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# Influence of Monsoon over the Warm Pool on Interannual Variation on Tropical Cyclone Activity over the Western North Pacific

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**ABSTRACT**

The relationship between the interannual variation in tropical cyclone (TC) activity over the western North Pacific (WNP) and the thermal state over the warm pool (WP) is examined in this paper. The results show that the subsurface temperature in the WP is well correlated with TC geographical distribution and track type. Their relation is linked by the East Asian monsoon trough. During the warm years, the westward-retreating monsoon trough creates convergence and vorticity fields that are favorable for tropical cyclogenesis in the northwest of the WNP, whereas more TCs concentrating in the southeast result from eastward penetration of the monsoon trough during the cold years. The steering flows at 500 hPa lead to a westward displacement track in the warm years and recurving prevailing track in the cold years.

The two types of distinct processes in the monsoon environment triggering tropical cyclogenesis are hypothesized by composites centered for TC genesis location corresponding to two kinds of thermal states of the WP. During the warm years, low-frequency intraseasonal oscillation is active in the west of the WNP such that eastward-propagating westerlies cluster TC genesis in that region. In contrast, during the cold years, the increased cyclogenesis in the southeast of the WNP is mainly associated with tropical depression type disturbances transiting from equatorially trapped mixed Rossby gravity waves. Both of the processes may be fundamental mechanisms for the inherent interannual variation in TC activity over the WNP.

**Key words**: monsoon, warm pool, interannual variation, tropical cyclone

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## 1. Introduction

East Asia summer monsoon systems not only impact the climate in the East Asian continent such as drought and flood, but also modulate tropical cyclone (TC) activity through circulation evolution. It is especially noteworthy that the presence of the monsoon trough over the western North Pacific (WNP) contributes to dynamic conditions that are favorable for TC activity. From a climatological perspective, the monsoon trough axis, which is typically located 5°–10° latitude poleward of the equator, is defined by low-tropospheric equatorial westerly or southwesterly winds and subtropical easterly trade winds. This low-level cyclonic circulation provides the favorable condition for TC formation. In addition, the vertical wind shear approaches zero in the region of the monsoon trough, which favors the maintenance of TC warm core structure and TC development. Wang et al. (2006) pointed out the close relationship between TC activity and monsoon trough intensity. From climatology of tropical cyclogenesis over the WNP, McBride (1995) found more than 75% of classifiable TC genesis occurred in the monsoon trough environment.

The western Pacific warm pool (WP) is known as a key air-sea coupled region with respect to global climate variability. The thermal states in the WP can greatly affect the interannual variations of the East Asian summer monsoon, such as convection activity and precipitation distribution (Nitta, 1987; Huang and Sun, 1992). The changes in position and intensity of the large-scale Hadley-Walker cells over the WNP are often significantly modified by tropical sea surface temperature (SST). In addition, the East Asian monsoon circulations coupled with the ocean in the WNP can have an impact on El Niño-Southern Oscillation

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(ENSO) cycle (Huang et al., 2004). It is shown that low-level westerly anomalies during the warm state in the WP region would trigger the warm Kelvin wave in the ocean to propagate eastwards, and eventually accelerate El Niño event development. The easterly anomalies corresponding to the cold state in the WP lead to the reverse influence. The easterly-westerly anomalies determine monsoon trough location and intensity to a large degree, and have significant impact on temporal and spatial variation in TC activity.

Regarding the interannual variation in TC activity, previous studies draw more attention to the relationship between ENSO and TC activity (Chan, 2000; Chia and Ropelewski, 2002; Wang and Chan, 2002). Due to the definition of ENSO events and analysis techniques as well as data homogeneity in TC datasets, there still exist some controversies in the impacts of ENSO events on interannual variation in TC activity over the WNP. Some researchers (Chan, 1985; Wu and Lau, 1992) accept the viewpoint that El Niño events are closely related to a decrease in the annual total of TC over the WNP. Some research results (Lander, 1993, 1994) hold the opposite point that El Niño events are not very closely related to most statistics of storm frequency. Apart from ENSO-induced impacts, little is known of what role the thermal states in the WP play in dominating monsoon circulation as well as TC activity. Actually, the phases of ENSO events usually peak in the winter season while the active signal in the subsurface of the WP leads by 3–5 months. In other words, the East-Asian summer monsoon coupled with the WP have established and persisted in the TC peak season from July to October. Therefore, it may be more reasonable to watch the monsoon circulation corresponding to the thermal states of the WP in terms of the interannual variation in TC activity over the WNP. This paper mainly focuses on how the changes in monsoon background circulation influence the interannual variation in TC activity during the different state years of the WP and also which aspects of TC activity are significantly modulated by monsoon circulation.

In addition, it should be noted that few research projects investigate what mechanisms determine interannual variability in tropical cyclogenesis corresponding to warm and cold thermal states in the WP. For case studies, some attempts are exerted to understand dominant processes triggering cyclogenesis in certain favorable conditions. Not only dynamical instability in the inner monsoon trough, but also initial disturbance originating out of the monsoon region can trigger cyclogenesis (Takayabu and Nitta, 1993; Liebmann et al., 1994; Dickinson and Molinari, 2002). Since those triggering processes also take on the interannual variation, it is hypothesized that there may be primary processes, which are different year by year, that govern TC activity from the interannual perspective. Based on thermal states in the WP, this study is devoted to investigating interannual variation in TC activity in the WNP in section 3 following the description for data used in section 2, and large scale background contrasts in section 4. Two dominant processes on distinct timescales determining the interannual variability in TC in section 5 are suggested. Conclusions will be presented in section 6.

## 2. Data

This study employs daily National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis variables with $2.5° \times 2.5°$ latitude-longitude grid from 1959–2003. We used TC data with the same time period which are archived by the Regional Specialized Meteorological Centers-Tokyo Typhoon Center. The data include names, positions, minimum surface pressures, and maximum wind speeds of TC in every 6-h interval. Due to the named tropical cyclones mainly including tropical storms and typhoons (TSTY), We divide TC into two classes depending on their maximum sustained wind speed: tropical storm (TS) (17 m s$^{-1}$ $\leqslant V_{\max} <$ 34 m s$^{-1}$) and typhoon (TY) ($V_{\max} \geqslant$ 34 m s$^{-1}$). The monthly optimum interpolation SST data with a horizontal resolution of $2.5°\times2.5°$ from NECP-NCAR reanalysis are used to investigate interannual changes in SST. Due to strong anomalous signal over the WNP appearing in subsurface thermocline, the subsurface ocean temperature data derived from the Joint Environmental Data Analysis Center are adopted to reflect the thermal state in the WP. Since the TC activity reaches peak during July–October (JASO), only this season period is considered in the following study.

## 3. TC activity related to thermal state in the WP

### 3.1 *TC number and formation distribution in the WP*

Many observations have shown that the SST perturbations generally vary within the interval of 0.5°C whereas the subsurface ocean temperature anomaly exceeds 3°C in the extreme years. Furthermore, the air-sea interaction depends not only on sea surface temperature (SST), but also on the ocean heat content (OHC). The variation of OHC, to a great extent, decides the change in intensity of energy exchange of air-sea interaction. The sea surface just acts as the

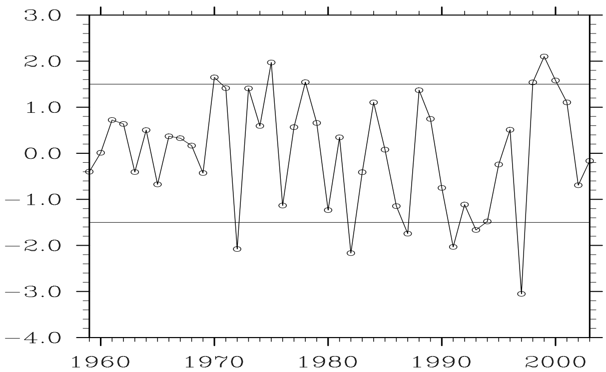


**Fig. 1.** Time series of SOTA in the warm pool during JASO from 1959 to 2003.

interface of energy exchange between them. On the other hand, since subsurface sea temperature is a major impact factor for the OHC over the WNP, subsurface sea temperature anomaly is identified as an index of thermal state of the warm pool. The WP domain is defined by 0°–6°N and 125°–165°E and 120 meters below mean sea level. Warm (cold) state years refer to those in which the sub-ocean temperature anomaly (SOTA) are above 1.5°C (below–1.5°C), as shown in Fig. 1. There are six warm state years (1970, 1975, 1978, 1998, 1999, and 2000) and six cold state years (1972, 1982, 1987, 1991, 1993, and 1997) selected respectively.

For ease of comparison, the Niño-3.4 sea surface temperature anomalies (SSTA), the South Oscillation Index (SOI) and the SOTA in the WP are computed to obtain the correlation coefficients with TSTY (TY) numbers over the WNP during the JASO period from 1959–2003. Table 1 has shown that there is nothing but the correlation coefficient between the SOTA in the WP and TY number over the WNP (including the South China Sea) slightly exceeding the 95% significant level. The results further confirm that these strong interannual signals in atmosphere and ocean do not significantly impact the total number of TCs which attained TS intensity or higher over the WNP basin. The intensities of the monsoon and the tropical upper-tropospheric trough (TUTT) over the WNP may be the dominant factors to determine the TC numbers,

**Table 1.** The correlation coefficients between the Niño-3.4 SSTA, SOI, warm pool SOTA and TSTY, TY numbers over the WNP during the JASO period from 1959 to 2003. Bold numbers denote those above 95% significance level.

| | TSTY | TY |
|---|---|---|
| Niño-3.4 | −0.07 | 0.21 |
| Warm pool | −0.05 | **−0.33** |
| SOI | 0.01 | −0.18 |

**Table 2.** The correlation coefficients between WP SOTA and TSTY, TY in four domains. (Bold numbers denote those above 95% significance level.)

| | Domain 1 | Domain 2 | Domain 3 | Domain 4 |
|---|---|---|---|---|
| TSTY | **0.41** | 0.14 | **−0.73** | 0.24 |
| TY | 0.25 | 0.05 | **−0.76** | 0.21 |

which needs to be investigated in the future.

Although the total number of TC over the WNP is not prominently associated with the SOTA in the WP, the spatial distribution characteristics of cyclogenesis corresponding to the distinct WP thermal states give rise to the intriguing results, providing the WNP is partitioned into four domains along the lines of 15°N and 150°E. The northwestern, southwestern, southeastern, northeastern quadrants are assigned by names d1, d2, d3, d4, respectively. The correlation coefficients between the SOTA in the WP and TSTY number in d1 and d3 regions exceed 95% significance level, even up to 99% significance level in the d3 region (Table 2). In comparison with TSTY, it is only the d3 region that the correlation coefficient with TY reaches up to 99% significant level, which suggests that TCs forming in the southeastern part of the WNP is favorable to develop into typhoons before encountering the continent or colder mid-latitude water. The results mentioned above suggest that WP thermal states may influence less on TC total number in the whole WNP, but more on TSTY or TY in d1 and d3 regions. Figure 2 shows the annual mean TSTY and TY number in the four domains for six warm years and six cold years. It is prominent that the number of TSTY and TY in the d1 region during the warm years is more than that during the cold years, while the situation reverses in the d3 region. The results also show that TCs forming farther to southeast over the WNP tend to last longer and are more likely to develop into typhoons.

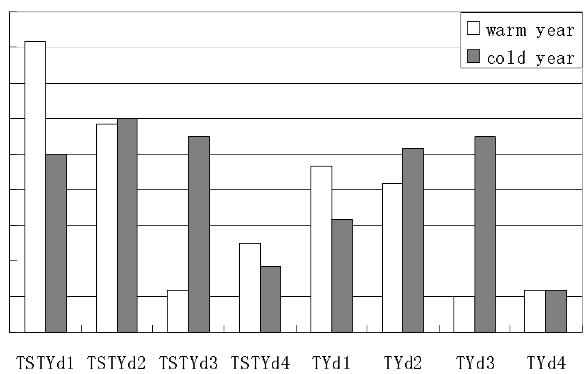


**Fig. 2.** The contrast of annual average of TSTY, TY within four domains during the warm and cold years.

### 3.2 *TC track difference*

To examine TC track difference, the WNP is separated into $5° \times 5°$ square grids. Based upon TC best track positions in every 6 hours interval, a grid point is considered to suffer one TC process once TC falls within its $\pm 2.5°$(lon) and $\pm 2.5°$(lat) domain. It is counted one time if the TC falls within the same grid box in two successive times. The climatology of TC tracks is obtained by counting the number of TCs influencing each grid point during the JASO period within the domain 0°–50°N and 100°–180°E. The number of TCs occurring in each grid box is contributed by the genesis of TCs within the box and by TCs moving into the box.

According to the above method, if the JASO mean number in each grid box in the cold years is subtracted from that in the warm years, spatial distribution difference of TC activity can be obtained (Fig. 3). The difference in annual mean TC activity indicates that TC activity is enhanced near the China coast and hence more TCs make landfall in China during the warm years. On the contrary, more TCs form and move in the eastern portion of WNP during the cold years. The difference in TC activity also infers the changes in TC prevailing tracks. A distinct characteristic appears to show that TCs in the cold years tend to take a recurving northeastward track, leading to more TCs impacting Japan. The circulation modulating the TC track type also can be interpreted by the 500 hPa steering flow as in the next section.

### 3.3 *Two typical cases*

In this subsection, in order to verify the above conclusions, we supplement two typical years, out of the sample years from 1959–2003, in which TC activity

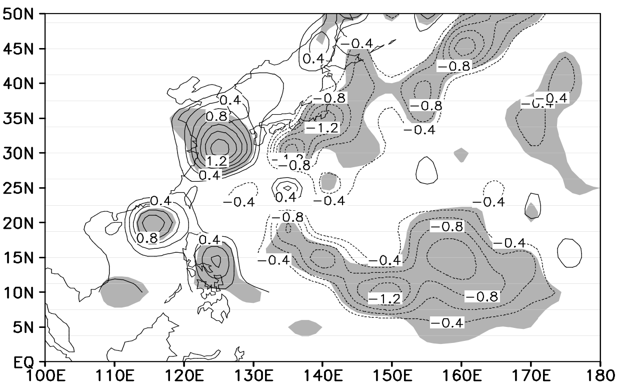


**Fig. 3.** Annual mean difference of TSTY tracks between the warm yeas and the cold years. The shaded areas denote the differences are statistically significant at the 90% confidence level.

well reflects the differences in characteristics corresponding to the cold and warm states in the WP. The cases in the years 2004 and 2006 are selected, since TC formation and track are apparently distinct in the two years. Though these two years are beyond the range of time analyzed above, seperate sea temperature data sources provided by Japan are added as a reference for the thermal state in the WP.

The formation and track of TCs in TC peak season from May to November during the two years are depicted in Fig. 4. It clearly appears that the total of 23 TCs in 2004 formed in the WNP basin, half of which occurred to the east of 150°E. In contrast, less than one third of TCs formed to the east of 150°E in year 2006 than the counterpart in 2004. The other difference in TC activity appears in TC track tendency. Most of the TC tracks in 2004 exhibit northwest-northeastwards recurvature so that the striking record in 10 typhoons landing Japan is documented, while westwards or northwards displacement of TCs is relatively dominant in 2006, therefore China suffered more TC influence.

The two distinct characteristics of TC activity are well related to the thermal states in the WP. The depth-latitude section of subsurface temperature anomaly along 137°E is shown in Fig. 5 provided by Japan Meteorological Agency monthly reports (2004, 2006). The minimum temperature in year 2004 is located at the WP subsurface in tropical region. The anomaly magnitude reaches up to −7°C. Compared with the counterpart in 2004, the subsurface temperature along 137°E cross section in 2006 is above the climatological reference state equatorward of 14°N, its anomaly peaking at 3°C. The typical cases as discussed in this subsection are consistent with those in former analysis. The low-mid level circulation features in the two years (not shown) are similar to those depicted in subsection 4.2, which determine differences in TC activity. These supplemental evidences aim for the confirmation that significant distinctions in TC activity appear during two kinds of years. The underlying factors controlling interannual variation in TC activity will be explained in the next section.

## 4. Large scale background influence

### 4.1 *SST*

In the first global climatology of tropical cyclogenesis, Gray (1968) established several environmental conditions as favorable for the formation and development of TCs. Among them, SST criterion above 26.5°C is required to be met, which is the critical condition for cyclogenesis. It is well known that the WP region usually accumulates a large amount of warm water such

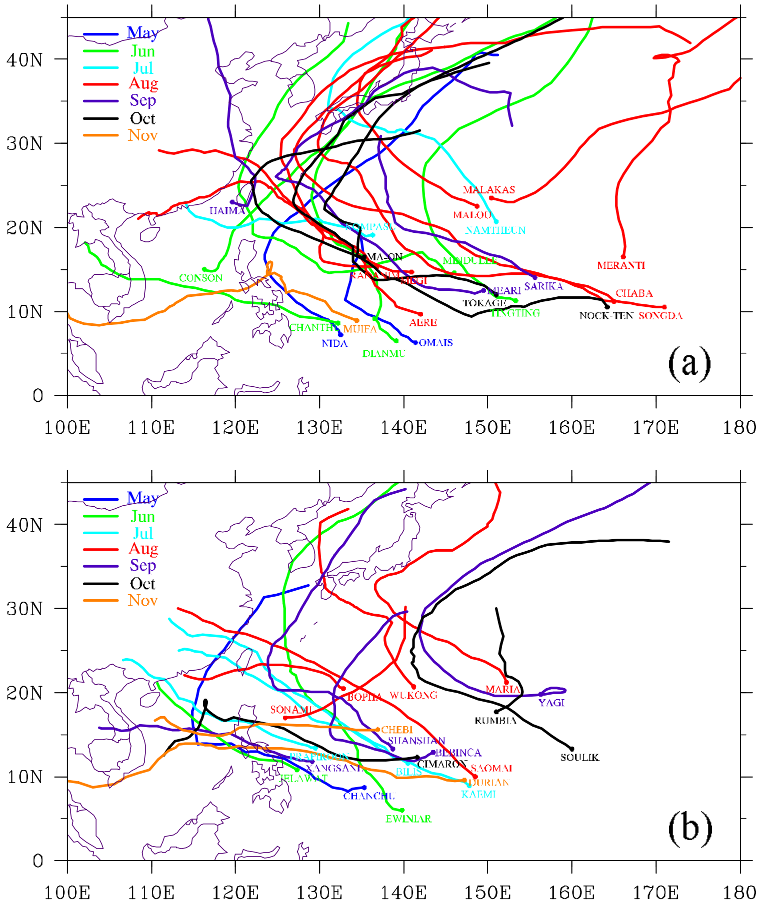


**Fig. 4.** The genesis locations and tracks of TC in (a) 2004 and (b) 2006. The dots represent TC formation loacation the dots represent TC formation location.

that the climatic SST exceeds 29°C over the WNP. By examining the composites of SST in the warm and the cold years (not shown), it appears that the prominent differences in SST distribution are not located in the WNP, but in the equatorial middle Pacific. In contrast to climatological SST for 45 years, the area of the 29°C SST contour in the cold years extends into the equatorial east Pacific, whereas it retreat slightly westwards in the warm years. As shown in Fig. 6, the positive correlation between TSTY number and SST during JASO over the North Pacific is located in the subtropical middle Pacific, while the negative correlation exists in the large part of the WNP, suggesting that there is not significant relation between TC number and local underlying SST. The other two thermodynamic factors including midlevel moisture and moist instability of the midlevel-low atmosphere over a considerable portion of the tropical ocean are almost beneficial to cyclogenesis in summertime, while the low level vorticity and vertical shear parameters can vary significantly on interannual timescale. Therefore, rather than thermodynamic factors such as local SST, the dynamic factors such as monsoon circulation in response to the thermal state in the WP determine the interannual variability in TC activity.

### 4.2 *Atmospheric circulation feature*

The monsoon trough is the region of low-level convergence between the equatorial westerlies and the trade easterlies. The presence of relatively low vertical wind shear and high relative vorticity in the monsoon trough could be extremely favorable for tropical cyclogenesis. The cyclogenesis is a process in which external background forcing is thought to be required to produce convection by perturbing the dynamic variable over a relatively large area sufficiently above their climatological values. Therefore, the purpose in following analysis is to identify the distinct circulation feature in response to the thermal state in the WP. Variable fields that relate to anomalous TC activity at 850 hPa and 200 hPa during JASO are discussed. When studying the movement of the TC, the 500 hPa steering flow is analyzed.

The 850 hPa streamline is composited for the warm

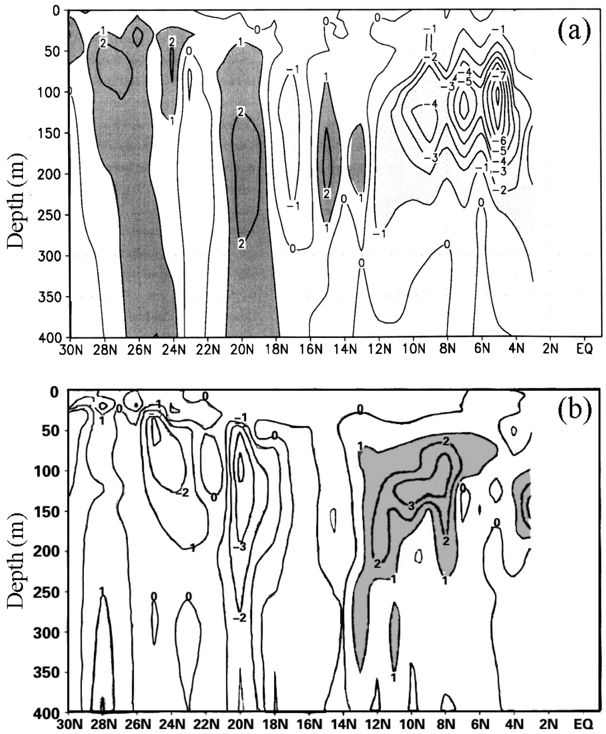


**Fig. 5.** Depth-latitude section of subsurface temperature anomaly along 137°E during July in (a) 2004 and (b) 2006. The areas with positive value are shaded. (Adapted from Japan Meteorological Agency monthly reports, 2004, 2006).

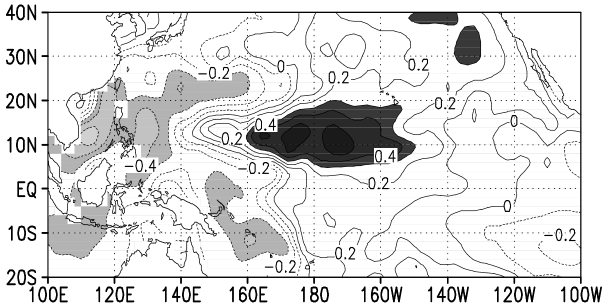


**Fig. 6.** The distribution of correlation coefficients between SST and TSTY number over the WNP. The shaded areas indicate the correlations are statistically significant at the 95% confidence level.

years and cold years respectively. During the warm years, the monsoon trough retreats westward and northward (Fig. 7a), so that a low-level cyclonic vorticity anomaly and upper-level divergence anomaly exist in the northwest quadrant (not shown) and hence more TCs tend to form in the northwest of WNP. On the contrary, there are fewer TCs in the southeast quadrant of WNP.

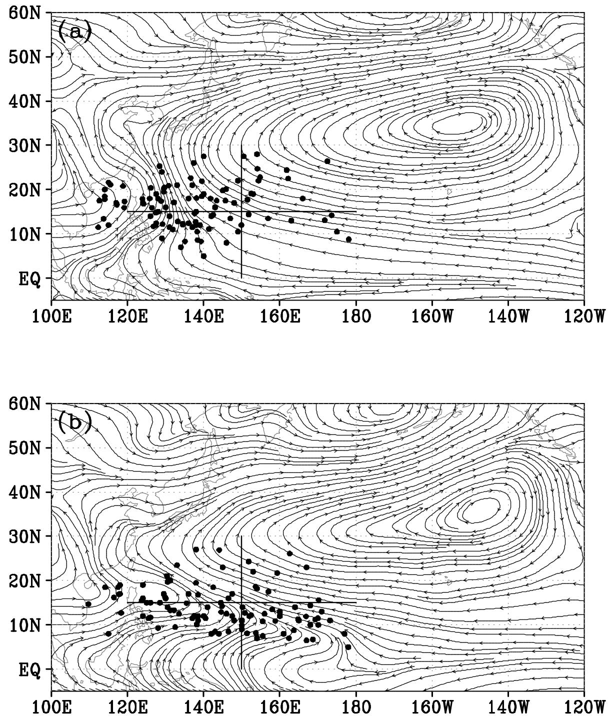


**Fig. 7.** 850-hpa composited stream field and TC genesis location (denoted by black dots). (a) during the warm years; (b) during the cold years. Dots represent tropical genesis locations. 150°E and 15°N are denoted by black lines.

During the cold years, westerly anomalies in the western equatorial Pacific extend to the dateline and even beyond (Fig. 7b). These anomalies, encountered with easterly trade winds, enhance the cyclonic shear so that the monsoon trough is located at lower latitudes and penetrates further eastward, which results in more TCs forming in the southeast quadrant of the WNP. The condition in the northwest quadrant is reversed. A low-level anticyclonic vorticity anomaly and up-level convergence anomaly are unfavorable for TC formation and development in that region.

In general, the TC tracks are attributed to the flow in the mid-level troposphere which plays a role in steering TC movement. Thus, the changes in TC tracks can be explained by the anomalous flow at 500 hPa during two kinds of years. According to the study by Huang and Sun (1994), when the western tropical Pacific warm pool is warming, the convective activities are active from the area around the Philippines to the Indo-China Peninsula. The subsidence branch of the Hadley cell associated with tropical convection is enhanced and shifts northwards. As a result, the subtropical high over the WNP intensifies and moves poleward. Therefore, anomalous easterlies prevail over a large area of the WNP shown in Fig. 8a, especially

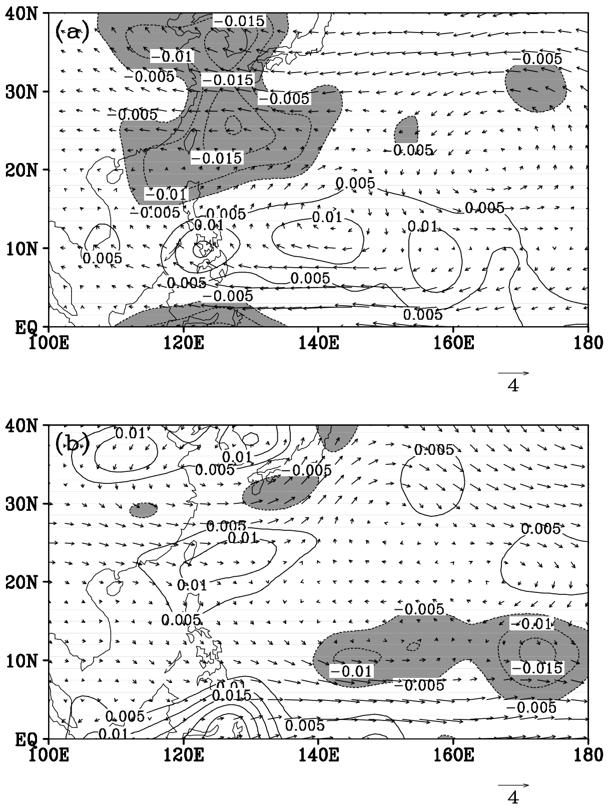


**Fig. 8.** 500-hPa composited wind vector (units: m $s^{-1}$) and vertical velocity (units: Pa $s^{-1}$). (a) during the warm years; (b) during the cold years. (The shading indicates anomalous ascent areas)

the region to the east of the China, which would tend to steer more TC to move westward into South China Sea (SCS) and the east China coast. On the contrary, when the warm pool is cooling and the convection above is inactive, the subtropical high shifts equatorward and the trough over East Asia to the northwest of it strengthens. Figure 8b shows that a large area of steady and significant anomalous westerlies at 500 hPa can be detectable in the tropics and to the south of Japan, and anomalous southwesterly flow, as a part of the anomalous cyclonic trough over the East Asia, is present over Japan. This flow pattern can explain a significant increase in the northeastward-recurving TC, which leads to more TCs impacting Japan.

Figure 8 displays the location migration of the vertical ascending branch for the warm and cold years. During the warm years, the organized anomalous ascending motion concentrates in the northwest quadrant of the WNP, whereas anomalous descending motion is found in the southeast quadrant. The opposite condition occurs during the cold years. The differences are consistent with the distribution of divergence and vorticity anomalies, which is significantly correlated with the monsoon trough retreat and extension. The anomalous rising motion in the Walker circulation, coupled with the warming state in the WP, establishes relatively westward in longitude. As the thermal state in the WP alters from warming to cooling, the warm water shifts eastwards up to the dateline, which is accompanied by an eastward extension of the monsoon trough and anomalous ascent.

## 5. Discussion on different triggering mechanisms for cyclogenesis

The above-mentioned results indicate that there appear two main distinct circulation features during the two types of years which modify the number and distribution of TCs in the four domains. For brevity, more tropical cyclogenesis concentrate in domain 1 and 2 during the warm years, whereas the more TCs form in domain 2 and 3 (shown in Fig. 5). The questions remain unknown whether the TC genesis associated with thermal states in the WP are triggered by different low-level initial disturbances originating from relevant regions, and furthermore whether these initial disturbances rely on atmosphere variability with different temporal scales. To answer these questions, we first exhibit the two distinct processes of TC genesis by composites corresponding to thermal states in the WP.

The genesis locations of TC within domain 1 or 2 during the warm years and those within domain 2 or 3 during the cold years were respectively selected as the domain center for composites, i.e. composite region is not fixed and is determined by the TC genesis location. The 850 hPa wind fields were composited within a $8000\times4000$ $km^2$ domain placed over the nearest grid point to the center of each TC at the time of genesis. Composites were computed for every 24-h time period back to 5 days before tropical cyclogenesis. This composite technique reduces the random and sampling errors inherent to an objective analysis and also resolves common features among the individual cases of tropical cyclogenesis. Therefore, if a composite reveals evidence of a relationship between genesis and environmental flow, the circulation feature observed is likely to be even stronger in individual cases.

During the warm years, the composite for 120 hours prior to tropical cyclogenesis shows a weak monsoonal cyclonic flow anchored about 1000 km to the west of the TC genesis location (Fig. 9a). Meanwhile the westerly flow greater than 5 m $s^{-1}$ is approximately 3000 km farther to the southwest of center. The strong trade easterlies prevail over the large portion to the east of the genesis center. Such patterns indicate the center lies in the confluence region of zonal

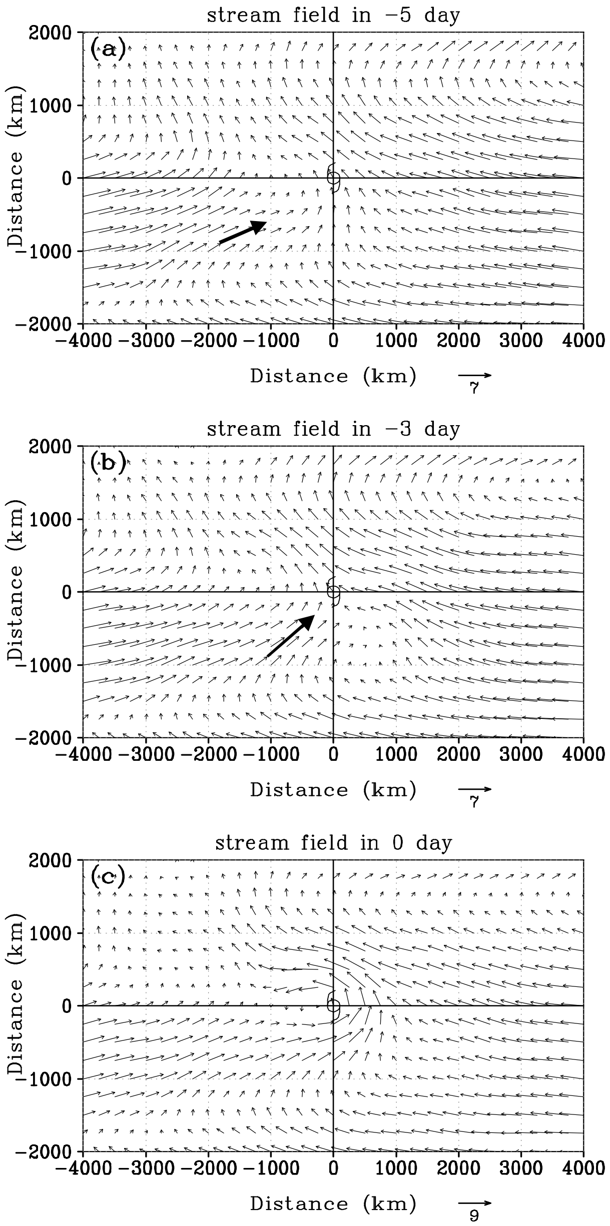


**Fig. 9.** Composites of the 850-hPa winds for TC within domain 1 and 2 during the warm years at (a) −120 h, (b) −72 h, (c) time of tropical cyclogenesis.

flow 5 days prior to cyclogenesis. The southwesterly flow gradually extends eastwards and strengthens with time, accompanied by cyclonic circulation approaching the genesis center at the time of 72 hours before genesis (Fig. 9b). By genesis time, the trade southwesterly flow to the south of the center has penetrated up to the southeast part and merged into the cyclonic wind surrounding the genesis location (Fig. 9c). To further reveal this process, the zonal wind in the latitude-band between 250 km and 1000 km to the south of the center is averaged for a time-latitude (represented by kilometers) Hovmöller diagram relative to genesis center. Figure 10 depicts the same process in which zonal flow extends eastwards as the plane plots in Fig. 9 for time evolution, and eastward-spread speed is comparable to the magnitude of low-frequency westerly flow. Modulation of TC activity by the low-frequency oscillation, especially the Madden-Julian oscillation (MJO), has been extensively examined (e.g., Hall et al., 2001; Maloney and Hartmann, 2000, 2001). They found that westerly 850-hPa wind anomalies associated with MJO event intensify tropical convection and enhance TC activity. Over twice as many tropical systems accompany equatorial 850-hPa westerly anomalies than accompany equatorial easterly anomalies. The study by Ren and Huang (2003) suggested that the characteristics of MJO are associated with the interannual variability of the thermal state in the WP. The composite results showed that the amplitude of MJO convection over the west of WNP tends to intensify (reduce) during the warm (cold) years. According to the previous studies, we imply that the correlation between enhanced TC activity and warm state in the WP is ascribed to the intensification of westerly flow and convection associated with MJO.

The composite changes in the feature during the cold years are evidence that the westerlies to the south have existed in the southeast quadrant relative to the genesis location by the time 72 hours prior to the genesis. The weak cyclonic circulation is positioned approximately 2000 km to the southeast of the center, and then displaces northwest towards the genesis center as vortex flow develops at 72 hours before genesis (Figs. 11a, b). At the time of tropical cyclogenesis, the cyclonic circulation shapes elliptically encircling the genesis location (Fig. 11c). In contrast to the zonal wind Hovmöller diagram during the warm years (shown

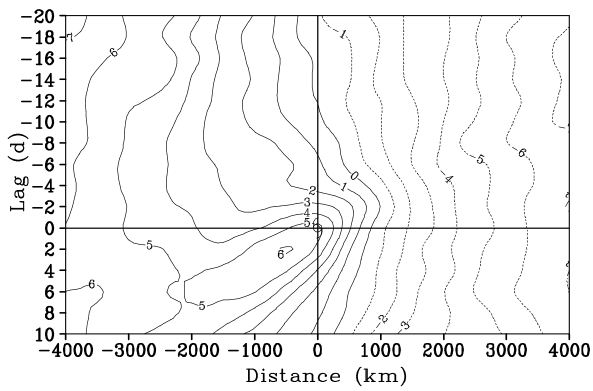


**Fig. 10.** Time-longitude (represented by distance in east-west direction) diagram of the zonal 850-hPa wind averaged from 250 km to 1000 km to the south of composited TC genesis location. TCs form within domain 1 and 2 during the warm years.

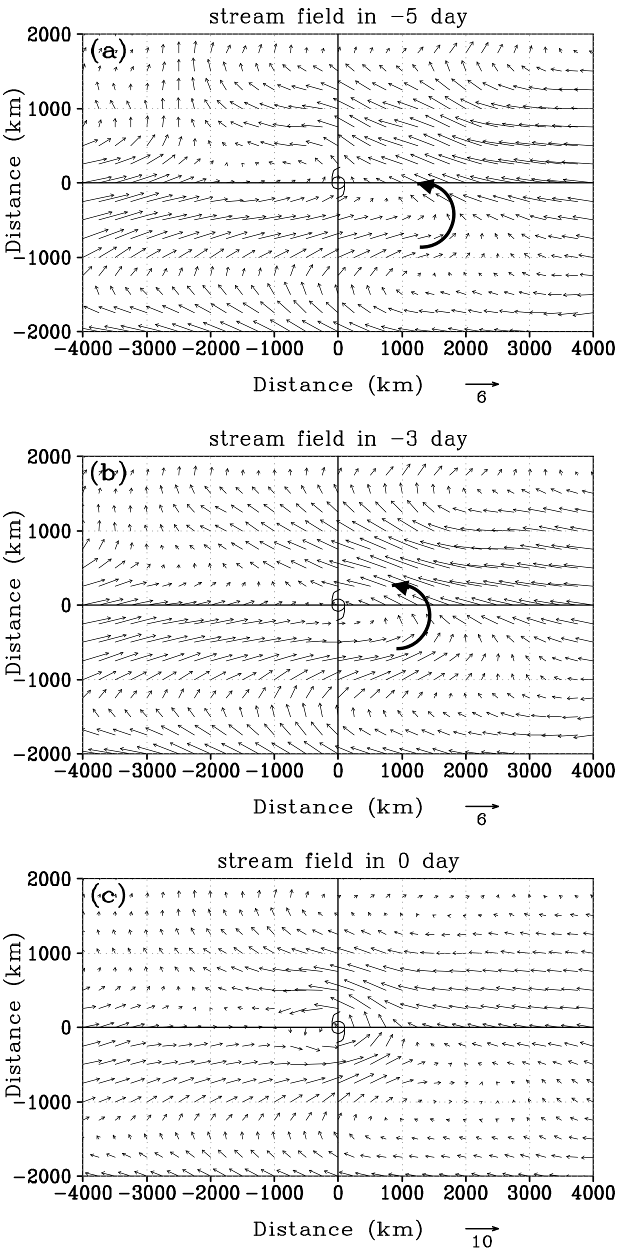


**Fig. 11.** Same as in Fig. 9 but for TC cases within domain 2 and 3 during the cold years.

in Fig. 10), the counterpart during the cold years does not exhibit the similar characteristic of eastward-displacement, and even presents slight westward-displacement (no shown). Based on the previous studies (Takayabu and Nitta, 1993; Chang et al., 1996; Dickinson and Molinari, 2002), equatorially-trapped mixed Rossby gravity (MRG) waves on synoptic scale could transform into off-equatorial tropical depression type disturbances in the WNP (so called TD-type disturbances). They found that TD-type disturbances are displaced northwestwards and intensify through interaction with monsoon trough, which tend to induce TC genesis. Since the monsoon trough penetrates southeastward and near the equator during the cold years compared with during the warm years, it is easy for monsoon flow to interact with equatorially-trapped waves and induce the change in wave property. This may be the major process triggering TC genesis in the domain 3 during the cold years.

The dynamic composites with respect to the designated TC corresponding to the warm and cold years might be the manifestation of two distinct processes in which the propagating oscillations or disturbances trigger cyclogenesis. It is hypothesized that the interannual variation of TC activity is, to a large extent, related to variability of the above two processes. It should be noted that we do not claim that the processes mentioned above can explain all aspects of TC formation over the WNP. It makes certain that the probability of TC genesis should increase in the presence of these two mechanisms.

## 6. Conclusion

This paper presents a comprehensive study on the interannual variations of TC activity over the WNP associated with the subsurface thermal state in the WP. Investigations are made on TC number, formation distribution and track type.

The monsoon circulations coupled with the WP play a role in modulating TC activity. During the warm state of the WP in summertime, the monsoon trough retreats westwards, leading to westward shift of the TC active region. The corresponding monsoon circulation is characterized by the anomalous convergence, vorticity, and ascent occurring in the northwest of the WNP. In contrast, during the cold state of the WP, the monsoon trough extends eastwards up to the dateline, hence the anomalous convections concentrate on the southeast part of the WNP in conjunction with eastward displacement of TC activity.

The steering flows at 500 hPa exhibit the pronounced differences during two thermal states in the WP, which are regarded as important factors in modulating the TC track type. The easterly anomalies in the warm state years steer more TC displacement westwards which may result in the frequent landfall in east China. The middle-latitude East Asian trough in the cold state years strengthens and penetrates southwards so that the southwesterly flows ahead of the trough easily recurve the TC motion towards northeast.

The composites centered in the cyclogenesis location are constructed to investigate two types of TC genesis respectively during the warm and cold years.

The circulation patterns in the several days leading up to cyclogenesis infer that the processes, in which westerlies associated with low-frequency oscillation surge eastwards and intensify, induce TC formation to a large extent during the warm years. However, during the cold years, it seems that initial disturbances for a large amount of cyclogenesis originate from the tropical mid-eastern Pacific. It is argued that interannual variation in above-mentioned triggering processes significantly impact the variability in TC activity over the WNP, which will be analyzed in detail in the future work.

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## REFERENCES

Chan, J. C.-L., 1985: Tropical cyclone activity in the northwest Pacific in relation to the El Niño/Southern Oscillation phenomenon. *Mon. Wea. Rev.*, **113**, 599–606.

Chan, J. C.-L., 2000: Tropical cyclone activity over the western North Pacific associated with El Niño and La Niña events. *J. Climate*, **13**, 2960–2972.

Chang, C.-P., J. M. Chen, P. A. Harr, and L. E. Carr, 1996: Northwestward propagating wave patterns over the tropical western North Pacific during summer. *Mon. Wea. Rev.*, **124**, 2245–2266.

Chia, H.-H., and C. F. Ropelewski, 2002: The interannual variability in the genesis location of tropical cyclones in the northwest Pacific. *J. Climate*, **15**, 2934–2944.

Dickinson, M., and J. Molinari, 2002: Mixed Rossby-gravity waves and western Pacific tropical cyclogenesis. Part I: Synoptic evolution. *J. Atmos. Sci.*, **59**, 2183–2196.

Gray, W. M., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.*, **96**, 669–700.

Hall, J. D., A. J. Matthews, and D. J. Karoly, 2001: The modulation of tropical cyclone activity in the Australian region by the Madden-Julian Oscillation. *Mon. Wea. Rev.*, **129**, 2970–2982.

Huang, R. H., and F. Y. Sun, 1992: Impact of the tropical western pacific on the East Asian summer monsoon. *J. Meteor. Soc. Japan*, **70**, 243–256.

Huang, R. H., and F. Y. Sun, 1994: Impacts of the thermal state and the convective activities in the tropical western Warm Pool on the summer climate anomalies in East Asia. *Chinese J. Atmos. Sci.*, **18**, 141–151. (in Chinese)

Huang, R. H., W. Chen, B. L. Yang, and R. H. Zhang, 2004: Recent advances in studies of the interaction between the East Asian winter and summer monsoons and ENSO cycle. *Adv. Atmos. Sci.*, **21**, 407–424.

Japan Meteorological Agency, 2004: Monthly Report on Climate System. Tokyo Climate Center, 32pp.

Japan Meteorological Agency, 2006: Monthly Report on Climate System. Tokyo Climate Center, 24pp.

Lander, M. A., 1993: Comments on "A GCM simulation of the relationship between tropical cyclone formation and ENSO." *Mon. Wea. Rev.*, **121**, 2137–2143.

Lander, M. A., 1994: An exploratory analysis of the relationship between tropical storm formation in the western North Pacific and ENSO. *Mon. Wea. Rev.*, **122**, 636–651.

Liebmann, B., H. Hendon, and J. D. Glick, 1994: The relationship between tropical cyclones of the western Pacific and Indian Oceans and the Madden-Julian oscillation. *J. Meteor. Soc. Japan*, **72**, 401–411.

McBride, J. L., 1995: Tropical cyclone formation. Chapter 3, *Global Perspectives on Tropical Cyclones*, R. L. Elsberry, Ed., WMO/TD-No. 693, World Meteorological Organization, Geneva, 63–105.

Maloney, E. D., and D. L. Hartmann, 2000: Modulation of eastern North Pacific hurricanes by the Madden-Julian oscillation. *J. Climate*, **13**, 1451–1460.

Maloney, E. D., and D. L. Hartmann, 2001: The Madden-Julian oscillation, Barotropic dynamics, and North Pacific tropical cyclone formation. Part I: Observations. *J. Atmos. Sci.*, **58**, 2545–2558.

Nitta, T., 1987: Convective activities in the tropical western Pacific and their impact on the Northern Hemisphere summer circulation. *J. Meteor. Soc. Japan*, **64**. 373–390.

Ren, B. H, and R. H. Huang, 2003: 30–60-day oscillations of convection and circulation associated with the thermal state of the western Pacific warm pool during boreal summer. *Adv. Atmo. Sci.*, **20**, 781–793.

Takayabu, Y. N., and T. Nitta, 1993: 3–5 day period disturbances coupled with convection over the tropical Pacific Ocean. *J. Meteor. Soc. Japan*, **71**, 221–245.

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

Wang, H., Y. H. Ding, and J. H. He, 2006: Influence of western North Pacific summer monsoon changes on typhoon geneis. *Acta Meteorologica Sinica*, **64**, 345–356. (in Chinese)

Wu, G., and N.-C. Lau, 1992: A GCM simulation of the relationship between tropical-storm formation and ENSO. *Mon. Wea. Rev.*, **120**, 958–977.