Propagation and Maintenance Mechanism of the TC/Submonthly Wave Pattern and TC Feedback in the Western North Pacific

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ABSTRACT

Propagation and maintenance mechanisms of the tropical cyclone/submonthly wave pattern in the western North Pacific are explored. The wave pattern exhibited an equivalent barotropic structure with maximum vorticity and kinetic energy in the lower troposphere and propagated northwestward in the Philippine Sea in the intraseasonal oscillation (ISO) westerly phase and north-northeastward near the East Asian coast in the easterly phase. The mean flow advection played a dominant role in the propagation in both phases. Barotropic energy conversion is the dominant process in maintaining the kinetic energy of the pattern. The wave pattern tended to occur in the confluent zone between the monsoon trough and the anticyclonic ridge, where the kinetic energy could be efficiently extracted from the westerly mean flow associated with the monsoon trough. The individual circulation circuit embedded in the pattern was oriented northeast–southwest (east–west) to have optimal growth and propagation during the ISO westerly (easterly) phase.

When tropical cyclones (TCs) developed in a development-favorable background flow provided by the submonthly wave pattern, they in turn enhanced the amplitudes of the vorticity and kinetic energy of the submonthly wave pattern by more than 50% and helped extract significantly more energy from the background ISO circulation. This TC feedback was much more significant in the ISO westerly phase because of the stronger clustering effect on TCs by the enhanced monsoon trough.

1. Introduction

The multiscale nature of circulation in the tropical western North Pacific (WNP) has become an interesting subject in recent years (e.g., Holland 1995; Hsu 2005). These multiscale features include monsoon circulation, intraseasonal oscillation (ISO), 3–8-day synoptic waves, and tropical cyclones (TCs). It has been reported in numerous studies that TCs tend to form and develop in the favorable condition provided by the large-scale tropical circulation (e.g., Carr and Elsberry 1995; Chang et al. 1996; Davidson and Hendon 1989; Dickinson and Molinari 2002; Frank and Roundy 2006; Fu et al. 2007; Ge et al. 2007; Krouse et al. 2008; Li and Fu 2006; Li 2006; Shapiro and Ooyama 1990; Sobel and Bretherton 1999). Our previous study (Ko and Hsu 2006, hereafter KH06) discovered a 7–30-day wave pattern that propagates north-northward from the northeast of Papua New Guinea to the area between Taiwan and Japan. The pattern was most active during mid to late summer (July–August) and closely tied to the fluctuation of the monsoon trough/subtropical high system in the WNP. More than 70% of the identified cases were associated with at least one recurving tropical cyclone when the cyclonic circulation in the pattern reached its peak phase near the East China Sea. The cyclonic circulation created a favorable environment (e.g., cyclonic background circulation, stronger moisture convergence, etc.) for recurving tropical cyclones to form, develop, and move along with this wave pattern. This pattern was named the TC/submonthly wave pattern because of its close coupling with TCs and a time scale (7–30 days) longer than the synoptic perturbation.

The ISO in the WNP has a modulating effect on the synoptic system and the TC/submonthly wave pattern...
mentioned above (e.g., Maloney and Dickinson 2003; Liebmann et al. 1994; Ko and Hsu 2009, hereafter KH09). KH09 examined the ISO modulating effect on the TC/submonthly wave pattern. Their results indicated that, in the ISO westerly phase, the TC/submonthly wave pattern was better organized in the cyclonic and moisture-convergence environment of a strong eastward extending monsoon trough, whereas the pattern was loosely organized in the easterly phase when the monsoon trough was weak and retreated westward. It was also shown in their study that the TCs associated with the submonthly wave pattern were more energetic in the ISO westerly phase than in the easterly phase. While the circulation characteristics of the TC/submonthly wave pattern were well explored by KH09, the propagation and maintenance mechanisms were still poorly understood.

Explaining the ISO modulating effect on the tropical disturbances in the WNP in terms of the barotropic dynamics has attracted more attention in the last decade (Hartmann and Maloney 2001; Maloney and Hartmann 2001; Aiyyer and Molinari 2008; Chen and Sui 2010; Hsu et al. 2011). Maloney and Hartmann computed and showed that the westerly jet in the westerly MJO periods provided more kinetic energy for the tropical disturbances to grow. Hsu et al. (2011) also found that the enhanced barotropic energy conversion favored the generation and development of synoptic seed disturbances for cyclogenesis during the ISO active phase. The upscale influence of synoptic perturbations and TCs on the large-scale circulations has attracted more attention in recent years. Hsu et al. (2008a,b) adopted the procedures developed by Kurihara et al. (1993, 1995) and Wu et al. (2002) in removing TCs from the data analysis. They conducted a series of statistical studies and found that TCs contributed significantly to the long-term mean, seasonal mean, and intraseasonal and interannual variance in the 850-hPa vorticity along the TC tracks in the tropical WNP. It was demonstrated that the TC effect could not be removed by long-term averaging and low-pass filtering. A similar upscale feedback from synoptic perturbation to the ISO was also reported by Zhou and Li (2010) and Hsu et al. (2011).

Although the TC effect on the submonthly wave pattern was briefly investigated by KH09, a quantitative assessment was not carried out. In view of the co-existence of TCs and the submonthly wave pattern, an exploration of the TC effect on the submonthly wave pattern should yield valuable information on multiscale interaction in the WNP. The objectives of this study are to 1) explore the propagation and maintenance mechanisms of the submonthly wave pattern and 2) estimate the TC contribution to the mechanisms. Following the previous studies by KH06, KH09, and Hsu et al. (2008a,b), this study pays more attention to vorticity and kinetic energy analysis at 850 hPa. One of the major reasons is that the TC removal procedure was only applied to the 850-hPa wind where the TC vortex in the global analysis was close to the observed TC center. Furthermore, the TC/submonthly wave pattern exhibited largest amplitude in the lower troposphere. Section 2 describes the data and analysis procedures. The results are divided into three parts. The structure and vorticity budget of the TC/submonthly wave pattern are shown in section 3. The kinetic energy and various conversion terms are discussed in section 4. The TC feedback is explored in section 5. Conclusions and discussion are presented in section 6.

2. Data and analysis procedures

The data used in this study were extracted from the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) (Uppala et al. 2005). The ERA-40 contains 6-hourly (0000, 0600, 1200, and 1800 UTC) temperature, humidity, horizontal winds, vertical $p$ velocity, and geopotential on a 2.5° $\times$ 2.5° latitude–longitude grid. This study analyzed the 23-yr data during June–October (JJASO) 1979–2001. A Butterworth band-passed filter (Kaylor 1977; Hamming 1989), following Hsu and Weng (2001), KH06, and KH09, was applied to extract the 7–30-day (submonthly) and 30–80-day (intraseasonal) fluctuations.

A TC removal routine proposed by Kurihara et al. (1993, 1995) in the Geophysical Fluid Dynamics Laboratory hurricane prediction system and Wu et al. (2002) in typhoon simulation was applied to the 850-hPa wind field of the ECMWF analysis to remove the TC wind from the global analysis. This TC-removed dataset is the same as that used in Hsu et al. (2008b). Readers are referred to their papers for details. The procedure is described briefly as follows. The wind fields were decomposed into the basic and disturbance fields. Tangential winds of the TCs (based on the Joint Typhoon Warning Center at Guam) were then detected and removed from the disturbance field and replaced by interpolated winds. The TC-removed disturbance field and the interpolated winds were then summed to create the non-TC component, which was then added back into the basic field to form the environmental flow.

The cases selected in this study are the same as those in KH09. The criteria are described briefly here: The submonthly cases were selected based on the 7–30-day filtered time series of 850-hPa wind speed averaged over the base region between Taiwan and Japan (20°–35°N,
125°–140°E) where a variance maximum of wind speed existed. The submonthly cases were selected when the positive anomalous maxima were greater than 1 m s\(^{-1}\), which was equivalent to 0.75 standard deviation. A TC/submonthly case was further selected when at least a TC appeared in the base region (with a 1.5° latitude–longitude buffer zone just outside the edge) between day \(-1\) and day \(+1\) of a selected submonthly case. The TC/submonthly cases were further classified into two categories: ISO westerly and easterly phases. A TC/submonthly case was classified as a case in the westerly (easterly) phase if the anomalous 30–80-day filtered zonal wind averaged over the ISO base region (5°–15°N, 100°–125°E), where maximum variance in the intraseasonal zonal wind was located, at the occurrence time of the submonthly case was greater than 1.5 m s\(^{-1}\) (less than \(-1.5\) m s\(^{-1}\)). The \(\pm 1.5\) m s\(^{-1}\) thresholds were approximately \(\pm 0.5\) standard deviation of the 30–80-day filtered zonal wind time series. The resultant number of submonthly cases is 40 for the ISO westerly phase and 24 for the ISO easterly phase.

The 1000–100-hPa kinematic fields are examined by performing a vorticity budget calculation based on Lau and Lau (1992). The linearized vorticity equation is

\[
\frac{\partial \zeta'}{\partial t} = -V' \cdot \nabla (\zeta + f) - \nabla \cdot V' \cdot \nabla \zeta' - V' \cdot \nabla \zeta' + \left[ (\zeta + f) \frac{\partial \omega'}{\partial p} \right] - \left( k \cdot V \omega \times \frac{\partial V'}{\partial p} \right) + VR. \tag{1}
\]

The variable \(V\) stands for the three-dimensional wind and \(\zeta\) is the vertical component of vorticity. The overbar represents the average over the 25-day period centered at the peak time for all cases, with the primes the 7–30-day filtered fields. The term on the left-hand side represents the perturbation vorticity tendency term. The first term on the right-hand side represents the mean absolute vorticity advection by the perturbation flow. This term can be further divided into the mean relative vorticity advection by the perturbation flow, \(-V' \cdot V'_z\) (eddy advection), and \(-V' \cdot Vf = -\beta \omega'\) (beta effect). The second term on the right-hand side (mean flow advection) describes the perturbation vorticity advection by the mean flow. The third term on the right-hand side represents the nonlinear perturbation vorticity advection by the perturbation wind. The fourth term on the right-hand side describes the stretching term. The fifth term and the last term represent the tilting term and residual, which will be ignored in the following discussion because of the small magnitudes (Lau and Lau 1992).

3. Vorticity budget

To demonstrate the horizontal structure of the background circulation features in the lower troposphere, the 25-day mean 850-hPa wind and vorticity for both ISO westerly and easterly phases are shown in Figs. 1a and 1b. The mean flow pattern in the westerly phase exhibited a strong monsoon trough, characterized by cyclonic circulation and a positive vorticity maximum between 10° and 25°N extending eastward from the northern South China Sea (SCS) to the Philippine Sea. Farther to the southeast of the monsoon trough was a confluent zone, a positive vorticity zone of smaller amplitude. To the south and north of the positive vorticity zone were two negative vorticity zones. As will be revealed later, the strong southeasterly between the positive and negative vorticity zones in the Philippine Sea was an important background circulation feature that significantly steered the TC/submonthly wave pattern.
propagation. In contrast to the westerly phase, the easterly phase is characterized by a weak and westward-retreating monsoon trough. As a result, the relative vorticity in the northern SCS and the western Philippine Sea was almost zero, while a weak positive vorticity belt still existed south of the subtropical Pacific anticyclone. The prevailing southeasterly in the Philippine Sea seen in the westerly phase no longer existed; instead, a weak southwesterly flow prevailed along the East Asian coast. As will be shown below, the different background circulation configuration between the westerly and easterly phase results in the distinct structure and propagation characteristics of the TC/submonthly wave pattern. The mean flow for each ISO phase is calculated individually and used in the energetic and vorticity budget term calculation for both TC and TC-removed cases.

a. Propagation tendency

Figure 2 shows the composite maps of the 7–30-day filtered 850-hPa vorticity and wind field. At day −3 in the westerly phase (Fig. 2a) a well-organized wave pattern existed in the WNP. The pattern was oriented in the northwest–southeast direction from the equatorial WNP toward the area between Taiwan and Japan, while the individual vorticity perturbation tilted roughly in the northeast–southwest direction. Stronger wind vectors (exceeding 95% confidence level) were evident surrounding the cyclonic circulation in the wave pattern. The wave pattern propagated northwestward toward eastern China in the next few days when both the vorticity and wind reached their maximum phase (Fig. 2c). After day 0 the wave pattern continued propagating northwestward and started decaying (Fig. 2e).

In contrast to the evidently wavy structure in the westerly phase, the day −3 pattern in the easterly phase (Fig. 2b) was confined to a much smaller area near Taiwan and Japan and exhibited less wavelike structure (KH09). A slightly better organized wave pattern emerged at day 0 (Fig. 2d). In the next few days, the perturbation in the eastern part of the wave pattern moved northward toward Japan, while the one on the western end moved northward toward southern China (Fig. 2f).

b. Westerly phase

The advection terms are examined below to reveal the relative influence of various advection processes on the propagation tendency of the TC/submonthly wave pattern. Shown in Fig. 3 are the advection terms at day 0 in the westerly phase. The beta effect term (Fig. 3a), which resulted in positive and negative vorticity tendency in the western and eastern part of the positive vorticity anomaly south of Japan, had a northwestward steering effect on the vorticity anomalies over the Philippine Sea because of the northeast–southwest tilting of the individual circulation circuit.

The eddy advection term (Fig. 3b) exhibited a more complex pattern due to the relative position of the wind perturbation and background vorticity distribution (Fig. 1a). A major eddy vorticity maximum, that is, the primary one near the core of the cyclonic anomaly, was found south of Japan. This primary vorticity anomaly was located to the northwest of the positive background vorticity center in the Philippine Sea. The advection effect of the anomalous cyclonic circulation (Fig. 2c) associated with positive anomalies therefore resulted in a negative (positive) vorticity tendency northwest (southeast) of the primary vorticity anomaly. This advection effect explains the quadrupole structure of the vorticity tendency surrounding the positive vorticity anomaly at day 0. Such a tendency distribution would tend to move the primary vorticity anomaly southeastward. Since the eddy advection term outweighed the beta effect, the total effect of the eddy advection term would prevent the primary vorticity anomaly from propagating northwestward.

The mean flow advection term (Fig. 3c) seemed to play a dominant role in steering the wave pattern toward the northwest. The primary positive vorticity anomaly was located in the background southeasterly to the northeast of the monsoon trough (Fig. 1a). The advection by the southeasterly, which resulted in the positive (negative) tendency in the northwest (southeast) of the major vorticity anomaly, tended to move the positive and negative anomalies northwestward. The nonlinear eddy advection (Fig. 3d) resulted in a larger negative tendency in the southern half of the primary vorticity anomaly and scattering of a smaller positive tendency in the northern half. Since the negative tendency in the south had larger amplitude and was better organized than its counterpart in the north, the nonlinear eddy term did not contribute to the northwestward propagation of the primary positive vorticity anomaly. Instead, it seemed to damp the positive vorticity anomaly while moving the negative vorticity anomaly northwestward. The positive tendency contributed by the stretching term (Fig. 3e) was collocated with the primary positive vorticity anomaly but with larger amplitude in the south. The collocation between the stretching term and the primary positive vorticity anomaly suggests that the stretching term acted mainly to enhance the amplitude of the vorticity anomaly but contributed little to the propagation.

The northwest–southeast (Fig. 2c) vertical cross sections of perturbation vorticity along with the budget terms at day 0 in the westerly phase are shown in Fig. 4.
The vertical structure of the vorticity anomaly exhibited a barotropic structure below 200 hPa and maximized in the lower troposphere. Superimposed on the vorticity anomaly were the various terms contributing to the vorticity tendency. The beta effect and mean flow advection contributed to the northwestward propagation (Figs. 4a,c). The nonlinear advection tended to damp the positive vorticity in addition to relatively weak contribution to the propagation (Fig. 4d). Conversely, the eddy relative vorticity advection acted to move the vorticity in the opposite direction (Fig. 4b). Among all advection terms, the mean flow advection term contributed dominantly to the northwestward propagation of the pattern throughout the troposphere, while the
beta term was largely canceled by the eddy relative vorticity advection term.

c. Easterly phase

As seen in Figs. 2b, 2d, and 2f, the primary positive vorticity anomaly in the easterly phase propagated essentially northward from day 2 to day 3. The 850-hPa vorticity budget terms, shown in Fig. 5, demonstrate what is responsible for this northward propagation. Similar to that as in the westerly phase, the beta effect (Fig. 5a) basically helped the vorticity anomaly to move westward. The eddy relative vorticity advection term (Fig. 5b) is small because the wind anomaly (Fig. 2d) occurred mainly in the region of small background relative vorticity (Fig. 1b). As a result, the beta effect (Fig. 5a) dominated the total eddy vorticity advection term.

**FIG. 3.** The 850-hPa eddy vorticity terms ($\times 10^{-11}$ s$^{-2}$, shaded) at day 0 in the westerly phase for the (a) beta effect, (b) eddy advection, (c) mean flow advection, (d) nonlinear term, and (e) stretching term. Also shown is the 7–30-day composite vorticity ($\times 10^{-6}$ s$^{-1}$, contour interval: 3) and the zero contours are omitted.
While the eddy advection term tended to move the positive vorticity anomaly westward, the mean flow advection (Fig. 5c) contributed to the northward propagation tendency because of the dominant southerly flow off the East Asian coast. The nonlinear eddy advection term (Fig. 5d) exhibited a positive tendency in the east and northwest of the positive vorticity anomaly and a negative tendency in the southwest and northeast. This pattern acted to squeeze the positive vorticity anomaly. The stretching term (Fig. 5e), though stronger than the other terms, tended to enhance the vorticity anomaly but contribute little to the propagation.

The vertical structure along 130°E (Fig. 2d) of the perturbation vorticity at day 0 in the easterly phase, shown in Fig. 6, illustrates the major processes leading to the propagation. Compared to that in the westerly phase, the vertical cross section of vorticity presented in Fig. 6 exhibits a weaker and more concentrated maximum centered near 25°–30°N. The beta effect (Fig. 6a) exhibits a broad area of weak negative tendency because it basically contributed to westward propagation. The eddy relative vorticity advection resulted in a negative vorticity tendency to the north of the positive vorticity anomaly (Fig. 6b), which was against the northward propagation tendency of the pattern. This eddy advection pattern could also be inferred from the perturbation wind (Fig. 2) and mean vorticity fields (Fig. 1). The mean flow advection term (Fig. 6c) dominated in the total advection term and the nonlinear eddy term (Fig. 6d) showed a weaker northward tendency near the vorticity maximum. The aforementioned advection terms indicate that the mean flow advection was also responsible for the northward propagation of the vorticity pattern as in the westerly phase.

4. Kinetic energy and barotropic conversion

Following Maloney and Dickinson (2003), the perturbation kinetic energy tendency equation is given by

\[
\frac{\partial K}{\partial t} = - \nabla_h (\nabla \cdot \mathbf{v}) \nabla_h - \mathbf{v} \cdot \nabla K - \nabla^2 \nabla K - \frac{R}{\delta} \omega T' - \mathbf{v} \cdot (\nabla \Phi') + D, \tag{2}
\]

where the perturbation kinetic energy (PKE) is represented by
and \( \Phi \) is the geopotential, \( P \) the pressure, \( \mathbf{V} \) the three-dimensional velocity vector, \( \mathbf{V}_h \) the horizontal velocity vector, \( \omega \) the pressure vertical velocity, \( T \) the temperature, and \( R \) is the gas constant for dry air. The primes and overbars are the same as in the vorticity budget equation. The first term on the rhs in (2) represents the barotropic energy conversion. The second term is the advection of PKE by the mean flow. The third term represents the advection of PKE by the perturbation wind field. The fourth term is the baroclinic conversion term, which also represents the perturbation available potential energy (PAPE) conversion to PKE. The fifth term represents the generation of PKE by the
perturbation geopotential flux convergence. Dissipation is represented by the last term.

Figures 7a and 7b present the vertically averaged PKE (25-day averages) for both westerly and easterly phases. The maximum areas of PKE were mostly located in midlatitudes centered around 45°N, 165°E. A branch of local maximum PKE near 130°E in the westerly phase (Fig. 7a), collocated with the axis of the TC/submonthly wave pattern, extended southward from 30°N, 130°E to 15°N, 130°E. Such a southward-extending PKE maximum was less evident in the easterly phase (Fig. 7b). The north–south cross sections of the composite PKE averaged over the axis of the maximum PKE (125°–135°E) are shown in Figs. 7c and 7d. The PKE revealed maxima near 15°–30°N at the lower level of the troposphere in the westerly phase and this PKE pattern was stronger than that in the easterly phase. This subtropical maximum is well separated from the large PKE in the extratropical upper troposphere.

According to Lau and Lau (1992) and Maloney and Dickinson (2003), the production of the perturbation available potential energy, denoted as $A$ in (4), can be approximated by

$$\frac{\partial A}{\partial t} \approx \gamma \frac{\partial^2 T'}{\partial T^2} + \frac{\rho \gamma C_p}{P} \frac{\partial}{\partial T} V_h \frac{\partial T}{\partial T'} \cdot V_h,$$

(4)

where $Q_1$ is the diabatic heating (Yanai et al. 1973) and $\gamma$ is the stability parameter $\Gamma_d(\Gamma_d - \Gamma)$ in which $\Gamma$ is the observed lapse rate and $\Gamma_d$ is the dry adiabatic lapse rate; $C_p$ is the specific heat at constant pressure. The first term on the right-hand side represents the generation of the PAPE by diabatic heating. The second term on the right-hand side is the conversion from PAPE to PKE and is opposite to the baroclinic energy conversion term in Eq. (2). The last term on the right-hand side is the energy conversion from mean to PAPE. Consistent with Maloney and Dickinson (2003), this term is very small over the tropical and subtropical WNP and is not discussed here.

The vertical cross sections (averaged over 125°–135°E) of major energetic budget terms in Eq. (2) and the diabatic term in Eq. (4) during the westerly phase are shown in Fig. 8. A maximum of positive barotropic energy conversion (Fig. 8a) was located below 400 hPa between 10° and 25°N with the maximum in the lower troposphere. Overlaying this positive anomaly is a broad
area of negative values. The baroclinic energy conversion term (Fig. 8b) and the diabatic term (Fig. 8d) are collocated and both maximized around 250 hPa. This collocation indicated that the PAPE generated by the diabatic heating was converted to PKE mostly in the upper troposphere. This collocated distribution was also identified in the synoptic tropical disturbances (e.g., Maloney and Dickinson 2003). This process occurred mainly in the upper troposphere and, therefore, could not explain the kinetic energy distribution, which was located below 400 hPa and peaked in the lower troposphere. Instead, the barotropic energy conversion from the background flow to perturbations (Fig. 8a) was the major kinetic energy source for the development of the wave pattern. Although the kinetic energy generation term (Fig. 8c) exhibited large maxima in the lower and upper troposphere, it only partially cancelled the barotropic energy conversion term through a local negative maximum between 15° and 25°N. The energetic budget terms in the easterly phase exhibited a similar distribution as in the westerly phase but with much smaller amplitudes (not shown).

These results suggested the dominance of the barotropic energy conversion term in the energy conversion from the background intraseasonal flow to perturbations. Since the amplitude of the wave pattern and the dominant energy conversion is maximized in the lower troposphere, the following analysis will focus on 850 hPa to explore the barotropic perspective of kinetic energy conversion between the intraseasonal mean flow and the TC/submonthly wave pattern.

a. Barotropic energy conversion in the westerly phase

The PKE map (Fig. 9a) for the westerly phase revealed the existence of a PKE maximum area exceeding the 95% confidence level between Taiwan and Japan where the TC/submonthly wave pattern was most active. The barotropic energy conversion term (Fig. 9b), which represented the kinetic energy exchange between the westerly-phase ISO circulation and the TC/submonthly wave pattern, also exhibited a positive barotropic conversion maximum to the southeast of the PKE maximum in the Philippine Sea.

The barotropic conversion can be broken down into four terms, namely

![Diagram](http://journals.ametsoc.org/jcli/article-pdf/25/24/8591/3991323/jcli-d-11-00643_1.pdf)
Assuming the horizontal nondivergent flow for the background flow \( \frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} \approx 0 \), the barotropic conversion can be rewritten as

\[
\mathcal{J} = \left( \bar{u}^2 - \bar{v}^2 \right) \frac{\partial \bar{u}}{\partial x} - \bar{u} \bar{v} \frac{\partial \bar{u}}{\partial y} - \bar{u} \bar{v} \frac{\partial \bar{v}}{\partial x}
\]

Since the last term is much smaller than the former two, only the first two terms are discussed here. In Figs. 9c and 9d, \( \bar{u}^2 - \bar{v}^2 \) and \( \bar{u} \bar{v} \) were plotted on the 850-hPa zonal wind to reveal how the energy conversion is maximized in this specific region and these two components were consistent with the \( E \) vector as in Hoskins et al. (1983). The intraseasonal 850-hPa zonal wind during the westerly phase was characterized by a strong westerly tongue located in the southern flank of the monsoon trough between the equator and 20°N and extending from the Indian Ocean to the Philippine Sea. North and east of this westerly tongue were the weaker easterly zones. The TC/submonthly wave pattern passed through the eastern edge of the westerly tongue where the zonal wind gradient was large and kinetic energy could be easily extracted from the mean flow by eddies with momentum fluxes of the proper phase. A similar spatial connection among the westerly tongue, the monsoon trough, and TCs was also identified in Frank (1982) and Briegel and Frank (1997).

Figure 9c shows that the northeastern corner of the westerly tongue, where both \( \partial \bar{u}/\partial x \) and \( \partial \bar{u}/\partial y \) were large, was the main region for converting kinetic energy from the mean flow to the TC/wave pattern. The large perturbation wind component of the TC/submonthly wave pattern, \( \bar{u}^2 - \bar{v}^2 \), (Fig. 2c) occurred in the northeastern end of the westerly tongue where the mean zonal wind decreased toward the east. Such a configuration allowed...
the TC/submonthly wave pattern to gain kinetic energy from the background ISO in the region and contributed to the eastern part of the barotropic conversion maximum. The northward momentum flux due to the northeast–southwest orientation of the TC/submonthly wave circulation transported momentum down the $\partial u/\partial y$ gradient and therefore tended to decrease the intraseasonal zonal wind and extract kinetic energy from the background westerly (Hoskins et al. 1983). This process contributed to the western part of the barotropic conversion maximum in the Philippine Sea.

A comparison between the anomalous wind vectors and background westerly distribution yields interesting insight about the eddy–mean flow interaction in this region. The discussion in the previous paragraph explained why the TC/submonthly wave pattern tended to occur between the monsoon trough and the anticyclonic ridge and why each circulation circuit was oriented in the northeast–southwest direction (Fig. 2c).

Eddies elongated in such an orientation could efficiently extract the kinetic energy from the mean flow to sustain growth in the region of large mean flow gradient (Figs. 9c,d). This perfect match is, indeed, what we have been observing in the western North Pacific during boreal summer.

Such a background configuration was also favorable for the propagation of the TC/submonthly wave pattern. The northeast–southwest orientation of the eddy, which was almost orthogonal to the mean southeasterly (Fig. 1a), was likely the optimal orientation to maximize the mean flow advection effect. However, the propagation of eddies would be slower than the speed of the southeasterly. This was because the anomalous eddy flow would create significant eddy advection of mean vorticity (Fig. 3b) to counteract the mean flow advection.

This discussion suggests, in a barotropic point of view, that the TC/submonthly wave pattern with a circulation circuit in the northeast–southwest orientation was the...
one to have optimal growth and propagation in the confluent zone between the monsoon trough and the anticyclonic ridge where kinetic energy could be extracted most efficiently. This is likely the reason why the TC/wave pattern with the specific configuration reported here is frequently observed in the WNP during boreal summer.

b. Barotropic energy conversion in the easterly phase

The kinetic energy and barotropic conversion distribution of the TC/submonthly wave pattern during the ISO easterly phase are shown in Figs. 10a and 10b. The amplitudes of PKE and barotropic conversion were about one-half and one-quarter of their westerly-phase counterparts, respectively. Additionally, most of the areas in Figs. 10a and 10b failed to make the 95% confidence level. The maximum PKE was confined between Taiwan and Japan and the maximum barotropic conversion of a much smaller area was found in the northeast of the Philippines. The locations of the relatively weaker PKE and barotropic conversion were consistent with the observation that the genesis and propagation of the TC/submonthly wave pattern in the easterly phase all occurred near the East Asian coast. Figures 10c and 10d present the background 850-hPa zonal wind, \( u^2 - v^2 \) and \( \overline{u'v'} \) during the ISO easterly phase. A much weaker westerly tongue retreated westward with the major core located to the west of the Philippines and the mean zonal wind gradient was much weaker than in the westerly phase. The maximum \( u^2 - v^2 \) occurred in the northeastern corner of the tongue where the maximum barotropic conversion and PKE were observed. A weak \( u'v' \) maximum was found in a region of weak mean zonal wind gradient covering the Philippines and the surrounding seas. As a result, \(- \overline{u'v'} \partial \omega / \partial y\) was negligible compared to \(- (u^2 - v^2) \partial \omega / \partial x\).

The weak zonal wind gradient associated with the weaker and westward-withdrawn westerly tongue in the
ISO easterly phase resulted in the confinement of the energy-extracting region near the East Asian coast. The zonally elongated eddies (like those shown in Fig. 2) are the ones that were favorable to grow and propagate northward in this region in view of the zonal wind distribution and the prevailing background southerly (Fig. 1b). If northeast–southwest oriented eddies as in the westerly phase appeared in the Philippine Sea, they would face an environment less favorable for further growth and propagation because of the weak ∂u/∂y and background mean flow. This again illustrates that the amplitudes, shape, and propagation of eddies in East Asia and the western North Pacific were strongly constrained by the configuration of the monsoon trough and the anticyclonic ridge.

A sensitivity test was done by switching the background flow patterns between the westerly and easterly phase. That is, the barotropic conversion terms in the westerly (easterly) phase were calculated based on the westerly (easterly) phase perturbations and the easterly (westerly) phase background flow. The results (not shown) indicated that both background flow and anomalies contributed to the amplitudes of energy conversion. Hypothetically, if the easterly perturbations were put in the westerly background flow, it would convert more kinetic energy than the observed westerly perturbation/easterly mean pair but less than the observed westerly perturbation/westerly mean pair. Conversely, the hypothetically westerly perturbations in the easterly background flow would convert more kinetic energy than the observed easterly perturbation/easterly mean pair but less than the observed westerly perturbation/westerly mean pair. Results of this comparison demonstrated the positive relationship between the background flow and perturbations: that is, stronger background flow produced stronger wave activity through a more vigorous eddy-mean flow interaction. It should be cautioned that the aforementioned results do not suggest that energy conversion is more efficient in one particular eddy–background flow combination than the others.

5. TC feedback

a. Propagation

Whether and how the tropical cyclones affected the propagation of the wave pattern is explored in this section. The TC-removed vorticity fields at day 0 are shown in Fig. 11. The vorticity near the center of the cyclonic circulation at day 0 in the westerly phase decreased by about 50% after removing TCs (Fig. 11a). Although the TC removal resulted in decreased amplitude, it hardly changed the overall structure, scale, and propagation tendency of the wave pattern (Figs. 3 and 11).

Also shown in Fig. 11 are the various vorticity budget terms for the TC-removed 850-hPa field in the westerly phase. The major difference between the original (Fig. 3) and TC-removed fields (Fig. 11) is again the reduction of the amplitudes while the spatial distribution patterns remain similar for every term except the nonlinear eddy term. It is not surprising because in the calculation TCs affected only the eddy amplitudes and the long-term mean flow was kept the same as in the original field during the calculation. A test was done to check the results using the TC-removed mean flow instead of the original mean flow. During the test, the mean flow was calculated from the TC-removed 850-hPa wind field. As pointed out in Hsu et al. (2008b), TCs contributed notably to the long-term mean circulation and variance but had a weaker effect on the spatial pattern. The test results indicated that using the TC-removed mean flow in the calculation only resulted in amplitude reduction in all linear terms. It follows that using the original mean flow does not affect our results notably.

Conversely, the TCs had a much larger effect on the nonlinear eddy term. The large positive and negative vorticity advections seen in Fig. 3d were no longer evident using the same plotting scheme. As noted above, the nonlinear eddy advection contributed much more to the negative vorticity tendency in the south than the positive tendency in the north of the primary positive vorticity anomaly and, therefore, had a squeezing effect on the primary positive vorticity anomaly to reduce the vortex meridional scale. Since the nonlinear term became negligible in the TC-removed fields, it suggested that TCs were the main cause of this squeezing effect. Most TCs reached peak strength before recurving toward higher latitudes (e.g., Evans and McKinley 1998; Harr 2010). It was therefore speculated that the amplitude reduction of TCs likely resulted in the squeezing effect on the large-scale vorticity anomaly discussed above because they would have a larger impact on the wave pattern in the south than in the north. The influence of removing TCs in the easterly phase showed a similar amplitude-decreasing pattern as in the westerly phase but with a larger reduction in amplitude near the center of the vorticity maximum (not shown).

b. Kinetic energy

The PKE and barotropic conversion of the TC-removed 850-hPa wind field in the ISO westerly phase are shown in Figs. 12a and 12b. While the patterns remained similar to those derived from the original fields (Figs. 9a and 9b), the amplitudes dropped by more than one-half for both PKE and barotropic conversion. This contrast
revealed that TCs contributed more than one-half of the kinetic energy of the TC/wave pattern and enhanced the energy conversion from the mean flow to eddies by about the same amount contributed by the large-scale eddies. However, the reduction did not prevent PKE and barotropic conversion from exceeding the 95% confidence level. The reduction in the barotropic conversion in the TC-removed field was contributed by the first two terms of the barotropic conversion, \(2(u^2 - \nu^2)\frac{\partial \bar{u}}{\partial x} - \bar{u} \nu^2 \frac{\partial \bar{u}}{\partial y}\) (Figs. 12c,d), with a larger reduction in the former. The TC contribution to energy conversion can be realized by a comparison between the anomalous circulation patterns with and without TCs.

The strengthening of wind anomalies due to the embedded TCs resulted in dramatically increased \(u^2 - \nu^2\) and \(\bar{u} \nu^2\) and therefore enhanced the energy conversion from the mean flow to eddies. The PKE and barotropic conversion of the TC-removed fields in the easterly phase also dropped by about the same amount as in the westerly phase with major contribution from \(-(u^2 - \nu^2)\frac{\partial \bar{u}}{\partial x}\) (not shown).

To quantify the extent of the TCs contribution to the eddy kinetic energy and conversion, the ratios of \((\text{Total} - \text{TC}_{\text{removed}})/\text{Total PKE}\) and the barotropic conversion term are presented in Fig. 13. More than 50% of the eddy kinetic energy in a large region was contributed by TCs for both ISO phases (Figs. 13a,c). The areas of decreasing kinetic energy were larger in the westerly than easterly phase over the WNP, indicating a greater spatial extent of the TC impact in the westerly phase. The \((\text{Total} - \text{TC}_{\text{removed}})/\text{Total}\) ratios of the barotropic conversion term for both ISO phases are shown in Figs. 13b and 13d. Since the mean-state flow was the same for the calculation with or without TCs, the ratios depended on the changes in the magnitude of \(u^2 - \nu^2\) and the momentum flux \((\bar{u} \nu^2)\). The ratios were sensitive to the areas where the denominator was close to zero and the ratio became unreasonably large. These sensitive areas are masked in Figs. 13b and 13d. Figure 13b shows that TCs contributed more than 50% of the barotropic conversion along the TC tracks in the westerly phase, whereas in the easterly phase the area of decreased...
barotropic conversion was confined to the area east of Taiwan and south of Japan (Fig. 13d). A test was done to evaluate the impact of the criteria used in the TC removal procedure on the energy budget. Results indicated that the discrepancy due to the methodology was insignificant compared to the more than 50% reduction in kinetic energy and energy conversion terms. However, it should also be noted that the percentage of reduction could be a bit overestimated because we cannot rule out the possibility that part of the submonthly circulation might be removed during the TC removal procedure.

Since TCs were more active and tended to occur in clusters during the westerly phase than in the easterly phase, the significant contribution to both PKE and barotropic conversion occurred in a much larger spatial domain. The results presented in this section indicate that, while TCs were provided with a favorable development condition by the submonthly wave pattern, they in turn acted to enhance the overall kinetic energy of the TC/submonthly wave pattern and helped extract significantly more energy from the background ISO circulation. This effect was seen in a much larger area in the ISO westerly phase due to an enhanced monsoon trough. This result does not imply an increase in the energy conversion efficiency due to the presence of TCs. To accurately answer the question, the same calculation has to be done for the submonthly wave pattern with no embedded TCs. This interesting issue is beyond the scope of the present study.

6. Summary and concluding remarks

This study explored the propagation and maintenance mechanisms of the TC/submonthly wave pattern and assessed the TC contribution to these mechanisms during the intraseasonal oscillation westerly and easterly phases in the tropical western North Pacific. The
TC/submonthly wave pattern exhibited equivalent barotropic vertical structure with a maximum in the lower troposphere. The vorticity budget was calculated to investigate the propagation tendency of the wave pattern at all levels from 1000 to 100 hPa during both ISO westerly and easterly phases. Results are summarized in the schematic diagrams shown in Figs. 14a and 14b. In the ISO westerly phase, the dominant effect of the background flow advection and beta effect tended to move the TC/submonthly wave pattern northwestward and westward, respectively, while the eddy relative vorticity advection acted against it. The nonlinear eddy advection had a weaker effect on propagation but tended to squeeze the perturbation vorticity meridionally by reducing the amplitude of the main vorticity anomaly in the south. In the easterly ISO phase, the mean flow advection tended to move the vorticity anomaly northward, whereas the beta effect tended to move the vorticity anomaly westward. The dominant effect of the mean flow advection over other advection terms resulted in the northward propagation. The stretching term in both phases acted mainly to enhance the amplitude of the vorticity anomaly in both phases and had a weaker effect on the propagation. The results indicate that the mean flow advection played the dominant role in TC/wave pattern propagation from 1000 to 400 hPa in both westerly and easterly phases. Stronger mean flow in the westerly phase resulted in a stronger propagation tendency of the TC/submonthly wave pattern than in the easterly phase.

A kinetic energy study was conducted to examine the maintenance mechanism. The wave pattern exhibited maximum kinetic energy in the lower troposphere. Among the four dominant terms in the energy budget equation, the barotropic energy conversion term was the only one that maximized in the mid to lower troposphere where the anomalous circulation of the submonthly wave pattern was located. Baroclinic conversion and diabatic heating, which were found in the upper troposphere, tended to cancel out and therefore contributed little to the maintenance of the wave pattern.
These results indicate that the kinetic energy of the wave pattern was mainly maintained through the barotropic energy conversion from the background ISO flow. In the westerly phase, a positive barotropic conversion maximum area existed to the southeast of the eddy kinetic energy maximum in the Philippine Sea (Fig. 14a). This region was located to the northeast of the background westerly maximum area in the southern flank of the monsoon trough, where the zonal and meridional gradients of the mean flow westerly were largest. The TC/submonthly wave pattern passed through this region and extracted energy from the mean flow with its southwest–northeast oriented eddy flows. This was likely the reason why the northwestward propagation of the northeast–southwest TC/wave pattern was frequently observed in the WNP during boreal summer because the wavelike perturbations in this configuration were more favorable to develop during the enhanced monsoon trough (e.g., the ISO westerly phase in this study). Eddies in other orientation would be much less favorable for further growth and even to decay (e.g., eddies oriented in northwest–southeast direction). Similar eddy–mean flow interaction occurred in the easterly phase. It was, however, much weaker because the barotropic energy conversion was confined near the East Asian coast because of the weaker and westward-withdrawn background westerly flow (Fig. 14b). The westward-retreated monsoon trough resulted in eddies of different orientation that propagated north-northeastward due to the prevailing south-southwesterly background flow.

A TC-removal technique was applied to the circulation data to study the feedback of TCs on the large-scale submonthly wave pattern during two extreme ISO phases. Removing TCs reduced the vorticity anomaly and budget terms by more than 50% in both phases. The nonlinear term, which almost vanished after removing the TCs, was affected most among all budget terms. This large effect is expected, considering the significant effect of TCs on eddy amplitude. While TCs had a strong feedback on the amplitude of the vorticity anomaly and budget, they had a smaller effect on the overall structure and propagation of the wave pattern.

Removing TCs also decreased the eddy kinetic energy and barotropic energy conversion by more than 50% in both phases but had a larger influence in the westerly phase in terms of the spatial extent. All of these results indicated that, while TCs developed in a favorable background flow provided by the submonthly wave pattern, they in turn enhanced the amplitudes of vorticity and kinetic energy of the TC/wave pattern and helped extract significantly more energy from the background ISO circulation. This feedback was stronger in the ISO westerly phase because of the stronger clustering effect of an enhanced monsoon trough on TCs.

This study focused only on the feedback of TCs to the submonthly wave pattern. Further studies on the feedback to the ISO and the moisture effect are underway to...
uncover the mechanism of the complex multiscale interaction over East Asian summer monsoon systems. This study revealed that TCs and the large-scale circulation in the WNP were mutually intertwined through rigorous eddy–mean flow interaction and therefore should be treated as an integrated multiscale system. It means that we need to understand the two-way interaction between different scales and take that into account to reach a more accurate interpretation of climate variability in the WNP. Another implication is that models need to properly simulate the interaction between various scales to correctly simulate the climate variability in the WNP.

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