Tropical Cyclone Formations-Tropical Transition

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Abstract

Davis and Bosart (2004) defined tropical transitions (TT) as those core-cold baroclinic cyclones that transfer to warm-core tropical cyclones (TCs). This process is contrasted with extratropical transition, defined as those warm-cold tropical cyclones that transfer to cold-core extratropical cyclones. In the Atlantic, there are many tropical cyclones depended on extratropical precursor.

This study analyzed the synoptic flow and the important process associated with TC formation embedded in a weak baroclinic environment located at the northern South China Sea (SCS) during the mei-yu season. A conceptual model is proposed for the typical frontal-type TC formations in the SCS that consists of three essential steps. First, an incipient low-level disturbance that originates over land moves eastward along the stationary mei-yu front. Second, the low-level circulation center with a relative vorticity maximum moves to the open ocean with the stationary front. Finally, with strengthened northeasterlies cyclonic shear vorticity continues to increase in the SCS, and after detaching from the stationary front, the system becomes a tropical depression. Results from simulations indicate the mergence of vorticity in the low troposphere play an important role during TC formations and the vorticity maximum become more symmetrical structure in the later stage of formation. The intensity change of the low-level vorticity during formation process is affected significantly by the upper-level divergence and the low level convergence. Superposition of strong divergence at upper level and strong convergence, vorticity maximum at low level enhance vorticity and help the mergence of vortices. Otherwise there are two-significant strengthens of vorticity. The first strengthens is induced by the large scale environmental forcing, and the second strengthens is likely triggered by the obvious increase of the upper-level divergence.

Keyword：Tropical cyclone formation, tropical transition, numerical simulation

1. Introduction

The mei-yu season in southeast Asia is from about mid-May to mid-June when a stationary front in the northern South China Sea (SCS) often occurs. The mei-yu frontal system is part of the East Asia monsoon system. The persistent southwesterlies associated with the summer monsoon and the frontal easterlies create a general cyclonic flow environment in the northern SCS. Chen and Chang (1980) showed that the mei-yu front and midlatitude fronts have similar structures in that they possess a large horizontal temperature gradient and vertical baroclinic structures. The major difference is that the mei-yu front is only weakly baroclinic and there can be strong low-tropospheric vertical wind shear, which is especially true for the frontal systems west of Japan (Ninomiya and Akiyama 1992).

Lander (1996) examined TC formations during 1978–1994 associated with the so-called reverse-oriented monsoon trough, which is similar to the frontal orientation in the East Asia mei-yu season. However, Lander (1996) did not explicitly identify the cases that originated from the mei-yu front. Such mei-yu formations may be related to the subtropical cyclone (STC), which Hebert and Poteat (1975) defined as a TC-like circulation that forms in the baroclinic subtropical environment associated with a front. The cloud coverage in a STC usually measures 15° latitude across, which is larger than a typical TC.

Different statistics have been given on tropical cyclogenesis associated with baroclinic or frontal systems. The results of Frank and Clark (1977) showed that less than 5% of all TC formations in the Atlantic occurred in close vicinity of a front or east side of a westerly trough. However, Gray (1998) indicated that about 25% of the global TC formations were not in a pure tropical environment. Bosart and Bartlo (1991) studied Hurricane Diana (in 1984) in the Atlantic, and showed the pre-Diana disturbance was also a STC that originated from a frontal system east of Florida. Bosart and Bartlo (1991) demonstrated an interaction between upper- and lower-level potential vorticity (PV) anomalies. The PV anomaly associated with the upper-level trough was advected toward the low-level disturbance such that the entire system was able to evolve to a more barotropic warm-core system. Davis and Bosart (2001) simulated

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the formation of Hurricane Diana using the fifth-generation Pennsylvania State University-National Center for Atmospheric Research (PSU-NCAR) Mesoscale Model (MM5) and found that the essential stage of transformation from a weak baroclinic disturbance into Diana was strongly modified by the effects of latent heating. In the first stage, the low-level circulation is strengthened through the axisymmetrization of remote PV anomalies that are generated by condensational heating and then advected toward the incipient storm. After a warm-core vortex and spiral bands of convection begin to form, the moisture in the core of the storm increases. Davis and Bosart (2002) explored the model sensitivities in simulating Diana. When the upper-level trough was removed from the initial condition, cyclogenesis did not occur, which indicates the importance of appropriate coupling between the upper and lower levels in transforming the baroclinic system into a tropical depression.

In a further study, Davis and Bosart (2003) collected 10 cases of transformation from a STC to a TC during September through November in 2000 and 2001. A rapid decrease in the 200-900-hPa vertical wind shear occurred before the STC became a TC. On the other hand, those subtropical cyclones that did not transform to a TC experienced vertical wind shear of about 15–20 m s^{-1}. Davis and Bosart (2003) also simulated the formation of Hurricane Michael (in 2000) and found that the vertical wind shear had to decrease rapidly from 30 m s^{-1} to realize the warm-core structure. Therefore, the reduction of the vertical wind shear of the initial baroclinic system is an essential requirement for its transformation to a TC.

Lee et al. (2006) used composites to analysis the synoptic flow of TC formations associated with the mei-yu front. However, this only can demonstrate the average patterns of synoptic flow and general change, some extreme phenomenon could be smoothed out. Because of the low spatial and temporal data resolution, some issues cannot be precisely determined. For instance, the timing of the baroclinic-to-barotropic transition during the weakening of the frontal structure is not precisely known. The timing of when the Rossby radius of deformation starts to decrease such that latent heat can efficiently build up the warm core also has to be examined further. Some successful numerical simulations might provide suitable fields for further diagnosis (Lee and Lee 2002). In order to well-understanding the mechanism of these processes, this study refers to the definition of Lee et al. (2006) to simulate the formation of Typhoon Noguri (in 2002) using MM5 to figure out which the key point resulting in TC formations in the weak baroclinic environment is.

2. Composites of frontal-type formations

Lee et al. (2006) examined the 119 tropical cyclone (TC) formations in the South China Sea (SCS) during 1972–2002, and in particular the 20 in May and June. Eleven of these storms are associated with the weak baroclinic environment of a mei-yu front, while the remaining nine are nonfrontal. Seven of the 11 initial disturbances originated over land and have a highly similar evolution. Comparison of the frontal and nonfrontal formation shows that a nonfrontal formation usually occurs at a lower latitude, is more barotropic, develops faster, and possibly intensifies to a stronger TC. Six nonformation cases in the SCS are also identified that have similar low level disturbances near the western end of a mei-yu front but did not develop further. In the nonformation cases (Fig.1b), both the northeasterlies north of the front and the monsoonal southwesterlies are intermittent and weaker in magnitude so that the vorticity in the northern SCS does not spin up to tropical depression intensity. Because of the influence of a strong subtropical high, convection is suppressed in the SCS. The nonformation cases also have an average of 2–3 m s^{-1} larger vertical wind shear than the formation cases (Fig.3). A conceptual model is proposed for the typical frontal-type TC formations in the SCS that consists of three essential steps (Fig.2).

1) In the incipient step, a low-level disturbance over land that originated to the west from cyclogenesis in a weakly baroclinic environment moves eastward along the stationary mei-yu front with a semiclosed surface isobar.
2) During the movement over sea step, the low-level circulation center moves over the SCS along the stationary front and with strengthened southwesterlies now has a relative vorticity maximum and a closed surface isobar. If the vertical wind shear over the disturbance decreases, the baroclinicity also weakens and vice versa.
3) During the transition step, the northeasterlies along the southeast China coast strengthen as the cold high over China moves to the Yellow Sea, and thus the cyclonic shear vorticity continues to increase over the SCS. Deep convection associated with latent heat release in the region reduces the Rossby radius of deformation of the system, and after detaching from the stationary front the system becomes a tropical depression.

3. Case study

TC *formation is a continued process that is* difficult to determine the genesis point (Ooyama 1982). As some TC formation studies (e.g., Cheung 2004, Lee et al. 2006), formation time is defined as the first time a TC reaches an intensity of 25 kt (~13 m s^{-1}) in the Joint Typhoon Warning Center (JTWC) best-track data. The other studies (e.g., Lee and Lee 2002), formation time is defined as TC formation alert (TCFA) issued by the JTWC. In general, the JTWC issues TCFA, which is based on the analysis of satellite data, when the *disturbance existing obvious character will develop* in next 24 hours. In this study, formation time is defined as the timing of which was declared first.

This study using ECMWF advanced data

analyzes formation cases of Typhoon Noguri (in 2002) and Tropical Storm Russ (in 1994) to examine various-environmental parameters quantitatively and to diagnosis large-scale heat and moisture budgets during formation process. In addition, using results of MM5 simulations discusses the mechanism of TC formation. The synoptic environment of both two TCs showed that a incipient disturbance originated from the Hainan Island and Luichow Peninsula and a high pressure system was located to the north moved to low latitude at the same time. Both circulations of high-pressure system north of the disturbance moved to east at the later period of formation process, but the phenomenon with Typhoon Noguri (in 2002) was not obvious. The 850-hPa potential temperature (Fig.4) also show an incipient disturbance was located at the southwest end of the mei-yu front, then the large potential temperature gradient at the end of the stationary front decreased and the low-pressure system was further from the stationary front. However, the two cases both had another low-pressure systems embedded in the mei-yu front that merged into the frontal zone finally. With cyclonic circulation surrounding the frontal zone made for the decrement of potential temperature gradient between the disturbance and the stationary front. At the initial formation of Typhoon Noguri (in 2002), the surface weather map showed that a low-pressure system intensified to tropical depression east of the incipient disturbance. The circulation of disturbance near east side of the Hainan Island with potential temperature gradient decreased. The low-pressure system east of Tropical Storm Russ (in 1994) did not developed to TD; the potential temperature gradient near the cyclonic circulation increased slightly when pre-Russ developed to TD. The difference of the synoptic baroclinity between the two cases can result in different scenarios of development at later formation process.

The satellite imageries showed that convective clusters of the incipient disturbance were located at the end of the stationary front. There was much cyclonic-rotating convection embedded in the stationary front and the convection in the SCS was stronger and persistent. The convection of disturbance in the both two cases with the stationary front moved eastward over the northern SCS. The interaction between the mei-yu front and convection in the northern SCS occurred during the formation process and convections of the disturbance with persistent southwesterlies and obvious-strengthening easterlies at the end of a mei-yu front, many meso-convective systems gradually merged together and then became well organized. In addition before 12-18 h of issued TCFA by the JTWC, satellite imageries showed that convection of disturbance in the both two cases weakened with stronger northeasterlies. But the low-level vorticity revealed that there was obvious cyclonic-wind shear to induce significant relative vorticity in the synoptic flow. This can make probabilistic the disturbance to develop quickly.

Further analyses revealed that the vertical distribution of convective heating and moisture in Russ (in 1994) was stronger than Noguri (in 2002), but the increase with time of Noguri (in 2001) was more obvious. Both incipient periods, the apparent heat source (Q_1) at low level was negative (Fig.5a) due to condensation cooling of precipitation. Therefore the apparent moisture sink (Q_2) between 600 and 800 hPa was maximum (Fig.5b) and Q_1 between 300 and 400 hPa was maximum (Fig.5a). These showed that the water vapor at low level can transfer to upper level by low-level convergence with upward-vertical motion, for this reason the latent heat release occurs at upper level inducing heating maximum. When the low-pressure system intensified gradually, the increase of water-vapor convergence was outstanding at low level; otherwise the total troposphere of low-pressure circulation was warmed up when the JTWC issued TCFA.

4. Analyses of simulation

Simulations using MM5 show that a incipient disturbance has two-maximum vorticity to rotate each other and then merge together. Gradually southwesterlies south of the mergence and northeasterlies north of the mergence were increasing; consequently the vorticity maximum with cyclonic-rotating flow accelerates to spin up (Fig.6a-c). Later simulations show that northeast-southwest vorticity exists east of the mergence of vorticity maximum and easterlies at the end of the mei-yu front increases obviously. Meanwhile the stretched-out vorticity rotates into the vorticity maximum of low-pressure circulation. Therefore the low-pressure system can develop faster and transfer to more symmetrical structure. Both the vertical cross sections reveal that before the mergence of stronger vorticity at the beginning of formation concentrates at low level and rotates persistently. After the mergence of vorticity, the low-level vorticity intensifies quickly. During later formation process, the stronger vorticity vertically extends to 300 hPa and positive temperature anomaly at upper level is vertically extends to low level, which makes the troposphere of vorticity maximum reveals the barotropic structure with warm core.

The deployment of the southwesterlie and northeasterlie provide a cyclonic-wind shear to for disturbance. Superposition of the low-level vorticity maximum, upper-divergent maximum and lower-convergent maximum show that the development of low-level vorticity has closely relation with upper divergence and lower convergence; when superposition of strong divergence at upper level and strong convergence at low level, the low-level vorticity intensifies persistently that is favorable to the mergence of vorticity. Meanwhile there are two-significant strengthens with aerial averages of vorticity (Fig. 7). The first strengthen is induced by the large scale environmental forcing that can maintain specified intensity of the low-level vorticity not to decay quickly during increase of vertical wind shear or decrease of upper divergence. The second strengthen is behind the increase of upper divergence about 6 hours, which shows that upper divergence provides favorable condition to induce the second strengthen. This is important factor to affect TC formation.

5. Conclusion

This study analyzed the circulation pattern and the important process associated with the formation of a typhoon embedded in a weak baroclinic environment located at the northern South China Sea (SCS) during the Mei-yu season. These analyses showed that there are many similar synoptic-environmental flow in this kind of formation process. Composites（Lee et al., 2006）reveal that the typical frontal-type TC formations in the SCS that consists of three essential steps. First, an incipient low-level disturbance that originates over land moves eastward along the stationary mei-yu front. Second, the low-level circulation center with a relative vorticity maximum moves to the open ocean with the stationary front. Finally, with strengthened northeasterlies cyclonic shear vorticity continues to increase in the SCS, and after detaching from the stationary front, the system becomes a tropical depression. Results from MM5 simulations of TCs formations about Typhoon Noguri (in 2002) and Tropical Storm Russ (in 1994) also indicate that there are two stronger-positive vorticity near the Hainan Island rotating each other and merging together. This accelerates the vortex to spin up as more symmetrical structure. For this reason, the mergence of vorticity in the low troposphere plays an important role during TC formations. The intensity change of low level vorticity during formation process is affected significantly by high level divergence and low level convergence. Superposition of strong divergence at upper level and strong convergence, vorticity maximum at low level enhance vorticity and help the mergence of vorticity. Otherwise there are two-significant strengthens s with aerial averages of vorticity within 100-km area of the low-level circulation. The first strengthen is induced by the large scale environmental forcing, and the second strengthen is likely triggered by the obvious increase of high level divergence.

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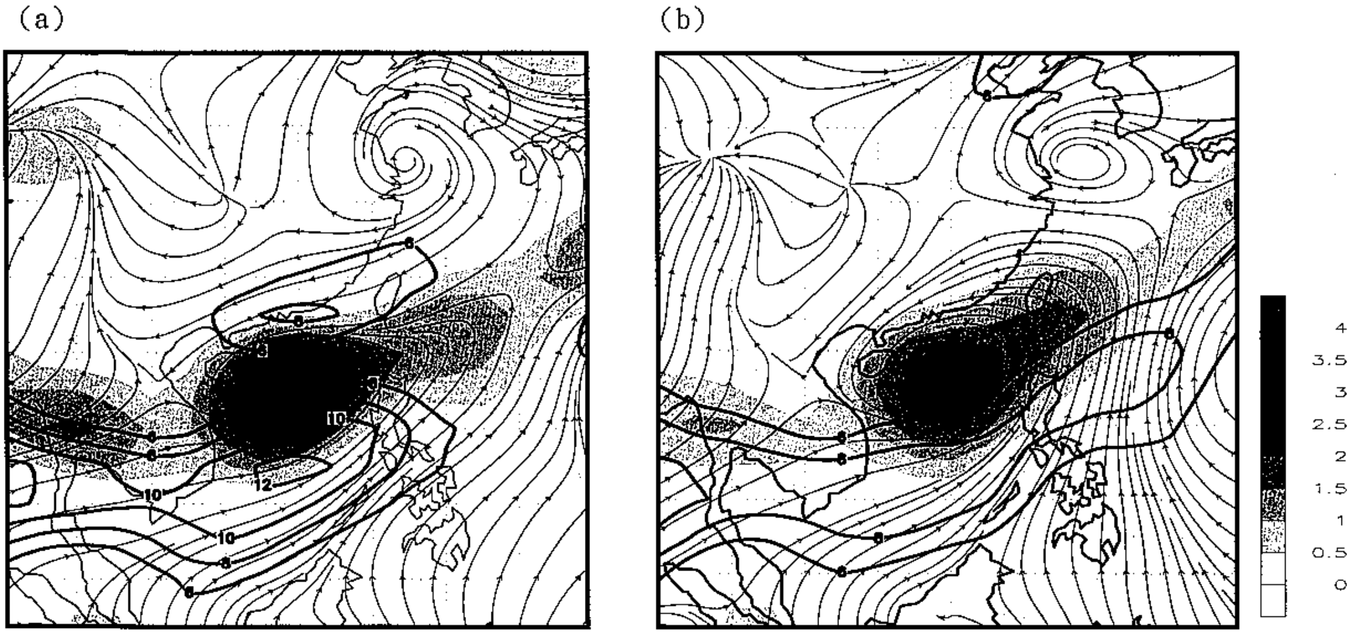
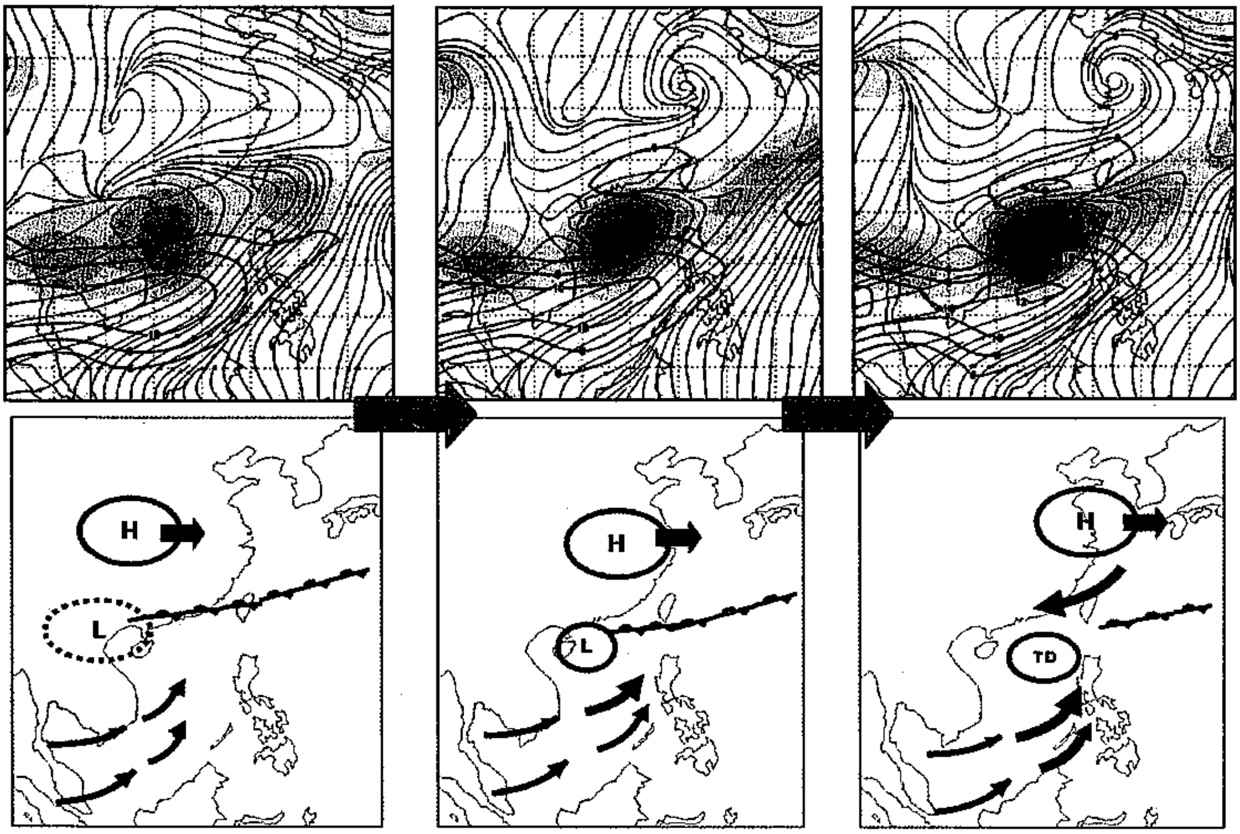


FIG. 1. Composite 925-hPa flow for (a) formation, (b) nonformation cases. The heavy contours indicate wind speed greater than 6 m s^{-1} (interval: 2 m s^{-1}) and the shaded contours are positive relative vorticity (interval: 0.5×10^{-5} s^{-1}).



Step 1 Incipient **Step 2 Movement over sea** **Step 3 Transition**

FIG. 2. Composite 925-hPa flow for frontal-type formations (upper) corresponds to three steps (lower) in the conceptual model of TC formation associated with a mei-yu front. The heavy contours (upper) indicate wind speed greater than 6 m s^{-1} (interval: 2 m s^{-1}) and the shaded contours are positive relative vorticity (interval: 0.5×10^{-5} s^{-1}).

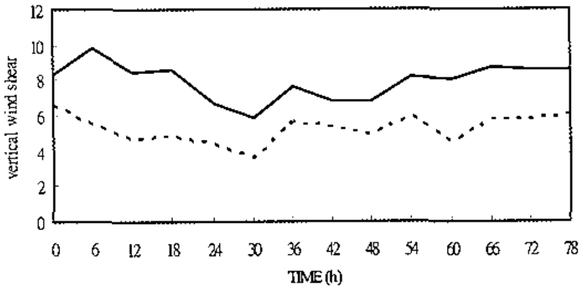
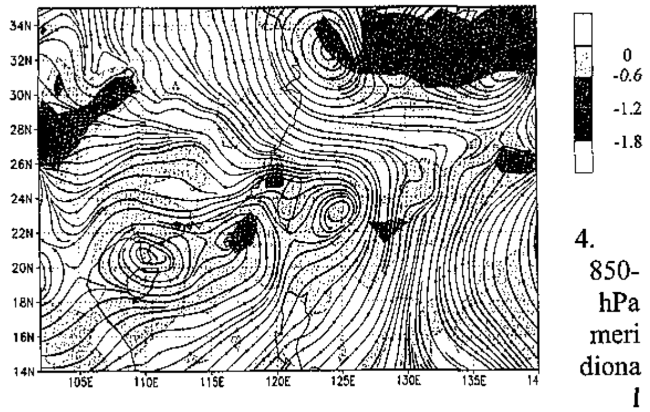


FIG. 3. 200-850-hPa vertical wind shear magnitude (unit: m s^{-1}) for the formation (dashed) and nonformation (solid) cases.

FIG.



4. 850-hPa meridional gradient of potential temperature association with Typhoon Noguri (in 2002) and the shaded contours are temperature gradient (interval: 0.6 K×100 km^{-1}).

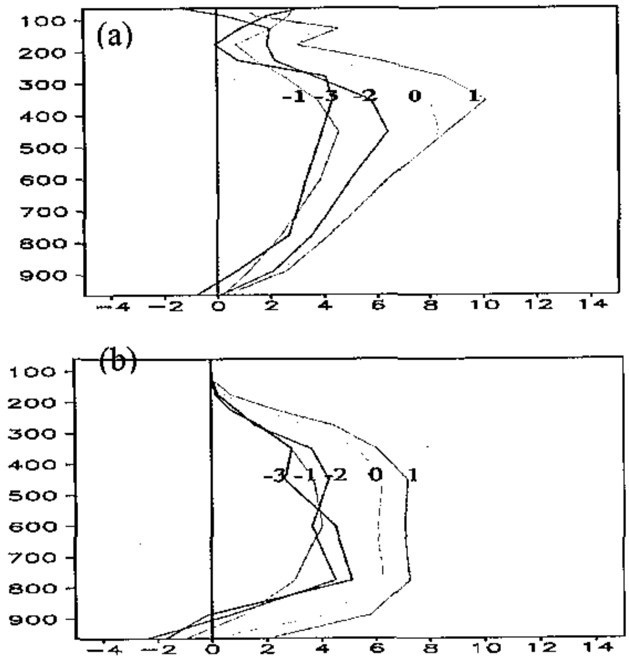


FIG. 5.Vectical distribution (unit: hPa) of (a) apparent heat source (Q_1) and (b) apparent moisture sink (Q_2) association with Typhoon Noguri (in 2002) and time series is before three (-3), two (-2), one (-1) days, TCFA (0) and after one (1) days. The abscissa indicates temperature (unit: K day^{-1}).

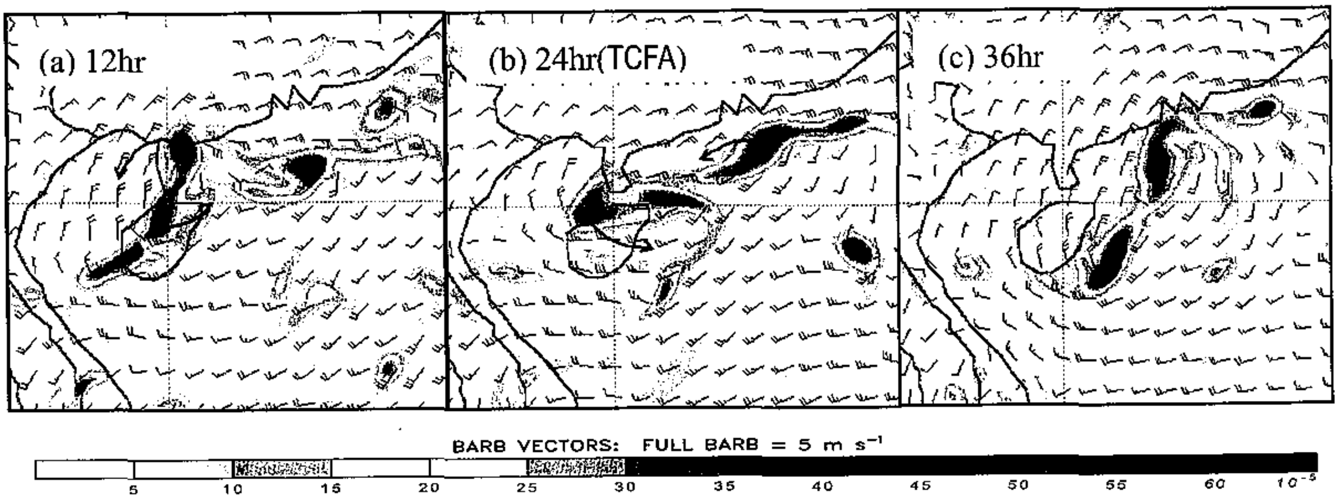


FIG. 6. 925-hPa relative vorticity of simulation association with Typhoon Noguri (in 2002) at integration of (a) 12, (b) 24, and (c) 36 hr. The shaded contours are positive relative vorticity (interval: 5×10^{-5} s^{-1}).

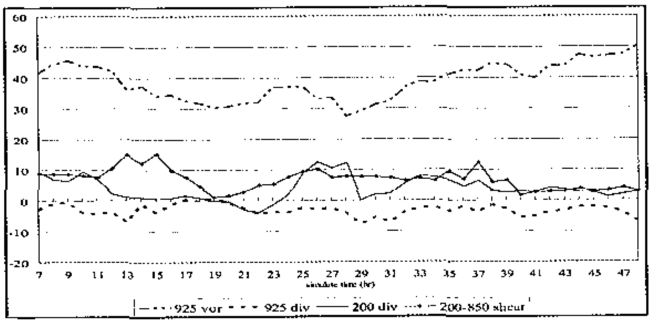


FIG. 7. 925-hPa relative vorticity, .925-hPa convergence, 200-hPa divergence (unit: 10^{-5} s^{-1}) and 200-850-hPa vertical wind shear (unit: m s^{-1})magnitude of simulation of simulation association with Typhoon Noguri (in 2002). The abscissa indicates integral time (unit: h).