Modulation of North Pacific Tropical Cyclone Activity by the Three Phases of ENSO

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July 2010
Submitted to J. of Climate

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Abstract

Pacific Ocean warming has been separated into two modes based on the spatial distribution of the maximum sea surface temperature (SST) anomaly: an East Pacific Warming (EPW) and a central Pacific Warming (CPW). When combined with East Pacific Cooling (EPC), these three regimes are shown to have different impacts on tropical cyclone activity over the North Pacific by differential modulation of both local thermodynamic factors and large-scale circulation patterns. In EPW years, the genesis and the track density of TCs tend to enhanced over the southeastern part in the western Pacific and suppressed in the northwestern part of the western Pacific by the strong westerly wind, the extension of the monsoon trough and the weak wind shear over the central Pacific all of which increase the likelihood of TC activity to the east of the climatologically mean TC genesis location. In CPW years, the TC activity is shifted to the west and is extended through the northwestern part of the western Pacific. The westward shifting of CPW-induced heating moves the anomalous westerly wind and monsoon trough through the northwestern part of the western Pacific and provides a more favorable condition for the TC landfall. The CPW, on the other hand, produces a large suppression of TC activity in the eastern Pacific basin area over the eastern Pacific basin. In EPC years, all the variables show an almost mirror image of the EPW.
1. Introduction

The influence of El Nino-Southern Oscillation (ENSO) on the tropical cyclone (TC) activity in the Pacific basin has been examined by many studies. Over the western North Pacific, the phase of ENSO affects significantly the genesis, tracks, duration and intensity of TCs (Chan 2000; Wang and Chan 2002; Camargo and Sobel 2005; Ho et al. 2005; Chen et al. 2006; Camargo et al. 2007b). In the warm phase of ENSO, the genesis frequency increases over the southeastern part of the western North Pacific and decreases over the northwestern part. The La Nina phase induces a reversed situation. The difference in the location of genesis in the different phases of El Nino-Southern Oscillation (ENSO) has been explained in terms of large-scale ocean-atmosphere interaction associated with regional changes in sea surface temperature (SST), a reduced vertical wind shear, the eastward extension of the monsoon trough and an increase of relative vorticity anomalies induced by stronger westerlies in the lower troposphere (Chen et al. 1998; Chan 2000; Chia and Ropelewski 2002; Wang and Chan 2002; Wu et al. 2004; Kim et al. 2005; Camargo et al. 2007b).

In addition to TC genesis, the lifetime and intensity of TCs have also been shown to be associated with the phase of ENSO. In the strong El Nino years, TCs tend to last longer and become generally more intense due to their formation nearer the equator than normal years, thus allowing a longer period in the warmest SST environment (Wang and Chan 2002; Camargo and Sobel 2005). TCs that formed farther east during El Nino are more likely to recurve toward higher latitudes before landfall and track to the east of China. In contrast, during La Nina, TCs tend to extend more westward, increasing the probability of landfall over China (Elsner and Liu 2003; Camargo et al. 2007b).

Because of these clearly defined impacts of the phase of ENSO on TC activity in the western Pacific, it is considered to be a strong predictor for TC forecasts (Chan et al. 1998; Chan et al. 2001; Wang and Chan 2002; Liu and Chan 2003). For example, for the summer TC forecast, the City University of Hong Kong uses the information of ENSO, the Nino 3.4 index and the equatorial Southern Oscillation Index in their prediction of typhoon numbers (Liu and Chan 2003). Tropical Storm Risk (http://www.tropicalstormrisk.com) uses the Nino 3.75 index to include ENSO information in their seasonal forecasts (Lea and Saunders 2006). The Nino indices are shown in Figure 1a.

ENSO influences TC activity in the eastern North Pacific as well as the western North Pacific. Recent studies, examining the relationship between ENSO and TC activity in the eastern North Pacific, have found both an increased number of intense hurricanes and westward shift in the genesis location and track density during the warm ENSO phase (Gray and Sheaffer 1991; Irwin and Davis 1999; Chu 2004; Camargo et al. 2008). The westward shift of the genesis region tends to allow TCs to propagate farther westward into the central Pacific (Chu 2004). Also, a decrease in vertical shear over the central Pacific during El Nino years produces favorable conditions for TC propagation into the central Pacific (Chu 2004; Camargo et al. 2007a). Based on these relationships, NOAA issues the seasonal hurricane outlook for the ENP basin by using the combined effects of climate factors including ENSO (http://www.cpc.noaa.gov/products/outlooks/hurricane-
In summary, the ENSO is one of the most important factors affecting the TC activity in the western and eastern sectors of North Pacific. However, the generality of the relationship between ENSO and TCs needs to be re-examined. Recent studies have shown that the warm phase of ENSO can be separated into two types based on the spatial distribution of the warm SST anomaly. The East Pacific Warming (EPW, the “traditional” El Nino) event is confined to the east Pacific, on the other hand, a Central Pacific Warming (CPW) is located 60° to 80° further west to the central Pacific with maximum SST anomaly near the dateline. This shifting of the warm SST anomaly appears to induce remote climate anomalies around the globe that are distinctly different to those produced by an EPW (Ashok et al. 2007, 2009; Weng et al. 2007, 2009; Kao and Yu 2009; Kim et al. 2009; Kug et al. 2009; Yeh et al. 2009). Furthermore, Kim et al. (2009) have found the two forms of tropical Pacific Ocean warming have substantially different impacts on the frequency and tracks of North Atlantic tropical cyclones.

A natural extension of the Kim et al. (2009) study is an investigation of the impact of two types of Pacific warming on North Pacific TC activity. This study is prompted by noting that CPW events have increased during the last few decades while EPW events have declined (Kim et al. 2009; Kug et al. 2009; Yeh et al. 2009). Furthermore, previous studies haven’t separated ENSO type to examine the relationship to TCs. Moreover, the use of the Nino 3.4 index does not allow discrimination between CPWs and EPWs (Kim et al. 2009). Recently, Chen and Tam (2010) found that the western North Pacific TC frequency is markedly different between the two forms of Pacific warming events, specifically the TC frequency. Here, we extend the study of Chen and Tam (2010) to include the entire North Pacific. Following Kim et al. (2009), we will also examine the change of genesis frequency and track densities during an EPW and a CPW and also consider the La Nina (eastern Pacific cooling: EPC) events, which are not examined in Chen and Tam (2010).

2. Data and method

TC activity is analyzed using the data from National Hurricane Center Hurricane Best Track Files (HURDAT, http://www.nhc.noaa.gov/pastall.shtml#hurdat) for the eastern Pacific and the Regional Specialized Meteorological Centre (RSMC) Tokyo–Typhoon Center for the western North Pacific (http://www.jma.go.jp/jma/jma-eng/jma-center/rsme-hp-pub-eg/trackarchives.html). Here we define a TC as having a maximum surface wind > 17m s⁻¹. The analysis is focused on the northern hemisphere active TC season from July to October (JASO). Atmospheric data are from the National Centers for Environmental Prediction/Nation Center for Atmospheric Research (NCEP/NCAR) reanalysis data (Kalnay et al. 1996) for the years between 1951 and 2006 which comes with a spatial resolution of 2.5° x 2.5°. The SST data used in this study is the Extended Reconstructed Sea Surface Temperature Version 2 (ERSSTv2, Smith and Reynolds 2004). All the variables, including the TC genesis frequency and track density, have been detrended to avoid the possible statistical influence of long-term trends found in previous
studies (e.g., Emanuel 2005; Ho et al. 2004; Webster et al. 2005; Chan 2008).

The Pacific warming and cooling events are classified using detrended SST anomaly fields averaged between July to October (JASO) following Kim et al. (2009). The SST anomaly is averaged over three regions (Fig. 1a): Niño 3.4 (5°N-5°S, 170°W-120°W), Niño 3 (5°N-5°S, 150°W-90°W) and Niño 4 (5°N-5°S, 160°E-150°W). EPW, CPW and EPC are defined by: Nino 3 warming greater than one standard deviation (SD) for EPW; Nino 3 or Nino 3.4 cooler than one SD for EPC; and Nino 4 warming exceeding one SD for CPW, with Nino 3 staying below this range (Kim et al. 2009). A total of 8 EPW years (1951, 1957, 1965, 1972, 1976, 1982, 1987 and 1997), 5 CPW years (1953, 1991, 1994, 2002 and 2004) and 8 EPC years (1954, 1955, 1964, 1973, 1975, 1988, 1998 and 1999) are thus identified (Fig. 1b). Figure 2 displays the composite SST anomalies during the JASO period for EPW, CPW and EPC events, respectively. The CPW (Fig. 2b) is confined to the central Pacific with a maximum SST anomaly near the dateline while EPW (Fig. 2a) is located in the east Pacific, in a similar location to the EPC maximum negative anomaly (Fig. 2c). Although the magnitude of the CPW SST anomaly is smaller than EPW, the background SST is greater than in the eastern Pacific and there is the potential for the formation of deep convection. For convenience, we refer the northwest WNP as region A (120°E-140°E, 20°N-35°N), southwest WNP as region B (110°E-140°E, EQ-20°N), the equatorial central to eastern Pacific as region C (140°E-180°E, EQ-20°N) and the eastern Pacific as region D (Fig 2a).

3. Tropical cyclone activity

   a. Genesis frequency

   The shifting of the maximum SST forcing changes the large-scale ocean and atmosphere circulation and thus TC characteristics over the entire North Pacific including the location of cyclogenesis and the tracks of TCs. Here, we compare the characteristics of genesis frequency by using the genesis density and the genesis potential index.

   Figure 3 shows the composites of mean genesis density anomalies from the 56-year climatology. Genesis density for a specific type of warming/cooling event is defined as the number of cyclones that formed in each grid box during the JASO period divided by the total number of years during which there was an EPW, a CPW, or an EPC. Then, the genesis density is smoothed by averaging the eight-grid points surrounding the main grid point with 1:8 weighting and the total divided by 2. The anomaly is obtained by removing the 56-year mean for the period 1951 to 2006. The track density is calculated in a similar way to genesis density except by counting the number by cyclones moving into each box. To determine the statistical significance of track density, a bootstrap technique is applied following Kim et al. (2009). For the EPW events, a composite anomaly is constructed with 8 years chosen at random from among the 56 years of data. The process is repeated 10,000 times to obtain a probability distribution at 90 and 95% levels. Light and dark contours in Figures 3-5 show statistical significance at the 90% and 95% level, respectively.
In the EPW case (Fig. 3a), positive genesis density anomalies span central to eastern Pacific (region C), while in the EPC, there is decrease over the broad area in region C. In the EPW summer, the TC formation tends to be enhanced over region C and decreases in region A and region B. These patterns are almost opposite during an EPC summer, when there is an increased risk of southeast China being subject to landfalling TCs. The eastward displacement of genesis in EPW in region C has been well documented in previous studies as noted above, and is generally explained by the generation of large-scale circulations that influence the extension/retreat of the monsoon trough (Chen et al. 1998), the low-level flow (Chan 2000; Wang and Chan 2002) and the vertical wind shear (Chia and Ropelewski 2002). In the CPW case (Fig. 3b), the western and eastern Pacific genesis locations are quite different from EPW. The positive genesis anomaly shifts to the west and extends through region A in a pattern very different from the EPW. The CPW TC formation over the northwestern part of the western Pacific (region A) increases the probabilities of TC propagation into the northern part of East Asia, including both Korea and Japan. The decrease of genesis over the southwestern part of the western Pacific (region B) may also be induced by the local thermodynamic effect caused by the negative SST anomaly (Fig. 2b) and associated subsidence. We will discuss these points in detail later.

During an EPW year, the genesis frequency is increased in the C-D region but decreases in the same region during an EPC year. The increase of TC activity during an EPW compared to an EPC over the eastern Pacific (region D) has been examined in previous studies in terms of environmental parameters affecting TC genesis (Irwin and Davis 1999; Chu 2004; Collins and Mason 2000; Carmargo et al. 2007b). The TC genesis in CPW years differs from EPW in the East Pacific, especially in region D (Fig. 3b) where large cyclogenesis suppression can be found in comparison with an EPW.

Emanuel and Nolan’s (2004) genesis potential (GP) index is analyzed over the North Pacific basin to assess the combination of climate factors for TC genesis. The GP index is a combination of parameters including the absolute vorticity, relative humidity, wind shear and the potential intensity \( PI \) (Emanuel 1988). The \( PI \) is obtained from the sea level pressure, SST, atmospheric temperature and mixing ratio (Bister and Emanuel 2002). The GP index is defined as

\[
GP = \left| 0.5 \eta \right|^{3/2} \left( \frac{H}{50} \right)^{3/2} \left( \frac{PI}{70} \right)^{3/2} \left( 1 + 0.1 \ V_{\text{shear}} \right)^2,
\]

where \( \eta \) is the absolute vorticity at 850 hPa, \( H \) is the relative humidity at 700 hPa and \( V_{\text{shear}} \) is the vertical wind shear magnitude between 850 hPa and 200 hPa. All data are from 1951-2006 NCEP/NCAR reanalysis product. Details of the calculation methods can be found in Emanuel and Nolan (2004) and Camargo et al. (2007a). The GP index has been shown to reproduce the variability of TC activity associated with both the annual cycle and ENSO (Camargo et al. 2007a).

Figure 4 shows the composite of genesis potential anomalies in JASO for EPW, CPW and EPC events, respectively. In an EPW year, TC activity is suppressed in region B and
enhanced in region C (Fig. 4a). An EPC year shows almost a mirror image of the EPW
distribution (Fig. 4c). In a CPW year, the positive GP anomaly appears over the WNP
with an extension to west of the date-line (Fig. 4b). The positive GP anomaly over region
D is contrary to the negative genesis density anomaly (Fig. 3b). The positive GP anomaly
over region D might due to the positive SST anomaly (Fig. 2b), positive relative humidity
in the mid-level, and weak vertical wind shear anomaly (Fig. 9b), which are parameters
used in calculating the GP index. However, the descending motion over region D in CPW
suppresses TC genesis. As ascending/descending motion is not considered specifically in
GP index, the GP anomaly is in contrast to the observed genesis frequency in region D
(Fig. 3b). The contribution of vertical motion on TC activity will be discussed in section
4.

b. Track density

The difference in the cyclogenesis patterns between each of warming events
influences the propagation patterns of TCs. To examine their differences, the track
density anomaly is calculated providing patterns consistent with the respective genesis
density anomaly. During an EPW year (Fig. 5a), the track density is concentrated over
region C and reduced over region A and B. During an EPC (Fig. 5c), a large suppression
in track density occurs over region C, again almost a mirror image of the EPW period.
Most of the TCs in EPC years have a recurving pattern that threatens Japan, Korea, and
northern China (Elsner and Liu 2003). The tracks during a CPW event (Fig. 5b) are
markedly different from those occurring either in EPW or EPC events. In CPW, TCs
generated over region A and C tend to penetrate through the entire western Pacific,
making landfall over the eastern coast of China and the southern parts of Korea and
Japan. Figure 6 shows the track density anomaly for the individual CPW years. Although
1994 seems to have a large impact on the composite analysis, the overall pattern of track
density anomaly is similar to Figure 5b even if 1994 case is excluded in the composite
analysis (not shown). Except for the 1953 case, which is similar to an EPW case, all
CPW years have a similar pattern.

The TC track density over the eastern Pacific also suggests significant influences by
the different forms of Pacific warming/cooling. In EPW, enhanced TC activity occurs
over the central to the eastern Pacific and suppression appears near the coast of
California. In an EPC year, a large suppression is shown over the overall western to
eastern Pacific. The CPW shows an increase in the track density over the central to the
western Pacific with a large suppression area over the eastern Pacific (region D), a
pattern consistent in all CPW case.

4. Large-scale environments

This analysis is based on the presumption that the significantly different characteristics
of TC activity between EPW, CPW and EPC can be explained by the thermodynamic and
large-scale circulation factors associated with the large-scale environments.
a. Thermodynamic factors

It has long been known that the thermodynamic factors (e.g. SST and mid-level moisture) influence TC activity. Although deep convection has been thought to depend on SST at least of 28ºC (Graham et al. 1987), most of the tropical western North Pacific region reaches 28ºC during the northern hemisphere summer. Therefore, the atmospheric circulation anomaly associated with the boundary SST forcing plays a fundamental role in determining TC activity. The second thermodynamic factor is the anomalous mid-troposphere moisture (Gray 1979; Camargo et al. 2007a), whereby dry mid-levels are not conducive in allowing the development of storm activity. Figure 7 shows the composite of the relative humidity (RH) anomaly at 500 hPa for each of three ENSO phases. The general pattern is consistent with the SST variation. In EPW (Fig. 6a), the moist air is located above the anomalous warm SST providing an opposite picture to that found with EPC (Fig. 7c). The decrease of mid-level RH near the Asian continent in EPW may lead to genesis suppression in regions A and B and also shift the genesis region to region C (Camargo et al. 2007b). In CPW (Fig. 7b), the positive anomaly is moved westward compared to the EPW and it is consistent with the shifting pattern of underlying warm SST.

Figure 8 shows the vertical profile of RH for the anomalous Walker circulation associated with each ENSO phase and computed for the zonal and vertical component of the wind. Variables are averaged from the equator to 10ºN. The EPW case contains maximum moisture in the tropical mid-troposphere over the central to eastern Pacific where there is anomalous ascending motion. To the west, dry descending air over the western Pacific coincides with the suppression of TC activity (Fig. 8a). However, in the CPW case (Fig. 8b), in accord with the westward shift of the maximum SST anomaly to the central Pacific, anomalous ascending motion accompanied by a mid-tropospheric moistening is also shifted to the west. The adjacent descending motion with dry air in the east Pacific induces the suppression that inhibits the TC activity in region D. Although positive moist anomalies occur near the surface on east Pacific, the RH throughout the mid-level (Fig. 8b) and the underlying SST anomaly does not appear to be sufficient to induce TC activity because of the strong subsidence. The descending motion over region B is also associated with the reduced TC activity. The EPC circulation (Fig. 8c) is again an almost mirror image of the EPW composite; specifically cold SST over the central-eastern Pacific suppresses convection thus confining TC activity to the northwestern part of the western Pacific with anomalous ascent in conjunction with moist mid-troposphere.

b. Atmospheric circulation

The atmosphere over the warm SST of the Pacific is sufficiently unstable to produce TCs if the atmospheric circulation is favorable (Gray 1979). Here, we describe the characteristics of atmospheric circulation field for the different forms of Pacific warming. The EPW enhances convective heating that is associated with the anomalous low-level (850-hPa) westerly wind anomalies over the equatorial western to central Pacific (Fig. 9a). The strong westerly anomalies are related to a positive relative vorticity anomaly that induces TC formation in region C (Gray 1979; Chan 2000; Wang and Chan 2002). The westward shifting of CPW-induced heating moves the anomalous westerly wind toward
region A (Fig. 9b). In the EPC summer, the low-level wind is almost opposite that of the EPW and is unfavorable to TC formation over the western Pacific (Fig. 9c).

The interannual variation of the wind shear differentiates the TC variability between the phases of ENSO. The strong vertical wind shear inhibits the formation and development of TCs whilst weak vertical wind shear promotes genesis development (Chia and Ropelewski 2002; Clark and Chu 2002; Gray 1979). Figure 9 (shading) shows the vertical wind shear magnitude for each of the three regimes. The wind shear is defined as the magnitude of zonal wind difference between the 850 and 200 hPa levels. An area with climatologically weak wind shear in conjunction with warm SSTs produces a region of active TC formation. There are large differences in the pattern of vertical wind shear magnitude and location for each of the three regimes. For the EPW (Fig. 9a), the weak vertical shear anomaly near the date line to the eastern Pacific favors TCs entering the central Pacific from the east Pacific (Clark and Chu 2002). Both the strong shear in the tropical west Pacific and the weak shear near the dateline occurring during an EPW increase the likelihood of TC activity enhancement to the east. The strong shear over the East Asia in EPW inhibits the TC steering toward region A, while the weaker shear has the opposite impact. The reduction of the wind shear over the eastern North Pacific contributes to the enhancement of TC activity in region D (Camargo et al. 2007a). In an EPC event, the strong shear anomaly near the date line and eastern North Pacific inhibits TC activity, while the reduction of shear in the western Pacific causes enhancement (Fig. 9c). In CPW years, the negative anomaly of the vertical wind shear (Fig. 9b) is shifted to the far west compared to EPW in northwestern part of the western Pacific (region A) and is near normal in the East Pacific basin. The weak vertical shear provides a favorable condition for TC formation allowing TC passages through the weak shear region near the east coast of China in a contrasting manner to the situation during traditional El Nino years.

It is known that the TC activity over the northwestern part of the western Pacific is also governed by the zonal and meridional location of the monsoon trough (Chan et al. 1998, Chia and Ropelewski 2002). Figure 10 shows the geopotential height anomaly and the total wind field at 850 hPa. The mid-latitude atmospheric response for EPW forcing shows an anomalous low-level cyclonic circulation over the entire central mid-latitude Pacific (Fig. 10a) which intensifies the eastward extension of the monsoon trough that shifts to the southeast the favorable conditions for TC. The anomalous anticyclone circulation over region B leads to the suppression of TC formation. The circulation pattern in EPC is nearly the mirror image of EPW conditions. Both the geopotential height anomaly and the streamline show a westward retreated trough during the EPC summer that induces enhanced (suppressed) TC activity over region A (region C). In a CPW case, the westward shifting of the Pacific warming moves the large-scale circulation field to the west compared to EPW (Fig. 10b). The anomalous cyclonic flow over the northwestern part of the western Pacific is crucial in enhancing TC activity. The monsoon trough is deeper over the Philippine Sea and extended into region A which enhances the TC activity. The deepening of the monsoon trough in the low troposphere also provides a favorable condition for the TC to propagate northward to the Asian continent.
6. Summary and conclusion

The influence of the three different regimes of ENSO on the North Pacific tropical cyclone activity has been investigated by diagnosing the observation in JASO season from 1951 to 2006. The warming and cooling events are classified based on the Nino indices that depict Pacific Ocean warming or cooling. To compare the characteristics for each of events, a composite analysis was made based on 8 EPW years, 5 CPW years and 8 EPC years.

During the EPW summer, both the genesis and the track density of TCs are enhanced broadly over the central to eastern Pacific. TC formation tends to be enhanced over the central to eastern Pacific and decreased in the northwestern part of the western Pacific. In the eastern North Pacific basin, the genesis and track density is increased in EPW summer. During an EPC event, the situation is almost completely reversed. In the CPW summer, TC activity is very different from EPW both in the western and eastern Pacific. The positive genesis potential index, genesis density, and track density anomaly are shifted to the west in the western Pacific and extend through the northwestern part of the western Pacific. These patterns are distinctive from the canonical summer El Nino pattern. The TC formation over the northwestern part of the western Pacific increases the probability of East Asian landfalls, including both Korea and Japan, consistent with the recent study from Chen and Tam (2010). During CPW years, TC activities are enhanced over the central to the western Pacific with a large suppression area over the east Pacific.

The significantly different TC characteristics between the three ENSO regimes are explained in terms of thermodynamic and large-scale circulation patterns of the large-scale environment. The TC activity anomaly shows consistency with the changes in the SST pattern over the entire North Pacific basin; the TC activity is enhanced (suppressed) as the positive (negative) SST anomaly occurs over the central to eastern Pacific in EPW (EPC) year. In a CPW year, as the SST positive anomaly is shifted to the central Pacific, the overall TC activity pattern also seems to be shifted to the west with a broad suppression area in the eastern Pacific. EPW events contain much of moisture in the broad mid-troposphere over the central to eastern Pacific associated with distinctive background ascending motion. The ascending motion in east Pacific is accompanied by the descending motion with dry air over the western Pacific that suppresses the TC activity. However, in the CPW case, according to the westward shift of the SST forcing, the anomalous ascending motion with mid-level moisture is also shifted to the west compared to the EPW case. The accompanying descending motion with dry air in the east Pacific induces the suppression of TC activity in eastern North Pacific.

To explain how different types of Pacific warming/cooling could affect TC activity, the variation of the atmospheric circulation is examined. During an EPW, strong westerly anomalies, related to the positive relative vorticity anomaly and extension of the monsoon trough over the western Pacific, induce TC formation in region C. Also, both the strong shear in the tropical western Pacific and the weak shear near the dateline increase the likelihood of TC activity enhancement to the east of the climatological TC
genesis location. The reduction of the wind shear over the eastern North Pacific enhances TC activity, quite opposite to what occurs during an EPC. The westward shifting of CPW-induced heating moves the anomalous westerly wind to extend through the western part of northwestern part of the western Pacific. The monsoon trough is enhanced over the Philippine Sea and extended into the northwestern part of the western Pacific. These circulation anomalies lead to the enhancement of TC activity over the northwestern part of the western Pacific. The deepening of the monsoon trough in the low troposphere also provides a favorable condition for the TC to propagate into the Asian continents.

Acknowledgements

This research has been supported in part by Climate Dynamics Division of the National Sciences Foundation under Award NSF-ATM 0531771 and 0826909.
References


Figure 2: Composites of SST anomalies (contours interval is 0.3°C) in JASO for (a) EPW, (b) CPW, and (c) EPC years. Dashed lines indicate boundaries of subregions mentioned in the text.
Figure 3: Composites of genesis density anomalies (multiplied by 10) in JASO for (a) EPW, (b) CPW, and (c) EPC years. Light (dark) contours show statistical significance at the 90% (95%) level.
Figure 4: Composites of genesis potential anomaly in JASO for (a) EPW, (b) CPW, and (c) EPC. Contours are indicated only on the positive value with interval in 0.5. Light (dark) contours show statistical significance at the 90% (95%) level.
Figure 5: Composites of track density anomaly (multiplied by 10) in JASO for (a) EPW, (b) CPW, and (c) EPC. Light (dark) contours show statistical significance at the 90% (95%) level.
Figure 6. Track density anomaly (multiplied by 10) in JASO for 5 CPW years (1953, 1991, 1994, 2002, and 2004). The contour interval is 5.
Figure 7: Composites of relative humidity anomalies (%) at 500 hPa in JASO for (a) EPW, (b) CPW, and (c) EPC. Contour interval is 2.
Figure 8. Composites of relative humidity anomaly (%, shading) and velocity anomaly (stream line) averaged over Equator to 10°N for (a) EPW, (b) CPW, and (c) EPC. The anomalous vertical velocity at the pressure levels has been multiplied by a factor of 50.
Figure 9. Composite of vertical wind shear magnitude anomaly (m s$^{-1}$, shading) and 850 hPa wind vectors (m s$^{-1}$, arrow) for (a) EPW, (b) CPW, and (c) EPC. The wind shear is defined as the magnitude of zonal wind difference between 850 hPa and 200 hPa.
Figure 10. Composite of geopotential height anomaly (meter, shading) and wind at 850 hPa (streamline) for (a) EPW, (b) CPW, and (c) EPC.