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ANALYSIS OF EXTRATROPICAL TRANSITION OF TROPICAL CYCLONE OVER MAINLAND CHINA

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ABSTRACT: Typhoon Winnie (1997) experienced three stages after landfall on China: weakening, transition, and re-intensification. The transition is similar to the "complex transition" model proposed by Matano and Sekioka. During the re-intensification stage, the transformed cyclone developed into a pattern of Shapiro-Keyser Cyclone model. From the diagnosis we can find that the cause of Winnie's transition is the intrusion of cold air from the mid- and upper- troposphere and the warm temperature advection in the lower. Winnie redeveloped after transition, which is the result of three vital factors: the warm temperature advection in the lower troposphere, the divergence on the right side of the upper jet entry and the cyclonic vorticity advection in the upper.

Key words: typhoon; extratropical transition; diagnostic analysis

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1 INTRODUCTION

The extratropical transition of tropical cyclones has long been received wide attention. Early influential studies focused on the region of northwestern Pacific Ocean, among which Sekioka[1, 2] and Matano [3] discover, in successive studies, that two types of systems can be formed due to interactions between recurvature-making tropical cyclones and mid-latitude synoptic regimes: the complex and compound ones. Brand and Guard [4] add a third type: the decaying one. Recently, Klein et al[5] put forward a three-dimensional conceptual model about transition, which takes into account processes of physics like ambient cooling/warming air flows, their relationship with the baroclinic bands, the weakening of the system / slanting of the warm core and the development of the asymmetric structure, after a review of extratropical transition of tropical cyclones over the northwestern Pacific in 1994 – 1998. Harr et al. [6, 7] group the circulation associated with the extratropical transition into northwestern and northeastern patterns. In addition, work on the extratropical transition of hurricanes moving deep into North America is both early and abundant[8 - 11], with the focus on the diagnosis of physical quantities and the analysis of 3-dimensional dynamic features. For the same issue concerning typhoons making landfall on China, associated heavy rains were mainly studied before the 1990's and work on the transition processes gradually increased afterwards[12 - 14]. The current paper emphasizes the transition and re-intensification of post-landfall typhoons.

2 TRANSITION / INTENSIFICATION OF TYPHOON WINNIE

Over the 30 years that span from 1970 to 1999, there are 17 cases of transition for typhoons

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that made landfall on mainland China, i.e. at a rate of 6.3% relative to the total of landfall storms. Though a small-probability incident, it deserves more attention as compared to dissipating and weakening post-landfall typhoons. Being a case of transition most recently taking place over the 30-year period, Winnie (1997) is representative of the evolution (Fig.1). Making landfall on the Zhejiang province in eastern China at 13:30 (UTC, the same below), August 18th, the typhoon moved northwest and decayed persistently. It turned north at 12:00 August 19th with pressure constantly rising till 00:00 August 20th when frontal features appeared with the tropical cyclone, suggesting the end of the transition stage. In the meantime, a secondary center was induced over the northern slope of the Taishan Mountain north of the original center, as shown in the surface map, with the former replacing the latter, which then moved northeast and strengthened gradually and became a mature extratropical cyclone at 12:00 August 21st. It is known from the transition of Winnie that it is similar to that experienced by the complex tropical cyclone defined by Sekioka et al.

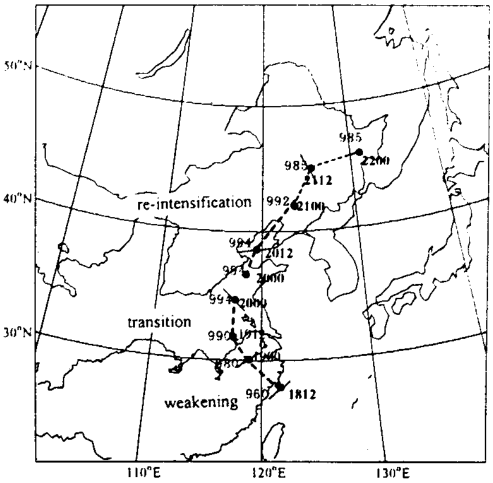
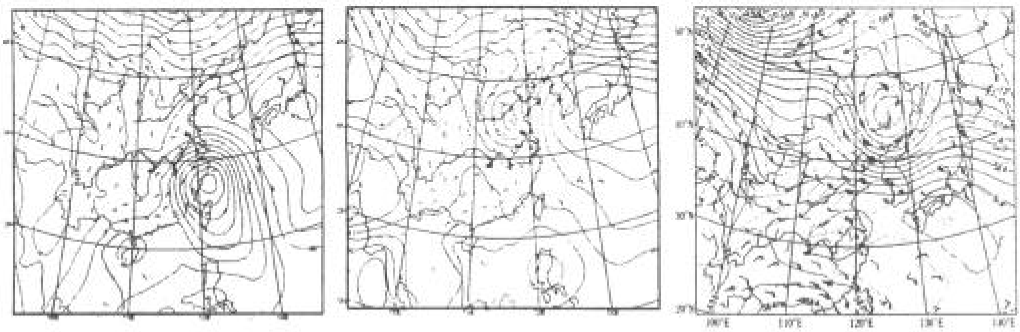


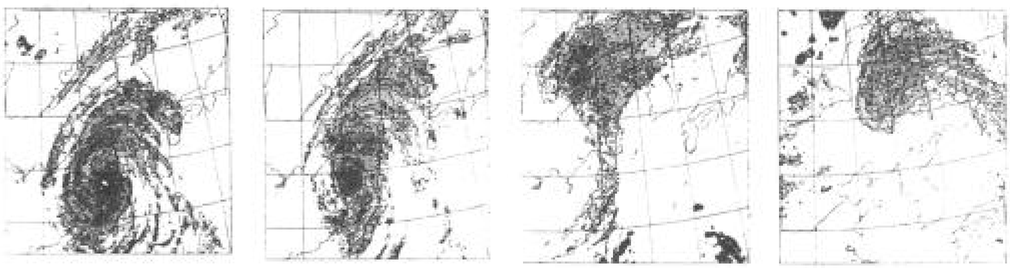
Fig.1 Track of Winnie, changes in pressure and stages divided.

2.1 *Analysis of the synoptic process*

At 12:00 August 18th, or an hour before the landfall, Winnie's warm core stretches from lower to upper layers in the temperature field while the mid-latitude front is around the lower reaches of the Yellow River, which is on the north side of its periphery. They are independent and do not interact with each other, which is reflected in relevant cloud imagery (Fig.2d). By 18:00 August 18th, the convective cloud system west of the eye began declining significantly so that a dry slot appeared on the south side (Fig.2e). Following the definition of transition stage by Klein (2000), Winnie's peripheral circulation started to enter the mid-latitude frontal area and interactions were taking place, signaling the beginning of the transition stage. At 00:00 August 19th, the cloud system in the reverted trough merged with that of a mid-latitude front and Winnie's peripheral circulation, as shown in the weather map, began moving into the mid-latitude front to cause cold advection west of it. After the convergence of clouds between middle and lower latitudes, the cold cloud cover expanded significantly north of the cyclone and the cold cloud center went northward, due to interactions between the baroclinic band and the airflow having cyclonic bending eastward and poleward of the storm, which strengthened the ascending motion. With the continued northward advancement of Winnie, its periphery circulation progressed further into the mid-latitude front, followed by the eye at 00:00 August 20th (Fig.2b). The northerly flow west of the tropical cyclone diverted cold air to its western and southwestern portions and the southeasterly flow east of it transported warm and humid air northward to increase frontogenesis in the mid-latitude front. For the lower layer (figure omitted), however, an obvious cold-temperature trough formed resulting from the descending drag of severe precipitation. By the time, the thermodynamic distribution was such that it was cold in the west part of Winnie but warm in the east. On the satellite imagery, the increasing cold advection caused the rapid decay of clouds west of the cyclone to form a frontal cyclone featured by a wide warm front and a narrow cold front (Fig.2f). The transition is known as the transition, in which a tropical cyclone that is basically thermodynamically symmetric has transformed to one that is thermodynamically asymmetric. In the evolution that followed, the baroclinic frontal cyclone had been developing until 12:00 August 21st when the surface pressure had a fall of 9 hPa. More detailed information on the variation is known from the study of cloud imagery evolution after the transition. There was frontolysis in the cold front zone after the transition, with only the warm front cloud system, imbeded with severe convection, remaining, showing a tendency to bend backward. At 12:00 August 21st, a structure was formed that look like the cyclone model of Shaprio-Keyser (Fig.2g). A warm ridge was with the weather map for the time (Fig.2c). In the evolution afterwards, the cloud system west of the cyclone kept on its cyclonic bending to form a ring-shaped system by 00:00 August 22nd, suggesting the occlusion of the cyclone.



a. 12:00, 18th b. 00:00, 20th c. 12:00, 21st



d. 12:00, 18th e. 18:00, 18th f. 00:00, 20th g. 12:00 21st

Fig.2 500-hPa weather map (a – c) analysis of *T*BB isolines in the infrared imagery (d – g).

2.2 *Analysis of the mechanism for transition and intensification in post-landfall typhoons*

Quite a number of studies have indicated that post-landfall typhoons weaken mainly due to insufficient supply of kinetic energy, e.g. heat and moisture, reducing much of the convection. What is it then that helps a weakened typhoon maintain its extended presence over land? The warm core is one of the outstanding features of the typhoon as its sustained life cycle plays a vital role in the development of the storm. It is by analyzing the temperature anomalies that the current work attempts to discuss in details the transition process and mechanism.

The temperature anomalies are determined within a mesh domain of 11×11 gridpoints that centers around the cyclone center and has intervals of 100 km, with nine layers vertically divided at 1000, 925, 850, 700, 500, 400, 300, 200 and 100 hPa, respectively. Let's now study the northwest-southeast vertical profile that cuts across the eye (figure omitted).

At 12:00 August 18th prior to the landfall, a vertically distributed warm core was at the mid- and lower- layer of the troposphere over the cyclone center, with the core center around 200 hPa, while a positive center of the temperature anomalies was on the southwest side of the storm. It may be related with the presence of a relatively cold water area existing north of the typhoon. For the vertical profile that goes northwest-southeast, weak temperature anomalies were with the low layers. In the 12 hours that followed, the warm core had little change but just shifted downward and eastward slightly. The most obvious change happened in the mid- and higher- levels of the troposphere northwest of the warm core, where there was dense distribution of negative temperature anomalies, which remained above low levels. By 12:00 August 19th, the warm core kept descending and weakening while the northwestern negative temperature anomalies were strengthening and inclining in expansion towards the lower troposphere till the center of the cyclone. It was due to insignificant positive temperature anomalies in the SE quadrant that a front was not generated. Nevertheless, one should note that a positive temperature anomalous center appeared right there that was just over 0.5°C. It is seen from the analysis of the advection of horizontal temperature for the process that warm temperature advection was increasing at lower levels and attained the life cycle maximum of 39.5×10^{-5} °C/s (Fig.3a), indicating that the positive temperature anomalies were going to increase and eventually leading to the enhancement of the front. 00:00 August 20th was a special moment when a significant cold/warm contrast had been very obvious in lower troposphere, as shown in the vertical profile. Under the conditions of inclining and descending cold air and warm advection at the low levels, the frontogenesis was made more vigorous to turn Winnie into an extratropical cyclone. The vertically stretched warm core at mid- and higher- levels of the troposphere had by then evolved into a warm sector that tilts southeast with pressure, whose inclining axis was almost parallel with the central axis of negative temperature anomalies. For evolution beyond it, however, a relatively cold center was gradually formed in lower troposphere where the cyclone center was located while a positive temperature anomalous center came into being in higher troposphere; the two centers were lining up in near verticality, suggesting the occlusion of the baroclinic system.

After the transition, the cyclone revived because the baroclinic unstable energy was strengthening. The low-level warm temperature advection not only accelerated and strengthened the transition of the tropical cyclone, but also favored the generation of precipitation and maintenance of low-value systems as the advection had been with the re-intensification process.

Studying the divergence and wind field at 300 hPa for 00:00 August 19th, it is found that the divergence at the right side of the upper-jet inlet and that over the tropical cyclone were two independent areas; as the upper-level divergence weakens, the central pressure started to fill and the weakening divergence merged with the divergence that formed on the right side of the northern jet, during the northward movement of Winnie. The weakening cyclone continued its northward journey to enter the area of divergence. Acquiring 67.4×10^{-6}/s at 00:00 August 20th, the divergence center increased to its maximum of 68.4×10^{-6}/s at 12:00 the same day (Fig.3b). Then, the cyclone center was again at the edge of the divergence because of the obvious eastward shift of the jet; weak divergence stayed over Winnie, changing accordingly with the evolution of the cyclone center. It indicates that the divergence at the right side of the upper-level jet inlet is in fact a dynamic factor for the cyclone to intensify for the second time.

Analyzing the variation of 300-hPa vorticity advection with time, one knows that the vorticity advection was relatively weak over the cyclone center before 00:00 August 21st (Fig.3c). Then a cyclonic vorticity advection appeared over the cyclone, which was highly consistent throughout all levels. The advection center had weakened from $72.6\times10^{-10}/s^2$ to $64.3\times10^{-10}/s^2$ by the next level of time before doing so rapidly. It shows that the upper-level vorticity advection plays a key role in the re-intensification of the cyclone over the time after 12:00 August 20th.

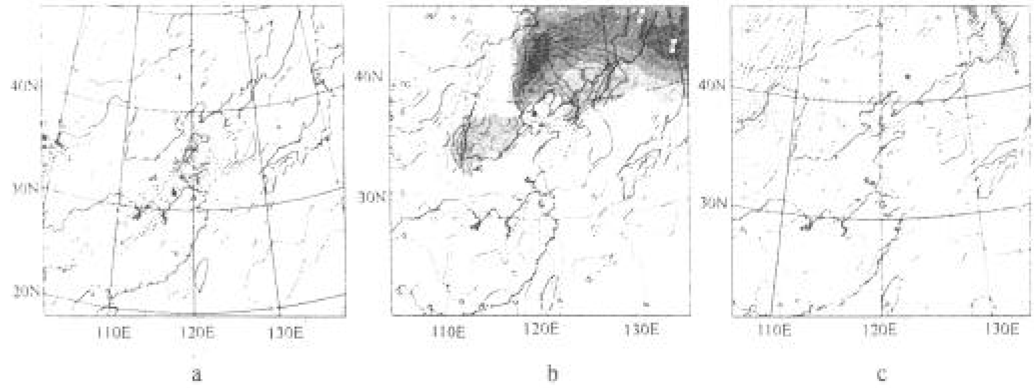


Fig.3 a. 850-hPa temperature advection at 12:00 of the 19th (the solid line is the warm advection and the dashed line is the cold advection); b. 300-hPa divergence (the solid line is above zero and the dashed line below it) and the jet stream (shaded areas) at 12:00 of the 20th; c. same as b but for vorticity advection.

Weighing comprehensively the performance of individual physical quantities over different stages, one knows why a weakening typhoon can maintain for a long duration over land. In the transition stage, the key is the descending progression of cold air from the mid- and higher-layers of the troposphere. Once in the mid-latitude front, Winnie strengthened it so that the warm advection increased east of the cyclone while in turn the warm advection accelerated the frontogenesis at low levels to turn it from a warm-cored tropical cyclone to a baroclinic extratropical cyclone. In the stage of re-intensification, in addition to low-level temperature advection, the divergence caused by the upper-level jet and upper-level vorticity advection later in the stage was playing a key role in the re-intensification.

3 CONCLUDING REMARKS

With an analysis of the evolution of Typhoon Winnie over the post-landfall time, we have concluded the following features of tropical cyclone development after transition:

a. The post-landfall typhoons experience three stages of evolution: weakening, transition and re-intensification.

b. The evolution of associated synoptic situations is similar to the complex transition process put forward by Sekioka et al. It is also clearly known from the cloud imagery how Winnie transformed to the Shapiro-Keyser cyclone model.

c. By diagnostic study of the physical quantities, we find that the cold air at the mid- and upper- level cold air was inclining in descent in the troposphere and there was a warm advection at low levels, which were the key to tropical cyclone transition. The well-defined warm advection that stayed in the low levels, the divergence for the upper-level jet and the upper-level vorticity advection were three important physical factors for the tropical cyclone to intensify again.

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