index exists at around 21°N in the WNP, where the absolute value of the correlation coefficient reaches the maximum (–0.48) above the 99% confidence level. Meanwhile, the most significant meridional negative correlation is evident at around 140°E, which also reaches the maximum (–0.48) above the 99% confidence level. This result corresponds to the finding of negative correlation between a TIO SSTA and TC genesis over the southeastern WNP.

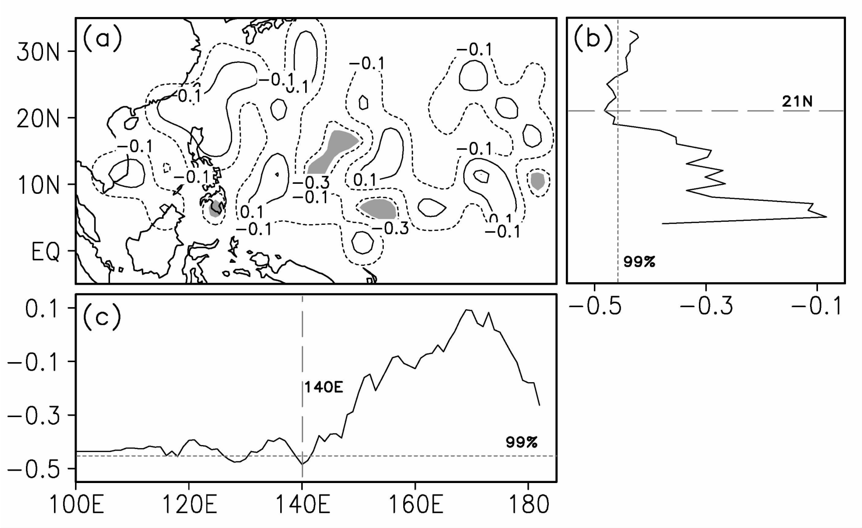


Figure 3. (a) TC genesis frequency on 2.5°× 2.5° grid correlation with the TIO SSTA index in JASO from 1979 to 2010; shades indicate areas where the correlation coefficients are statistically significant at the 95% confidence level. (b) Latitudinal and (c) Longitudinal distribution of TC genesis frequency correlation with the TIO SSTA index in JASO from 1979 to 2010, for example, the correlation coefficient at 21°N in (b) indicates that between the TC genesis frequency south of 21°N and the TIO SSTA index, and the correlation coefficient at 140°E in (c) indicates that between the TC genesis frequency east of 140°E and the TIO SSTA index. Short and long dashed lines in (b) and (c) indicate significance test at the 99% level and the most significant latitude or longitude, respectively.

We examined the numbers of TCs formed over the WNP (Table 1). It was established that 15.5 TCs formed during JASO in warm TIO years annually, i.e., 2.3 fewer than the climatological mean (17.8) during 1979–2010. There were 14.0 (6.8) TCs that formed to the south (east) of 21°N (140°E), significantly fewer by 2.5 (3.1) than the climatological mean of 16.5 (9.9). Furthermore, the number of TCs to the north (west) of 21°N (140°E) was 1.5 (8.7), i.e., 0.2 (0.8) more than the climatological mean of 1.3 (7.9). Therefore, the distributions of TC genesis frequency are discrepant over the different regions of the WNP in warm TIO years following El Niño events. This suggests that a warm TIO SSTA strongly suppresses TC genesis to the south of 21° N and to the east of 140° E during the season of peak TC activity following El Niño, but that it slightly enhances TC activity to the north of 21°N and to the west of 140°E.

Table 1. TC genesis frequency over the WNP, positive (negative) value in parentheses indicates TC frequency in the warm TIO years annually larger (smaller) than that in the climatological mean.

	Warm TIO mean	Climatological mean
Entire WNP	15.5 (–2.3)	17.8
South of 21°N	14.0 (–2.5)	16.5
North of 21°N	1.5 (0.2)	1.3
East of 140°E	6.8 (–3.1)	9.9
West of 140°E	8.7 (0.8)	7.9

4 MECHANISMS

Figures 4 and 5 show the environmental variables of JASO in the composite warm TIO year and the climatological mean, respectively. The warm SSTA in the TIO during the spring of the El Niño decaying year forces an equatorial baroclinic Kelvin wave to trigger easterly anomalies over the tropical western Pacific. These maintain the anomalous anticyclone and negative relative vorticity anomalies in the lower troposphere over the WNP, which persist through the subsequent fall and winter (Klein et al.[26]; Ha et al.[27]). The anomalous circulation induced by the equatorial Kelvin wave is consistent with the Matsuno-Gill pattern (Matsuno[28]; Gill[29]), which can be seen in the pattern of tropospheric warming shown in Fig.4a. During summer and the subsequent fall, the warm SSTA in the TIO dissipates gradually, and the largest warm SSTA shifts eastward toward the Maritime Continent and the WNP (Fig.4a). The anomalous anticyclone is located over the WNP, centered on 20°N, 150°E (Fig.4b). The weak monsoon trough with negative relative vorticity anomalies is observed in a band from southern China to the date line, close to the equator (Fig.4b), which forms in response to the reduced land-sea thermal contrast associated with the underlying warm SSTA over the WNP.

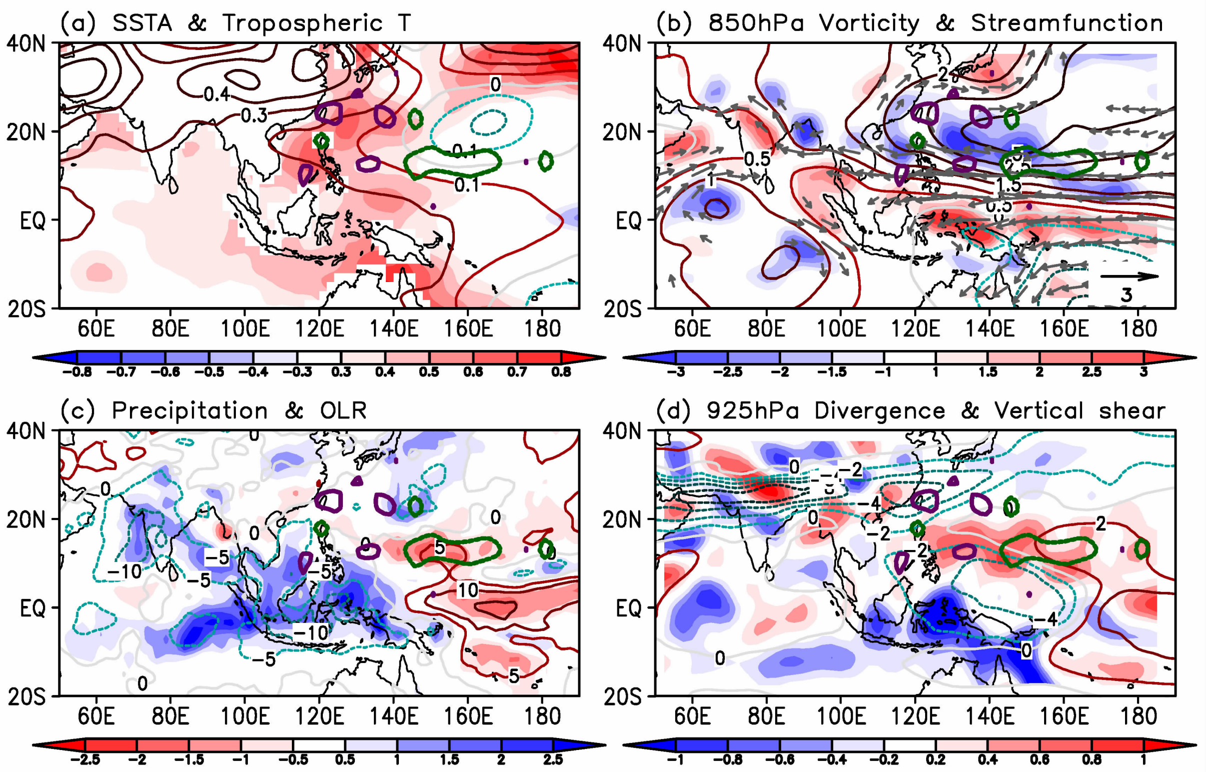


Figure 4. Environmental variables in JASO in the composite warm TIO year. (a) SSTA (shades; ℃) and tropospheric (200–925 hPa) temperature anomaly (contour; ℃); (b) wind field (arrow; m s^{-1}), streamfunction (contour; 10^6 m^2 s^{-1}), and relative vorticity (shades; 10^{-6} s^{-1}) anomalies at 850 hPa; (c) precipitation (shades; mm day^{-1}) and OLR (contour; W m^{-2}) anomalies; (d) 925 hPa divergence (contour; 10^{-6} s^{-1}) and vertical shear (200 hPa–850 hPa) magnitude (shades; m s^{-1}) anomalies. Regions enclosed by purple solid (green dashed) thick contours indicate areas where the positive (negative) anomalies of TC genesis frequency in JASO in the composite warm TIO year are statistically significant at the 95% confidence level by *t*-test.

The decreased TC genesis frequency over the southeastern WNP during the summer and subsequent fall of an El Niño decaying year can be attributed to three factors. First, the extensive warm SSTAs over the Maritime Continent area and the WNP reduce the land-sea thermal contrast (Fig.4a), which weakens the East Asian summer monsoon observed south of 20°N with negative relative vorticity anomalies. Previous studies have suggested the genesis of most TCs over the WNP is linked to the summer monsoon trough (e.g., Lander[30]); therefore, a weak monsoon leads to suppressed TC activities and negative anomalies of TC genesis frequency south of 21°N. Second, the easterly anomalies associated with the equatorial Kelvin wave induce anomalous divergence in the lower troposphere south of 20°N, 120–180°E (Fig.4d), and the resultant subsidence anomalies in this region provide contributions to reduced precipitation and suppressed convection (Fig.4c). These conditions are unfavorable for TC genesis. Third, the anomalous anticyclone (centered on 20° N, 150° E) is superimposed on the easterly over the WNP (Fig.4b), which strengthens the easterly flow in the equatorial region and reduces that off the equator. The intensified (reduced) easterly along the southern (northern) flank of the anomalous anticyclone triggers the wind–evaporation–SST (WES) feedback mechanism (Xie and Philander [31]) with increased (decreased) evaporation and decreased (increased) heat within the sea surface south (north) of 20°N. This results in the extension of a colder (warmer) SSTA in (off) the equatorial region (Lau and Nath[32]). The negative (positive) precipitation anomalies and suppressed (enhanced) convection south (north) of 20°N over the WNP are closed to the local SSTA associated with the process of WES feedback. Furthermore, the moisture and convection conditions have considerable effect on TC activities over the WNP, which exhibit negative anomalies of TC frequency south of 21°N, but slightly enhanced TC activities over higher latitudes. The reduced magnitude of vertical shear also provides some contribution to increased TC genesis in the SCS and western WNP (Fig.4d). This results from the superimposition of intense easterly anomalies in the lower troposphere to the climatological mean easterly vertical shear to the west of 150°E over the subtropical WNP.

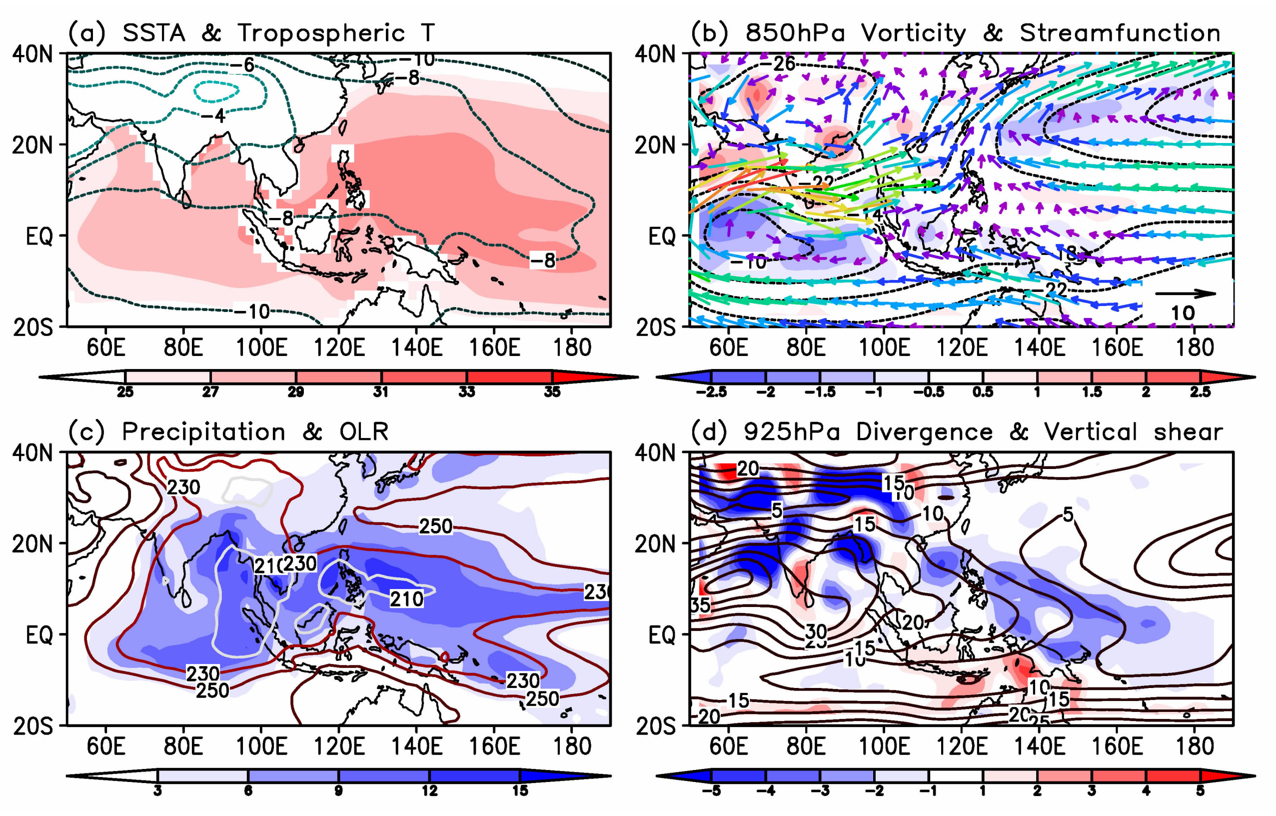
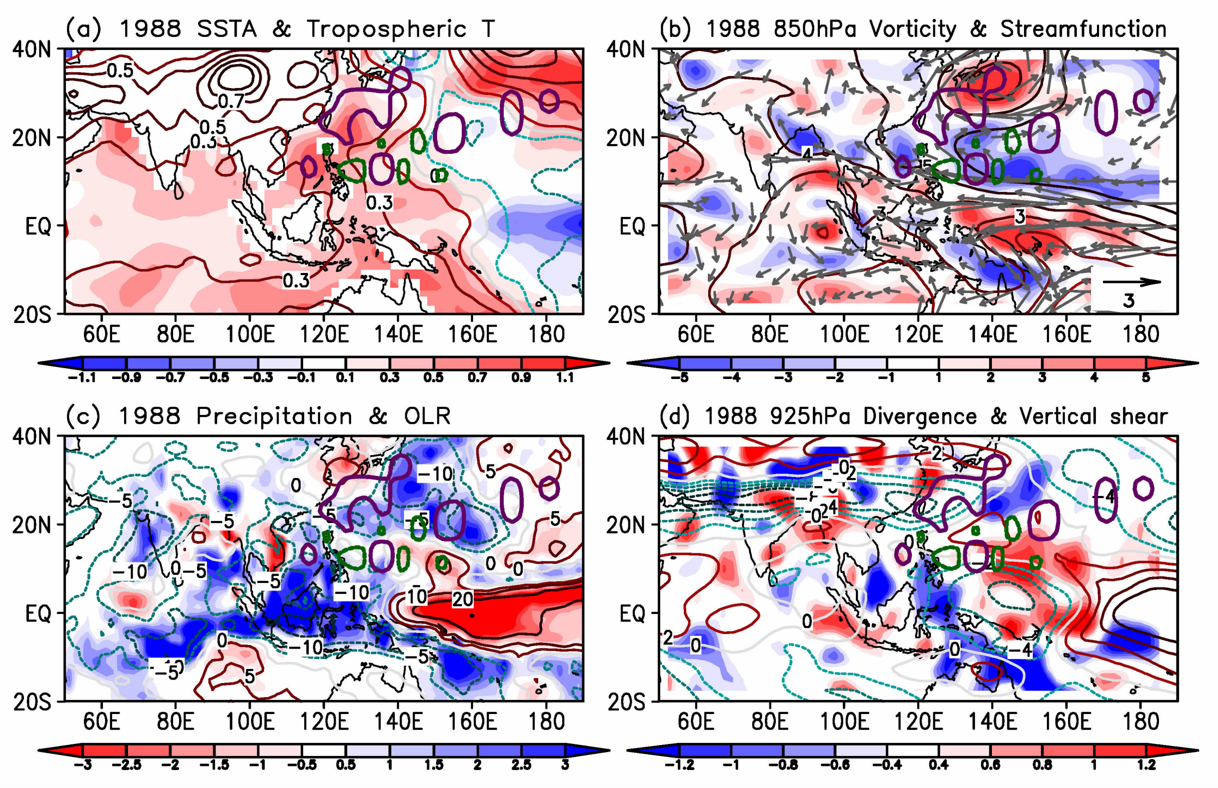


Figure 5. Same as in Fig.4, but for the climatological environmental variables.

Although 1988 was a warm TIO year following a strong El Niño event, it should be noted that TC activities in JASO during that year showed some peculiar features compared with other years in the composite analysis. For instance, TC numbers over the entire WNP in JASO were 14.0 and 23.0 averaged over warm TIO years (1983, 1998, 2003, 2005, and 2010) and in 1988, respectively, but there were 1.6 and 10.0 TCs to the north of 21°N, respectively. It is suggested that total TC frequency in 1988 was significant higher than the climatological mean of warm TIO years over the entire WNP. Moreover, enhanced TC activities were confined mainly to the higher latitudinal regions over the WNP but not south of 21° N. Although the environmental variables in JASO in the composite warm TIO years (except 1988) were very close to the composite results shown in Fig.4 (not shown), it remains important to determine why so many TCs formed north of 21° N over the WNP in 1988. The environmental variables in JASO in 1988 are shown in Fig.6. A warm SSTA stretched from the TIO to the WNP, which heated the troposphere and forced an equatorial Kelvin wave to propagate eastward along the equator (Fig.6a). The easterly anomalies in the tropical Pacific enhanced the negative vorticity and divergence anomalies in the lower troposphere to the south of 21°N (Fig.6b and 6d), and decreased (increased) the magnitude of vertical shear in the west (east) of the tropical Pacific. Compared with the variables in Fig.4, it is clear that the environmental conditions as well as the TC activities south of 21°N in 1988 strongly resembled those in other warm TIO years. However, the environmental variables to the north of 21°N exhibited some differences. As shown in Fig.6c, enhanced convection with strong precipitation dominated in the region 18–35°N, 110–170°E (Fig.6c), which led to further TC genesis. The anomalous atmospheric circulation in JASO during 1988 near 30°N in the WNP (Fig.6b) is similar to the teleconnection of Pacific-Japan (PJ) wave trains in the boreal summer (Nitta[33]), indicating that the intraseasonal variation and teleconnection had greater impact on TC activity in the higher latitudinal regions in JASO during that year. Therefore, the influence of a warm SSTA in the TIO on TC activity over the WNP is concentrated mainly in lower latitudinal regions of the WNP, which is a feature common with warm TIO years following El Niño. Moreover, other climate signals(e.g., the PJ teleconnection) in higher latitudes could be dominant factors that modulate TC activity in certain anomalous years such as 1988. In addition, a cold SSTA in the equatorial central-eastern Pacific (Fig.6a), also has significant impact on the atmospheric circulation through the Rossby wave response shown in the pattern of tropospheric cooling in the lower latitudes (Fig.6a). Thus, the intensified anomalous anticyclone induced by this cold SSTA suppressed convection in the eastern WNP, which further reduced TC frequency south of 21°N in 1988.


(a) 1988 SSTA & Tropospheric T

(b) 1988 850hPa Vorticity & Streamfunction

(c) 1988 Precipitation & OLR

(d) 1988 925hPa Divergence & Vertical shear

Figure 6. Environmental variables during JASO in 1988. (a) SSTA (shades; ℃) and tropospheric (200–925 hPa) temperature anomaly (contour; ℃); (b) wind field (arrow; m s^{-1}), streamfunction (contour; 10^6 m^2 s^{-1}), and relative vorticity (shades; 10^{-6} s^{-1}) anomalies at 850 hPa; (c) precipitation (shades; mm day^{-1}) and OLR (contour; W m^{-2}) anomalies; (d) 925 hPa divergence (contour; 10^{-6} s^{-1}) and vertical shear (200 hPa–850 hPa) magnitude (shades; m s^{-1}) anomalies. Regions enclosed by purple solid (green dashed) thick contours indicate areas where the positive (negative) anomalies of TC genesis frequency during JASO in 1988 are larger (smaller) than 0.5 (–0.5).

5 CONCLUSIONS

This study investigated the anomalies of TC genesis frequency over different regions of the WNP during the season of peak TC peak activity following El Niño. Furthermore, it examined the influences of TIO warming on the large-scale circulation and environmental conditions over the WNP to illustrate the mechanisms responsible for the TC frequency anomalies. The main conclusions derived are as follows. TC genesis frequency is discrepant in different regions of the WNP in JASO following El Niño. Negative anomalies occur in a zonal band between 10°N and 20°N of the WNP, and significant negative anomalies are localized in the southeastern WNP. Significant positive anomalies of TC genesis occur in the SCS and western WNP, but with smaller spatial scales and in higher latitudinal regions relative to the negative anomalies. The significant negative correlation between TC frequency and the TIO SSTA index in JASO during

1979–2010, concentrated in the southeastern WNP (but especially in the region to the south of 21°N and to the east of 140° E), indicates that a warm TIO SSTA strongly suppresses TC genesis in the southeastern WNP during El Niño decaying years; however, it provides some contribution to enhanced TC activity to the north of 21°N and to the west of 140°E.

The decreased TC genesis frequency over the southeastern WNP during the El Niño decaying summer and the subsequent fall can be attributed to three factors. Extensive warm SSTAs over the Maritime Continent area and the WNP reduce the land–sea thermal contrast, which weakens the East Asian summer monsoon observed south of 20°N with negative relative vorticity anomalies. Thus, the weak monsoon leads to negative anomalies of TC genesis south of 21°N. Easterly anomalies associated with an equatorial baroclinic Kelvin wave induce divergence and subsidence anomalies in the lower troposphere south of 20°N, 120–180°E, which are also unfavorable for TC genesis. An anomalous anticyclone superimposed on the easterly over the WNP strengthens the easterly flow in the equatorial region and reduces that off the equator. The intensified (reduced) easterly along the southern (northern) flank of the anomalous anticyclone triggers the WES feedback mechanism with increased (decreased) evaporation and decreased (increased) heat contained within the sea surface south (north) of 20°N, which results in extension of the colder (warmer) SSTA in (off) the equatorial region. Therefore, the negative (positive) precipitation anomalies and suppressed (enhanced) convection south (north) of 20°N, associated with the local SSTA, significantly affect TC activities over the WNP, which exhibit negative anomalies of TC frequency south of 21° N but slightly enhanced TC activities over higher latitudes. In addition, the reduced magnitude of vertical shear contributes to increased TC genesis in the SCS and the western WNP because of the superimposition of intense easterly anomalies in the lower troposphere to the climatological mean easterly vertical shear west of 150°E over the subtropical WNP. Furthermore, the special case of 1988 indicates that reduced TC frequency modulated by a warm TIO SSTA is concentrated mainly in lower latitudinal regions of the WNP, which is a feature common with warm TIO years following El Niño. However, other local modulation could have a more dominant impact on TC activity over higher latitudes. Better understanding of the contributions of TIO warming could help improve seasonal prediction of TC activities over different regions of the WNP for El Niño decaying years.

Acknowledgement: The authors appreciate the comments from the reviewers of this paper.

REFERENCES:

[1] CHAN J C. Tropical cyclone activity over the western North Pacific associated with El Niño and La Niña events [J]. J Clim, 2000, 13(16): 2960-2972.

[2] WANG B, CHAN J C. How strong ENSO events affect tropical storm activity over the western North Pacific [J]. J Clim, 2002, 15(13): 1643-1658.

[3] CAMARGO S J, SOBEL A H. Western North Pacific tropical cyclone intensity and ENSO [J]. J Clim, 2005, 18 (15): 2996-3006.

[4] CHIA H, ROPELWSKI C. The interannual variability in the genesis location of tropical cyclones in the Northwest Pacific [J]. J Clim, 2002, 15(20): 2934-2944.

[5] CHEN T, WANG S Y, YEN M C. Interannual variation of the tropical cyclone activity over the western North Pacific [J]. J Clim, 2006, 19(21): 5709-5720.

[6] DU Y, YANG L, XIE S. Tropical Indian Ocean influence on Northwest Pacific tropical cyclones in summer following strong El Niño [J]. J Clim, 2011, 24 (1): 315-322.

[7] ZHAN, R, WANG Y, LEI X. Contributions of ENSO and East Indian Ocean SSTA to the interannual variability of Northwest Pacific tropical cyclone frequency [J]. J Clim, 2011, 24(2): 509-521.

[8] HA Y, ZHONG Z, HU Y, et al. Influences of ENSO on western North Pacific tropical cyclone kinetic energy and its meridional transport [J]. J Clim, 2013, 26(1): 322-332.

[9] JIN F, BOUCHAREL J, LIN I. Eastern Pacific tropical cyclones intensified by El Niño delivery of subsurface ocean heat [J]. Nature, 2014, 516(7529): 82-85.

[10] HE H, YANG J, GONG D, et al. Decadal changes in tropical cyclone activity over the western North Pacific in the late 1990s [J]. Clim Dyn, 2015, 45(11): 3317-3329.

[11] MA Z, FEI J, HUANG X, et al. The effects of ocean feedback on tropical cyclone energetics under idealized air-sea interaction conditions [J]. J Geophys Res, 2013, 118(17): doi:10.1002/jgrd.50780.

[12] MA Z, FEI J, LIU L, et al. Effects of the cold core eddy on tropical cyclone intensity and structure under idealized air-sea interaction conditions [J]. Mon Wea Rev, 2013, 141(4): 1285-1303.

[13] MA Z, FEI J, HUANG X, et al. Contributions of surface sensible heat fluxes to tropical cyclone. Part I: Evolution of tropical cyclone intensity and structure [J]. J Atmos Sci, 2015, 72(1): 120-140.

[14] MA Z, FEI J, LIU L, et al. An investigation of the influences of mesoscale ocean eddies on tropical cyclone intensities [J]. Mon Wea Rev, 2017, 145(4): 1181-1201.

[15] YANG J, LIU Q, XIE S, et al. Impact of the Indian Ocean SST basin mode on the Asian summer monsoon [J]. Geophys Res Lett, 2007, 34 (2): L02708, doi: 10.1029/2006GL028571.

[16] XIE S, HU K, HAFNER J, et al. Indian Ocean capacitor effect on Indo-western Pacific climate during the summer following El Niño [J]. J Clim, 2009, 22(3): 730-747.

[17] XIE S, KOSAKA Y, DU Y, et al. Indo-western Pacific ocean capacitor and coherent climate anomalies in post-ENSO summer: A review [J]. Adv Atmos Sci, 2016, 33(4): 411-432.

[18] WANG B, WU R, FU X. Pacific-East Asian teleconnection: How does ENSO affect East Asian climate? [J] J Clim, 2000, 13(9): 1517-1536.

[19] WU B, ZHOU T, LI T. Seasonally evolving dominant interannual variability modes of East Asian Climate [J]. J

Clim, 2009, 22(11): 2992-3005.

[20] WU B, ZHOU T, LI T. Relative Contributions of the Indian Ocean and Local SST Anomalies to the Maintenance of the Western North Pacific Anomalous Anticyclone during the El Niño Decaying Summer [J]. J Clim, 2010, 23(11): 2974-2986.

[21] ZHAN R, WANG Y, WEN M. The SST gradient between the southwestern Pacific and the western Pacific warm pool: A new factor controlling the northwestern Pacific tropical cyclone genesis frequency [J]. J Clim, 2013, 26 (7): 2408-2415.

[22] TAO L, WU L, WANG Y, et al. Influence of Tropical Indian Ocean Warming and ENSO on Tropical Cyclone Activity over the Western North Pacific [J]. J Meteor Soc Jpn, 2012, 90(2): 127-144.

[23] XIE S, ARKIN P. Global precipitation: A 17-year monthly analysis based on gauge observation, satellite estimate, and numerical model outputs [J]. Bull Amer Meteor Soc, 1997, 78(11): 2539-2558.

[24] SMITH T, REYNOLDS R, PETERSON T, et al. Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880-2006) [J]. J Clim, 2008, 21(10): 2283-2296.

[25] KALNAY E, et al. The NCEP/NCAR 40-Year Reanalysis Project [J]. Bull Amer Meteor Soc, 1996, 77(3): 437-471.

[26] KLEIN S, SODEN B, LAU N. Remote sea surface temperature variations during ENSO: Evidence for a tropical atmospheric bridge [J]. J Clim, 1999, 12 (4): 917-932.

[27] HA Y, ZHONG Z, YANG X, et al. Contribution of East Indian Ocean SSTA to Northwest Pacific Tropical Cyclone Activity under El Niño/La Niña Conditions [J]. Inter J Clim, 2014, 35(10): 506-519.

[28] MATSUNO T. Quasi-geostrophic motions in the equatorial area [J]. J Meteor Soc Jpn, 1996, 44(1): 25-43.

[29] GILL A. Some simple solutions for heat-induced tropical circulation [J]. Q J Roy Meteor Soc, 1980, 106 (4): 447-462.

[30] LANDER M. An exploratory analysis of the relationship between tropical storm formation in the western North Pacific and ENSO [J]. Mon Wea Rev, 1994, 122 (4), 636-651.

[31] XIE S, PHILANDER S. A coupled ocean-atmosphere model of relevance to the ITCZ in the eastern Pacific [J]. Tellus, 1994, 46A(4): 340-350.

[32] LAU N, NATH M. Impact of ENSO on the variability of the Asian-Australian monsoons as simulated in GCM experiments [J]. J Clim, 2000, 13(24): 4287-4309.

[33] NITTA T. Convective activities in the tropical western Pacific and their impact on the Northern Hemisphere summer circulation [J]. J Meteor Soc Jpn, 1987, 65(3): 373-390.

Citation: JIN Shuang-long, WU Shu-hui, LIU Zheng-qi, et al. Regional discrepancies of the impact of tropical Indian Ocean warming on northwest Pacific tropical cyclone frequency in the years of decaying El Niño [J]. J Trop Meteor, 2018, 24(3): 314-322.