Eddy Energy along the Tropical Storm Track in Association with ENSO

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Abstract

The interaction between the seasonal mean circulation and the transient eddies over the western North Pacific (WNP) during El Niño-Southern Oscillation (ENSO) warm and cold years was investigated by the three-dimensional eddy kinetic energy (EKE) and eddy available potential energy (EAPE) budget equations for total eddy, high-frequency (< 10 days) and low-frequency (20–70 days) components. Composites of the energy results indicate that low-level anomalous cyclonic circulation, westerly jet and ascending motion associated with the eastward extension of warm SST during warm ENSO years are favorable for eddy barotropic energy conversion (CK) and eddy baroclinic energy conversions (CE). The enhancement of CK and CE might provide kinetic energy for the growth of high- and low-frequency transient eddies including tropical storms (TSs) from the Philippine Sea to the date line over the tropical WNP during warm ENSO years. In contrast, high- and low-frequency eddies convert EKE to seasonal mean circulation over the subtropical and mid-latitude WNP during warm years. Enhanced eddy baroclinic energy conversion plays an important role in the maintenance and enhancement of the subsequent development of transient eddies including TSs as they propagate northward.

The loss of EAPE to EKE due to the eddy baroclinic energy conversion is mainly supplemented by the generation of EAPE associated with eddy diabatic heating. However, the energy conversion from mean available potential energy (MAPE) to EAPE is also important due to the eddy vertical heat transport which is neglected in the two-dimensional EAPE budget equation. It is suggested that high- and low-frequency eddies including TSs may be self-development and intensify through their enhanced diabatic heating and vertical heat transport.

1. Introduction

El Niño-Southern Oscillation (ENSO), a highly coupled air-sea system, may affect the interannual variability of the tropical storms (TSs) over the western North Pacific (WNP) by altering the thermodynamic and dynamic states of the large-scale environments in which TSs are formed and propagate (e.g., see the reviews in Landsea 2000 and Chan 2005). One of the important large-scale environments that affect the position of tropical storm genesis is the monsoon trough (Gray 1979; McBride 1995). It can increase low-level vorticity and provide a favorable environment for the...
growth and development of tropical storms. A statistical analysis of the classifiable genesis proposed by Ritchie (1995) indicated that more than 75% of tropical cyclone genesis occurred in the monsoon trough.

Chen et al. (1998), Chia and Ropelewski (2002), Wang and Chan (2002) and Chen et al. (2006) all noticed that during El Niño (La Niña) years, the warm sea surface temperature (SST) and monsoon trough extend (retreat) southeastward (westward). These conditions provide a favorable environment for the formation and development of tropical cyclone in the southeast (northwest) region of the WNP during El Niño (La Niña) years (Chia and Ropelewski 2002; Wang and Chan 2002). The shift in the location of TS formation associated with ENSO events may indirectly influence the intensity (Chan and Liu 2004; Camargo and Sobel 2005) and life span of the tropical storm (Wang and Chan 2002). Tropical storms tend to have longer life spans (Wang and Chan 2002), and are stronger during El Niño years (Chan and Liu 2004; Camargo and Sobel 2005).

While shifts in genesis location, longer life span and greater intensity of TS during El Niño years appear to be related, and the relationship and interaction between the mean flow environment and tropical storm characteristics are not fully understood (Camargo and Sobel 2005). Camargo and Sobel (2005) suggested that the variation in TS intensity might be due, in part, to other effects of ENSO on the mean regional climate of the WNP. The numerical experiments performed by Li (2006) indicate that in the absence of perturbation convective heating and convection-frictional convergence feedback, summer mean flow alone is unable to lead to the synoptic-scale perturbation growth.

To understand the interaction between the mean flow environment and transient eddies, this study investigated the energy processes between the tropical mean flow and the tropical eddies including tropical storms during different ENSO phases. Following the pioneer work of Lorenz (1955), who developed the concept of available potential energy (APE), the traditional energy form is decomposed into zonal mean flow and deviations from it, as eddies. It has been widely applied to investigate the general circulation of atmosphere for closed systems (e.g., Lorenz 1967; Oort 1964; Hu et al. 2004), extratropical cyclones (Kung 1977; Robertson and Smith 1983) and African easterly wave (Norquist et al. 1977; Hsieh and Cook 2007) for open systems. On the other hand, fewer studies have partitioned the kinetic and available potential energy in the time domain to understand the energy conversions between the time-mean flow and transient mode for open domains. Based on the three-dimensional eddy kinetic energy (KE) analysis and the simplified two-dimensional eddy APE budget equation partitioned in the time domain within a limited region, Lau and Lau (1992) noted that the local barotropic energy conversion between the mean flow and transient eddies at low-levels could intensify the 3–10 day transient eddies associated with tropical cyclogenesis. Using the perturbation KE and APE tendency equations in a manner similar to that of Lau and Lau (1992), Maloney and Dickinson (2003) found that both the barotropic and baroclinic energy conversions increase during the Madden and Julian oscillation (MJO) westerly phase, which favor the eddy growth and tropical cyclone formation.

In the tropics, both Walker circulation and Hadley cell change significantly during ENSO warm and cold years. The modulation of Walker circulation associated with ENSO may not be represented by the zonal mean process which precludes longitudinal variation. It may be appropriate to divide the energy forms into time mean and eddy energy forms for investigating the interaction between background mean flow and the development of transient disturbances including tropical storms. Thus, the three-dimensional eddy KE and APE energy budget equations partitioned in the time domain were applied in this study to investigate the energy processes over the WNP during ENSO warm and cold phases. The data and analytical method are described in section 2. The three-dimensional eddy kinetic energy (EKE) and eddy available potential energy (EAPE) budget equations applied in this study are presented in section 3. The results of the interannual variability of large-scale circulations and tropical storms over the WNP are presented in section 4. The energy processes for generation and maintenance of the APE and KE of eddies are examined in section 5. A summary of eddy energetics is presented in section 6.

2. Data and analysis methods

2.1 Data

The National Centers for Environmental Prediction (NCEP)—Department of Energy (DOE) re-
analyses (Kanamitsu et al. 2002) from 1979 to 1998 were used in this study to examine large-scale circulations and eddy energetics over the WNP. The horizontal resolutions of these thermodynamic and dynamic variables are 2.5° longitudes by 2.5° latitudes. These data are utilized at 17 pressure levels, ranging from 1000 hPa to 10 hPa. The monthly Sea Surface Temperature (SST) with 2° × 2° resolution obtained from the NCEP-NCAR (Reynolds and Smith 1994) was also adopted in this study for classification of ENSO events.

The 6-hourly best track data of tropical cyclones published by the Joint Typhoon Warning Center (JTWC 2008) were obtained for examination of the interannual variability of TS activity over the WNP. Only those tropical cyclones with a maximum wind speed of at least 17 m/s (intensity of tropical storms) were considered in the calculation of TS frequency and other TS activity indices.

2.2 Classification of warm and cold ENSO years

Wang and Chan (2002) found that the relationship between TS activity and the Pacific SST depends on the location of SST anomalies. Among different Niño indices, the Niño3.4 sea surface temperature anomaly (SSTA) is better correlated with TS activity over the WNP, because the occurrence of organized convection depends on the total SST and SST gradient, rather than on the SST anomaly itself. In addition, they found that the correlation between the interannual variability of tropical storms over the WNP and Niño3.4 SSTA has a strong seasonal dependence. During TS peak season (July–September), TS activity is closely related to Niño3.4 SSTA during July–September, although the ENSO forcing is strongest during the winter (Wang and Chan 2002; Chan 2005). Therefore, the ENSO classification in this study was stratified by the July–September SSTA in the Niño3.4 region into warm years (SSTA ≥ 0.8 standard deviation), cold years (SSTA ≤ −0.8 standard deviation) and normal years (−0.8 standard deviation < SSTA < 0.8 standard deviation). Based on these criteria, four major warm (1982, 1987, 1991, 1997) and cold (1981, 1985, 1988, 1998) years were identified during the period from 1979 to 1998.

3. Diagnostic energy equations

3.1 Eddy kinetic and available potential energy budget equations

The diagnostic tool adopted in this study is a primitive equation (PE) form of the three-dimensional eddy kinetic energy and available potential energy equations for an open system. To investigate meridional, as well as longitudinal, variation associated with ENSO, we used the concept of available potential energy developed by Lorenz (1955), but partitioned the kinetic and available potential energy into the time domain. The eddy kinetic energy (EKE, $K'$) and the eddy available potential energy (EAPE, $A'$) can be expressed as (1) and (2), respectively.

$$K' = \frac{1}{2}(u'^2 + v'^2)$$  
(1)

$$A' = \frac{c_p}{2\gamma} \frac{T'^2}{\Gamma}$$  
(2)

In the above expression, the symbol “—” represents the time mean from July to September, while “’” is the deviation from the July–September time mean. The variables $u$ and $v$ are the eastward and northward components of the winds, respectively. “[ ]” represents the global average and “’” represents the deviation from the global average. $T$ is the temperature and $c_p$ is the specific heat at constant pressure. $\gamma$ is defined as $\Gamma_d/\Gamma$, and $\Gamma_d = g/c_p$ and $\Gamma = -\partial T/\partial z$ are dry-diabatic and environmental lapse rates, respectively.

To derive the EKE and EAPE energy equations, we first multiplied the eddy momentum equations by $u'$, $v'$ and thermodynamic equation in $\theta$ form by $(\Omega F)^2 c_p T_{\theta}'\theta_{\theta}'$, respectively. Then, we added the two momentum equations associated with the eddy kinetic energy equation and applied both the continuity and hydrostatic equations to the resulting equations. Finally, the budget equations of EKE and EAPE for an open system can be written as equations (3) and (4), respectively, which are similar to those from Oort (1964), but include boundary flux terms.

$$\frac{\partial K'}{\partial t} = \left(\nabla' \cdot \left(\nabla' V_3 \right)\right)_{\text{CK}} - \frac{R}{\rho} \frac{T'}{\omega'}_{\text{CE}}$$  
(3)

$$- V_3' \cdot V_3 K' - V_3' \cdot V_3 K'$$

$$- V_3' \cdot (V_3' \phi') + D$$
\[
\frac{e^2A}{e^2t} = -\frac{\epsilon_p}{\gamma} \left[ T' \cdot (V' \cdot \nabla)T + \left( \frac{P}{F_0} \right)^{\kappa} T\omega^3 \frac{\partial \theta}{\partial \rho} \right]_{CA} + \frac{R}{P} T\omega^3 \left[ V' \cdot \nabla_a V' - \nabla_a (\nabla_a V') \right]_{BA'} + \frac{\gamma}{\gamma} T'\mathcal{Q}'_{GA'}
\]

where \( t \) is time, \( V \) is the horizontal velocity vector, and \( \nabla \) is the horizontal gradient operator (the suffix \( 3 \) presents the three-dimensional components), \( \omega = \frac{dP}{dt} \) vertical velocity, \( P \) is pressure, \( \theta \) is geopotential, \( \Theta \) is potential temperature, \( \kappa \equiv R/\epsilon_p \), and \( Q \) is diabatic heating rate.

The physical mechanisms of the eddy energy generation and conversion processes can be explained as follows. The term, \( CK \), represents the eddy barotropic energy conversion from mean kinetic energy (MKE) to EKE. \( CE \) is referred to as eddy baroclinic energy conversion from EAPE to EKE. This term is identical to the generation of EKE in a closed system. For an open domain in the present study, \( CE \) can be regarded as the sum of the generation of EKE and \( B\theta/\Theta \), where term \( B\theta/\Theta \) represents the boundary flux by eddy geopotential. Terms \( BK' \) and \( BA' \) indicate the boundary flux terms of eddy kinetic energy and eddy available potential energy by the mean flow and eddies, respectively. \( D \) presents EKE dissipation by frictional and subgrid-scale effects. \( CA \) is the energy conversion from MAPE to EAPE. Only the horizontal component of this term was used in the study by Lau and Lau (1992). In contrast, the present study compared the contributions from the horizontal and vertical components of this term. \( GA' \) represents the generation of EAPE. Diabatic heating, \( Q \), of this term was estimated from the thermodynamic energy equation.

The matter of greatest interest in this study is the source of eddy kinetic energy and eddy available potential energy associated with transient eddy formation and development. Thus, we focused on the eddy kinetic and available potential energy generation and conversion processes, including \( CK \), \( CE \), \( CA \) and \( GA' \).

### 3.2 Energetics of high- and low-frequency eddies

To focus on the energy generation and conversion processes of synoptic-scale disturbances which may closely link to TS activity, the total transient eddies are further partitioned into high-frequency disturbances with periods below 10 days and low-frequency disturbances with periods of 20–70 days. The former is dominated by the synoptic-scale disturbances including TSs. The latter is suggested as an important factor on the development of TSs (e.g. Maloney and Dickinson 2003). For convenience, the high- and low-frequency transient eddies are donated by superscripts \( h \) and \( l \), respectively.

If the product of high- and low-frequency components approaches zero after integration over a long-time interval (Example: \( \overline{u^l v^h} = 0 \)), the eddy energy budget equations for individual scales can be obtained. This is generally true for two orthogonal components at different scales. In this study, the transient eddies are partitioned into high- and low-frequency transient eddies by an orthonormal wavelet transform (Daubechies 1988). Then, the partitioned form of eddy generation and conversion terms for high- and (low-) frequency transient eddies can be expressed as:

\[
CK^h(CK^l) = V^h \cdot (V'^h \cdot \nabla_3) \overline{(V'^l \cdot (V'^l \cdot \nabla_3) V^l)}
\]

\[
CE^h(CE^l) = \frac{R}{P} \overline{T^h \omega^h} \left( \frac{R}{P} \overline{T^l \omega^l} \right)
\]

\[
CA^h(CA^l) = -\frac{\epsilon_p}{\gamma} \left[ T^h \cdot (V^h \cdot \nabla)T^l + \left( \frac{P}{F_0} \right)^{\kappa} \overline{T^h \omega^h \frac{\partial \theta}{\partial \rho}} \right] + \left( \frac{P}{F_0} \right)^{\kappa} \overline{T^h \omega^h \frac{\partial \theta}{\partial \rho}} \overline{T^l \omega^l \frac{\partial \theta}{\partial \rho}} + \left( \frac{P}{F_0} \right)^{\kappa} \overline{T^h \omega^h \frac{\partial \theta}{\partial \rho}} \overline{T^l \omega^l \frac{\partial \theta}{\partial \rho}}
\]

\[
GA^h(GA^l) = \frac{\gamma}{\gamma} \overline{T^h \mathcal{Q}^h} \left( \frac{\gamma}{\gamma} \overline{T^l \mathcal{Q}^l} \right)
\]

The term \( CK^h(CK^l) \) indicates the barotropic energy conversion between MKE and high-frequency (low-frequency) EKE, while the term \( CE^h(CE^l) \) represents the conversion from high-frequency (low-frequency) EAPE to EKE. \( CA^h(CA^l) \) and \( GA^h(GA^l) \) are the energy conversion from MAPE to high-frequency (low-frequency) EAPE conversion and the generation of high-frequency (low-
frequency) EAPE, respectively. The energy generated by high- or low-frequency transient eddies and their interactions with seasonal mean circulations could be explored in this study by examining these partitioned forms of energy conversion and generation terms.

4. Interannual variation of large-scale circulation and TS activity

The characteristics and interannual variation of large-scale circulation and TS activity during warm and cold ENSO years are investigated in this section. The TS activity examined in this study includes TS frequency, TS formation frequency, TS number, accumulated cyclone energy (ACE), TS life span and TS intensity. TS frequency is determined by the number of tropical storms passing over a $2.5^\circ \times 2.5^\circ$ grid box. The TS formation frequency is the number of TS genuses in each grid box of $2.5^\circ$ latitude by $2.5^\circ$ longitude. Genesis is defined as the first point for all named TS cases in the JTWC record. The definition of the ACE index (Bell et al. 2000) is the sum of the squares of the maximum sustained wind speed for all periods during which the TSs are in the WNP basin (here defined as the region between $120^\circ$E–$170^\circ$W and $0^\circ$–$40^\circ$N). TS life span was counted by the total length of time from the first point to the last point for a named TS case in the JTWC record. The maximum surface wind speed of each TS during its entire life span was used to represent TS intensity.

Figure 1 depicts the frequency of tropical storms, SST and 850 hPa wind fields for warm and cold composites, respectively. Two prominent TS tracks, which were defined as the axes of the maximum and secondary maximum TS frequencies, are superimposed on Figs. 1a–c. The primary TS tracks coincided with the monsoon trough during both warm and cold years (Figs. 1a, b). This result indicates that the monsoon trough, which is a low pressure region characterized by positive relative vorticity (not shown), is a vital factor for TS formation and development (Holland 1995).

The large-scale circulations, including the monsoon trough over the WNP, undergo significant interannual variability associated with ENSO variation. During warm years, the monsoon trough and warmest SST region extend southeastward (Figs. 1a, d), while the monsoon trough and warm SST region retreat westward during the cold years (Figs. 1b, e), similar to the finding of Chen et al. (1998). A strong low-level westerly appears and stretches from the Bay of Bengal to the central Pacific along $5^\circ$–$15^\circ$N during warm years (Fig. 1d). Thus, the westerly and easterly converge between $5^\circ$–$10^\circ$N in the tropical central Pacific. In contrast, during cold ENSO years, the westerly retreats to the west of $120^\circ$E, while the equatorial easterly strengthens and prevails over the WNP (Fig. 1e). Hence, the easterly and westerly convergence region between $5^\circ$–$10^\circ$N migrates eastward during warm years, but westward during cold years. Accompanied by the eastward extension (westward retreat) of the monsoon trough and convergence region, the frequency of TS over the region from $150^\circ$E to the date line dramatically increases (decreases) during the warm (cold) ENSO years (Figs. 1a, b), as discussed by Chen et al. (1998).

The differences in frequency of tropical storms, SST and circulation between the warm and cold years are shown in Figs. 1c, f. An anomalous cyclonic (anticyclonic) circulation occurs to the northwest of warm (cold) SST anomalies over the central Pacific (western Pacific) (Figs. 1c, f). These atmospheric responses associated with the SST anomalies are similar to Gill’s (1980) solution with a Rossby wave pattern. However, the strong anomalous westerly jet stream that appears along $0^\circ$–$15^\circ$N may also induce cyclonic shear to the north of the jet. The cause of this anomalous westerly jet remains unclear. It may be related, in part, to the anomalous cyclonic circulation and the anomalous Walker circulation (Fig. 2), which is confined to the equator with ascending motion over the eastern Pacific and descending motion over the western Pacific.

The low-level cyclonic vorticity (Fig. 3a) induced by the anomalous westerly jet and cyclonic circulation might be beneficial for the moisture convergence and convection north of the jet. Thus, the enhanced seasonal mean diabatic heating and ascending motion occur north of the jet during warm years (Fig. 3b). These seasonal mean diabatic heating and ascending motions might provide favorable conditions for the southward and eastward extension of the TS formation region from the tropical western Pacific to the central Pacific during warm years (Fig. 3a). On the other hand, the anomalous anticyclonic vorticity, diabatic cooling and descending motion that appear north of $20^\circ$N may restrict the formation of tropical storms in this region (Figs. 3a and 3b).

Once the TSs form in the southeastern part of the WNP during warm years, they tend to be long-lived
and have greater intensity over the ocean (Table 1), which is in agreement with the results of Wang and Chan (2002). The ACE, which represents the combined effect of the number, life span and the strength of TS, was also significantly greater during warm years than during cold years, similar to the findings of Camargo and Sobel (2005). However, TS numbers over the entire WNP during warm
years were only slightly greater than during cold years (Table 1). This feature has been noticed by Wang and Chan (2002) who found that the interannual variation in TS formation number is insignificant even between strong warm and cold ENSO years. The mechanisms responsible for tropical storm genesis and development might be different. The relationship between the seasonal mean environments and interannual variability of TS activities over the WNP with regard to eddy energetics will be explored in the next section.

5. Eddy energetic results

5.1 Diagnosis of eddy kinetic energy

The horizontal distributions of the vertically integrated kinetic energy for total, mean flow and eddy during the period from July to September for warm minus cold composites are shown in Fig. 4. Total kinetic energy increases significantly over almost the entire western North Pacific during warm years (Fig. 4a). Comparing the mean kinetic energy (MKE) in Fig. 4b and eddy kinetic energy (EKE) in Fig. 4c with the total kinetic energy, it is obvious that the increase in total kinetic energy is primarily associated with the increase in EKE. The increment

Table 1. Interannaul variations in TS number, ACE, life span and maximum wind speed for the JTWC best-track data. The numbers shown are the values of TS activity indices for warm and cold years, as well as the ratio between warm and cold years.

<table>
<thead>
<tr>
<th>TS activity indices</th>
<th>W</th>
<th>C</th>
<th>W/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>54</td>
<td>49</td>
<td>1.10</td>
</tr>
<tr>
<td>ACE ($10^4$ m$^2$/s$^2$)</td>
<td>55.14</td>
<td>25.41</td>
<td>2.17</td>
</tr>
<tr>
<td>Lifespan (day)</td>
<td>9.75</td>
<td>6.59</td>
<td>1.48</td>
</tr>
<tr>
<td>Max wind (m/s)</td>
<td>47.57</td>
<td>37.46</td>
<td>1.27</td>
</tr>
</tbody>
</table>
in MKE is much less than that of EKE (Fig. 4c). In addition, MKE decreases in the region south of 10°N. The decrease in MKE may be partially due to the decrease in wind speed that results from the out-of-phase relationship between the anomalous westerly jet and prevailing easterly, as discussed in the previous section (Fig. 1f). To further explore the processes responsible for the enhanced EKE during warm ENSO years, which might contribute to transient eddies including TSs activity, the source of the EKE was examined.

Figure 5 depicts the vertically integrated eddy barotropic and baroclinic conversions superimposed with the TS primary track. During warm years, both the eddy barotropic and baroclinic energy conversions are positive in the region extended from the Philippine Sea (130°E–150°E) to the date line (Figs. 5a, d), consistent with the eastward extension of the low-level westerly and convergence (Fig. 1d). These results are similar to those reported by Lau and Lau (1992) who demonstrated that the major energy sources for summertime synoptic-scale disturbances over the WNP are the barotropic and baroclinic energy conversions. However, during cold years, the positive barotropic energy conversion is confined to regions west of 140°E, in accordance with the westward retreat of the westerly jet (Fig. 1e). Negative values of barotropic conversion appear in the regions east of 150°E (Fig. 5b), which may be unfavorable for the formation of TS. Indeed, TS formation is restricted to regions west of 150°E during cold ENSO years.

As tropical storms propagated northward into subtropical regions over the western Pacific, the barotropic energy conversion became negative for both warm and cold years (Figs. 5a, b). This might weaken the tropical storms. Eddy baroclinic energy conversion plays an important role in the maintenance of eddy growth in the subtropical and mid-latitude regions (Figs. 5d, e), as reported by Kung (1977). This implies that the eddy baroclinic energy effect may strongly impact subsequent TS development. Emanuel et al. (2004) suggested that baroclinic effects may be important for the late development of hurricane intensity.

Figs. 5c, f show the differences in eddy barotropic and baroclinic energy conversions between warm and cold years, respectively. Apparently, both the enhancement of eddy barotropic and baroclinic energy conversions contribute to the growth of EKE in the region extending from the Philippine Sea (130°–150°E) to the date line during warm ENSO years. This might lead to the southeastward extension of the TS formation region, as well as the intensification of the TS from the Philippine Sea to the date line during warm years. However, the eddy barotropic energy conversion is more negative over the subtropical regions of the western Pacific during warm years than during cold years. This indicates that the seasonal mean environments are unfavor-
able for the development of eddy including TS during warm years over the subtropical WNP. Again, eddy baroclinic energy conversion plays an important role in the maintenance and subsequent development of eddies as they propagate northward to the subtropical and mid-latitude regions.

Fig. 5. Distribution of vertically integrated eddy barotropic energy conversion (Wm$^{-2}$) for (a) warm composites, (b) cold composites and (c) warm minus cold composites. (d)–(f) are same as (a)–(c), but for the eddy baroclinic energy conversion (Wm$^{-2}$). The black and gray arrows are the TS primary tracks of warm and cold composites, respectively.
Zonal (10°–15°N averaged) vertical cross sections of eddy barotropic and baroclinic energy conversions over the TS formation and early-development regions for warm minus cold composites are shown in Fig. 6. Eddy barotropic conversion increased significantly at low levels and coincided with the enhanced low-level westerly jet along 5°–15°N (Fig. 6a). The enhancement and eastward extension of the positive barotropic energy conversion associated with the low-level westerly jet and cyclonic circulation during warm years play a crucial role in eddy growth at low-levels within both the TS formation and early-development regions (Fig. 6a). In contrast to the barotropic energy conversion, eddy baroclinic energy conversion increases significantly at upper levels (Fig. 6b), in agreement with the results of Lau and Lau (1992). This anomalous eddy baroclinic energy conversion at upper levels may enhance the synoptic-scale activity at upper levels (e.g., Lau and Lau 1992; Tam and Li 2006). However, the direct effect of the surface heat flux associated with ENSO forcing on eddy baroclinic energy conversion in the lower troposphere is less evident. This phenomenon might result from the small amplitude of vertical motion. Latent heat release at upper levels is more efficient for eddy baroclinic energy conversion.

Eddy baroclinic energy conversion depends on the covariance between transient eddy temperature and transient eddy vertical motion. They tend to be positively correlated in time over the entire WNP for both warm and cold ENSO years (Figs. 5d, e). However, transient eddy temperature and transient eddy vertical motion along the TS track during warm ENSO years are greater than during cold ENSO years (not shown). The intensification of the seasonal mean diabatic heating and ascending motion over the TS formation and early developing region during warm ENSO years may provide a favorable condition for the enhancement of warm eddy temperature and eddy upward motion at upper levels over these regions (Figs. 3b, 6b).

To examine the relative importance of the eddy momentum transport associated with eddy barotropic energy conversion, each term of the barotropic energy conversion was investigated. Fig. 7 displays the spatial distributions of vertically integrated barotropic energy conversion for each term. Because the magnitudes of $-\bar{u}'\bar{v}'\frac{\partial T}{\partial z}$ and $-\bar{v}'\bar{q}'\frac{\partial T}{\partial z}$ are much smaller than the other terms (not shown), these two terms are not depicted in Fig. 7. The enhanced barotropic energy conversion over the TS formation and early development regions during warm years is mainly contributed by the terms, $-\bar{u}'\bar{v}'\frac{\partial T}{\partial z}$ and $-\bar{w}'\bar{q}'\frac{\partial T}{\partial z}$ (Fig. 7a, b). The former is related to the strong zonal wind convergence ($\frac{\partial u}{\partial z} < 0$) induced by the enhancement and eastward extension of the low-level westerly jet and monsoon trough at low levels associated with the warm ENSO years. Both the zonal wind convergence...
and EKE over these regions during warm years are stronger than those during cold years (not shown). The importance of this term supports disturbance growth via wave accumulation mechanism (Sobel and Bretherton 1999; Kuo et al. 2001; Tam and Li 2006). Meanwhile, the latter is induced by the increment in cyclonic shear anomalies \( \frac{\partial q}{\partial y} < 0 \) associated with the strengthened low-level westerly and monsoon trough at low levels. This result indicates that the enhancement and eastward extension of the low-level westerly and monsoon trough induce a favorable environment for eddy barotropic energy conversion and wave accumulation during warm ENSO years.

The term \(-\overline{u'\partial q'/\partial y}\) associated with the eddy vertical momentum transport also increases in the westerly jet stream region between 5°–10°N (Fig. 7d) at low levels during warm years. This effect not only generates eddy kinetic energy, but also reduces vertical wind shear of the mean circulation, which, in turn, may provide an environment with low vertical wind shear during the warm ENSO years.

### 5.2 Diagnosis of eddy available potential energy

Based on the analysis of EKE budgets in the previous subsection, eddy barotropic and baroclinic energy conversions are responsible for the growth of EKE during warm years. Once the eddy available potential energy (EAPE) converts to EKE, it has to be replenished by other mechanisms. In this subsection, we will inspect the two major energy processes that supply EAPE. One is energy conversion from MAPE to EAPE via eddy horizontal and vertical heat transport associated with the mean flow temperature gradients (Figs. 8a–c). The other is the generation of EAPE through either the heating over warm areas or cooling over cold regions (Figs. 8d–f). Apparently, the primary source of the EAPE is the generation of EAPE, which is consistent with many previous studies of tropical disturbances (e.g., Norquist et al. 1977; Lau and Lau 1992; Maloney and Dickinson 2003; Hsien and Cook 2007). However, energy conversion from
MAPE to EAPE is significant over the WNP during both warm and cold years, although the horizontal temperature gradient in the tropics is small. In addition, both the MAPE to EAPE energy conversion and generation of EAPE increase along the TS track during warm years (Figs. 8c, f). These results suggest that the loss of EAPE to EKE through the eddy baroclinic energy conversion is furnished by both the generation of EAPE and the MAPE to EAPE energy conversion.
The question arises how the energy conversion from MAPE to EAPE is positive in the tropical region where the horizontal temperature gradient is small. Comparison of the relative contributions of the horizontal and vertical components of this energy process (Figs. 9a, b) reveals that the enhancement of energy conversion from MAPE to EAPE results mostly from the vertical component. The horizontal component of this energy process changes slightly or decreases during warm ENSO years. It is worth noting that the vertical component of this energy process is excluded in the two-dimensional EAPE equation used by Lau and Lau (1992) and Maloney and Dickinson (2003). Eddy vertical heat transport may play an important role in the maintenance of EAPE over the tropical WNP during warm years.

5.3 Energetics of high- and low-frequency transient eddies

The energy generation and conversion process of high-frequency eddies with periods below 10 days and low-frequency disturbances with periods of 20–70 days are further investigated in this subsection. The distribution of energy generation and conversion process of high- and low frequency eddies generally resemble those of total sub-seasonal transients discussed in previous subsections 5.1. For brevity, only warm minus cold composites are displayed in this subsection.

Figures 10a, c depict the high-frequency eddy barotropic and baroclinic energy conversions for warm minus cold composites superimposed with the major TS track. Both $CK_h$ and $CE_h$ enhance in the region extending from the Philippine Sea to the date line during warm ENSO years, in agreement with Lau and Lau (1992). This indicates that the eastward extension of the monsoon trough, westerly jet and mean convergence area associated with warm ENSO are favorable for the growth of high-frequency disturbances from $130^\circ$E to $180^\circ$E during warm years.

Again, synoptic-scale eddies convert more kinetic energy to mean flow as they propagated northward to subtropical and mid-latitude regions (Fig. 10a). The enhancement of subsequent development of TS in subtropical and mid-latitude regions during warm years is mainly contributed by eddy baroclinic energy conversion (Fig. 10c). It is suggested that baroclinic effect may play an important role on the late development of TSs, in agreement with the hypothesis of Emanuel et al. (2004).

The enhancement of EAPE for high-frequency eddies during warm years is mainly contributed by the generation of EAPE through latent heating associated with high-frequency eddies (compare Figs. 10b, d). The interannual variation of MAPE to EAPE conversion for high-frequency eddies is small (Fig. 10b). This feature of high-frequency eddies is different from that of total transient eddies. Although MAPE to high-frequency EAPE during both warm and cold years are not small, they are comparable (not shown) which leads to the small interannual variation of MAPE to EAPE conversion.

The seasonal mean environments convergence associated with warm ENSO is also favorable for
the enhancement of low-frequency eddy barotropic and baroclinic energy conversions from 130°E to 180°E during warm years (Figs. 11a, c). In addition, the enhancement of low-frequency EAPE during warm years is contributed by both $CA^f$ and $GA^f$ (Figs. 11b, d). It is interesting to note that the effect of vertical heat transport associated with MAPE to EAPE is important to the interannual variation of low-frequency eddies by using the three-dimensional energy budget equations. On the other side, the interannual variation of seasonal mean vertical temperature gradient which is related to the static stability is significantly modulated by the low-frequency eddies.

The direct EKE and EAPE conversion from seasonal mean circulation to low-frequency eddies are generally larger than that of high-frequency eddies during warm ENSO years (Figs. 11a, c). It is likely that the enhancement of low-frequency eddies during warm ENSO years may further induce the interaction between the low- and high-frequency eddies. Many studies have suggested that the intra-seasonal oscillation (ISO) strongly impacts the circulation of tropical depression (TD)-like disturbances (e.g., Maloney and Dickson 2003). On the other hand, TD-like disturbances may be responsible for a portion of the circulation changes associated with the ISO (Straub and Kiladis 2003). This implies that the interaction between ISO and TD-like disturbances may directly modulate the ISO signal, which in turn may indirectly modulate the seasonal mean circulation. Monsoon trough and

Fig. 10. Horizontal distribution of vertically integrated (a) barotropic energy conversion, (b) MAPE to EAPE conversion, (c) baroclinic energy conversion and (d) EAPE generation of high-frequency eddies for warm minus cold composites. Unit: Wm$^{-2}$. 

<Warm minus Cold>
anomalous westerly jet might be directly and indirectly influenced by the high- and low-frequency eddies. The complex relationship among seasonal mean circulation, ISO and TD-like disturbances associated with ENSO needs to be further studied.

6. Summary

ENSO has been suggested as an important mechanism responsible for the interannual variability in TS activity over the WNP by modulating the large-scale environments in which the tropical storms are formed and develop (e.g., Wang and Chan 2002; Chia and Ropelewski 2002; Camargo and Sobel 2005). This implies that the relationship between ENSO and TS involves interactions among ENSO, large-scale circulation and TS that are complicated and not fully addressed. This study explored this issue through the three-dimensional primitive equation (PE) form of eddy kinetic and available potential energy diagnostics. The classification of warm and cold ENSO years in this study for composite analysis was based on the July–September averaged SST anomaly in the Niño3.4 region (Wang and Chan 2002). Consistent with previous studies (e.g., Chen et al. 1998; Chia and Ropelewski 2002; Wang and Chan 2002), the tropical storm formation region extends southeastward accompanied by southeastward extension and intensification of the monsoon trough and westerly jet during warm ENSO years. Meanwhile, the TSs are stronger and have longer life spans, which lead to the increase of accumulated cyclone energy (ACE).
during warm years, as previously reported by Camargo and Sobel (2005).

From the energy point of view, the intensification and eastward extension of the westerly jet and monsoon trough during warm ENSO years establish a favorable environment for eddy barotropic conversion at low levels and eddy baroclinic energy conversion at upper levels for both high-frequency (<10 days) and low-frequency (20–70 days) eddies between the Philippine Sea (130°–150°E) and the date line. Thus, the EKE increases over the region of vigorous TS activity from the Philippine Sea (130°–150°E) to the date line during warm years.

Figure 12 illustrates the mechanisms responsible for the growth of EKE over the WNP during both the TS formation and eastward-propagating stages (Fig. 12a) and the northward-propagating stage (Fig. 12b). During warm ENSO years, an anomalous low-level cyclonic flow to the northwest of warm SST anomalies and the anomalous westerly jet, which is associated with anomalous Walker circulation, extend from the Philippine Sea (130°–150°E) to the central Pacific (Fig. 12a). Such mean environments with enhanced mean zonal wind convergence \( \frac{\partial \bar{\mathbf{u}}}{\partial x} < 0 \) and cyclonic shears \( \frac{\partial \bar{\mathbf{v}}}{\partial y} < 0 \) are favorable for the two barotropic energy conversion processes \( -\bar{\mathbf{u}}'\mathbf{u}' \frac{\partial \bar{\mathbf{u}}}{\partial x} \) and \( -\bar{\mathbf{v}}'\mathbf{v}' \frac{\partial \bar{\mathbf{v}}}{\partial y} \) of high- and low-frequency eddies during warm years. Thus, these two eddy barotropic processes of high-frequency eddies significantly increase during both the TS formation and early-development stages. The increase in the former over the TS formation region supports the wave accumulation mechanism (Sobel and Bretherton 1999; Kuo et al. 2001; Tam and Li 2006).

The anomalous cyclonic circulation and westerly jet associated with the warm ENSO are also beneficial for the eastward extension of mean upward motion and establishment of tropical convection to the north of the westerly jet from the Philippine Sea (130°–150°E) to the date line (Fig. 12a). Thus, positive eddy baroclinic energy conversion from EAPE to EKE appears from the Philippine Sea (130°–150°E) to the date line during warm years. The greatest eddy baroclinic energy conversion occurs at the upper levels, which is consistent with the study of Lau and Lau (1992). This result indicates that eddy baroclinic energy conversion is mainly supplied by the latent heat release associated with cumulus convection in the WNP and central Pacific regions (Lau and Lau 1992; Maloney and Dickinson 2003).

As high- and low frequency transient eddies propagate to 130°–140°E (Fig. 12b), they start to propagate northward, and encounter anomalous anticyclonic circulation and descending motion in
the subtropical and mid-latitude regions (Fig. 12b). Both high- and low frequency transient eddies lose eddy kinetic energy to mean flow. Such mean environments in the subtropical and mid-latitude regions are unfavorable for the subsequent development of tropical storms (Fig. 12b). The subsequent development and intensification of tropical storms are mainly attributed to the enhanced eddy baroclinic energy conversion through eddy ascending motion in warm regions and descending motion in cold regions as they propagate northward into subtropical and mid-latitude regions, consistent with the results of Kung (1977). It is suggested that the baroclinic effects play an important role in TS intensity during the late stages of development, which is in support of the hypothesis of Emanuel et al. (2004).

Once EAPE of high- and low frequency eddies is converted to EKE, the loss of EAPE due to conversion is mainly replenished by the generation of EAPE through the condensation heating associated with eddy convection. These results are similar to the findings of Lau and Lau (1992) and Maloney and Dickinson (2003) who used a two-dimensional EAPE budget equation. However, the magnitude of energy conversion from MAPE to EAPE is comparable to the EAPE generation through a three-dimensional EAPE budget equation in this study, despite that the horizontal mean temperature gradient in the tropics is small. The MAPE to EAPE energy conversion process is mainly contributed by its vertical component associated with eddy vertical heat transport. These results suggest that the eddy vertical heat transport by high- and low-frequency eddies, which is neglected in the two-dimensional EAPE budget equation (Lau and Lau 1992; Maloney and Dickinson 2003), plays an essential role in the maintenance of EAPE over the tropical storm formation and development regions.

The anomalous mean circulations and corresponding eddy barotropic and baroclinic energy conversions modulated by ENSO events may explain the coincidence of the eastward displacement of the monsoon trough, westerly jet and TS formation region (e.g., Chen et al. 1998; Chia and Ropelewski 2002; Wang and Chan 2002; Chen et al. 2006). However, the subsequent development and intensification of high-frequency transient eddies, particularly as they propagate northward into subtropical and mid-latitude regions, are mainly attributed to the enhanced eddy baroclinic energy conversion. It is suggested that tropical high-frequency transient eddies including tropical storms may be self-developing and intensify through both their latent heat release and vertical heat transport.

Enhanced latent heating associated with warm ENSO episodes may directly enhance the low-level cyclonic vorticity and convergence by the eddy baroclinic energy conversion and indirectly increase the baroclinicity (temperature gradient) and upward motion. The latter in turn may enhance both the latent heating and vertical heat transport. This positive feedback between convection and circulation continuously may provide energy for the development of transient eddies.

This study illustrates the importance of wave-mean interaction on the enhancement of high- and low-frequency eddies including TSs during warm ENSO years. On the other side, monsoon trough and anomalous westerly jet are modulated by the high- and low-frequency eddies. The simultaneous occurrence of ENSO-related anomalous SST, mean circulations and high- and low-frequency eddies makes it difficult to clarify the active and passive roles of ENSO, mean circulation and high- and low-frequency eddies. The interaction between the high-frequency and low-frequency eddies, which involves triple products in terms of energy, may also enhance the TS activity during warm ENSO years. To explore these issues in greater depth, the wave-wave interaction, the active and passive roles of anomalous SST, large-scale circulation and tropical storms will be investigated using numerical experiments.

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