Observational Analysis of Sudden Tropical Cyclone Track Changes in the Vicinity of the East China Sea

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ABSTRACT

An observational analysis of observed sudden typhoon track changes is conducted with a focus on the underlying mechanism and the possible role of slowly varying low-frequency flows. Four typhoons that took a generally northwestward track prior to sharply turning northeastward in the vicinity of the East China Sea are investigated.

It is found that the sudden track changes occurred near the center of the Madden–Julian oscillation (MJO)-scale cyclonic circulation or at the bifurcation point of the steering flows at 700 hPa, and they were all associated with a well-developed quasi-biweekly oscillation (QBW)-scale gyre. Calculation of vorticity advection suggests that the peripheral ridging resulting from the interaction between the typhoons and the flows on the MJO and QBW scales can compress the typhoon circulation, leading to an area of high winds to the east or south of the typhoon center. The enhanced synoptic-scale winds shifted the typhoons northward and placed them in a northeastward orbit under the steering of the flows associated with the Pacific subtropical high. The sudden track change can be likened to the maneuvering of satellite orbit change in that the enhanced synoptic-scale winds act as a booster rocket to shift the typhoons northward to the southwesterly steering flows.

1. Introduction

A tropical cyclone that forms over the western North Pacific generally takes one of three prevailing tracks: westward moving, northwestward moving, or northeastward recurving (Wu and Wang 2004; Wu et al. 2005). While the southern provinces of China, including Guangdong, Guangxi, and Hainan, are primarily affected by west-moving storms, tropical cyclones that make landfall over southeastern coastal regions (Fujian and Zhejiang provinces) usually take a northwestward track. Recent studies have revealed that Fujian and Zhejiang provinces experience the most economic loss from tropical cyclones among the coastal provinces of China because of strong intensity at landfall (Zhang et al. 2009; Zhang et al. 2010). A survey of historical typhoon tracks shows that a few typhoons would hit Fujian and Zhejiang provinces within 24 h, but they otherwise underwent a sudden northeastward turn in the vicinity of the East China Sea to affect the Korean Peninsula and Japan. Obviously the sudden track change represents a forecasting challenge for forecasters in the East Asia and thus it is important to understand the associated mechanisms.

A pioneering study on the sudden tropical cyclone track change over the western North Pacific was conducted by Carr and Elsberry (1995), who argued that many sudden track changes that typically consist of rapid slowing of the westward movement and a substantial northward acceleration might be explained as the interaction between a tropical cyclone and a monsoon gyre. The latter is a specific pattern of the evolution of the low-level monsoon circulation and can be identified as a nearly circular cyclonic vortex with a radius of about 2500 km, which roughly occurs once per year and lasts 2–3 weeks over the western North Pacific during the summer (Lander 1994). Chen et al. (2004) indicated that nearly 70% of tropical cyclones over the northwestern Pacific are associated with a monsoon gyre.

Using a barotropic vorticity model, Carr and Elsberry (1995) found that tropical cyclones can coalesce with monsoon gyres and then exhibit sudden northward track changes, which are very similar to the sudden poleward track changes observed in the western North Pacific.
During the coalescence phase, the large and relatively weak monsoon gyre undergoes a $\beta$-induced dispersion, producing strong ridging to the east and southeast of the tropical cyclone and an intermediate region of high southerly winds that resemble the observed monsoon surge. Although Carr and Elsberry (1995) compared their simulations with several real cases in terms of the flow pattern and the position of the monsoon gyre relative to a typhoon, so far it is not clear whether and how the proposed mechanism works in observed sudden track changes.

Tropical cyclone activity in the western North Pacific is always accompanied with prominent atmospheric variability ranging from the synoptic-scale tropical disturbance (Liebmann et al. 1994; Lau and Lau 1990; Chang et al. 1996) to the quasi-biweekly oscillation (QBW) (Murakami and Frydrych 1974; Murakami 1975; Kikuchi and Wang 2009) to the Madden–Julian oscillation (MJO) (Madden and Julian 1971, 1972; Wang and Rui 1990). Both the QBW and MJO, called tropical intraseasonal oscillations (ISOs), are associated with the active/break cycles of Asia summer monsoon (Yasunari 1981; Goswami et al. 2003; Chen et al. 2000; Chan et al. 2002). As an important component in the Asian summer monsoon, QBW convection is closely associated with tropical wave disturbances that propagate northwestward (Kikuchi and Wang 2009). It can be identified as an alternating cyclonic and anticyclonic wave train with a wavelength of about 3500 km in the northwestern Pacific (Chen and Sui 2010). Little attention has been paid to its influence on tropical cyclone activity.

**FIG. 1.** 700-hPa wind fields associated with Typhoon Sinlaku (2008) at 1800 UTC 10 Sep 2008 with closed dots indicating the typhoon center: (a) total FNL winds, (b) 20-day low-pass filtered winds, (c) 10–20-day bandpass filtered winds, and (d) synoptic-scale winds.
With a global-scale wavenumber-1 or -2 feature, the MJO typically propagates eastward in the tropics and is dominated by large-scale regions of enhanced and suppressed deep convection and precipitation across the tropical Indian and Pacific Oceans (Wang and Rui 1990). Kemball-Cook and Wang (2001) identified the northwestward-moving of MJO anomalies across the western North Pacific, which may affect the activity of the monsoon trough. Liebmann et al. (1994) showed that the active phase of the MJO is associated with the increase in tropical cyclone activity. Studies revealed that tropical cyclone tracks alternate between clusters of straight and recurving paths with an MJO time scale (Harr and Elsberry 1991, 1995; Chen et al. 2009). At this time, however, little is known about how the slowly varying MJO affects sudden tropical cyclone track changes.

Following Carr and Elsberry (1995), this study provides an observational analysis of the observed sudden typhoon track changes that occurred in the vicinity of the East China Sea with a focus on the associated mechanism. Special attention is paid to the roles of the slowly varying ISOs in sudden tropical cyclone track changes. A description of the data and analysis method used in this study is given in section 2. The selected sudden track change cases associated with Typhoons Saomai (2000), Maemi (2003), Sinlaku (2008), and Jangmi (2008) are briefly described in section 3. The ISO time scale flow patterns associated with the sudden track changes and the influence of the synoptic-scale flows on the sudden track changes are discussed in sections 4 and 5, respectively. The results of vorticity advection analysis are presented in section 6, followed by a summary in section 7.

2. Data and analysis method

This study employs the National Centers for Environmental Prediction (NCEP) Final (FNL) Operational Global Analysis data on 1.0° × 1.0° grids at every 6 h (http://dss.ucar.edu/datasets/ds083.2). This product is from the Global Forecast System (GFS) that is operationally run 4 times a day in near-real time at NCEP. The data are available on the surface, at 26 pressure levels from 1000 to 10 hPa, including surface pressure, sea level pressure, geopotential height, temperature, relative humidity, and wind. The tropical cyclone data in the western North Pacific are the best-track dataset from the Joint Typhoon Warming Center (JTWC), including tropical cyclone position and intensity also at 6-h intervals.

In previous studies three prominent categories of atmospheric variations were identified in the tropical Pacific. The first is the MJO on the time scale of 40–50 or 30–60 days (Madden and Julian 1971, 1972, 1994). The second is the QBW on the time scale of 10–20 days (Murakami and Frydrych 1974; Murakami 1975; Krishnamurti and Ardanuy 1980; Chen and Chen 1993; Kiladis and Wheeler 1995). The third category is synoptic-scale disturbances with periods between 3 and 10 days (Lau and Lau 1990; Chang et al. 1996), which may be associated with tropical
cyclogenesis over the western North Pacific (Dickinson and Molinari 2002). To examine the influences of the ISO-scale environmental flows on sudden tropical cyclone track change, we use Lanczos filters in time at each grid point (Duchon 1979). A low-pass filter with a 20-day cutoff period is used to isolate the MJO and the background state, which for convenience is called the MJO component in this study. A bandpass filter with a 10–20-day period is

![Fig. 3](image-url)
used for the QBW component. The synoptic-scale disturbances including tropical cyclones are the difference between the unfiltered field and the field from a 10-day low-pass filter.

As an example, Fig. 1 shows the 700-hPa total and filtered wind fields associated with Typhoon Sinlaku (2008) at 1800 UTC 10 September 2008, when the intensity of Sinlaku was 125 kt (64.3 m s$^{-1}$). It is clear that the intensity was underrepresented in the FNL data (Fig. 1a). In fact, the cyclonic circulation of Sinlaku includes three components: an MJO cyclone centered north of the typhoon center (Fig. 1b), a QBW cyclone roughly collocated with the typhoon (Fig. 1c), and a synoptic-scale cyclone that mainly represents the outer strength of Sinlaku (Fig. 1d). Note that the MJO and QBW cyclones have a larger size than the synoptic-scale cyclone. The decomposition of the wind fields in Fig. 1 indicates that tropical cyclones over the western North Pacific can be a combination of the flows with a time scale ranging from MJO to the synoptic time scale.

3. Overview of the selected sudden track change cases

Four typhoons that underwent sudden track changes in the vicinity of the East China Sea are selected in the study. Except for Sinlaku (2008), with a peak intensity of 125 kt (64.3 m s$^{-1}$), Saomai (2000), Maemi (2003), and Jangmi (2008) all reached supertyphoon intensity (130 kt or 66.9 m s$^{-1}$) or equivalent category-5 hurricane intensity. These typhoons all occurred in September and took a generally northwestward track prior to making a sharp northeastward turn (Fig. 2). Over a 24-h period, the sharp
turn exceeded 60° and the northwestward movement was replaced by the northeastward one with a translation speed less than 4.4 m s\(^{-1}\) (16 km h\(^{-1}\)).

Supertyphoons Saomai (2000) and Maemi (2003) made landfall on the Korean Peninsula. Saomai developed into a tropical storm on 2 September 2000 and a typhoon 2 days later. After 6 September, as shown in Fig. 2a, it took a generally northwestward track before it suddenly changed its track and moved northeastward over the East China Sea on 14 September. Saomai became a super-typhoon (category 5) on 10 September and made landfall on the southern coast of the Korean Peninsula on 15 September. After forming as a tropical depression near Guam on 4 September 2003, Maemi moved to the northwest and took a fairly straight track until it sharply changed its direction to the north-northeast over the East China Sea on 11 September (Fig. 2b). Maemi became a typhoon on 6 September and a supertyphoon (category 5) on 10 September. As one of the worst typhoons ever to hit the Korean Peninsula, it made landfall on the southern coast of Korean Peninsula at typhoon intensity on 12 September.

Sinlaku (2008) and Jangmi (2008) occurred in the field experiment called Tropical Cyclone Structure 2008 (TCS08), which was conducted during August and September 2008 and sponsored by the Office of U.S. Naval Research and the Naval Research Laboratory as part of the U.S. Air Force and the Observing-System Research and Predictability Experiment (THORPEX) Pacific Asian Campaign (T-PARC). Both of the typhoons made landfall on Taiwan Island and took a northeastward track toward Japan after their sudden track changes.
Sinlaku strengthened to a tropical storm on 8 September 2008 and reached peak intensity with maximum sustained winds of 125 kt (64.3 m s⁻¹; category 3) on 10 September. On 13 September it made landfall on Taiwan with a maximum sustained wind of 90 kt (46.3 m s⁻¹). As moved through Taiwan Island, Sinlaku turned sharply to the northeast on 14 September and moved toward Japan.

Jangmi became a tropical storm on 24 September 2008 and intensified into a super typhoon with winds of 140 kt (72.0 m s⁻¹; category 5) on 27 September. It took a generally northwestward track before 28 September, but it turned sharply to the northeast over the East China Sea on 29 September and weakened its intensity rapidly after it hit Taiwan on 28 September.

It has been long known that a tropical cyclone is largely steered by the large-scale environmental flow and the ventilation flow that results from the interaction between the tropical cyclone and its environment (Holland 1983; Carr and Williams 1989; Fiorino and Elsberry 1989; Wu and Wang 2000, 2001). The zonal and meridional speeds of the steering flows associated with the four typhoons are calculated and compared with the typhoon translation speeds (Fig. 3). In this study the steering flow is calculated as the mass-weighted mean wind averaged within a radius of 440 km between 850 and 300 hPa. As shown in Fig. 3, the calculated steering is considerably consistent with the typhoon translation speeds.

The sudden track changes were accompanied with an eastward acceleration of the typhoon movement, which started at least 24 h prior to the occurrence of the northeastward recurving (left panels of Fig. 3). The acceleration can be the westward (eastward) speed decrease (increase). Unlike the typhoon tracks shown in Fig. 2, the zonal translation speed did not show an
abrupt change around the occurrence of the sudden track changes. In the meridional direction, Maemi and Sinlaku started to accelerate northward about 24 h prior to the recurving, while Saomai and Jangmi started to accelerate northward at the recurving. The sudden track changes can be characterized with rapid slowing of the westward movement and then a northeastward acceleration, as described by Carr and Elsberry (1995).

Notice that the deviation of the steering from the typhoon translation in Fig. 3 may be due to uncertainties in the FNL data, the typhoon track information, and the definition of steering in this study. In addition, physical processes other than the steering may also affect the typhoon motion (Chan and Williams 1987; Wu and Wang 2000, 2001). Figure 3 also suggests that, although typhoon intensity is underestimated, the outer asymmetric structure of the typhoons is reasonably captured in the FNL dataset since previous studies have demonstrated that the outer asymmetric structure is important to tropical cyclone motion (Holland 1983; Chan and Williams 1987; Wu and Wang 2000, 2001).

4. The ISO-scale flows associated with the sudden track changes

Although the sudden track changes all occurred during late summer over the East China Sea, the low-frequency flow patterns were very different. Figure 2 also shows the 20-day low-pass filtered 700-hPa wind fields, primarily including the MJO component and the background flow at the occurrence of the sudden track changes. Since 8 September 2000, Saomai generally took a track along the axis of the monsoon trough, which was oriented from the northwest over the East China Sea to the southeast over the subtropical northwestern Pacific (Fig. 2a). The monsoon trough had basically evolved into a large MJO-scale
monsoon gyre. The sudden track change occurred when Saomai was located near the center of the cyclonic circulation.

The sudden track changes of Maemi and Jangmi did not occur in a monsoon trough, which was oriented from the west over the South China to the east over the Philippine Sea (Figs. 2b,d). The sudden track changes occurred when Maemi and Jangmi were located at a location where the southeasterly flow bifurcated into easterly and south-easterly winds. Sinlaku was associated with a reversed-oriented monsoon trough, which was oriented from the southwest over the South China Sea to the northeast over the subtropical western Pacific (Fig. 2c). The typhoon was primarily influenced by the northeasterly flow prior to and during the sudden turning.

On the other hand, the sudden track changes were all associated with a QBW cyclonic gyre. Figures 4–7 show the 3-day evolution of the 10–20-day bandpass filtered 500-hPa wind fields immediately before the occurrence of the sudden track changes. As shown in Fig. 4, Saomai was coalescing with a QBW cyclonic gyre during 11–14 September 2000. The center of the QBW cyclonic gyre moved northwestward from the northwestern Pacific to the East China Sea. During 11–12 September, Saomai was located slightly to the north of the center of the QBW gyre (Figs. 4a,b) and became nearly concentric with the QBW gyre about 24 h prior to the sudden track change (Figs. 4c,d). Unlike Typhoon Saomai, Maemi did not become concentric with the QBW gyre (Fig. 5). It was steered by the westerly flow during 8–10 September and by the southerly flow on 11 September. Sinlaku moved

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1 MJO- and QBW-scale gyres in this study are the cyclonic circulation identified from the 20-day low-pass and 10–20-day bandpass filtered wind fields, respectively.
northwestward with a well-developed QBW gyre (Fig. 6). The center of Sinlaku was generally located near the center of the QBW gyre during 11–14 September 2008. This approach to the QBW gyre center also occurred for Jangmi, which was located to the southeast of the gyre center during 26–27 September and became concentric with the gyre on September 28, 24 h prior to the sudden track change (Fig. 7).

Carr and Elsberry (1995) argued that the $\beta$-induced dispersion of a cyclonic vortex is associated with the quantity $V_m/R_m^2$, where $V_m$ and $R_m$ are the maximum tangential wind and the radius of $V_m$, respectively. The quantity measures the radial shear of the angular tangential wind and the stability of the vortex to the $\beta$-induced dispersion (Carr and Williams 1989; Carr and Elsberry 1995). With a relatively small maximum wind and a relatively large $R_m$, the energy of the QBW gyre can be more easily lost to the $\beta$-induced dispersion (or Rossby wave dispersion) than that of a tropical cyclone. In agreement with Carr and Elsberry (1995), as shown in Figs. 4–7, the well-defined anticyclonic gyres on the QBW time scale can be clearly identified for the cases of Saomai and Sinlaku (Figs. 4 and 6). Since both Saomai and Sinlaku were closely associated with a monsoon trough (Figs. 2a,c), it is likely that the background flows may be an important factor for the formation of the Rossby wave train observed on the QBW time scale. In a shallow water model, Aiyyer and Molinari (2003) showed that the MJO enhanced monsoon trough can make the westward-moving equatorially trapped mixed Rossby–gravity waves excite

![Fig. 9. 10-day high-pass 700-hPa wind vectors and wind speeds (contour) for Typhoon Maemi (2003) with closed dots indicating the typhoon center at (a) 0000 UTC 8 Sep, (b) 0000 UTC 9 Sep, (c) 0000 UTC 10 Sep, and (d) 0000 UTC 11 Sep 2000. Contour intervals are 5 m s$^{-1}$ with wind speeds less than 5 m s$^{-1}$ suppressed.](image-url)
a secondary wave train that propagates along the monsoon trough axis. Further study on how the background flows affect the development of a Rossby wave train is required.

Previous studies suggest that wave trains associated with tropical cyclones have a wavelength of 2000–2500 km (Li and Fu 2006; Ge et al. 2008). In the barotropic simulation, Carr and Elsberry (1995) found that an anticyclone is located approximately 1200 km to the east or southeast of the monsoon gyre. The QBW-scale anticyclone that remains about 1200 km to the southeast of Sinlaku during 13–14 September 2008 is consistent with the prediction in the previous studies, but the wavelength is larger for the Saomai case, in which the anticyclone remains about 2000 km to the southeast of the typhoon during 13–14 September 2000.

5. Influence of synoptic-scale flows on the sudden track changes

In their barotropic experiments, Carr and Elsberry (1995) found that an area of enhanced winds forms approximately 500–600 km primarily to the east of the tropical cyclone that is coalescing with a monsoon gyre. They argued that the high-wind region corresponds to the large streamfunction gradient between the combined tropical cyclone and monsoon gyre and the dispersion-induced anticyclone. Such a high-wind region can also be found in the observed sudden track changes. Figures 8–11 display the 700-hPa synoptic-scale wind fields for the four typhoons, which mainly represent 72-h evolution of the synoptic-scale flows prior to the sudden track changes. Note that no well-developed wave trains on the synoptic
time scale can be found, in agreement with the argument that a more intense tropical cyclone tends to be more stable with the Rossby wave energy dispersion.

The enhanced winds to the east of the typhoon center are very clear in the cases of Saomai, Sinlaku, and Jangmi. As shown in Fig. 8a, a secondary high-wind region appeared to the east of the center of Saomai at 0600 UTC 11 September 2000, while the synoptic winds were mainly enhanced to the west of the center. The two high-wind regions were combined as the western part of the strong winds enhanced and shifted cyclonically at 0600 UTC 12 September (Fig. 8b). As Saomai and the QBW gyre were concentric on 13 and 14 September (Figs. 4c,d), the high winds to the east of the typhoon center enhanced and became dominant (Figs. 8c,d). In the case of Sinlaku (Fig. 10), the high winds to the east of the typhoon center can be seen during 11–14 September 2008, but they were also dominant on 13 and 14 September, about 24 h prior to the sudden track change. Jangmi is similar to Sinlaku in that the high winds were dominant about 24 h prior to the sudden track change although the high-wind areas to the east of the typhoon center were observed during 26–28 September 2008 (Fig. 11). In agreement with Carr and Elsberry (1995), these cases suggest that the coalescing of the typhoon and the QBW gyre is accompanied with enhanced synoptic-scale winds to the east of the typhoon center.

Compared to the other three typhoons, the synoptic-scale winds associated with Maemi (2003) were relatively weak on 8 and 9 September 2003 (Figs. 9a,b). The enhanced northeasterly winds tended to shift the typhoon southward on 10 September. However, the winds to the south of the typhoon center were enhanced significantly on 11 September 2003 (Fig. 9d). The possible mechanism for the enhanced synoptic-scale winds will be discussed in the next section.

To identify the influence of the enhanced synoptic-scale winds on the sudden track changes, following the
In Fig. 3, we calculate the steering flows on individual time scales (Fig. 12). Except for Typhoon Saomai, the zonal movement of the three other typhoons was dominated by the 20-day low-pass filtered winds, even after the sudden track changes (left panels of Fig. 12). For Saomai, although its zonal movement resulted from the combined effect of the three components, the increase in the zonal translation speed since 11 September 2000 was

![Fig. 12](image-url)
primarily a result of the change in the 20-day low-pass filtered winds. This suggests that the key to turning the typhoons with a northeast heading is to make them be steered by the flows associated with the subtropical high (Fig. 2).

As shown in the right panels of Fig. 12, such a northward shift was fulfilled by an abrupt increase in the meridional steering of the synoptic-scale winds prior to the sudden track changes. This contribution was very small or southward before the abrupt increase but started to intensify at least 24 h prior to the occurrence of the sudden track change. It is clear that the abrupt increases in the steering of the synoptic-scale winds were associated with the asymmetric flows that were enhanced to the east or south of the typhoon center (Figs. 8–11). For example, the westward and southward steering associated with Maemi started to decrease on 10 September 2003, when the enhanced winds to the south of the typhoon center started to replace those to the northwest.

Based on the above analysis, the sudden track changes may be likened to the maneuvering of satellite orbit change, and the enhanced synoptic-scale winds act as a booster rocket to place the typhoons in a northeastward orbit. The enhanced synoptic-scale winds can effectively push the typhoons into the northeastward orbit under the steering flows associated with the subtropical high because the sudden track changes occur near the center of the MJO-scale cyclonic circulation or at the bifurcation point of southeasterly and westerly winds (Fig. 2).

6. Peripheral ridging due to interaction between typhoons and ISO flows

Note that the area of the enhanced synoptic-scale winds in Figs. 8–11 formed about 200 km from the typhoon center, much closer than the barotropic simulations conducted by Carr and Elsberry (1995), who found that an area of enhanced winds (monsoon surge) was approximately 500–600 km from the tropical cyclone center, midway between the tropical cyclone and the resulting anticyclone. As discussed in section 4, the QBW-scale anticyclones associated with Sinlaku and Saomai were about 1200 and 2000 km apart from the typhoons, respectively, while no well-defined wave train can be found in the cases of Maemi and Jangmi. That is, in the cases of Maemi and Jangmi, the enhanced pressure gradient cannot account for the enhanced synoptic-scale winds specifically to the east of the typhoon center. It is suggested that the enhanced synoptic-scale winds that formed about 200 km from the typhoon center are not due directly to the resulting streamfunction gradient between the typhoon and the QBW-scale anticyclone. Although the peripheral ridging was not always sufficiently strong to form the anticyclonic circulation, the anticyclones can be identified 500–800 km to the southeast of the typhoon center in Figs. 8b, 10d, and 11c, suggesting that the synoptic-scale peripheral ridging plays a role in producing the high-wind area to the east and south of the typhoons. Carr and Elsberry (1995) suggested that nonlinear vorticity advection can induce peripheral ridging (troughing) that compresses (stretches) the axisymmetric structure of a tropical cyclone, leading to asymmetries in the tropical cyclone circulation.

To examine the influence of the peripheral ridging due to the interaction between the typhoon circulation and the ISO flows, we impose an idealized vortex on the ISO flows at the observed typhoon center with the observed maximum sustained wind speed. The radial profile of tangential wind speed is the one used by Carr and Elsberry (1995) with a radius of maximum wind at 100 km. The interaction is indicated by the advection of the MJO and the QBW vorticity by the symmetric typhoons and the advection of the typhoon vorticity by the background and MJO and the QBW flows. These advection terms associated with 700-hPa QBW and the MJO flows are shown in the left and middle panels of Figs. 13–16. Notice that the vorticity advection that is associated with the typhoon movement does not contribute to the peripheral ridging and troughing. This part in this study is estimated with the advection of the typhoon vorticity by the MJO and the QBW steering flows, which is calculated as the flows averaged within a radius of 440 km between 850 and 300 hPa. The resulting ridging (troughing) is shown in the right panels of Figs. 13–16.

As shown in these figures, the vorticity advection associated with the MJO and the QBW components mainly show a wavenumber-1 pattern with the maxima (minima) at about 200 km away from the typhoon center. Further examination indicates that the advections are dominated by the advection of the typhoon vorticity by the background and MJO and the QBW flows. In the case of Saomai, the maximum positive (negative) vorticity advection associated with the QBW component occurred to the northwest (southeast) of the typhoon center on 11 and 12 September 2003, when the typhoon was steered by the southeasterly flow of the QBW gyre (Figs. 4a,b). In the meantime, maximum positive (negative) vorticity advection associated with the MJO component remained to the northwest (southeast) of the typhoon center during 11–13 September 2003 since Saomai was also steered by the southeasterly flow associated with the monsoon trough. Consistent with the enhanced synoptic-scale winds, the peripheral ridging was enhanced prior to the sudden track changes and remained
FIG. 13. 700-hPa vorticity advection associated with (left) the QBW flows and (middle) the background and MJO flows and (right) their contribution to ridging/troughing associated with Saomai (2000) at (a) 0000 UTC 11 Sep, (b) 0000 UTC 12 Sep, (c) 0000 UTC 13 Sep, and (d) 0000 UTC 14 Sep 2000. Contour intervals are $50 \times 10^{-10} \text{ s}^{-2}$ for the left and middle columns and $10 \times 10^{-10} \text{ s}^{-2}$ for the right column with the typhoon center denoted by a closed dot in the center of the 590 km $\times$ 590 km domain.
FIG. 14. As in Fig. 13, but associated with Maemi (2003) at (a) 0000 UTC 8 Sep, (b) 0000 UTC 9 Sep, (c) 0000 UTC 10 Sep, and (d) 1800 UTC 10 Sep 2003.
FIG. 15. As in Fig. 13, but associated with Sinlaku (2008) at (a) 1800 UTC 9 Sep, (b) 1800 UTC 10 Sep, (c) 1800 UTC 11 Sep, and (d) 1800 UTC 12 Sep 2008.
FIG. 16. As in Fig. 13, but associated with Jangmi (2008) at (a) 1200 UTC 26 Sep, (b) 1200 UTC 27 Sep, (c) 1200 UTC 28 Sep, and (d) 1200 UTC 29 Sep 2008.
to the east or southeast of the typhoon centers in the cases of Saomai, Sinlaku, and Jangmi and to the south of the center of Maemi, suggesting that the peripheral ridging plays an important role in producing the high-wind areas that shifted the typhoons into the northeastern orbit under the steering flows associated with the subtropical high. However, it is difficult to distinguish how much the vorticity advections associated with the QBW and MJO components contribute to the peripheral ridging. Figures 13–16 suggest that both of the MJO and QBW components play a role in the peripheral ridging. For example, it is clear that the MJO contributes to the peripheral ridging to the southeast of the center of Maemi during 9–10 September 2003 (Figs. 14b,c).

7. Summary

In this study an observational analysis of the observed sudden typhoon track changes is conducted with a focus on the mechanism responsible for the observed sudden track changes and the roles of the slowly varying ISOs in sudden tropical cyclone track changes. Four typhoons that underwent sudden track changes in the vicinity of the East China Sea are investigated. These typhoons all occurred in September and took a generally northwestward track prior to turning sharply northeastward. Except for Sinlaku (2008) with a peak intensity of 125 kt (64.3 m s⁻¹), Saomai (2000), Maemi (2003), and Jangmi (2008) reached super typhoon intensity [130 kt (66.9 m s⁻¹)] or equivalent category-5 hurricane intensity.

The flows associated with the four typhoons are decomposed into the background and MJO, QBW, and the synoptic-scale components. The combined steering flows of these components can generally account for the movement of these typhoons. The sudden track changes occurred near the center of the MJO-scale cyclonic circulation for Saomai and Sinlaku or at the bifurcation point of the steering flows of the background and MJO flows for Maemi and Jangmi. The sudden track changes were all associated with a well-developed QBW gyre and the typhoons tended to approach the QBW gyre center. As suggested by Carr and Elsberry (1995), the sudden track changes were accompanied with an area of enhanced synoptic-scale winds to the east or south of the typhoon centers. The enhanced synoptic-scale winds formed about 200 km from the typhoon center, much closer than those in the barotropic model (Carr and Elsberry 1995). Calculation of the nonlinear vorticity advection associated with both of the ISO flows and typhoons suggests that the enhanced synoptic winds were associated with the strong peripheral ridging resulting from the interaction between the typhoons and the ISO flows.

The enhanced synoptic-scale winds provide a significant northward acceleration and placed the typhoons in the northeastward orbit under the steering of the flows associated with the subtropical high. The sudden track changes are similar to the maneuvering of satellite orbit change in that the enhanced synoptic-scale winds act as a booster rocket to shift the typhoons northward to the southwesterly steering flows. It seems that both of the MJO and QBW components play a role in producing the high-wind area associated with these observed sudden track changes.

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