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A Simple Introduction of Extratropical Transition of Tropical Cyclone (TC) and a Case Study on the Latest Three TCs: Shanshan (0613), Yaki (0614), and Soulik (0618)

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태풍의 온대성 저기압화에 대한 간단한 소개 및 최근 세 태풍의 사례분석: 산산(0613), 야기(0614), 솔릭(0618)을 중심으로

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Abstract: In this article, the extratropical transition (ET) of tropical cyclone (TC) was investigated based on the case study covering the latest three TCs (Shanshan, Yaki, and Soulik) associated with ET evolution (onset and completion) using the objective ET diagnostics of Evans and Hart (2003) and Hart (2003). At 500-hPa level, on an onset of ET, all three TCs entered the baroclinic zone. In a vertical cross-section analysis, three TCs before and at an onset of ET kept warm and humid throughout all levels around the TC center. However, these TCs after ET onset became relatively cold and dry over the western part of TC as the typical characteristics of ET concept model. Although our case study was not sufficient, it is concluded that the diagnostics of the ET onset and atmospheric structure change associated with Evans and Hart (2003) and Hart (2003) will be useful in ET operational forecast.

Keywords: extratropical transition, western North Pacific, atmosphere structure change

요 약: 이 연구는 태풍의 온대성 저기압화에 대해 간단히 소개하고 Evans and Hart(2003)와 Hart(2003)의 객관적 온대성 저기압화 판별식을 이용하여 최근 온대성 저기압화를 거친 세 태풍(Shanshan, Yaki, Soulik)에 대한 사례분석이 이루어졌다. 500-hPa 고도장분석에서 온대성 저기압화 시작시 세 태풍 모두 중위도 경압지역으로 북상하는 공통된 특성을 보였다. 그러나 연직단면 분석에서는 온대성 저기압화의 시작전·시 태풍 중심부근의 모든 층에서 온난·다습한 특성을 보였다. 온대성 저기압화 이후에는 이 개념모델의 전형적 특성인 태풍의 서쪽영역에 한랭 · 건조한 특성을 나타내었다. 따라서 Evans and Hart(2003)와 Hart(2003)의 객관적 온대성저기압화의 판별식은 태풍의 온대성저기압화 시작 및 구조변화를 잘 반영하므로 기상청 예보현업에서도 유용하게 사용될 수 있을 것으로 판단된다.

주요어: 온대성저기압화, 북서태평양, 대기구조변화

Introduction

According to many previous studies on tropical cyclones, it has been reported that 46% of Atlantic tropical storms (Hart and Evans, 2001), 27% of western North Pacific storms (Klein et al., 2000), and 10% of storms in western Australian waters (Foley and Hanstrum, 1994) undergo extratropical transition (ET). Until now, no universally accepted definition of the ET of tropical cyclone (TC) has not been established (Malmquist, 1999), due to a large case-to-case variability in the process of ETs (Evans and Hart, 2003). Thus, some national meteorological services have tried to define and forecast the ET onset and completion themselves. The definition of ET by National Hurricane Center (NHC) in the United States

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referred to a storm that is in its extratropical from tropical phase after it becomes more asymmetric based on the satellite imageries at some point in its lifetime (Hart, 2003). And, in order to emphasize the importance of the ET, the Meteorological Service of Canada has labeled storms that have undergone ET as "post-tropical" and has continued to use the name of storm issued by NHC-thus, a storm such as hurricane Floyd (1999) moving into Canadian waters would be referred to as "Post-Tropical Cyclone Floyd" (WMO IWTC-Ⅶ report, 2006). In the western North Pacific (WNP), Japan Meteorological Agency has carried out operational synoptic analysis of extratropical transformation of TC mainly based on satellite imagery, since its transformation often occurs over the ocean, i.e., the data-sparse region (Kitanabe, 2002). In general, the completion of the ET has been judged from the dissipation of central dense overcast in satellite imagery or surface frontogenesis at the cyclone center in the surface analysis.

On the other hand, various definitions of ET have been studied by many researchers. In particular, forecasters and researchers in Japan have been more interested to ET, since TCs are often transformed into extratropical cyclones around the Japan Islands. Matano and Sekioka (1971a) defined two types of ET, i.e. complex and compound transformations based on surface pressure analysis. Brand and Guard (1979) added the dissipation type to the definition of Matano and Sekioka (1971a). Recently, Suzuki (2000) summarized the features of ET as follows: 1) the "roundness" of the cloud pattern was similar to that at its mature stage, 2) the significant cirrus streak associated the upper outflow in the northwest quadrant of the cyclone center, 3) a convective cloud line extending to the southwest from near the cyclone center (although a surface cold front did not correspond to it), and 4) the distinct dark zones in water vapour imagery were to the west and to the east of the cyclone center, which were associated with a 300-hPa trough and a subtropical anticyclone, respectively.

Concerning the TCs in the Atlantic and western Australian basins, Klein et al. (2000), Evans and Hart (2003), and Hart (2003) used the frontal nature of the cyclone and its feature as the fundamental indicators of ET onset and the stage of TC evolution. They showed that this frontal nature is defined as the storm-motion-relative 900-600-hPa thickness asymmetry across the cyclone within 500-km radius.

To date, compared to the structure change of TC extensively studied, the ET of it has not been paid an attention yet (Thorncroft and Jones, 2000). In Korea, ET-related paper is difficult to find except for Kwon and Kim (2005). However, wind and precipitation during the extratropical transformation of TC are even stronger than those during the typhoon grade, causing considerably damages to the human life and property. Under the environment of the incorrect prediction of the timing of ET onset, the definite definition of ET that can be communicated to the general public is as important as the genesis and development of TC from a point of view of the damage reduction of human life and property.

The focuses of this paper are two parts: to simply introduce ET of TC and to apply the objective diagnostic on the extratropical transformation to the three TC cases over WNP. The objective diagnostic was selected from those described in the studies of Klein et al. (2000), Evans and Hart (2003, hereafter EH2003), and Hart (2003, hereafter H2003) over the Atlantic and western Australian basins. Eventually, this paper aims to support the operational forecasting of ET evolution and predictability.

Data and methodology

Data

In order to select the 61 ET cases of TC, the present study used the dataset of TC best-track for the WNP that has been archived by the Regional Specialized Meteorological Centers (RSMC)-Tokyo during the period of 2002-2006. This dataset includes 6-hourly latitude-longitude positions and intensity such as central pressure (hPa) and maximum sustained wind (MSW; kt) of TCs. Here, the MSW along the

TC intensity is divided into 4 grades such as tropical depression (TD; MSW <34kt), tropical storm (TS; 34kt ≤ MSW ≤ 47kt), severe tropical storm (STS; 48kt ≤ MSW ≤ 63kt) and typhoon (TY; MSW ≥ 64kt).

We also use the 6-hourly National Center for Environmental Prediction (NCEP) Aviation model (AVN; Kanamitsu, 1989) in order to define the transition onset and to examine the ET-related atmospheric circulation features. These data are available on a $1^{\circ}\times 1^{\circ}$ grid at 26 pressure levels for 5 years (2002-2006).

Introduction of ET transition

In this study, the first one of the three parameters of EH2003 and H2003 was used to describe the general structure of cyclones of the lower-tropospheric thermal asymmetry. EH2003 pointed out that this first parameter is more successful in succinctly describing and differentiating the structure of tropical and extratropical cyclones than other parameters (e.g., potential vorticity, conveyor belts, secondary circulations, jet streak configuration, cyclone tilt). They also found parameters of the latter presented above are difficult to describe the various aspects of extratropical transition of TC and their complex of interpretation is not easily utilized to define the extratropical transition of TC. On the contrary, there is an advantage that the parameter of EH2003 and H2003 are simply calculated from only three dimensional height field and is easy to interpret the result. The additional details of this parameter are given in the EH2003 and H2003. Here, we are going to briefly introduce these parameters in this study.

Definition of ET onset: Parameter

As a TC commences ET, i.e. begins to take on nontropical characteristics, it becomes decreasingly symmetric. This asymmetry of TC is characterized by the gradual loss of upper-level warm-core and low-level frontogenesis. This is in agreement with the diagnostics of Harr and Elsberry (2000) and Klein et al. (2000), who describe low-level frontogenesis as an indicator of ET for WNP systems. Foley and Hanstrum (1994) showed an interaction with a midlatitude trough and subsequent frontogenesis as key stages in the evolution of the western Australian ET cases. This increasing asymmetry in the lower troposphere is critical in detecting the onset of transition. Therefore, the formula of the EH2003 were used to explain the feature of structure change of TC during the ET as follows; For a transition of TC moving into the westerlies, cooler environmental air will be to its left(north) and warmer, tropical air will be to its right (south). And the low-level frontogenesis described above can be characterized as a shift to a sustained asymmetry in the thickness field in the region of the storm. Hence, the indicator of TC symmetry (for any tropical or extratropical system) is the storm-relative right minus left asymmetry in the thickness field:

$$B = h(\overline{(z_{600}-z_{900})_R} - \overline{(z_{600}-z_{900})_L}) \qquad (1)$$

where the overbar indicates the areal mean over the semicircle with respect to storm motion and h indicates the hemisphere [1 = Northern Hemisphere (NH), −1 = Southern Hemisphere (SH)]. The pressure range used to calculate thickness was chosen to avoid the boundary layer and potential interpolation below ground. For an appropriate radius of B, H2003 confirmed the 500-km radius is a reasonable horizontal area to describe the TC evolution from the exploration of the complete dependent dataset of 61 storms and dozens of midlatitude in the Atlantic.

ET onset is defined according to

$$B > 10\,m \qquad (2)$$

where 10m is the empirically determined threshold calculated by EH2003 on 61 ET cases for 1998-2001 in the Atlantic. A mature TC has a value for B that is approximately zero (thermally symmetric or nonfrontal), while a developing extratropical cyclone has a large positive value for B (thermally asymmetric or frontal).

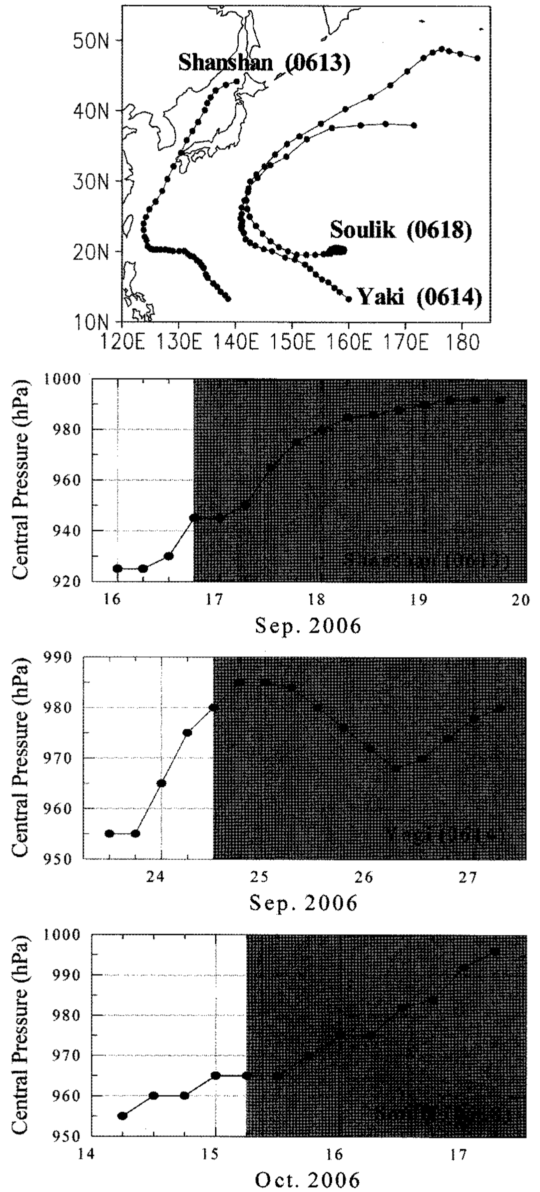

Fig. 1. Tracks and central pressure change for Shanshan (0613) in Cluster 1, Yaki (0614) in Cluster 2, and Soulik (9618) in Cluster 3. Gray part in central pressure change denotes the ET period based on the diagnostics of EH2003 and H2003.

Case study

Case selection

In order to examine the 500-hPa geopotential height field and the vertical atmospheric structure associated with ET evolution (onset, completion), three ET cases of 2006 year are selected from the four clusters classified by the Choi et al. (2007). In particular, the ET evolution was investigated using the diagnostics (formula 2) of EH2003 and H2003. The selected ET cases with different intensity change after ET onset is as follows:

- Cluster 1: Shanshan (0613) - gradual weakening
- Cluster 2: Yaki (0614) - reintensification, and
- Cluster 3: Soulik (0618) - rapid weakening

The Cluster 4 showing irregular track after ET was not considered in the case study for easily making the finding on relationship between intensity change after ET onset and the evolution of atmospheric circulation. Also, the time of ET onset from the diagnostics of EH2003 and H2003 was defined in each case (Fig. 1). Shanshan occurring at 00 UTC 9 September was calculated as an ET at 18 UTC 15 September from the diagnostics of EH2003 and H2003. In the case of Yaki, it made a transition to extratropical cyclone from the diagnostics of EH2003 and H2003 at 12 UTC 24 September. Soulik, similar to Yaki in the track, did not move northward of 40° N. It's ET onset time by the diagnostics of EH2003 and H2003 was at 06 UTC 15 October.

Atmospheric features before and after the ET onset

500-hPa horizontal field analysis

In order to examine the possibility of applying the diagnostics of EH2003 and H2003 as a operational ET onset time, the 500-hPa geopotential height field before and after ET onset was analyzed (Fig. 2). Within one day before ET onset, three TCs do not reach the baroclinic zone yet. On an ET onset day, the TCs eventually are located in the baroclinic zone, but are still far away from a midlatitude trough (dotted lines). In the case of Yaki, the lows associated with midlatitude trough are located in the south sea of Korea and around the Sea of Okhotsk, providing a good circumstance for Yaki to reintensify. In the case of Shanshan, midlatitude troughs, which are not as strong as those of Yaki, appeared over areas of the Sea of Okhotsk to around the Korean peninsula.

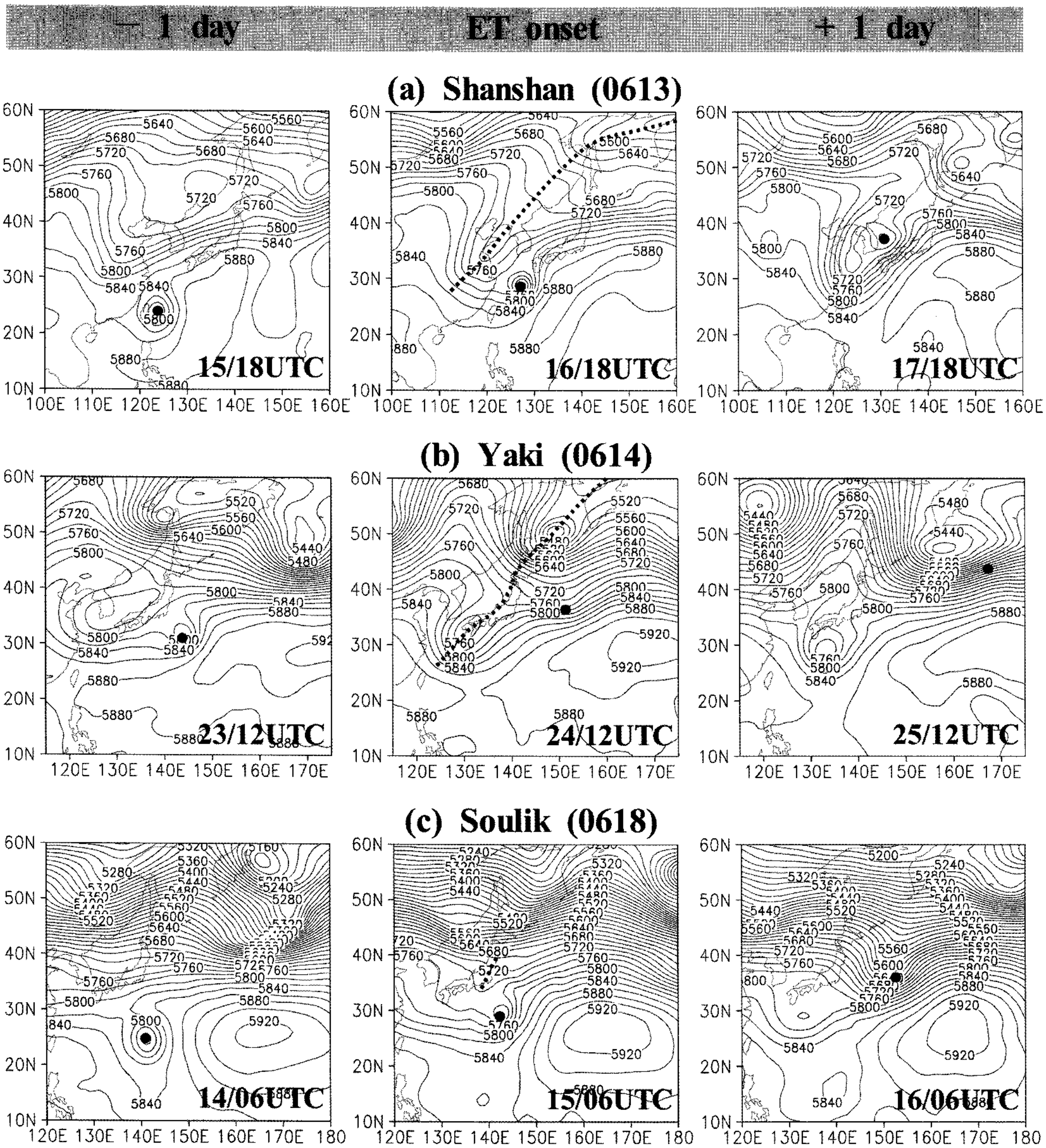

Fig. 2. 500-hPa geopotential height maps on one day before ET onset (left panel), ET onset day (middle panel), and one day after ET onset (right panel) for (a) Shanshan (0613) in Cluster 1, (b) Yaki (0614) in Cluster 2, and (c) Soulik (0618) in Cluster 3. Dotted lines in middle panel indicated trough. Dots within each figure denotes the positions of typhoon.

However, a weak midlatitude trough in Soulik case is only located around the east of the Korean peninsula. In one day after ET onset, Shanshan is merged into midlatitude trough and Yaki and Soulik are definitely located within the baroclinic zone. In particular, Shanshan experiences the gradual weakening onward that time (Fig. 1). This coincides with the result of Foley and Hanstrum (1994) that the combination of a midlatitude trough with TC can retard the TC weakening during the extratropical transformation.

Vertical corss-section analysis

The TC undergoing ET exhibits an increasingly asymmetric thickness field in response to its interaction with the baroclinic midlatitude environment and develops a cold-core structure through its thermal

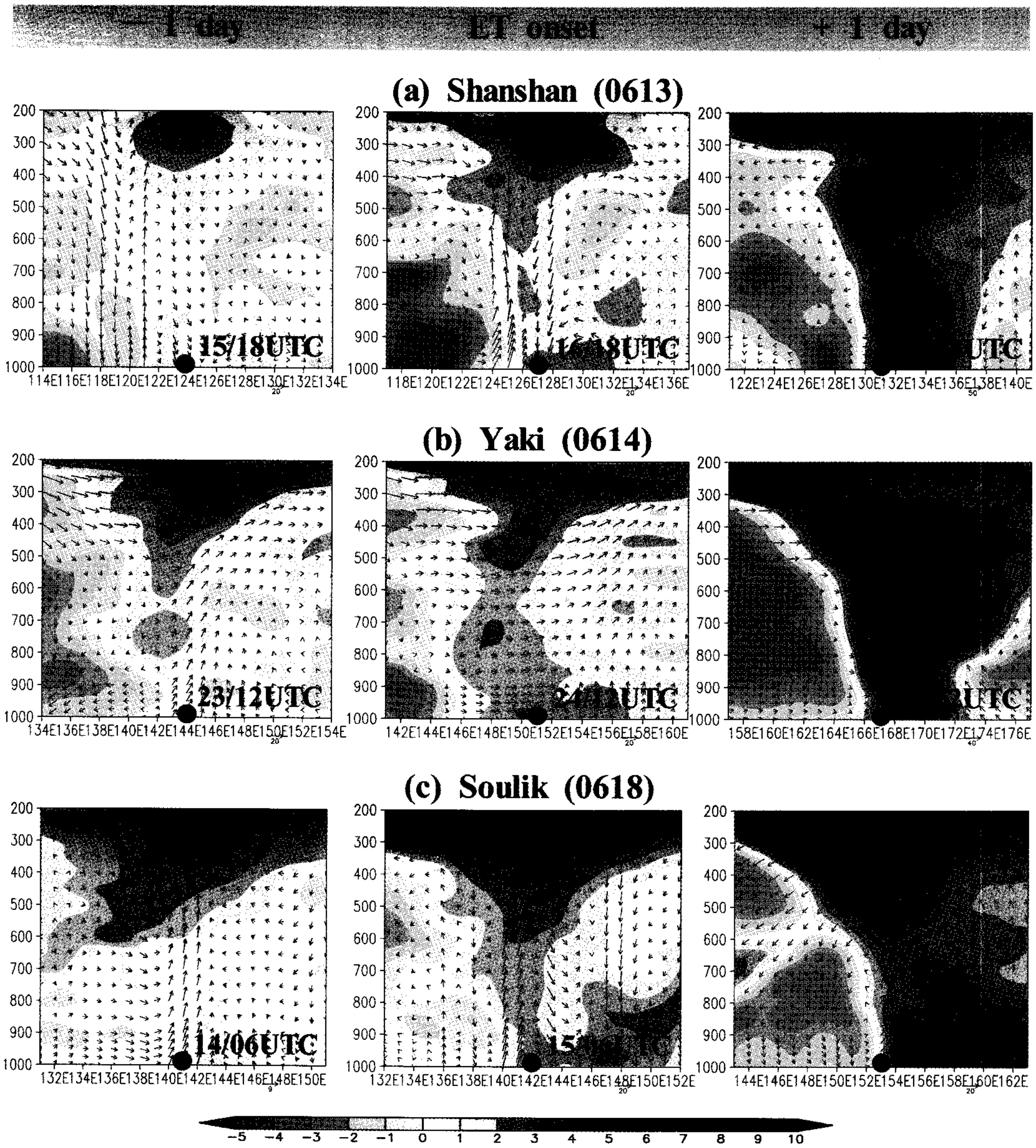

Fig. 3. As in Fig. 2 but for the vertical cross-sections of air temperature (unit: °C) and wind anomalies (unit: m s^{-1}). Vertical velocity is multiplied by −100.

profile. Therefore, the vertical cross-section of air temperature anomaly for three TC cases is analyzed before and after ET onset (Fig. 3). These anomalies are obtained by the subtraction of September mean (Shanshan and Yaki) and October mean (Soulik) air temperatures for 5 years (2002-2006 year) from air temperature of each time. In all three cases, warm-cores associated with TC in one day before ET onset are located in the upper-level above TC center. They continuously exist in the upper-level in an onset day, even if air temperature in the mid- and lower-levels is higher than that in one day before ET onset. However, the typical warm-core system located in the upper-level disappears on one day after ET onset and then air temperature rapidly rises throughout the whole troposphere. And, the ascent and descent flows are predominant in the eastern and western parts of TC, respectively.

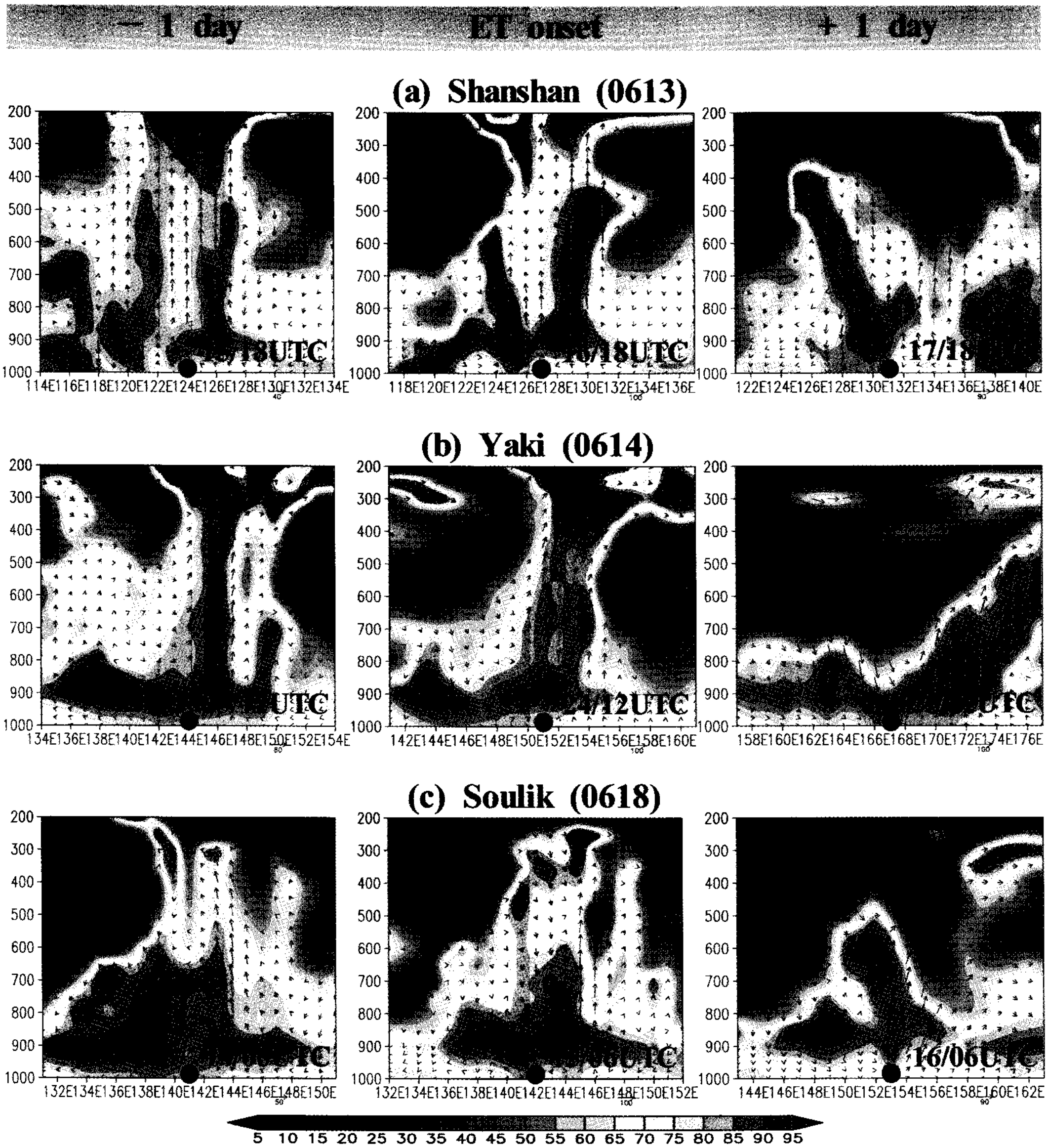

Fig. 4. As in Fig. 3 but for relative humidity (unit: %) and wind.

In the analysis of relative humidity before and after ET onset, relative humidity keeps high throughout all levels until the day of ET onset (Fig. 4). However, relative humidity in one day after ET onset is relatively high in the eastern part of TC. On the contrary, relative humidity in the western part of TC is considerably low. This is due to the environmental flow of cooler and drier air from upper-level trough in the western part of the storm as the ET concept model indicated in Kleins et al. (2000). In the air temperature anomaly field (Fig. 3), we can confirm that cold air is dominant in the western part of TC along the evolution of ET.

We can see from the analysis of so limited cases with different intensity change during the extratropical transformation of TC that atmospheric circulation associated with evolution of TC structure is remarkable during ET period based on the diagnostic of EH2003 and H2003. Therefore, the ET onset diagnostics introduced in this study seem to be helpful

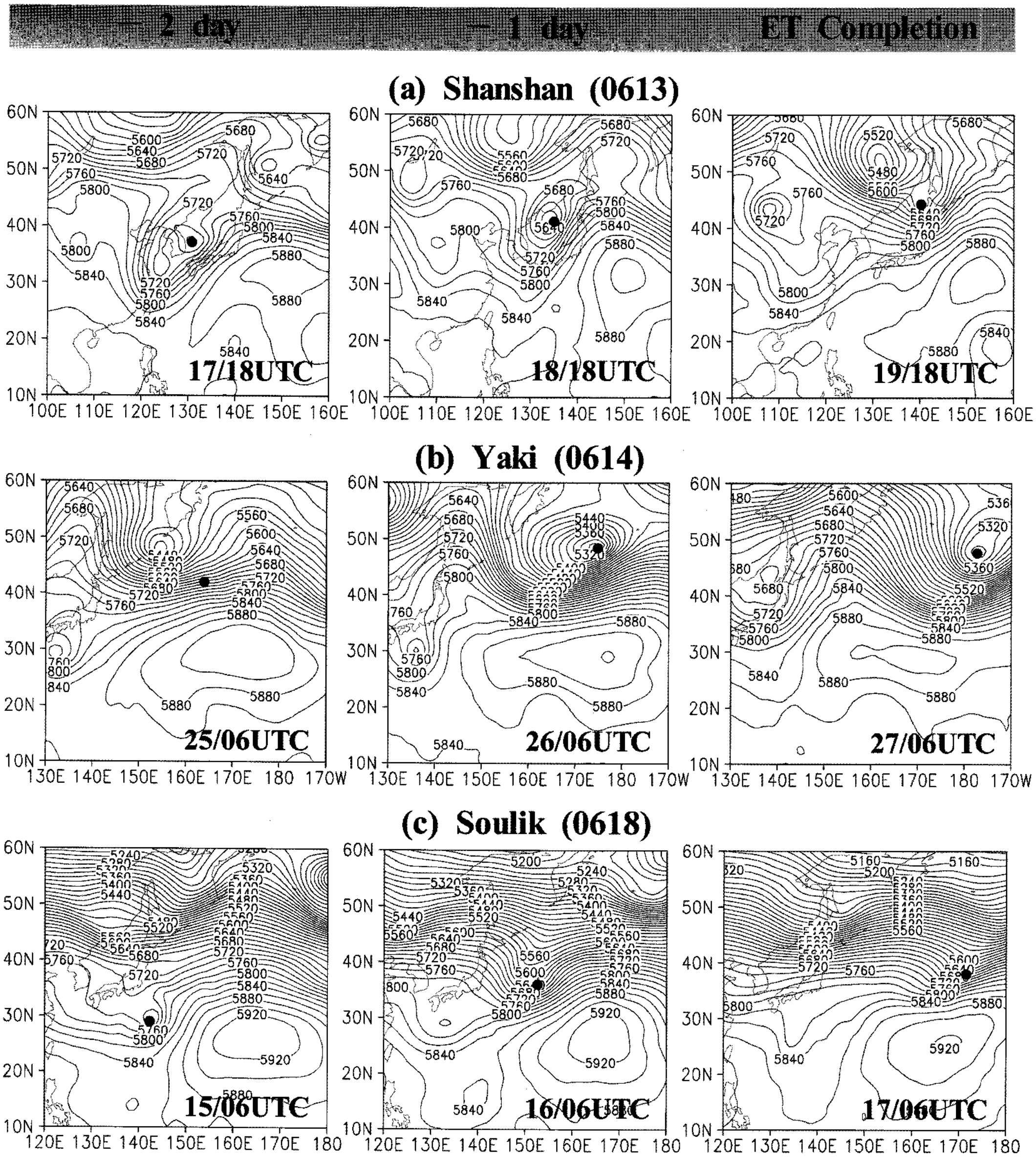

Fig. 5. As in Fig. 2 but for 500-hPa geopotential height maps on two days before ET completion (left panel), one days before ET completion (middle panel), and ET completion day (right panel) before ET completion.

in the ET operational forecasting.

Reintensification of Yaki (0614)

Yaki intensifies again before the ET completion as seen in Fig. 1. That is, the central pressure at 06 UTC 26 September suddenly deepens to the second minimum central pressure (968 hPa). This sudden change can be explained in Fig. 5. At one day (06 UTC 25 September) before Yaki reaches the second minimum of its central pressure, it is still far away from midlatitude trough. The combination of Yaki with trough is occurred onward 06 UTC 26 September, which is consistent with a day when the central pressure of Yaki deepens a 968 hPa. This situation is very similar to the concept model of “Complex” extratropical transformation suggested by

Sekioka (1956). It means that when an extratropical cyclone is combined with a TC through march together in midlatitude, the system tends to suddenly reintensify. Then, Yaki (0614) at 06 UTC 27 September completes the ET with keeping the structure like Shanshan case. Shanshan also combines with the midlatitude trough at 18 UTC 18 September, so that it undergoes the gradual weakening of intensity. However, these characteristics are not clear in Soulik case.

Summary and discussion

The vertical atmospheric structures associated with ET evolution (onset and completion) have been examined for three TC cases of 2006 year such as Shanahsn (0613), Yaki (0614), and Soulik (0618) using the ET objective diagnostics of Evans and Hart (2003; EH2003) and Hart (2003; H2003). In spite of limited cases, we could confirm that atmospheric circulation associated with evolution of TC structure is remarkable during ET period defined by the diagnostic of EH2003 and H2003. At 500-hPa level, within one day before ET onset, three TCs did not reach the baroclinic zone yet and on an ET onset day, the TCs eventually were located in the baroclinic zone. However, onward after ET onset, Shanshan was merged into a midlatitude trough so that it gradually weakened. On the contrary, Soulik nearly did not interact with midlatitude trough so that it rapidly weakened. For a Yaki, it intensified again before the ET completion. That is, its reintensification also was due to the combination of Yaki with midlatitude trough. In a vertical cross-section analysis, TC before and at ET onset kept warm and humid throughout all levels, but one after ET onset became relatively cold and dry in the western part of TC.

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