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GENERATION AND DEVELOPMENT OF MESOSCALE CLOUD ON HEAVY RAIN BELT ON THE PERIPHERY OF TYPHOON 9608 (Herb)

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ABSTRACT: Typhoon-induced heavy rains are mostly studied from the viewpoint of upper-level westerly troughs. It is worthwhile to probe into a case where the rain is caused by tropical cyclone system, which is much heavier. During August 3 ~ 5, 1996, an unusually heavy rainstorm happened in the southwest of Hebei province. It was caused by 3 mesoscale convective cloud clusters on the periphery of a tropical cyclone other than the direct effects of a westerly trough. Generating in a weak baroclinic environment that is unstable with high energy, the cloud clusters were triggered off for development by unstable ageostrophic gravity waves in the low-level southeast jet stream on the periphery of the typhoon. There was a vertical circulation cell with horizontal scale close to 1000 km between the rainstorm area and westerly trough in northeast China. As shown in a computation of the *Q* vector of frontogenesis function, the circulation cell forms a mechanism of transforming energy between the area of interest and the westerly trough system farther away in northeast China. Study of water vapor chart indicates that high-latitude troughs in the northeast portion of the rain migrate to the southeast to enhance anti-cyclonic divergence in upper-level convection over the area of heavy rain and cause rain clusters, short-lived otherwise, to develop vigorously. It is acting as an amplifier in this case of unusually strong process of rain.

Key words: typhoon; mesoscale convective cloud cluster; environmental condition; analysis of water vapor imagery

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1 INTRODUCTION

For most of the studies on typhoon-generated heavy rains in north China, the focus has been on the dynamic role of increasing and maintaining these processes by the advection of positive vortex in front of westerly troughs at upper levels and the divergence to the right of the inlet of a corresponding upper-level jet stream[1, 2]. The troughs and jet streams are thought to be having direct impact on the type of heavy rain in the area and forecasts based on it also achieve good results. There are other arguments that a semi-tropical frontal zone exists over the area of heavy rain that releases baroclinic potential energy and condensation latent heat and zones of heavy rain are usually found outside the core circulation of typhoon or inside the inversed trough of typhoon. This structure of frontal zone may give detailed account of physics responsible for typhoon-generated heavy rains in north China[3]. It was in such situation, in which the heavy rain area was separated from large-scale westerly trough and upper-level jet stream, that an unusually heavy rain took place on the periphery of Typhoon 9608 (Herb). It is not common to see this kind of heavy rain in north China which does not have direct contribution from the westerly trough. Zhou[4] observes that

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such particular circulation situation produces more intense regional heavy rains in north China without direct interactions with the westerly trough than the ones with.

In order to understand the mechanism causing such heavy rains without direct interactions with westerly trough and compare it with the environmental condition for typhoon-generated heavy rains and tropical cloud clusters interacting directly with large-scale westerly troughs and upper-level jet streams, as well as circulation condition, triggering and maintaining mechanisms and systems of westerly troughs that are responsible for this process of unusually heavy rain, conventional observations, diagnostic analyses based physical quantities and water vapor imagery by GMS-5 are used in the study.

2 SITUATION OF LARGE SCALE CIRCULATION & SUMMARY OF RAINFALL

On August 1, 1996, Typhoon Herb made landfall on the Fujian province before weakening to a depression with the central pressure staying around 980 hPa. The intensity was similar to Typhoon 7503 (Nina), a landfall in August 1975. At 200 hPa, a strong anti-cyclonic circulation (monsoonal high pressure) was dominant over the continent of eastern China (figure omitted) and strong subtropical high was controlling from the coast of China to the Sea of Japan. As the typhoon moved northwest on the south side of the subtropical high and arrived in the Hubei province, a westerly trough passed over the Mongolian region in the northern edge of the typhoon, causing the mid-latitude high to merge with the west Pacific subtropical high to the southeast. The typhoon was in the easterly steering flow south of a high pressure "dam" extending southeast to northwest (refer to the contour 588 in Fig.1). At the lower tropospheric levels (below 700 hPa), a southeasterly low-level jet stream formed between the typhoon depression and subtropical high, which is associated with the ITCZ (figure omitted). Although at the near-surface layer weak cold air advanced southward to come near the typhoon system (figure omitted), large-scale westerly troughs and corresponding cold advection in the mid-and-higher levels of troposphere are separated from the circulation of the depression. The upper-level divergence, abundant supply of water vapor and easterly steering current at 500 hPa are all favorable for the maintenance and westward movement of the typhoon.

When the eye of Herb migrated northwest to the Hubei province on August 3, a mesoscale convective cloud cluster developed to the northeast on the periphery to cause an unusually heavy rain to occur in areas of southwest Hebei province and those bordering the Shanxi and Henan provinces from August 3 ~ 5. The total rainfall exceeded 500 mm in the 3 days with the center falling 670 mm in the western mountainous region of Shijiazhuang City (Fig.2). The hard rain had caused losses worth of 63,600 million yuan (RMB), of which 45,630 million yuan in the Hebei province alone.

Three mesoscale cloud clusters are the systems that directly affect this particular process of heavy rain. They originate in the same locality — around the east side of an inverted trough north of the depression and the top end of the lower-level jet stream, which is near Zhenzhou. Studying the energy and wind field, we know that a current of weak cold air is coming southward from north of Zhenzhou to merge with warm and humid southeast flow on the right of typhoon to form a convergent shear line. The 3 convective cloud clusters (denoted as A, B, C) are separately generated at 1500 ~ 1600 (figure omitted) on August 3, 0200 and 1200 on August 4, at intervals of about 10 hours, in areas of high potential energy (gradient $\leqslant$ 2°C / km) south of the converging shear line (Fig.1). The cloud clusters then move to the areas of low potential energy (gradient $\geqslant$ 4°C / km) north of the line. In place where the easterly flow on the periphery of the depression cuts the Taihang Mountains orthogonally, there is the maximum divergence at 200 hPa (figure omitted). The

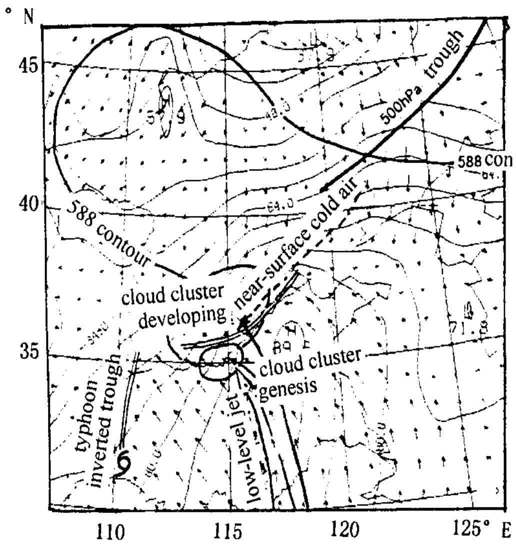

Fig.1 Synthetic pattern at 500 hPa (588 line and trough) at 2000 August 3, 1996 and the typhoon, inverted trough, low-level jet, development area of cloud cluster and q_{se} (thin line, unit: ℃) and streamline field (arrow) at 1000 hPa at 0800 August 4,1996.

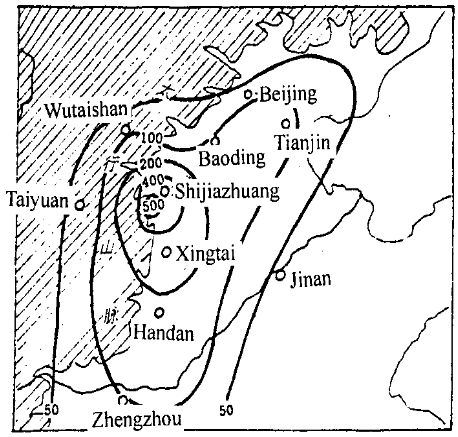

Fig.2 Rainfall distribution (unit: mm) at Beijing, Tianjin and Hebei province from 0800 August 3 to 2000 August 5, 1996.

mesoscale convective cloud clusters have matured to become hard rain clusters stretching 200 ~ 300 km on the horizontal scale and stop east of the Taihang Mountains to form unusually heavy rain. It shows that the baroclinic dynamic mechanism of cold air near the surface does have some role in the formation of the heavy rain. It should be noted that the three cloud clusters generate around Zhenzhou and move northward in a regular pattern to approach the northern side of the near-ground shear line before developing into clusters of intense convective rainstorms. It is then clear that the study should include dynamic and thermodynamic points in addition to the differences in near-surface baroclinic energy condition and topographic effects as presented in the discussion above.

3 RESULTS OF NUMERICAL EXPERIMENTS AND DISCUSSION

By analyzing the physical quantities computed using objective gridpoint data over Zhen-zhou, where the clusters generate south of the near-ground shear, and Xingtai, where they develop north of the shear, we find that there are other significant features in addition to deep wet layers and deep ascending motion that are typical of average heavy rain.

3.1 *Dynamic environment*

For the areas of generation and development, positive relative vortexes are below 400 ~ 500 hPa and strong negative vortexes above it in the troposphere. In contrast, the layer of positive vortex can be extending up to 250 hPa if the typhoon-generated heavy rain directly interacts with the westerly system[5]. It highlights the presence of two different mechanisms for rainstorm development. For the former mechanism, the CISK is favored as positive vorticity and cyclonic circulation develops above the boundary layer but negative vorticity and anti-cyclonic circulation develops in upper troposphere; for the latter, the deep positive vorticity in the troposphere, as analyzed in reference [6] by means of apparent source of vorticity, is formed due to upper-level westerly troughs being close to the typhoon, a circumstance in which baroclinic dynamics develops inevitably. Throughout the process, the development area is on the converging line of the near-surface layer and produces stronger convergence at lower levels than in the generation area. In the upper troposphere, the development area is closer to the center of maximum divergence. For the average difference in diversity between 200 hPa and lower level, it is $6 \cdot 10^{-5}/s$ in the development area and $2 \cdot 10^{-5}/s$ in the generation area. It is then known that the condition is more favorable for dynamic updraft of divergence to appear vertically in the area of heavy rain development than in the area of cloud cluster generation.

The easterly prevails throughout the entire troposphere of the generating area, resulting in small vertical shear of horizontal wind speed (2 m/s) of u component at 200 ~ 850 hPa. The vertical shear is, however, quite large and shows some degree of baroclinity in the developing area.

3.2 *Thermodynamic environment*

In the area of generation, warm advection is distributed in the whole troposphere with higher intensity at the lower levels, which is favorable for property of highly unstable tropical air mass to appear there with $\partial q_{se}/\partial p > 0$ at the mid-and-lower levels and $q_{se} > 348$°K in the whole column, and thus favorable for the development of convection. In the area of development, however, strong warm advection at low level (925 hPa) is accompanied by weak cold advection in the mid-and-high levels and near-surface level, showing coexistence of cold and warm air. There are two layers of frontal zone above the hard rain area, i.e. a wet baroclinic frontal zone inclining with height towards the southwest warm sector from surface to mid-and-lower layer and a subtropical frontal zone inclining with height towards the northeast cold sector in the mid-and-higher layer (figure omitted). Such semi-tropical frontal structure, combining baroclinic potential energy with latent energy by condensation, has thermodynamic conditions that are similar to typhoon-generated hard rain drawn up in previous work[3]. The difference is that the cold air is so weak near the surface that the baroclinic frontal zone cannot be analyzed. The layer of wet baroclinic latent heat by condensation is deeper in this process than a typhoon-generated heavy rain interacting directly with the westerly.

4 TRIGGERING MESOSCALE CLOUD CLUSTERS BY LOW-LEVEL SE JET

In previous study on westerly troughs or flow before troughs combining inverted troughs of typhoon in their role of triggering hard rain, northeasterly fluctuations below 2 km of the boundary layer north of the inverted trough are emphasized as being a driving force for cloud clusters of heavy rain.

For this case, one learns from studying wind speed of the southeasterly jet stream along 850 hPa and temporal profiles of cluster development (Fig.3) that a northeasterly flow is present (0800 August 3) as Cluster A develops (1500 August 3) in Xingtai to the north, suggesting some degree of triggering effect of low-level northeasterly cold air on the development of Cluster A; as Clusters B and C develop and move inland to the northwest with the typhoon, so do the warm shear and low-level southeast jet to its north (ESJ in Fig.3); when B and C develop (0200 and 1200 August

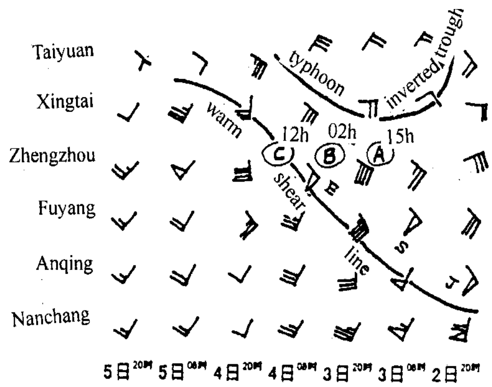

Fig.3 Time cross section of development of cloud cluster and SE low-level jet at 850 hPa from 2000 Aug. 2 to 0800 Aug. 5, 1996.

4), the air flow has turned to east-southeast in Xingtai (2000 August 3 ~ 0800 August 4). It is clear that the evolution of Clusters B and C is closely linked with north-going low-level southeasterly.

All three cloud clusters originate near Zhenzhou, at the top of the low-level southeasterly jet, with a wind core upstream on the periphery of typhoon fluctuating by the nature of mesoscale gravity inertia wave[7]. It triggers off thunderstorms and helps form the relation of $\partial V/\partial Z > \partial V/\partial Z$ underneath the maximum wind in the jet axis, owing to its own ageostrophic performance. Such thermal wind is a stimulating factor for the gravity wave[8] and becomes the kinetic energy of disturbance in the development of mesoscale convective cloud clusters in the heavy rain of interest.

Computing the major component of ageostrophic winds, the allobaric wind①, from $v = -\left(\nabla p(\partial H/\partial t)_r\right)\cdot 9.8/f^2$, we locate a large zone of such feature at 850 hPa lingering from 2000 August 3 to 2000 August 4 in Zhengzhou and areas south of it (as shown in Fig.4). It is conclusive that through local adjustment of general circulation, there has been increase in wind speed in favor of jet stream development due to drastic changes taking place in the regional pressure field.

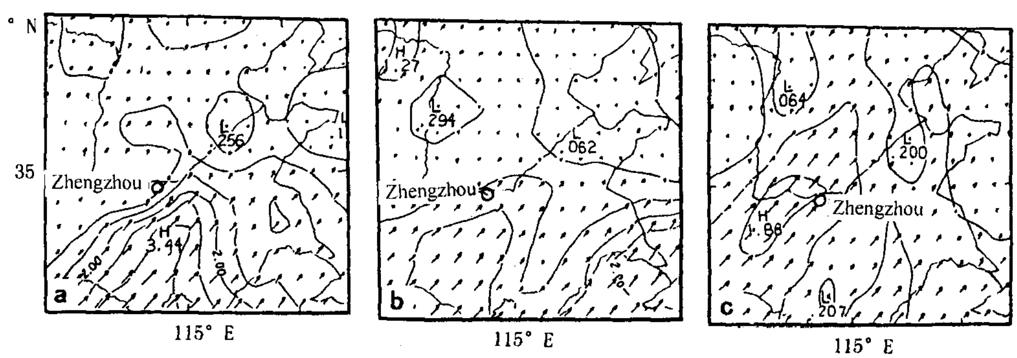

Fig.4 The allobaric wind field (equiscalar line $\cdot\,\mathrm{m\cdot s^{-1}\cdot d^{-1}}$) at 850 hPa.
a. 2000 L.T. Aug.3; b. 0800 L.T. Aug.4; c. 2000 L.T. Aug.4, 1996.

By an expression which is simplified as $x'_r = \Delta x - \Delta x_{g0}$, where Δ is the difference of values between 500 hPa and 850 hPa isobaric surfaces. Fig.5 clearly reveals that a region in which $x'_r > 0$ at all times near the center south of Zhengzhou at 2000 August 3, 0800 and 2000 August 4,

① The allobaric wind, diversity and regional heavy rain hyetal, the course of numerical prediction products 1995.

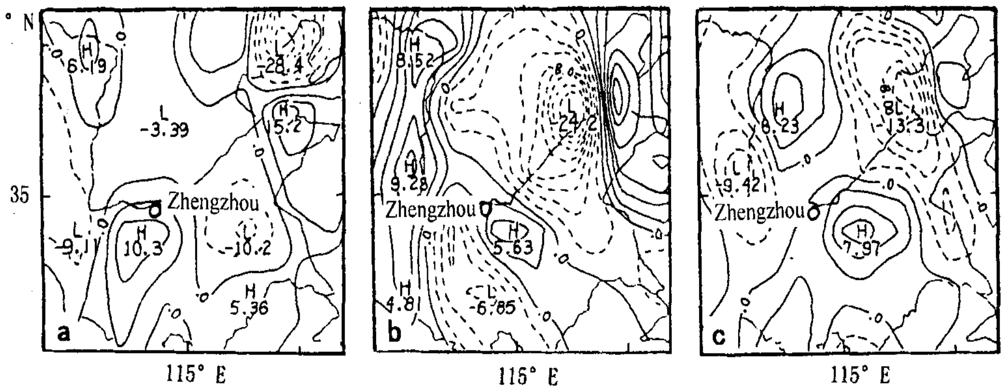

Fig.5 The non-thermal wind vorticity (equiscalar line $\cdot 10^{-5} \cdot s^{-1}$) from 500 hPa to 850 hPa.
a. 2000 L.T. Aug.3; b. 0800 L.T. Aug.4; c. 2000 L.T. Aug.4, 1996.

suggesting that the atmosphere is in ageostrophic equilibrium. It surely increases the updraft to adjust to the atmospheric ageostrophic state, which in turn helps strengthen lower-level convergence. By $x_r' > 0$, we also know that the shear vorticity of stream flow field is larger than that of thermal wind in the temperature field. The mechanism of thermal wind is so unbalanced that it will end up with unstable gravity condition when there are sufficient water vapor supply, unstable stratification, disturbance scale (i.e. fluctuation scale of the jet) being smaller than the adaptive scale of thermal wind and uplifting motion[9]. It is then possible for the potential unstable energy that is otherwise hidden to release. The cloud clusters happen to occur near Zhengzhou, which justifies the argument that the ageostrophic and gravity instability, which is excited by the wind speed fluctuations in the low-level southeasterly jet, are important original driving force for initiating and maintaining the development of three convective cloud clusters over the hard rain course.

5 COUPLING LOW AND HIGH LEVEL SYSTEMS & MAINTAINING LARGE-SCALE ASCENDING MOTION

Fig.6 illustrates the vertical profile of stream flow field and frontogenesis of Q vector traversing through the typhoon and 3 heavy rain cloud clusters. It shows that there is a vertical circulation cell with horizontal scale near 1000 km to the northeast of the clusters, which is coupled by an upper-level southwesterly flow, which exists between a monsoonal high in upper tropospheric level above the clusters and a westerly trough in northeast China, and a lower tropospheric northeasterly flow. Examining this synoptic vertical cell, we learn that dynamic energy decreases and potential energy increases on the side of westerly zone where there is frontogenesis due to Q vector sink while potential energy decreases and dynamic energy increases on the side of hard rain zone where there is frontolysis due to Q vector rise. It is a clear sign that transformation of baroclinic energy is going on among the heavy rain areas, tropical and westerly systems in an orderly manner. Studying the energy field corresponding to it, we discover that low energy potential sinks on the side of westerly trough but high energy potential rises on the side of heavy rain area, indicating that the circulation cell is directly driven by thermal force and the baroclinic dynamics is one of the mechanisms that power it. It also shows that the hard rain in question is one in which the large scale ascending motion over the hyetal region is supported by a baroclinic dynamic mechanism. As inferred from Figs 1 & 6, the vertical and synoptic cell of circulation is a product of interactions

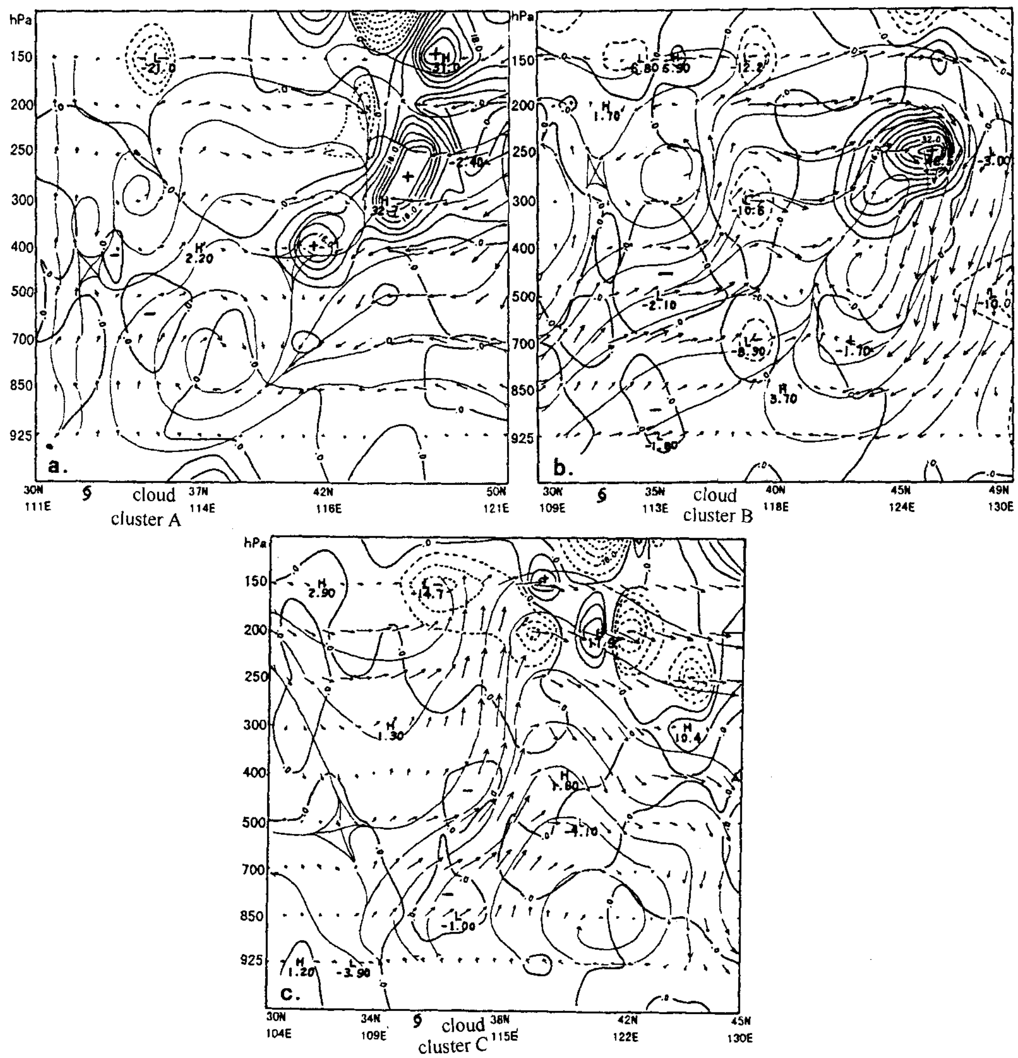

Fig.6 The vertical section of *Q* vector frontogensis function (equiscalar line $\cdot \mathrm{K}^2 \cdot 10^{-16} \cdot \mathrm{m}^2 \cdot \mathrm{s}^{-1}$) (grid spacing 100 km) traverse the typhoon and heavy rainfall cloud cluster.
a. 2000 L.T. Aug. 3; b. 0800 L.T. Aug. 4; c. 2000 L.T. Aug. 4, 1996.

and vertical coupling by the typhoon, low-level jet on its periphery, 200-hPa high, subtropical high in west Pacific and a number of other systems in the westerly trough and these components contribute to a stable mechanism of maintenance.

6 DYNAMIC AMPLIFIER OF HEAVY RAIN BY POLAR FRONT

Making diagnosis by means of GMS-5 water vapor imagery and other physical quantities, we have identified the role of minor, regular westerly troughs of high latitudes in dynamic amplifying this particular rainstorm during the southward advancement. On the water vapor chart, Cluster B is found to be formed around Zhengzhou at 0200 August 4 and moving on northward to the Hebei province where it matures to have well-outlined and bright boundary of convection. Around 0600 Cluster B drops in brightness and turns irregular in boundary (figure omitted), showing signs of weakening. The cluster further reduces in strength at 0700 and splits into a number of loose lumps. After 0800, however, the lumps reunite to become bright and well-outlined clusters again. Cluster B has a course of gradual decrease in the two hours ever since, though somehow manages to stay good for 12 hours more. Over this period, Cluster C is seen north of Zhengzhou to head north to join Cluster B and develop into a convective system on remarkable scale. It is just in the period of development and maintenance of Clusters B and C (0200 ~ 2000 August 4) that intense precipitation concentrates in the province. In particular, Cluster B plays some role in strengthening and maintaining the hard rain by developing once again, which is supposed to have indirectly linked with south-advancing minor westerly troughs from high-latitude polar fronts near the Lake Bajkal.

On the water vapor chart corresponding to the time, the eastern continent of China is covered with wet sectors extending from mid-and-high latitudes and ITCZ, as indicated by the light grey zones south of 41° (figure omitted). The large-scale wet region, which is adjacent to ITCZ, is usually in close relation with synoptic anti-cyclones or ridges of high. Although there may be a cyclonic circulation system in lower troposphere, only the upper-level anti-cyclonic part could be isolated on the chart. It is therefore reasonable to name the distribution a tropical "base ridge" pattern. For this case, the northern boundary is connected with water vapor zones in the cloud bands of a cold front in northeast China. After 0200 August 4, anti-cyclonic rotation has taken place in northeast border (NJ) between the "base ridge" and water vapor sector in the cloud bands of the northeast China cold front, which is marked by northward protruding of NJ's western segment corresponding to the water vapor imagery boundary of the "base ridge" and southward concaving of its eastern segment corresponding to the darkened area to the north of water vapor imagery boundary of the cold front. It shows that there is synoptic descending motion on the side of dry sector of the water vapor boundary and dry, descending motion swelling towards the south. It is the so-called "base swelling" in the analysis of water vapor imagery[11]. By integrating weather situations, we know that it is caused by the draft of polar northerly transferred southeastward by polar fronts in northwestern part of Lake Bajkal, which is most clearly displayed at the level of 300 hPa. When the base swelling happens, the water vapor imagery boundary that is protruding clearly would for on both sides of the swell that concaves. For the wind field in upper troposphere, local ridges on the synoptic scale are formed in two wet sectors with protruded boundary. The eastern ridge is called "R1" and the western one "R2", which is more commonly seen in chart analysis[10]. To study relevant relationship, we find that the descending area of "base swell" is distributed from northeastern part of north China to southern part of northeast China while the "R2" ridge in the west of the "base swell" is just where the central and western parts of north China (Cluster B) is located. Usually, the occurrence of "R2" ridge is thought to be an indicator of high probability for deep convection weather.

The variation of local weather entities resulted from "R2" region can be described by computations of vorticity and comparisons of the intensity of anti-circulation at 200 hPa around the occurrence of base swell. Before the base swell takes place, the negative vortex is $-7.7 \cdot 10^{-5}/s$ along the middle reaches of the Yellow River at 2000 August 3; after the appearance, the vortex center intensifies to $-14.5 \cdot 10^{-5}/s$ and moves northward to the eastern part of north China at 0800 August 4. At 2000, with intensity dropped to $-12.8 \cdot 10^{-5}/s$ it moves eastward to the eastern part of north China (Fig.7). Correspondingly, the divergence center at 200 hPa, which is over the middle reaches of the Yellow River at 2000 August 3, has moved northward by 0800 August 4 to arrive in the central and western part of north China with the intensity risen from $4.0 \cdot 10^{-5}/s$ to $9.0 \cdot 10^{-5}/s$ (figure omitted).

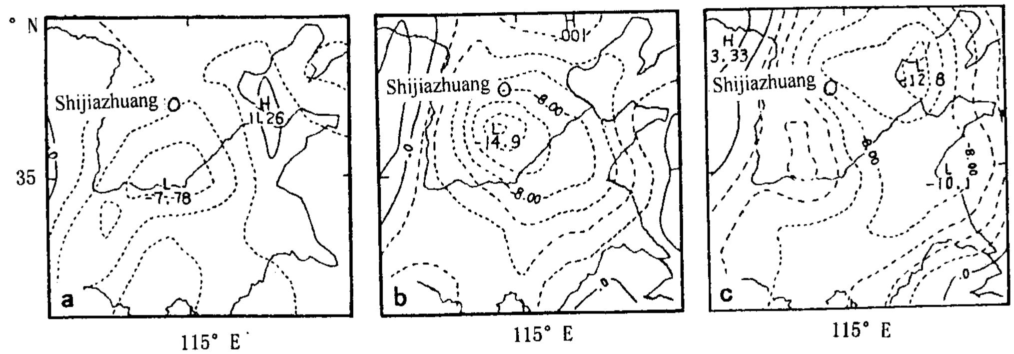

Fig.7 The vorticity (equiscalar line $\cdot 10^{-5} \cdot s^{-1}$) at 200 hPa.
a.2000 L.T. Aug. 3; b. 0800 L.T. Aug. 4; c. 2000 L.T. Aug. 4, 1996

The generation of "R2" ridge area is, as shown above, related with enhanced divergence of negative vorticity in the upper-level anti-cyclone and therefore favorable for the generation and development of deep convection. It can be used to interpret the fact that Cluster B, which had weakened by early morning on August 4 in the Hebei province, re-developed after 0800 the same day, moved northward to approach the maxima of 200 hPa divergence (figure omitted) and stayed intense till around 1200 when it merged Cluster C, a fresh development. It contributed to convective heavy rain that lasted from 0800 to 2000 in the region of Shijiazhuang. It is obvious that the heavy rain is amplified dynamically to some extent because of indirect role of teleconnected polar systems in high latitudes, which intensified anti-cyclonic divergence above western hyetal and re-activized mesoscale cloud clusters that are normally short-lived. The amplifying effect may also be attributed to minor westerly troughs in the polar fronts that have traveled long distance from north. It is in fact the effect well known by the forecaster that downstream troughs deepen in association with intensified upstream ridges. With existing large intervals in both space and time concerning real conventional data, applying the method of water vapor imagery can have timely and illustrative description of such indirect action of high-latitude minor troughs.

7 CONCLUDING REMARKS

a. During the unusually heavy rain on the periphery of Typhoon 9608 (Herb), the upper troposphere is dominated by a high ridge in the eastern continent of China and a strong anti-cyclone at 200 hPa. The typhoon is separated from the large scale westerly trough at mid-and-upper tropospheric layers and its corresponding frontal zone of westerly jet stream. A southeast jet, which is associated with ITCZ, is on the periphery of depression. Such distribution is favorable for the maintenance and westward travel of typhoon.

b. What pose direct impact on this process of hard rain are three mesoscale convective cloud clusters, which originate from the same source at the top of southeast low-level jet. Generating about every 10 hours, the clusters move northward regularly to arrive north of a converging 1000-hPa shear where they develop to have horizontal scale of 200 ~ 300 km for intense convective rainstorm. The easterly flow on the periphery of typhoon depression has an obvious orthogonal crossing with the Taihang Mountains. It is over this area that the three cloud clusters merge one after another consecutively and stagnate to give precipitation that is extremely heavy.

c. In the region of generation and development of cloud clusters for the heavy rain, there is deep reversed-circulating divergence of negative vorticity, which is similar to the dynamic environment in which tropical converging systems develop but different from the convergence of deep positive vorticity in the troposphere, over the course of typhoon-generated rainstorm having direction interactions with westerly troughs.

d. In the generation area of clusters, warm advection is prevailing over the entire troposphere with $q_{se} > 75°C$ throughout the whole air column, falling into the category of tropical air mass with highly unstable potential energy. The easterly exists for the whole of troposphere with little difference of vertical shear with respect to horizontal wind speed u in all layers, having weak baroclinity that is similar to the environment in which tropical cloud clusters develop.

e. In the development area of clusters, strong warm advection in lower troposphere is accompanied with weak cold advection in the near-surface and mid-and-high levels. The frontal zone of energy is so structured that it has baroclinic potential energy and latent heat energy from condensation, a typical distribution of semi-tropical fronts. The westerly prevails in the upper levels and easterly in the lower levels, with some extent of vertical shear of u and baroclinity. It is similar to the condition with which the westerly trough directly interacts with typhoon-generated heavy rains. In addition, for the maxima of divergence at 200 hPa where the rain clusters develop, the easterly on the periphery of depression has an orthogonal crossing with the Taihang Mountains so that large-scale dynamics and topographic lifting are both advantageous over those in the generation region of convective cloud clusters.

f. The fluctuations of wind speed of the low-level southeasterly are closely related with the development of convective cloud clusters. A large ageostrophic change has occurred in the low-level wind field, the source of convective cloud clusters, along the northern side of the jet. Correspondingly, the vorticity is above zero in the non-thermal wind between 500 hPa and 850 hPa. It suggests that the shear vorticity of the stream flow field is greater than that of thermal wind of the temperature field and therefore contains initiating condition for unsteady gravity inertia waves and important driving force for the development and organization of convective cloud clusters.

g. Owing to interactions by the typhoon, a reversed trough, southeast jet on the periphery of typhoon, west Pacific subtropical high, 200-hPa high, westerly trough and a number of other systems, two asymmetric vertical circulation cells are formed that maintain ascending motion above the heavy rain (Fig.6a & 6b). In particular, the synoptic vertical cell, lying between the heavy rain and the westerly trough about 1000 km to the northeast, is formed by the coupling of the upper-level southwest flow, which is between the monsoon high in upper troposphere above the hyetal and the westerly trough in northeast China, and the northeast flow in lower troposphere. As indicated in the study of frontogenesis of Q vector and energy field, the vertical cell of circulation is driven by baroclinic dynamics existing between the area of heavy rain and westerly system in teleconnecting distance, being important in maintaining the large-scale ascending motion over the hyetal. What this cell differs from a secondary cell as coupled by jet streams between upper and lower levels is that the latter transverses the polar frontal zone and upper-level jet[12] with smaller horizontal scale (500 km or below) and secondary vertical cells of stronger transformation of baroclinic dynamics. Polar frontal systems are of more direct baroclinic dynamics for typhoon-generated heavy rains. For this particular case, the vertical cell is formed as a result of converging descent and coupling over west Pacific subtropical high in mid-tropospheric layer between the southwest outflow in the upper layers of the high pressure anti-circulation and the northerly behind westerly trough almost 1000 km away to the northeast, which suggests that polar frontal systems exert long-distant and indirect impact on the baroclinic dynamic process of the heavy rain. Apart from it, the wind speed is relatively small in upper air. Examining Fig.6b and 6c, we know that the deep, descending and compensating air flow, which forms by accumulation of air mass due to the development of strong convection rainstorm at upper levels, is in effect disturbing and destroying the vertical cell, which is featured by large spatial span and capability of transforming weak baroclinic energy, to the extent that it deforms it and deprives it of the transformation and consequently weakens or prohibits the large-scale ascending motion of air, affecting the maintenance and development of convective hard-rain systems. Given the stable condition with typhoon depression, low-level jet, 200-hPa high, west Pacific subtropical high and westerly trough, such weak mechanism of baroclinic maintenance is repeatedly disturbed, destroyed and then restored, re-established by deep convective systems, contributing to an unusually heavy rain containing intense convection cloud clusters that interact within a limited domain.

h. By studying water vapor field from GMS-5 imagery and computed divergence and vorticity at 200-hPa, we know that when minor troughs of polar upper-level fronts are moving southward over northern Lake Bajkal, the northerly flow transmitting after the trough intensifies the descending motion in northeast China and areas to the south and increases the anti-cyclonic divergence in upper troposphere in central and western parts of north China. The situation reinforces the convective cloud clusters starting from 0600, which have been weakened only 6 hours into the development in the Shijiazhuang and Xingtai. They merge with newly-matured cluster around 1200 to form a convective hard rain that lasts from 0800 to 2000 August 4 in Shijiazhuan area. It suggests that the indirect role of high-latitude, long-distant polar systems are significantly amplifying the heavy rain of interest, which can be diagnosed from the water vapor imagery in a timely and illustrative manner.

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