Influences of ENSO on Western North Pacific Tropical Cyclone Kinetic Energy and Its Meridional Transport

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ABSTRACT

This study investigates the influences of ENSO on tropical cyclone (TC) kinetic energy and its meridional transport in the western North Pacific (WNP) using the TC wind field obtained after a method for removing TC vortices from reanalysis data is applied. Results show that ENSO strongly modulates TC kinetic energy and its meridional transport in the WNP, but their effects and regions differ. The TC kinetic energy is positively correlated with the Niño-3.4 index in the entire WNP, and its poleward transport is positively (negatively) correlated with the Niño-3.4 index in the eastern WNP (the western WNP and the South China Sea); these correlations are statistically significant. The maximum TC kinetic energy is located around 25°N, 135°E (25°N, 125°E) in the warm (cold) year, showing an east–west pattern during different ENSO phases. The meridional transport of TC kinetic energy exhibits a dipole pattern over the WNP, with the poleward (equatorward) transport in the eastern (western) WNP. Both poleward and equatorward transports strengthen (weaken) and shift eastward (westward) in El Nin˜o (La Nin˜a) years. Therefore, El Nin˜o has strong influences on TC kinetic energy and its meridional transport.

1. Introduction

The interannual variability of tropical cyclone (TC) activity in the western North Pacific (WNP), including genesis location, frequency, intensity, track, and life span, has been examined by many authors (e.g., Lander 1994; Chan 2000; Sobel and Maloney 2000; Wang and Chan 2002; Wu et al. 2004; Camargo and Sobel 2005; Chen et al. 2006; He and Jiang 2011). Although sea surface temperature anomalies (SSTA) in the tropical Indian Ocean can significantly affect both TC genesis frequency and intensity in the WNP, as explored in the recent studies (Du et al. 2011; Zhan et al. 2011a,b), especially during the summer of a decaying El Niño, El Niño–Southern Oscillation (ENSO) is still considered to play the most dominant role in modulating the TC activity over the WNP, and distinct spatial–temporal characteristics of TC activity correspond to different ENSO episodes. For example, TC activity in the eastern (western) WNP has a higher (lower) genesis frequency and longer (shorter) life span, and stronger (weaker) intensity during El Niño events, while opposite characteristics appear during La Niña events (Chan 2000; Chia and Ropelewski 2002; Wang and Chan 2002; Camargo and Sobel 2005; Chen et al. 2006; Yang and Jiang 2008; Zhan et al. 2011a). Previous studies paid more attention to ENSO effects on TC genesis frequency in the WNP. Wang and Chan (2002) pointed out that TC genesis frequency over the entire WNP changed little during different phases of ENSO, but that increased (decreased) in the southeastern quadrant (0°–17°N, 140°E–180°) and decreased (increased) in the northwestern quadrant (17°–30°N, 120°–140°E) during warm (cold) years. Zhan et al. (2011a) further determined, through more detailed analysis, that 145°E was the east–west dividing line of the two quadrants. The increased TC activity in the eastern WNP is ascribed to the enhanced lower-troposphere shear vorticity associated with positive equatorial westerly anomalies, and the decreased TC activity in the
western WNP is attributed to the strengthening of the WNP subtropical high and the anomalous subsidence associated with upper-troposphere convergence during El Niño (Chan 2000; Wang and Chan 2002; Zhou et al. 2009; Wu et al. 2009). Zhan et al. (2011a) suggested that ENSO modulates barotropic energy conversion over the WNP, which contributes both to TC genesis location and number of intense TC in the WNP.

TC intensity and meridional transport of TC kinetic energy have significant differences in terms of interannual variation, which is modulated by the anomalous environmental conditions associated with ENSO. Camargo and Sobel (2005) used the accumulated cyclone energy (ACE) index to examine the relationship between ENSO and TC activity over the WNP, suggesting that more intense and longer-lived TCs appear in warm years than in cold years. ACE, as a continuous variable, can be used to represent the interannual variability of TC intensity as a measure of the TC kinetic energy, which is calculated by the sum of individual TC kinetic energy from the TC best-track dataset and is efficient to represent interannual variability of TC intensity by the TC kinetic energy (Bell et al. 2000; Camargo and Sobel 2005). Wang and Chan (2002) found a significant increase in mean TC life span, number of TCs that recurve northward across 35°N, and annual total days of TC occurrence in warm years after examining the seasonal TC activity during ENSO, suggesting that the meridional exchange of heat and energy induced by TCs is greatly enhanced during the warm years and that there is significant variation in the meridional transport of TC kinetic energy modulated by ENSO. However, hitherto there has been no direct calculation of TC kinetic energy and its meridional transport in the WNP to detect the relationship between ENSO and TC activity. Therefore, we consider obtaining the annual TC kinetic energy and its meridional transport by removing TC vortices from reanalysis data to investigate the influences of ENSO on TC kinetic energy and its meridional transport. We try to focus on the following two issues: (i) Could TC intensity characterized by TC kinetic energy be an appropriate variable for indexing the TC intensity during ENSO, like the ACE index by Camargo and Sobel (2005)? (ii) What are the spatial–temporal characteristics of TC kinetic energy and its meridional transport during ENSO?

The rest of this paper is organized as follows. Datasets and methodology are described in section 2. Statistical characteristics of ENSO effects on TC kinetic energy and its meridional transport in the WNP are presented in section 3. Spatial–temporal distributions of TC kinetic energy and its meridional transport during ENSO are discussed in section 4, and the main conclusions are presented in section 5.

2. Data and methodology

We investigate TC kinetic energy and its meridional transport over the WNP during the TC season from June to October (JJASO) in the period 1979–2007. We use the TC best-track dataset from the Joint Typhoon Warning Center (JTWC 2011) to locate TCs that reached at least tropical storm intensity. The dataset covers the WNP and the South China Sea (SCS) and includes 6-hourly TC positions. It gives the best-track data with improved quality when it includes satellite data after the 1970s, providing an advantage to locate TCs in terms of their positions. The Niño-3.4 index is provided by the Climate Prediction Center (CPC), and the reanalysis data are from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR; Kalnay et al. 1996). The NCEP–NCAR data include meridional and zonal winds with a spatial resolution of 2.5° × 2.5° and a temporal resolution of 4 times daily. A composite analysis method is applied in obtaining spatial–temporal distribution of TC kinetic energy and its meridional transport section, and the Student’s t test with 95% confidence level is used to show the statistical significance of the composite analysis. El Niño and La Niña years in the period 1979–2007 are defined based on the threshold of one standard deviation from the averaged Niño-3.4 index over JJASO. Therefore, the El Niño years are 1982, 1987, 1991, 1997, 2002, and 2004, and the La Niña years are 1985, 1988, 1998, 1999, 2000, and 2007.

Hsu et al. (2008) used a method of removing TC vortices from the reanalysis data, and analyzed the removed part as TC wind field to study the climatic effect of TCs in the WNP. In their study, the reanalysis wind field at 850 hPa was decomposed into TC component and background component. Moreover, the method of removing TC from the reanalysis data is a sophisticated practice in hurricane simulation and forecast (Kurihara et al. 1993, 1995; Wu et al. 2002), and also in the study of TC influences on climate variability (Zhong and Hu 2007; Hsu et al. 2008). We derive the horizontal TC wind field from the reanalysis data using the method that has been used in the TC bogusing scheme (Low-Nam and Davis 2001) for the fifth-generation Pennsylvania State University–NCAR Mesoscale Model (MM5) following two steps. First, the first-guess vortex area is located. Position of observed TC is identified at the nearest grid point of the reanalysis based on the TC best-track dataset, and the area of analysis TC, which can be considered as TC vortex domain, is determined by searching.
the maximum vorticity point within a prescribed radial distance from the center of the observed TC. Second, the reanalysis wind field in the first-guess vortex area can be decomposed into TC component and background component. The horizontal wind field of the reanalysis data is decomposed into nondivergent wind, velocity potential, and the residual, and the streamfunction corresponding to nondivergent wind and the velocity potential can be calculated based on the best-track dataset at each time. The nondivergent wind \( \psi \) is calculated by \( \nabla^2 \psi = \zeta \) and \( \psi = k \times \nabla \psi \), where \( \psi \) is the streamfunction for the nondivergent wind and \( \zeta \) is the relative vorticity. The velocity potential \( \psi \) is derived from \( \nabla^2 \chi = \delta \) and \( \psi = V \chi \), where \( \chi \) is the velocity potential and \( \delta \) is the divergence. Then, the sum of nondivergent wind and velocity potential is regarded as the TC wind component. More details of the method can be found in Low-Nam and Davis (2001). It should be mentioned that, although the reanalysis data with the spatial resolution of 2.5° seems relatively coarse to give sharp features of TC wind field, it is able to represent the interannual variability of TC activity over the WNP for TC climatology studies. Hsu et al. (2008) revealed that the identification of TC vortices from reanalysis data with different spatial resolution was done well by comparing the TC wind fields between the reanalysis data with spatial resolutions of 2.5° and 1.125°. The TC wind fields also showed very similar spatial patterns between these two spatial resolutions, in case studies and in terms of seasonal means (see their Figs. 10 and 11). To demonstrate the procedure is effective in separating TC wind field from its environmental field, the 850-hPa wind and vorticity fields on 1200 UTC 27 August 1997 are shown in Figs. 1a–c. Figure 1a shows three TCs embedded in the positive latitudinal vorticity band near 20°N (where there was a summer monsoon trough). The western and eastern TCs were weak with the maximum sustained surface wind speeds of 25 and 20 kt, respectively, and the middle TC was intense with that of 110 kt. Figure 1b shows the separated wind and vorticity fields of the three isolated TC vortices. After having removed the TCs from the reanalysis, the weaker positive zonal vorticity and wind vectors can still be seen (Fig. 1c), suggesting that the summer monsoon trough is retained in the background field. To show the method is effective at depicting the characteristics of seasonal wind field, the 850-hPa wind and vorticity fields over JJASO in 1997 are given in Figs. 1d–f. The TC field exhibited the positive vorticity in the southeastern WNP (Fig. 1e), indicating the intense TC activity existed in this region during the TC peak season in 1997. This corresponds to the modulation of the WNP TC activity by the strongest El Niño in the twentieth century. Compared to the seasonal fields (Fig. 1d), the wind and vorticity fields without TCs became weaker in the southeastern WNP (Fig. 1f), and the reduction was due to the seasonally averaged TCs. Therefore, the procedure cannot only extract wind field of TCs but also effectively retain the characteristics of large-scale circulation, which indicates that the results by this method are objective and reliable for this study.

3. ENSO effects on TC kinetic energy and its meridional transport in terms of statistical characteristics

We investigate the interannual variation of TC kinetic energy (hereafter TE) and its meridional transport (hereafter TET) in the period 1979–2007, and the accumulated TE and TET in the WNP (0°–45°N, 100°E–180°) over JJASO integrated from 1000 to 10 hPa are expressed with \( \Sigma_{t=1}^{9} T_{E,n=1}^{w} N \Sigma_{t=1}^{9} L \) \( [1/(2)(u^2 + v^2)] \) and \( \Sigma_{t=1}^{9} \Sigma_{n=1}^{N} L \Sigma_{l=1}^{17} [(1/2)(u^2 + v^2) \cdot (u^2 + v^2) \cdot v^2] \), respectively, where \( u \) and \( v \) are zonal and meridional winds of TC field, respectively. Here \( t = 1 \) to \( T \) means the first to the last time over JJASO, \( N \) is the total grid point in the WNP, and \( L = 17 \), which is the total number of vertical levels of the reanalysis data. The definitions of disturbance kinetic energy and its meridional transport are referred from Peixoto and Oort (1992).

Figure 2 shows the time series of TE and TET averaged over JJASO from 1979 to 2007. The TEs in five El Niño years out of six are above the climatological mean, except for 1982, whose TE is slightly lower than the climatological mean value; and those in five La Niña years out of six are below the climatological mean (Fig. 2a), suggesting that TE is higher (lower) in the warm (cold) years. TE values are all positive except for 1986 (Fig. 2b), indicating that poleward transport of TE is a persistent feature over the entire WNP. TETs in three El Niño years out of six are above the climatological mean, and those in four La Niña years out of six are below the climatological mean (Fig. 2b). The characteristics of high (low) TET in warm (cold) years are not as robust as TE. To examine the relationship between TE/TET and ENSO, Fig. 3 shows the scatter diagram of the Niño-3.4 index, TE, and TET over JJASO with linear regression polynomials. The TE is significantly correlated with the Niño-3.4 index and their correlation coefficient is 0.67 at the 99% confidence level, but TET is not correlated well to the Niño-3.4 index with the correlation coefficient of only 0.15. In general, TE has a linear variation with the Niño-3.4 index during the ENSO cycle (Fig. 3a). In contrast, the basin-scale TET shows no significant change with the Niño-3.4 index from the linear regression in Fig. 3b. The characteristics of TE during ENSO are similar to the ACE index after
the 1970s by Camargo and Sobel (2005) in their Figs. 1b and 2, which have a higher correlation with the Niño-3.4 index over the WNP, suggesting that TE characterized by the TC kinetic energy is able to measure the TC intensity during ENSO. TC is one of the most important eddy or synoptic-scale disturbances, and it is well documented that TC activity strengthens (weakens) in the warm (cold) years over the WNP in many previous studies (e.g., Chan 2000; Sobel and Maloney 2000; Wang and Chan 2002; Camargo and Sobel 2005; Chen et al. 2006; Zhan et al. 2011a). However, the magnitude of ENSO impacts on TC activity relative to other synoptic-scale disturbances in the TC season is not clear. To detect the annual variation of the percentage of TE (TET) in total atmospheric eddy kinetic energy (and its poleward transport) over the WNP during ENSO, the atmospheric eddy kinetic energy and associated poleward transport are integrated over JJASO in the WNP (0°–45°N, 100°E–180°). The atmospheric eddy or synoptic wind field is described as follows: an environmental variable can be decomposed into a basic state (defined as an 11-day running mean) and an eddy or synoptic component (defined as the residual), and the atmospheric eddy kinetic energy and its poleward transport are calculated from the latter (Lau and Lau 1992). Table 1 lists the ratios of TE and TET to total.

![Fig. 1.](image-url)
atmospheric eddy kinetic energy and associated poleward transport over the entire WNP in the warm and cold years, respectively. TE and TET account for 15.5% and 13.4% of total atmospheric eddy kinetic energy and poleward transport over JJASO, respectively. The percentage of TE in four (five) warm (cold) years is higher (lower) than the climatological mean, and the percentage of TE is higher than the climatological mean in the composite warm year by 3.7%, and lower than that in the composite cold year by 3.2%, suggesting that ENSO not only highly modulates TC intensity in the WNP, but also changes the percentage of TC kinetic energy in total atmospheric eddy kinetic energy over the WNP. The percentage of TET in only two warm years (four cold years) is higher (lower) than the climatological mean, and the percentage of TET is slightly lower (higher) than the climatological mean in the composite warm (cold) year, which is not consistent with the characteristics of basin-scale TE over the WNP.

To further explore the regional characteristics of ENSO influences on TE and TET, the correlation between TE/TET over the WNP and the Niño-3.4 index over JJASO during the period 1979–2007 is shown in Fig. 4. Significant correlation between TE and the Niño-3.4 index exists in most of the WNP except for the SCS and the edge of North Pacific, and the correlation reaches the maximum around 5°–15°N, 135°–140°E with the coefficient above 0.8 (Fig. 4a). In contrast, significant correlation between TET and the Niño-3.4 index exhibits a dipole pattern, with the positive in the eastern WNP and negative in the western WNP and the SCS. The absolute value of correlation coefficient is above 0.6 both around 5°–20°N, 110°–120°E and around 5°–20°N, 150°–175°E (Fig. 4b). The opposite relationship of TET and the Niño-3.4 index in the east and west parts greatly weakens its total

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### Table 1. Ratios of TE and TET to total atmospheric eddy kinetic energy and its poleward transport over the entire WNP, respectively.

<table>
<thead>
<tr>
<th>Year</th>
<th>TE</th>
<th>TET</th>
</tr>
</thead>
<tbody>
<tr>
<td>El Niño cases</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1982</td>
<td>0.136</td>
<td>0.150</td>
</tr>
<tr>
<td>1987</td>
<td>0.154</td>
<td>0.118</td>
</tr>
<tr>
<td>1991</td>
<td>0.172</td>
<td>0.086</td>
</tr>
<tr>
<td>1997</td>
<td>0.237</td>
<td>0.072</td>
</tr>
<tr>
<td>2002</td>
<td>0.258</td>
<td>0.327</td>
</tr>
<tr>
<td>2004</td>
<td>0.194</td>
<td>0.025</td>
</tr>
<tr>
<td>Warm mean</td>
<td>0.192</td>
<td>0.130</td>
</tr>
<tr>
<td>La Niña cases</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1985</td>
<td>0.092</td>
<td>0.126</td>
</tr>
<tr>
<td>1988</td>
<td>0.099</td>
<td>0.370</td>
</tr>
<tr>
<td>1998</td>
<td>0.100</td>
<td>0.089</td>
</tr>
<tr>
<td>1999</td>
<td>0.124</td>
<td>0.141</td>
</tr>
<tr>
<td>2000</td>
<td>0.151</td>
<td>0.087</td>
</tr>
<tr>
<td>2007</td>
<td>0.173</td>
<td>0.133</td>
</tr>
<tr>
<td>Cold mean</td>
<td>0.123</td>
<td>0.158</td>
</tr>
<tr>
<td>Climatological mean</td>
<td>0.155</td>
<td>0.134</td>
</tr>
</tbody>
</table>
correlation in the entire WNP; therefore, little correlation coefficient is shown between TET and the Niño-3.4 index in Fig. 3b. Considering different regions over the WNP, we note that the percentage of TET in total atmospheric eddy kinetic energy transport is higher (lower) than the climatological mean around 5°–20°N, 150°–175°E in the composite warm (cold) year (not shown). Although the correlation between TET and the ENSO index is not significant over the entire WNP (Table 1), the increased (decreased) TET over the southeastern WNP during El Niño (La Niña) indicates evident regional discrepancy of ENSO impacts on TET during ENSO. Regions with the maximum coefficients in 5°–15°N, 135°–140°E (hereafter the area is marked as TEA), 5°–20°N, 150°–175°E and 5°–20°N, 110°–120°E (hereafter the areas are marked as TETA1 and TETA2, respectively) can be defined as the key regions of ENSO influences on TE and TET, respectively. It should be pointed out that, although the TC activity in TEA and TETA is not the most intense, and TE/TET is also not the largest over the WNP, ENSO has the strongest modulation on TC kinetic energy and its meridional transport in these regions. The correlation coefficients of Niño-3.4 index with TE in TEA and with TET in TETA are above 0.8 and 0.7, which exceed the 99% confidence level, respectively; that is to say, the effects of ENSO can explain above 60% (as much as 50%) in the total variance of TE (TET) variability in the key regions. Previous studies revealed TC genesis frequency over the WNP was significantly positive (negative) correlated with the ENSO index in the southeastern quadrant of the WNP (the SCS; Wang and Chan 2002; Zhan et al. 2011a), which is consistent with the regions of TEA and TETA1, and our results further point out the regional discrepancies of ENSO influences on the TE and TET exist over the WNP. During El Niño (La Niña), strong lower-troposphere westerly (easterly) anomalies are triggered by the warm (cold) underlying SSTA over the equatorial central-eastern Pacific, as a direct Rossby wave response to the equatorial Pacific heating (cooling). The intense (weak) WNP monsoon trough with strong positive (negative) relative vorticity anomalies extends eastward (retreats westward) to (from) the TEA and TETA1, and enhanced (suppressed) convection with increased (decreased) precipitation is also observed in these regions (not shown), which are favorable (unfavorable) for TC activity. In contrast, the increased (decreased) magnitude of vertical shear suppresses (enhances) TC activity over the TETA2 during El Niño (La Niña), as a result of the superimposition of the intense low-level westerly (easterly) anomalies to climatological mean easterly vertical shear west of 150°E over the subtropical WNP (Du et al. 2011). Large-scale circulation and environmental conditions exhibit evident variances over the TEA and TETA in the different ENSO phases, leading to the significant correlation between TE (TET) in the TEA (TETA) and the ENSO index. Therefore, it is indicated that ENSO not only modulates TC genesis location and frequency in the WNP, but also influences the spatial distributions of both TE and TET.

4. ENSO effects on TC kinetic energy and its meridional transport in terms of spatial–temporal characteristics

In this section, the spatial–temporal characteristics of TE and TET in the warm and cold years are investigated. The left panels of Fig. 5 show the distributions of TE and its anomalies in the composite warm and cold years. The maximum TE in the warm year is located around 25°N, 135°E (Fig. 5a), while that in the cold year is located around 25°N, 125°E (Fig. 5c), which is west of the location in the warm year, indicating that there are more intense TCs with longer life span formed in the eastern WNP during the warm years. The east–west
pattern of TE is different from the northwest–southeast pattern of TC genesis during warm/cold years by Wang and Chan (2002). The TE in the composite warm year is nearly twice of that in the composite cold year, indicating that despite little variance in the TC genesis frequency over the entire WNP, El Niño still has significant influences on TC intensity in the WNP. An important reason is that more TCs form in the southeastern WNP during El Niño summer and fall, and those would be intensified continuously as moving northward and westward. Thus, it is quite possible that more TCs can reach the intensity of typhoon or intense typhoon in their life spans. Therefore, the results comprehensively exhibit the maximum TE in 20°–30°N, 120°–140°E. Compared with the TC genesis location in El Niño years, more TCs form in the northwestern WNP during La Niña, and the TC activity region in the WNP is smaller, therefore, they have fewer chances to intensify and develop.
Figures 5c,g show the anomalies of TE in the composite warm and cold years, respectively. The anomalous TE is very similar between the composite warm and cold years in both spatial distribution and quantity but with the opposite phase, and the significant positive anomalies are located near 20°N, 155°E in the warm year and the negative are located near 25°N, 135°E in the cold year. The absolute values of significant anomalies in the warm year are greater than those in the cold year, indicating El Niño has a stronger effect on TC activity, which results in larger amplitude of TE in El Niño year over the WNP. The right panels in Fig. 5 show the evolutions of TE and its anomalies in the composite warm and cold years. The maximum center of TE gradually moves to high latitudes from late June in the warm year and reaches 20°N in late August. Subsequently, the center moves to low latitudes with a reduction in strength (Fig. 5b). In the composite cold year, the mean intensity center of TE appears in early July and reaches the maximum in late September near 26°N. The intensity center weakens and moves to low latitudes subsequently (Fig. 5f). Therefore, meridional shift is the primary evolving characteristics of maximum TE from June to October, which are concentrated at low to middle to low (middle to low) latitudes in El Niño (La Niña). Wang and Chan (2002) had a similar conclusion for the temporal evolution of TC genesis frequency in the WNP. It should be mentioned that, the duration of significant TC activity is from mid-June to November in the warm year, compared with that from mid-July to mid-November in the cold year, which is shorter than the duration in the warm year by more than 1 month. Additionally, the maximum intensity and the influence region in the cold year are significantly less than those in the warm year. Figures 5d,h show the evolution of anomalous TE in the composite warm and cold years, respectively. Positive anomalies in the warm year are concentrated south of 35°N, with the maximum anomaly during August (Fig. 5d), while negative anomalies in the cold year exhibit a wider spatial distribution south of 30°N, but positive anomalies appear around 10°–40°N in mid-September (Fig. 5h).

The left panels in Fig. 6 show the distributions of TET and its anomalies in the composite warm and cold years. TET exhibits a dipole pattern in the warm year, with the northwest–southwest-oriented poleward transport from the south of Japan to the eastern WNP and the equatorward transport in the western WNP including the SCS (Fig. 6a). The anomalies of TET show positive (negative) in the eastern (western) WNP in the composite warm year, which has a similar spatial pattern to TET itself but with smaller amplitude (Fig. 6c). In the composite cold year, the poleward transport dominates 10°–45°N, 125°–150°E, and the equatorward transport dominates west of 125°E, except around 12°N, 115°E (Fig. 6e). In general, the poleward and equatorward TETs in the cold year become weaker and move westward than those in the warm year. Therefore, the overall anomalous TET shows negative (positive) in the eastern (western) WNP in the composite cold year (Fig. 6g), which exhibits an opposite pattern relative to the anomaly in the warm year. It is thus suggested that the poleward transport in the eastern WNP and the equatorward transport in the western WNP both strengthen (weaken) and move eastward (westward) in El Niño (La Niña) years. The right panels in Fig. 6 show the evolutions of TET and its anomalies in the composite warm and cold years. The poleward transport in the warm year occurs from late June to late October between 15° and 35°N, with the maximum intensity in late July and September, and the weaker equatorward transport concentrates south of 15°N (Fig. 6b). The anomalies of TET exhibit a similar distribution to TET itself in the warm year, and the significant anomalies appear in late July and September (Fig. 6d). In the composite cold year, the poleward transport of TET is weak and concentrates around 30°N in late September (Fig. 6f), and the anomalies are also insignificant except around 30°N in late September (Fig. 6h). In general, the poleward (equatorward) transport of TET and the anomalies concentrate north (south) of 15°N in the warm year, but the meridional transport is weak in the cold year.

5. Discussion and conclusions

Camargo and Sobel (2005) proposed the ACE index to explain the influences of ENSO on TC intensity in the WNP. Gray (1979), Emanuel and Nolan (2004), and Camargo et al. (2007) described the interannual variability of TC with potential intensity (PI) and genesis potential (GP) indices, which were based on environmental variables. These studies captured the characteristics of TC activity during different ENSO episodes with the above effective indices. In this study, we investigate the influences of ENSO on TC kinetic energy and its meridional transport using the TC wind field obtained after the method of removing TC vortices from the reanalysis data. The main conclusions are as follows.

First, the statistical characteristics of ENSO effects on TE and TET in the entire WNP are investigated. TE is high (low) in the warm (cold) years and is significantly correlated with the Niño-3.4 index. The characteristics of TE during ENSO are similar to the ACE index after the 1970s, which is significantly correlated with the Niño-3.4 index over the entire WNP, suggesting that TE characterized by the TC kinetic energy is able to measure the TC intensity during ENSO. To detect whether
the modulation of ENSO on TC activity may be more significant relative to other synoptic-scale disturbances in the TC season, the percentages of TE and TET in total atmospheric eddy kinetic energy and its poleward transport are calculated over the WNP, respectively. The results show that ENSO not only modulates the TC intensity in the WNP but also increases (decreases) the percentage of TC kinetic energy in the total atmospheric eddy kinetic energy over the WNP in the warm (cold) years. Furthermore, the regional characteristics of ENSO influences on TE and TET suggest that significant correlation between TE and the Niño-3.4 index widely exists in the WNP except for the SCS and the edge of North Pacific, and the correlation coefficient between TET and the Niño-3.4 index exhibits a dipole pattern, with a significant positive (negative) correlation in the eastern WNP (the western WNP and the SCS). The opposite relationship weakens its total correlation coefficient between TET and the Niño-3.4 index in the entire WNP. Regions with the most significant correlation coefficients in TEA and TETA can be defined as the key regions of ENSO influences on TE and TET, respectively. Although the TC activity in TEA and TETA is not the most intense, ENSO has the strongest

![Fig. 6. As in Fig. 5, but for TET (m^3 s^-3).](image-url)
modulation impacts on TE and TET in these regions. Therefore, ENSO not only modulates TC genesis location and frequency in the WNP, but also influences the spatial distributions of TE and TET.

Second, the spatial–temporal characteristics of ENSO effects on TE and TET are investigated. The maximum TE is located around 25\(^{\circ}\)N, 135\(^{\circ}\)E (25\(^{\circ}\)N, 125\(^{\circ}\)E) in the composite warm (cold) year, presenting an east–west pattern. TE in the composite warm year is nearly twice that in the cold year. The absolute values of anomalies in the warm year are greater than those in the cold year, indicating that El Niño has more significant influences on TE in the WNP. TET exhibits a dipole pattern over the WNP in the composite warm year, with the poleward (equatorward) transport from the south of Japan to the eastern WNP (in the western WNP and the SCS), and the anomalies of TET also show positive (negative) in the eastern (western) WNP in the warm year. The poleward and equatorward TETs in the cold year both become weaker and move farther westward than those in the warm year, and the overall anomalous TET in the cold year exhibits an opposite pattern relative to that in the warm year. It is thus suggested that the poleward transport in the eastern WNP and equatorward transport in the western WNP both strengthen (weaken) in El Niño (La Niña) years, indicating that El Niño has greater influences on both TE and TET. Therefore, we guess that other meridional energy transports associated with TC activity would become more pronounced in the warm years relative to those in other ENSO phases.

It should be mentioned that better estimates of the TE and TET could be derived from the higher-spatial-resolution reanalysis data, because the TC wind field will be more intense with higher resolution relative to the present results. Although the TC vortices cannot be totally removed from the reanalysis data, it is believed that the TC wind field obtained by this method is appropriate for studying climatological characteristics of TC interannual variability. TE and TET as the continuous variables based on the TC wind field are able to represent the characteristics of TC activity. Previous works show that the climate issues of TC activity can be improved by this methodology. Hsu et al. (2008) found that TC activity has significant influences on the summer climate variability in the WNP by a similar method with different spatial resolution reanalysis data. In addition, the removal TC method was also employed in the regional climate model investigating the effect of TCs on the East Asian summer climate (Zhong and Hu 2007). It is found that TCs significantly affect the regional climate in terms of weakening the western Pacific subtropical high or interrupting the WNP summer monsoon.

ENSO has significant influences on TC genesis, intensity, and life span, which play an important role in global energy transport and balance through the atmospheric energy exchange between tropics and extratropics; patterns of regional and global climate would also be changed by TC activity. Under the influences of ENSO, what roles TC activity plays over the WNP in terms of regional and global energy transports and balances needs further study.

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REFERENCES
Kurihara, Y., M. A. Bender, and R. J. Ross, 1993: An initialization 
scheme of hurricane models by vortex specification. *Mon. 
——, ——, R. E. Tuleya, and R. J. Ross, 1995: Improvements in the 
2791–2801.

between tropical storm formation in the western North Pacific 

Lau, K.-H., and N.-C. Lau, 1992: The energetics and propagation 
dynamics of tropical summertime synoptic-scale disturbances. 

Low-Nam, S., and C. Davis, 2001: Development of a tropical cy-
clone bogusing scheme for the MM5 System. *Proc. 11th PSU/
NCAR Mesoscale Model Users Workshop*, Boulder, CO, Na-
tional Center for Atmospheric Research, 130–134. [Available 
online at http://www.mmm.ucar.edu/mm5/workshop/ws01/ 
lownam.pdf.]

Peixoto, J. P., and A. H. Oort, 1992: *Physics of Climate*. Springer-
Verlag, 520 pp.


Wang, B., and J. C. L. Chan, 2002: How strong ENSO events af-
fect tropical storm activity over the western North Pacific. 

Wu, B., T. J. Zhou, and T. Li, 2009: Seasonally evolving dominant 
interannual variability modes of East Asian climate. *J. Climate*, 
**22**, 2992–3005.

Wu, C.-C., T.-H. Yen, Y. Kuo, and W. Wang, 2002: Rainfall simu-
lation associated with Typhoon Herb (1996) near Taiwan. Part 

Southern Oscillation events on tropical cyclone land falling ac-

Yang, Y., and J. Jiang, 2008: The impacts of sea surface tempera-
ture anomaly in the equatorial central and eastern Pacific on 

Zhan, R. F., Y. Wang, and X. T. Lei, 2011a: Contributions of ENSO and 
est Indian Ocean SSTA to the interannual variability of north-
——, ——, and C.-C. Wu, 2011b: Impact of SSTA in east Indian 
Oceans in the frequency of northwest Pacific tropical cyclones: A 

Zhong, Z., and Y. Hu, 2007: Impacts of tropical cyclones on the 
regional climate: An East Asian summer monsoon case. 

general circulation models capture the leading modes of the 
terannual variability of the Asian–Australian monsoon? 