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DIAGNOSTIC ANALYSIS OF THE RE-INTENSIFICATION OF HIGOS IN SOUTHERN CHINA AFTER LANDFALL

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Abstract: The NCEP Global Data Assimilation System analysis of grid data, satellite products of Naval Research Laboratory, conventional meteorological data and observations of automatic weather stations in Guangdong province were used together with environmental conditions, atmospheric circulation, and physical characteristics to diagnose the cause and mechanism of the intensification of tropical cyclone Higos in Southern China. The results showed that favorable environmental conditions of high temperature, humidity of the underlying surface, strong upper divergence, weak vertical wind shear, and the persistence of a southwest jet stream beside the southern Higos were the necessary ingredients that contributed to the maintenance of intensity and re-intensification of Higos. The sinking intrusion of cold air from the lower troposphere was the critical condition for its intensification over land. The frontal genesis caused by weak cold air increased the lower tropospheric convergence and updraft, and the condensation latent heat released by heavy rains promoted convergence. From this positive feedback process, Higos obtained an increasing of positive vorticity and re-intensified over land. The re-intensification was due not only to the build-up of wind and the reduction of pressure but also to the simultaneous warm-up of its warm core.

Key words: Higos; intensification over land; cold air; warm core

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1 INTRODUCTION

The south of China is an area most frequently affected by tropical cyclones that hit the country. Generally, tropical cyclones tend to weaken and disappear or move into the eastern Pacific without evolving into extratropical cyclones [1, 2]. By reviewing changes in the northwest Pacific between 1994 and 1998, Klein et al.[3] proposed a three-dimensional conceptual model that considers four aspects of the development of physical processes, including the relationship between warm and cold air environment and the baroclinic zone, weakening of systems, tilting of the warm core, and development of the asymmetrical structure. According to a study by Wang et al.[4], there is no simple proportional relationship between the intensity of tropical cyclones making landfall and the duration of its maintenance over land. These studies have improved knowledge on the evolution of tropical cyclones after landfall and provided significant guidance for forecasting tropical cyclones. On October 5, 2008, tropical cyclone Higos (coded 0817) weakened into a low pressure zone after landfall in Guangdong and then strengthened once again to a tropical depression when it reached southern China. It was the only event of its kind ever recorded in China. There are also no reports of a similar phenomenon abroad. The issuance of alerts and the rise of wind balls against a tropical cyclone once more some time after lifting relevant warnings are unprecedented in the history of weather services in Guangzhou Central Meteorological Observatory. This unique event brought a new proposition to the forecasting and warning of tropical cyclones. To determine the intrinsic factors of the incident and improve forecast and warning of tropical cyclones, this paper attempts to diagnose the re-intensification process of Higos based on such factors as environmental conditions, atmospheric circulation, and physical characteristics among others.

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2 DATA SOURCES

The data used in this paper include:

(1) National Centers for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS, USA) analysis of grid data, including the horizontal wind field, vertical velocity, temperature, relative humidity, geopotential height, and other factors that have a horizontal resolution of 1°×1° and vertical levels from 1000 hPa to 100 hPa (total: 21 layers),

(2) Conventional meteorological data and observations of automatic weather stations (AWSs) in Guangdong province, and

(3) A variety of meteorological satellite products of the Naval Research Laboratory (NRL), USA.

3 OVERVIEW OF HIGOS AND ATMOSPHERIC CIRCULATION BACKGROUND

3.1 *Overview of Higos after landfall*

On October 4, 2008 at 0910 UTC, tropical storm Higos (hereinafter referred to as Higos) weakened into a tropical depression in the north of the South China Sea. Higos landed in Wuchuan, Guangdong province, having winds at the Beaufort force 7 (15 m/s) and a minimum pressure of 999 hPa near the centre. At 1500 UTC, Higos weakened into a low pressure, with a wind force of 5 (10 m/s) and a pressure of 1002 hPa near the centre. The low pressure zone continued to move east-northeast and upgraded to a tropical depression in the north of Pearl River Delta at 1200 UTC October 5. It had centre winds at force 7 and a central pressure of 1000 hPa (Fig. 1) before continuing to head towards east-northeast. According to the wind records of AWSs, at 0800 UTC October 5, the average wind of Higos ranged from force 4 to force 5 (2-min. average) with gusts at force 6 (figure omitted), but at 1200 UTC October 5 the average wind had risen to force 6 and then to force 7, with gusts between force 8 and force 9 (Figs. 2a and 2b). Moreover, pressure variations showed that at 0000 UTC October 5, the centre pressure of Higos was 1000 hPa (figure omitted), but it dropped to 998 hPa at 1200 UTC. This confirmed that our measurement of the intensity of Higos was correct. At around 1200 UTC October 5, the centre wind force of Higos had indeed intensified to force 6.

From October 3 to 6, most parts of Guangdong province were hit by rain storms because of Higos. Heavy rainfall was recorded mainly on October 5. According to the records, 870 AWSs had a total accumulated rainfall exceeding 50 mm and another four had over 300 mm (figure omitted).

3.2 *Background of atmospheric circulation*

As shown in the 500-hPa synoptic field for October 4-5, 2008, zonal circulation play a dominant role in Asian middle latitudes, with the ridge of the subtropical high near 20°N, the north of the South China Sea covered by the subtropical high, the Tibetan Plateau in control of a ridge area, and a westerly trough moving toward the southeast. By 0000 UTC October 5, this trough had already cut across 115°E and the cold advection behind the trough had entered the south of China. Meanwhile, Higos approached the northwest of the subtropical high and southeast of the trough (Fig. 3). The surface map shows that weak cold air entered the north of Guangzhou at 0000 UTC October 5, and at around 0600 UTC, the peripheral circulation of Higos encountered the cold air in northwest Guangdong (Fig. 4). Satellite imagery clearly showed the cloud belt of the frontal zone intensifying in the north of Higos. In addition, the South China Sea monsoon remained active until around October 4, and a southwest jet in the south of Higos lasted until the midnight of October 5, weakening significantly on October 6.

4 DIAGNOSIS OF HIGOS INTENSIFICATION

Various studies have pointed out that the attenuation of a tropical cyclone after landfall is mainly due to the build-up of underlying surface friction and unfavorable environmental conditions. The study aims to find the cause of the re-intensification of Higos, a weakened low pressure zone, into a tropical depression over land based on an analysis of its geographical conditions, evolution of synoptic systems, and some characteristics of relevant physical quantities. This paper attempts to identify the environmental and dynamic conditions, variation of thermal structures, and strengthening mechanism responsible for this phenomenon.

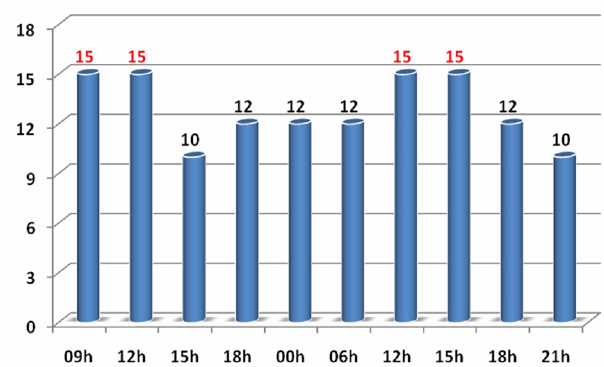

Fig.1 Variations of Higos centre wind speed after landfall between 0900 UTC October 4 and 2100 UTC October 5, 2008 (unit: m/s).

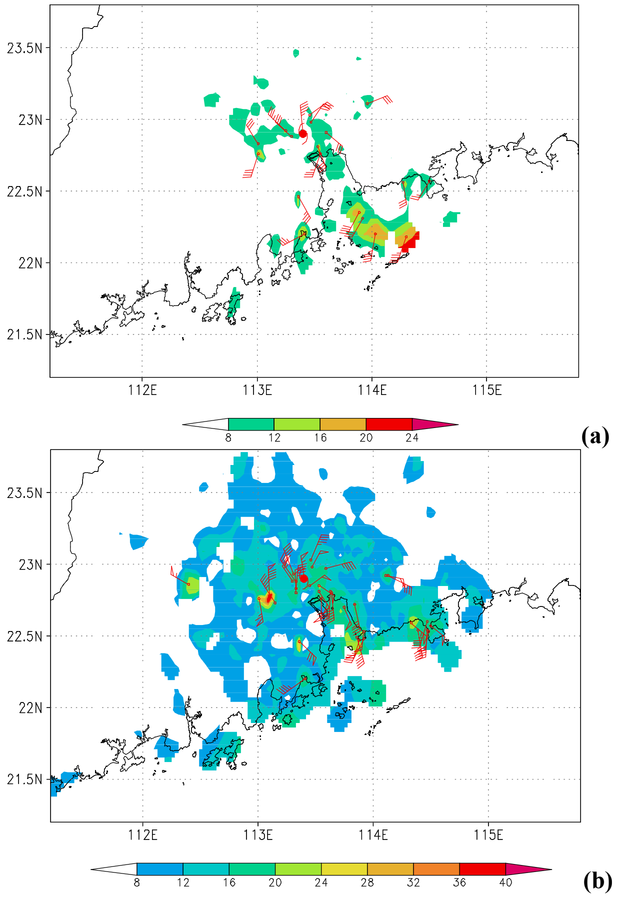

Fig.2 (a) Distribution of 2-min average wind of AWSs around the centre of Higos at 1200 UTC October 5, 2008 (shaded area: speed 8 m/s, wind shaft force 6); (b) Distribution of max. wind of AWSs around the Higos centre at 1200 UTC October 5, 2008 (shaded area: speed 8 m/s, wind shaft force 6).

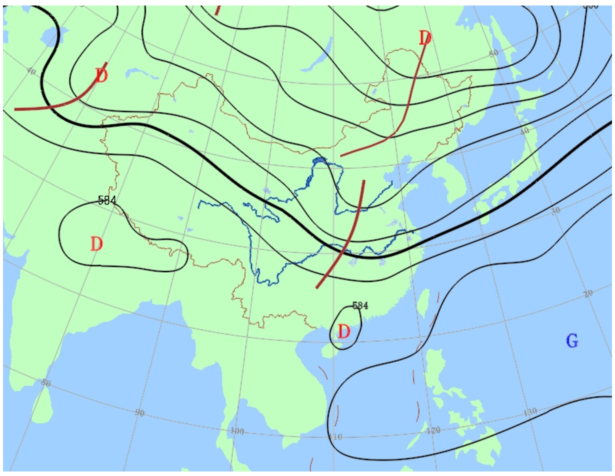

Fig.3 500-hPa chart for 0000 UTC October 5, 2008.

4.1 *Analysis of environment conditions*

4.1.1 GEOGRAPHICAL ENVIRONMENT

Different underlying surfaces produce different damping effects on tropical cyclones. The Pearl River Delta is a low-altitude, highland delta (about 50 m or so) that developed within a gulf with criss-crossing rivers stretched across both the length and breadth of the delta. The large water surface provide rich vapor. Before Higos made landfall, the highest temperatures recorded were up to 31-32 °C, and the relative humidity was 90-95% in the Pearl River Delta. Therefore, the underlying surface that Higos entered was hot and highly humid. The pseudo-equivalent potential temperature analysis showed that the area of Pearl River Delta had high temperatures and humidity in the lower troposphere. The θ_{se} distribution for October 5 at 850 hPa (Fig. 5) revealed that the west and north of the Pearl River Delta was located in an area of $\theta_{se} \geqslant 346$ K. In addition, while Higos moved east-northeast along the coastal areas of Guangdong after its landfall, nearly all of the southern part of the Higos circulation was located over coastal waters and was accompanied by the southwest jet carrying warm and humid air, thereby securing sufficient energy supply for Higos.

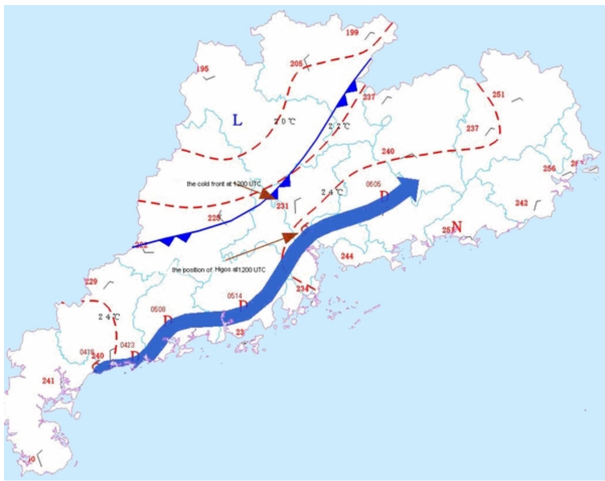

Fig.4 Illustration of the surface cold front, Higos track, and temperature contours at 0600 UTC October 5, 2008 (red dash: temperature contours, blue arrow: Higos track after landing).

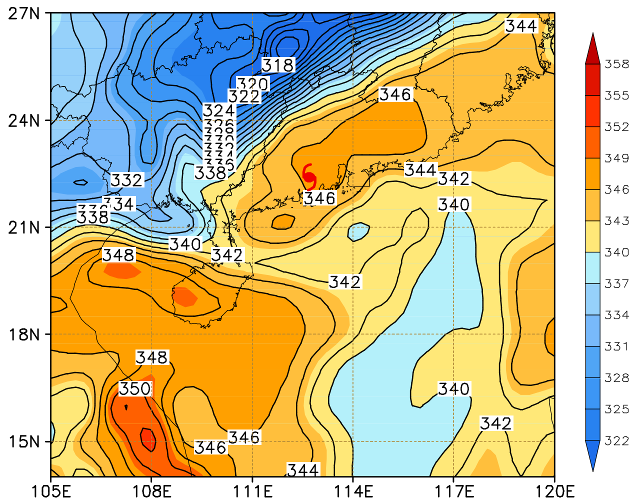

Fig.5 Pseudo-equivalent potential temperature distribution at 850-hPa for 0600 UTC October 5, 2008 (unit: K).

4.1.2 DISTRIBUTION OF DIVERGENCE

Figure 6 illustrates the time-height variation diagram of the regional (21 to 24°N, 111 to 115°E) divergence. It indicates that during daylight October 5, there was a strong divergence centre between 200 and 150 hPa, and the central intensity reached a peak value of 4 × 10^{-5} s^{-1} around 0600 UTC. Simultaneously, the distribution of 200-hPa divergence and wind field (Fig. 7) also showed that there was a divergence centre as strong as 8 × 10^{-5} s^{-1} on the upper levels of the Pearl River Delta. Analysis of the corresponding weather maps showed that this location was the exact area of the high pressure ridge and the fan-shaped divergence opening of the wind field. This is the typical distribution of upper tropospheric divergence favorable to southern China rainstorms [5]. This pumping effect induced by strong divergence in the upper troposphere was favorable for the persistence of the updraft and the development of the convection. This effect also contributed to an increase of lower tropospheric convergence. Moreover, Figure 6 also reveals the evolution of lower tropospheric convergence. The convergence built up on the night of October 4 while Higos landed. It began to weaken but then regained strength in the afternoon of October 5, forming a –4×10-5 s^{-1} convergence centre. This phenomenon clearly indicates that Higos had gone through the process of over-land re-intensification.

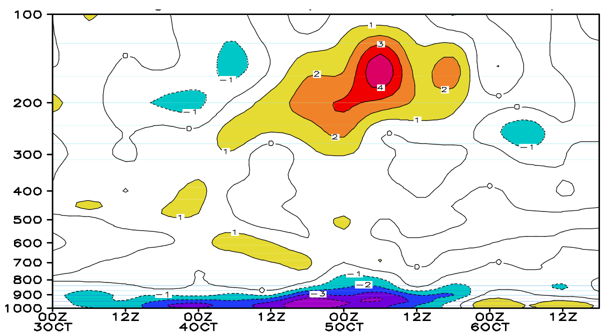

Fig.6 Divergence of time-height variation of the region (21 to 24 °N, 111 to 115°E) (Shaded area: divergence centre unit: 10^{-5} s^{-1}.

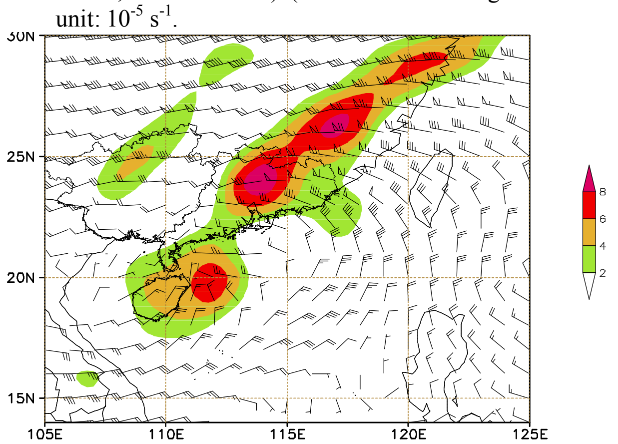

Fig.7 200-hPa divergence field and wind field for 0600 UTC October 5, 2008 (Shaded area: positive divergence, unit: 10^{-5} s^{-1}.

4.1.3 VERTICAL WIND SHEAR

The observation in this study and many research have shown that weak vertical wind shear is favorable for the formation and development of tropical cyclones. Zehr et al. [6] pointed out that the critical condition of tropical disturbance development was a speed less than 12 m s^{-1} of the vertical wind shear. Figure 8 shows the variations of average vertical wind shear (200 to 500 hPa) in the region (21 to 24°N, 111 to 114°E) of the mid-north Pearl River Delta from October 3-6, 2008. The vertical wind shear in the region during the period was at 3-7 m/s, an environmental condition (vertical wind shear) small enough to maintain the warm core of Higos.

The high temperature and humidity in the underlying surface, strong upper tropospheric divergence, and weak vertical wind shear contributed to environmental conditions favorable for the persistence and intensification of Higos. Nearly all the southern part of Higos was over coastal waters. Thus, the persistent southwest flow south of Higos was an important ingredient in sustaining and intensifying Higos. Consequently, although Higos was only a tropical depression at landfall, it slowed down the rate of intensity reduction and basically maintained its whole structural characteristic as an individual tropical cyclone.

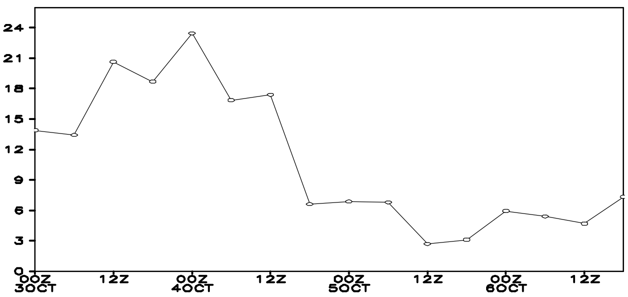

Fig.8 Variations of average vertical wind shear between 200 and 500 hPa for the region (21 to 24°N, 111 to 114°E) (Unit: m/s)

4.2 *Effect of cold air*

Adequately intense cold air stimulates the intensification of tropical cyclones[7, 8]. Weak cold air led by the westerly trough crossed Nanling Mountains into northern Guangdong when Higos was making landfall. As is shown in the sectional drawing of temperature advection at 112°E (Fig. 9, left panel) and 23°N (Figure omitted) on 0000 UTC October 5, cold advection slanted and sank southward between 30 and 23°N at levels below 400 hPa, and the cold air near

23°N extended only up to 800 hPa. The distribution of wind and temperature advection at 925 hPa clearly showed that cold air moved southeastward passing Hunan and Guangxi. A cold advection tongue reached the rear of Higos from southern Guangxi, forming a temperature field that was colder in the west than in the east on 0600 UTC October 5 (Fig. 9, right panel). The frontogenesis was seen on the surface chart for 0600 UTC, with a weak cold front extending from Nanxiong to Yunan of Guangdong and the postfrontal 24-h temperature dropping 2 to 5 °C. The temperature field also revealed that there was a quasi-northeast-southwest weak temperature frontal zone near the cold front, which was maintained and strengthened as a result of the constant warm and humid air flow south of Higos. It gave rise to heavy rains in the Pearl River Delta.

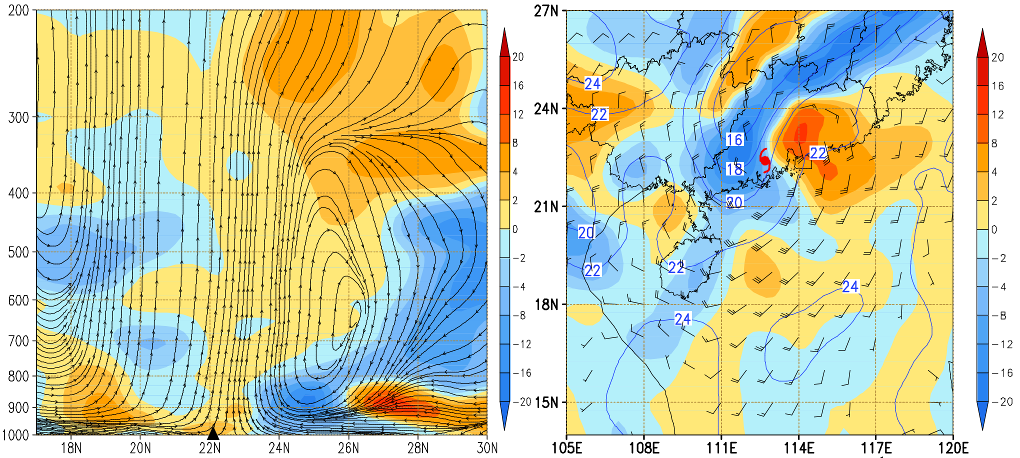

Fig.9 Vertical circulation and temperature advection (temperature advection unit: °C s^{-1}) at 112°E for 0000 UTC October 5 (left panel); and horizontal wind field and temperature advection at 925 hPa for 0600 UTC October 5 (right panel).

Higos moved along the coastal area from the daytime of October 4 to the morning of October 5. Although the water vapor supply was abundant, the friction of the underlying surface causing the decline of lower air flow convergence caused Higos to weaken cyclonically. After the morning of October 5, Higos turned to the northeast to enter the northern part of the Pearl River Delta. According to previous experiences, Higos should have continued to weaken. In fact, all relevant weather observatories had forecasted that Higos would dissipate further. Instead, Higos intensified right in this area. This phenomenon was mainly attributed to the favorable environmental conditions presented above as well as the intrusion of weak cold air at lower levels of the troposphere (below 850 hPa). The effect may be explained by the following: The intrusion of weak cold air resulted in frontogenesis in the northwest of Higos and increased the convergence and updraft of the lower troposphere, subsequently enhancing heavy rain. The release of condensation potential heat resulting from heavy rain added diabatically to the convergence and updraft, and together with strong divergent sucking effect at the high level, the convection intensified further and more potential heat was released. This positive feedback process intensified Higos cyclonically, resulting in its intensification over land.

As shown in the vertical distribution of pseudo-equivalent potential temperatures along 113°E at 0600 UTC October 5 (Fig. 10), a frontal zone was formed between the dry, cold air moving southward and the moist, warm flows heading north near 24°N. The θ_{se} contours were dense and steep near the frontal zone, with a high moist area near the southern edge of the front in the mid-lower troposphere that is convectively unstable (where θ_{se} reached 346 to 350 K and $\frac{\partial \theta_e}{\partial p}>0$). According to the conservation characteristics of moist potential vorticity[9], the tilting of the θ_{se} plane will result in a significant development of vertical vorticity in the developing stage of the induced tilting vorticity. The more the θ_{se} plane is tilted, the stronger the cyclonic vorticity. Therefore, the mid- and lower-levels near the southern edge of the frontal zone was the most likely area for the development of cyclonic vorticity (indicated by the box in Fig. 10). Higos gained increasing cyclonic vorticity in this area. The regional chart (Fig. 11) of average vorticity height-time variation in the area (111 to 115°E, 21 to 24°N) around Higos revealed that positive vorticity was gradually increasing below 300 hPa from 0600 UTC October 4 to 1200 UTC October 5. Positive vorticity reached its maximum of 12 m/s around 1200 UTC October 5, with the peak centre located between 800 and 900 hPa. Higos had increased cyclonic vorticity. It re-intensified due to the invasion of cold air and reached its peak force at around 1200 UTC October 5.

In general, spring and autumn are the only seasons when cold air encounters the tropical cyclone in southern China. The two seasons are the only time when the temperature and moisture of the underlying surface are relatively low and the Southwest Monsoon shifts to the south of South China Sea. During this period, the upper easterly flow component adjusts gradually to a westerly flow, and the vertical wind shear increases. The analysis and statistics of landfall of tropical cyclones in the south of China from 1998 to 2007 showed that the structure of landfall of tropical cyclones in transitional seasons were destroyed due to cold air intrusion or to the separation of the lower levels from the upper ones because of strong vertical wind shear. There is usually no situation similar with Higos, when multiple favorable environmental conditions coexisted with cold air in adequate amounts and intensities, allowing for re-intensification over land. Thus, Higos is a unique phenomenon.

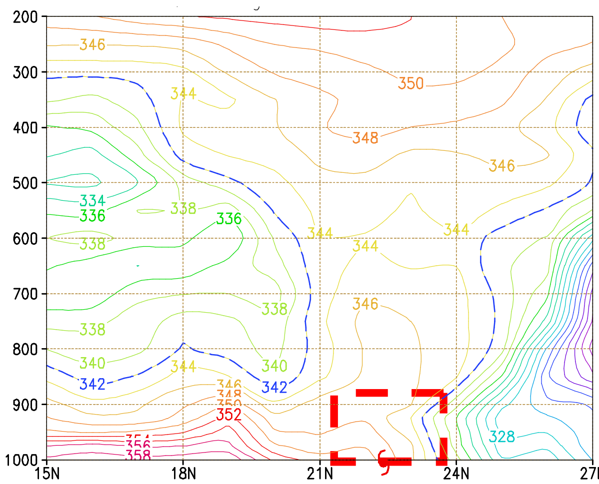

Fig.10 Pseudo-equivalent potential temperature distribution along 113°E for 0600 UTC October 5 (unit: *K*, red typhoon signal: latitude of Higos location, red box: area likely for development of cyclonic vorticity).

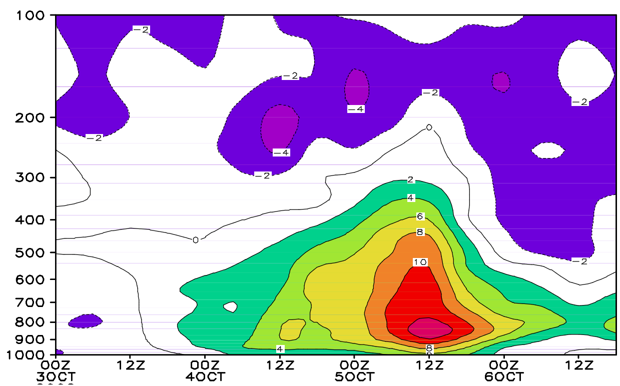

Fig.11 Regional height-time cross-section of the variation of average vorticity around Higos (111 to 115°E, 21 to 24°N). Unit: 10^{-5} s^{-1}

Satellite imagery also showed the process of spiral cloud bands intensifying in the north of Higos and convection developing near the eye with the intrusion of cold air. The infrared satellite imagery for 0535 UTC October 5, 2008 (Fig. 12) showed the cold front cloud bands in the north of Higos and active convective cells on the frontal cloud bands. The cloud structure of the low centre of Higos was loose. At 0946 UTC (Figure omitted), Higos' northern spiral cloud bands strengthened due to the involvement of the cold frontal cloud system. The vortex cloud system structure of the eye became clear, and a central dense cloud region developed. All these factors indicate that cold air intrusion led to the re-intensification of Higos.

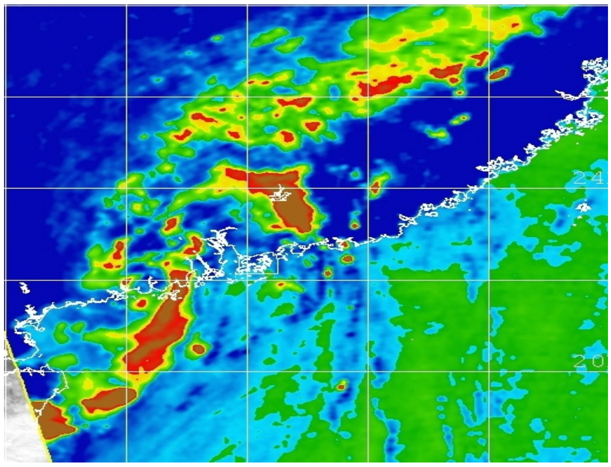

Fig.12 Imagery from satellite AQUA-1 85H for 0535 UTC October 5, 2008.

4.3 *Higos structural changes and strengthening mechanisms*

As an important characteristic of the genesis and evolution of the tropical cyclone, the distribution of its spatial structure in the arm core is also studied. The presence of a warm core signifies that the tropical cyclone is still alive. Therefore, the structural change characteristics after landfall were used to analyze the temperature anomaly of Higos.

At 1200 UTC October 3, a quasi-circular warm core maintained between 650 and 350 hPa above the eye and the warm core was in the vicinity of 400 hPa. After landfall, the warm core was distorted and broken up. At 0000 UTC October 5, there were two disrupted warm cores at 550 and 300 hPa, respectively. Moreover, there was a new weak warm core with a central value of 0.9 between 800 and 700 hPa. At 1200 UTC October 5, Fig. 13 shows that the lower weak warm core warmed significantly (by more than 1.5 °C), and the temperature anomaly centre between 600 and

350 hPa joined the lower one between 700 and 850 hPa and moved downward. There is a close relationship between the descent of Higos' warm core and the release of unstable baroclinic energy triggered by cold air. The observational records of AWSs showed that the 6-h accumulated rainfall was less than 10 mm at 0000 UTC October 5 around the centre of Higos, particularly in the middle and northern part of the Pearl River Delta. However, beginning from 0600 UTC October 5, the rainfall increased to 10-20 mm per hour with the intrusion of weak cold air when the 6-h accumulated rainfall added up to 60 to 80 mm at 1200 UTC. The release of potential heat during the rainstorm resulting from weak cold air may explain why Higos' warm core was descending.

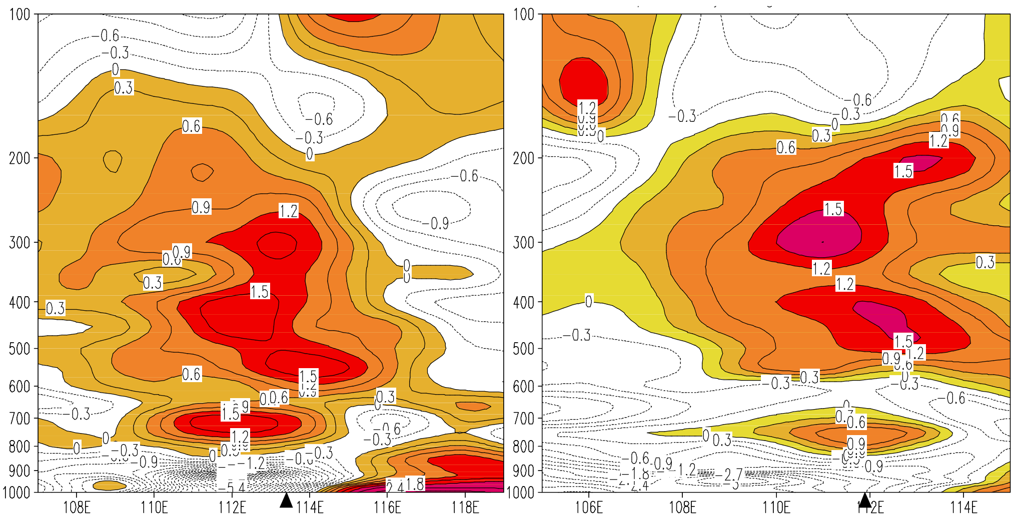

Fig.13 Height-longitude cross-sections of temperature anomaly around Higos for 0000 UTC (left panel) and 1200 UTC (right panel) October 5, 2008. Unit: °C

Existing research has revealed the evolution of symmetric warm cores into asymmetric ones, which are half-warm and half-cold in tropical cyclone landfalls due to the intrusion and descent of strong cold air from the mid-latitudes. In southern China, however, the intruding weak cold air tends to increase the rainfall and intensity of tropical cyclones. From the above analysis of temperature anomaly variation, we learned that Higos' warm core was still in the process of landfall to re-intensification at the time of the intrusion. Thus, its warm core did not change to the half-warm and half-cold structure. Instead, the warm core warmed at around 1200 UTC. It is for this reason that we believe that Higos did not evolve to an extra-tropical cyclone but intensified into a tropical depression.

To summarize the above analysis, we believe that the sinking and intrusion of cold air to the lower troposphere was critical to the intensification of Higos over land. The high temperature and humidity of the underlying surface, strong high-level divergence and low-level convergence, as well as the weak vertical wind shear, were the necessary conditions for the intensification. After midday October 5, 2008, when Higos moved into the north of the Pearl River Delta, where both temperature and humidity were high, strong divergence in the upper troposphere and weak vertical wind shear encountered weak cold air moving southward, resulting in frontogenesis in the northwest of Higos and the intensification of convergence and updraft. Baroclinic energy was then released in the form of torrential rain. The warm and moist air flows in the south of Higos reinforced low-level frontogenesis and contributed to the maintenance of torrential rain. The release of the latent heat of condensation increased not only the convergence of the lower troposphere under the diabatic effect but also the internal vorticity of Higos, making it possible for Higos to intensify over land.

5 CONCLUSIONS

The causes and mechanisms responsible for the non-transformative intensification of Higos over land were diagnostically studied based on the environmental conditions, atmospheric circulation, and characteristics of physical quantities. The results are as follows:

(1) The favorable environmental conditions of high temperature and humidity of underlying surface, strong upper-level divergence and weak vertical wind shear, and the persistence of southwest jet streams beside the southern Higos were the necessary factors leading to the persistence and re-intensification of Higos.

(2) The descending intrusion of cold air from the lower troposphere was the critical condition for Higos to intensify over land. The frontogenesis was caused by weak cold air that increased the lower tropospheric

convergence and updraft. This, in turn, increased the condensation latent heat released by heavy rains that enhanced the convergence. It was under this positive feedback that Higos gained increments of vorticity and upgraded over land.

(3) The re-intensification of Higos was displayed not only in the built-up wind and reduced pressure but also in the simultaneously increased warm core.

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