Analyzing the characteristics of vortex heavy rainfall in Henan during 16~19 July 2010

Su aifang\textsuperscript{1,2,3} Yin yan\textsuperscript{3} Cui liman\textsuperscript{1,2} Xu wenming\textsuperscript{1,2}

1. Henan Provincial Meteorological Office, Zhengzhou, 450003, China
2. Key Laboratory of Agrometeorological Safeguard and Applied, CMA, Zhengzhou, 450003, China
3. College of Atmospheric Physics, NUIST, Nanjing, 210044, China
Afsu011@sohu.com

Abstract

Based on the conventional meteorological observations, the regional automatic stations, Doppler radar and NCEP reanalysis data, characteristics of two vortex heavy rainfalls occurred in Henan during 16 and 19 July 2010 were analyzed. The result shows that the interaction between the warm and wet air flowing on the edge of Subtropical High and the spreading south cold air benefits the formation of western Huanghuai meso-scale vorticity; while the warm and wet air on the edge of Typhoon and Subtropical High flows up north in a far distance to provide abundant water vapor for rainfalls. The coupled dynamic structure between high-level divergence and low-level convergence near the center of vortex is in favor of the development of vertical ascending motion, which also increases the convergence and lifting of water vapor. The thermal instability structures are different during the two vortex-storm process: Convective instability and conditionnal symmetric instability coexisted during the 7.17 process, and the convective instability is the atmospheric major character; While in the 7.19 process, the frontal zone was strong and deep, the Conditional symmetric instability is the atmospheric major character, which led to a relatively weak rainfall. Analysis of vorticity suggests that the peak values of local vorticity transfers down from the top, and vertical transport is the major contribution of local vorticity increasement.

Keywords: Heavy Rain; Subtropical high; Mesoscale Vortex; Vorticity Budget

1. Introduction

The vortex on mid and low layer developing on the shear line is one of the important weather systems causing rainstorm (Tao 1980 and Ding 2009), which is the focus of many scholars. Hu et al. (1996) has studied on the cyclonic disturbance during “Meiyu” period over Yangtze and Huaihe valleys, and pointed out the serial small weak cyclonic disturbance on “Meiyu” shear line is closely associated with rainstorm, even if the vortex is not obvious, careful analyses can determine the existence of the weak vortex which will cause heavy rainfall. Sun et al. (1996) pointed out that in many cases, the low pressure (disturbance) affecting the mid and low Yangtze River valley, is not the eastward southwest vortex, but the local newborn vortex disturbance in the favorable terrain in the mid and low Yangtze River valley by dynamic and thermal causes. The mesoscale vortex in the low Yangtze River valley, whose horizontal scale is generally within 400km, exists in the lower troposphere below 700hPa, forming in the environmental conditions of high energy and high humidity and on the Dabie mountains as well as both sides of the mountain, anymore, the positive vorticity advection in front of trough is one of the necessary conditions to form vortex. Rainstorm mainly occurs in the south or southeast of the vortex, and the high and low jet configuration, the lower water vapor transportation and terrain conditions all play an important role to trigger heavy rain (Yang et al., 2010). The analyses on the abrupt extraordinary heavy rainfall in the middle of Yangtze River valley in July 1998 showed that the heavy rainfall was directly related to the formation and development of mesoscale-β vortex (Cheng et al., 2001). Bei et al. (2002) thought that the concentration of large amount of water vapor in the middle and low troposphere during “98.7” heavy rainfall process and the convective instability provide a favorable environment for the development of the mesoscale systems. With heavy precipitation are the activity characteristics and the four-dimensional structure of 5 vortexes closely related to heavy rainfall on Meiyu front are comprehensively analyzed, revealed three air flows forming the vortex the by calculating the trajectory and the individual variation of the air physical properties, and analyzed the sources of cold...
air and water vapor and the vortex and the formation of wet baroclinic frontal zone (Gao et al., 2001). In addition, some researches performed detailed analyses on the evolution and structure of vortex from the environmental characteristics (Li et al., 2009 and Zhou et al., 2010). However, the rainstorm system’s structure is complex, the current study on mesoscale vortex heavy rainfall is still limited. The heavy rainfall in Huang-Huai River Basin is often related to the development of the mid and low layer vortex on the shear line, but the corresponding systematic studies are carried out less.

From 16th to 19th in July 2010, affected by the mesoscale vortex, there are successive heavy rain and severe convective weather in Henan Province, which leading to the Yellow River and Huaihe River’s water level rising and peak appearing. Heavy rain also triggers landslides, flash floods and other geological disasters. According to the statistics, there are 13 cities in Henan seriously affected and the direct economic loss is 9.8 billion, unfortunately, ten people died and one person missed. In this paper, the mesoscale characteristics and origin of the rainstorm are analyzed using the conventional and unconventional meteorological observation data as well as NCEP (1° × 1°) reanalysis data.

2. The rainfall characteristics

There are two heavy rainfall processes from 16th to 19th in July 2010, one is from 1200UTC on 16th to 1200UTC on 17th(7.17 process) and the other is from 1200UTC on 18th to 1200UTC on 19th (7.19 process). During 7.17 process, heavy rainfall is in Huaihe River Basin and in east of Nanyang, there are six stations in Henan Province with daily rainfall over 100mm, and maximum daily precipitation is 199mm/d in Tongbai. During 7.19 process, heavy rainfall appeared in the west and north of Huang and Huaihe river, there are seventeen stations with daily rainfall over 100mm, and Nanzhao suffered the maximum precipitation (180mm/d).

Rainstorms are accompanied by severe thunderstorm as well as local tornado, and the characteristics of convective precipitation are obvious. The hourly rainfall in regional automatic stations in Henan shows that short-time heavy rainfall belt is located in Huaihe basin during 7.17 process, the Maximum hourly rainfall appear in Tongbai (170200UTC) and Suixian (171600UTC), respectively 103.3mm/h and 99.9mm/h. During 7.19 process, the short-time heavy rainfall belt lies in the western, northern and central of Henan, and the Maximum hourly rainfall appears in Zhengzhou(60.4mm/h) at 2200UTC on 18th. The strong rainfall belts are both distributed SW-NE, and the range of rainstorm is wider but rain intensity is weaker during 7.19 than 7.17 process.

3. Circulation background and the formation of mesoscale vortex

3.1 Circulation background and water vapor transportation

In July 2010, the circulation over the Northern Hemisphere is with stronger polar vortex and subtropical high(SH) as well as the prevailing westerly zonal flow over the Eurasian mid-latitude leading to many coel-air activities(Sun,2010). On 500hPa, near northeast China is the stable low system and the subtropical high is strong in the middle and low latitude. 588 lines lie in the north of Yangtze and Huaihe basin, in one word, the tropical systems are active. During 7.17 process, the typhoon "Conson" lands in the south of Hainan, and its outside southerly flow converges with the southerly flow on the edge of the Subtropical High, which strengthens the northward transportation of warm air, forms a great water vapor flux belt from South China Sea by the Yangtze River to the upper reaches of the Huaihe River, and provides favorable moisture conditions to heavy rain. In the bottom of the Northeast eddy and in the east of the plateau a short-wave trough moves eastward, leads the cold air to interact with the southwest warm wet air, results in the southeasterward withdrawal of the north edge of the subtropical high, and benefits the heavy rain (Figure 1a). Cold air and warm air on the mid and low level converge in the upper reaches of the Huaihe River and the mesoscale vortex system forms. During 7.19, the northeast cold vortex strengthened than previously, at 0000UTC on 18th, in the bottom of the cold vortex, that is, in central Shaanxi, a cyclonic circulation develops. In the low latitude although "Conson" weakens to a tropical low pressure, a new tropical system moves to the northwest in the South China Sea, which strengthens into typhoon "Chan thu" at night on 19th, and so the warm air is more powerful than 7.17 (Figure 1b), still accompanied by a great water vapor flux belt from the South China Sea to the upper reaches of the Huaihe River, carrying the water vapor to the north. At the same time, a low trough moves eastward on 500hPa in the mid-latitude and the convergence of cold and warm air is in western Henan on the medium and low-level, which results in the development of low vortex system. It is thus clear that the relatively stable position of the southwestern cold air, the remote typhoon and the subtropical high, the high-level convergence and stable southwest water vapor channel are in the circulation
background characteristics of such Vortex Heavy Rainfall to some extent.

Figure 1. 500hPa geopotential height field and 850hPa water vapor flux at 1200UTC on 16(a) and 18(b) July 2010. (black solid line: geopotential height; filled area: water vapor flux; thick solid line: 500hPa trough line; arrows: 700hPa jet stream.)

3.1 Circulation background and water vapor transportation

The time series of the temperature 700hPa range, the zonal average of V wind and height on 500hPa from 110°E to 114°E show that at 1200UTC on 16th and at 1800UTC on 18th, there are the spread of the two cold air southward and the decline and southward withdrawal of the SH correspondingly, which shows that the formation and development of the mesoscale vortex result in the interaction of warm and cold air. Further analyses show that during 7.17 process the vortex firstly develops near the shear line on 700hPa. At 1800UTC on 16th, the vortex center on 700hPa is located in mountainous areas in western Henan (Fig. 2a), and on 850hPa in the southwest of Henan is a shear line. At 0000UTC on 17th, in the north of the vortex on 700hPa the northerly flow strengthens, in Nanyang sounding station the northerly wind velocity is up to 10m/s, under the interaction of the strengthening northerly flow and steering flow on high level, the vortex center moves to the northeast of Nanyang, meanwhile, the flows in both sides of shear line on 850hPa strengthen and in the east of Nanyang appears the vortex structure. From 0600 to 1200UTC, the vortex on 850hPa develops, strengthens and moves northeastward with the high-level steering flow, causing significant thunderstorms and short-term strong precipitation. The development of vortex in 7.19 is different from in 7.17, that is the vortex develops simultaneously in mid and high level. At 0600UTC on 18th, the high-level vortex firstly develops in the west of Shaanxi Province, on 700hPa from the east of Sichuan to the Yellow River valley is a SW-NE shear line, and in its west is the southwest vortex, moves northeastward along it, and then fades away. At 1800UTC, high-level vortex stretches up to 400hPa, at the same time, the southwest jet on 700hPa in the south of the shear line strengthens and moves to the North, which converges with the strong southward cold air from north with maximum wind speed of 8m/s over the mountain areas in western Henan, and the obvious vortex structure forms on the shear line once again (Fig. 2b). At 0000UTC on 19th, the vortex system develops and moves northeastward to northern Henan.

It is obvious that the vortex firstly forms over the shear line near 700hPa during 7.17, when it moves northeast, the vortex center declines and the vortex near 850hPa strengthens. The difference is the mid layer vortex moves eastward, stretches downward, also develops upwards, and connects with the high layer vortex in 7.19, which makes a deep vortex system declining northwest from bottom to the top in the west of Huang-Huai, with significantly larger spatial scale. During 7.17 process, the maximum rainfall intensity is over 100mm/h, while duing 7.19 the maximum rainfall intensity is 60.4mm/h, which is similar to the precipitation characteristics "a small vortex heavy rain, large eddy drizzle" (Sun et al 1996)in Yangtze River.
3.3 The surface mesoscale (Sc) cyclones and short-term heavy rain

At 0000UTC on 17th, the surface cyclone generates in the southeast of vortex on 850hPa, develops from 0000UTC to 0300UTC, but its location is stable. Then it moves northeastward with the vortex on high level, and causes heavy rainfall concentrated in two periods, from 0000 to 0300UTC and from 1400 to 1700UTC on 17th. During 7.19, from 1800 to 1900UTC on 18th, the Sc forms near Pingdingshan in the convergence center on 850hPa, and then moves northeastward (figure 3b1), and heavy rain appears from 1800UTC to 2200UTC on 18th intensively.

The short-term heavy rainfall during two processes is mainly distributed in two regions (Figure 3a1, b1), one is in the southerly flow convergence region in the southeast of Sc, and the other is in the east to northeast inflow area in the north of cyclone. During 7.17 process, from 0000 to 0200UTC, the cyclone center is located in the northeast of Nanyang, and the heavy rainfall appears in Tongbai County in the southeast of the cyclone, with rainfall intensity up to 103.3mm/h. The formation and evolution characteristics of vortex rain belt can be clearly observed on the radar in Zhumadian, that is, at 0206UTC on 17th, heavy rainfall is caused by a narrow and strong echo band in front of the vortex rain belt, with the strongest echo of 60dBz, which is similar to the narrow cold front rain belt in front of the mid latitude cyclone. According to Hobbs et al (1982), this narrow cold front rain belt contains large amount of liquid water and small amount of ice crystals, its water vapor mainly comes from the low-level southerly jet, and the air convergence in the boundary layer often produces strong and narrow ascending flow, about 5km wide, which causes heavy rain. On the echo band inside the inflow area in the north of cyclone center, in the rage of about 100km, there are also a number of γ mesoscale convective systems, resulting in heavy rainfall near and in the north of the cyclone center (Figure 3a2). At 0600UTC, the vortex rain belt moves northeastward, the wind speed convergence strengthens near the cyclone center, the narrow band echo in its southeast weakens, while the echo in the east to northeasterly inflow region in its north strengthens, the reflection rate of the γ mesoscale convective system is 52dBz, and after this moment, a strong precipitation of 68mm / h occurs in Linying (Figure 3a3). At 0838UTC, the cyclone continues to move northeastward, the northeast flow in the north continues to strengthen and the echo intensity is 56dBz. The section through the strong echo center shows the echo ≥ 55dBz over the rainfall center stretches from bottom to 5.5km, and the echo is low centroid strong echo, which results in the rain intensity of 99.9mm / h in Suixian (Fig. 3a4). From 0900 to 1000UTC (not shown), affected by strong convective systems, Suixian, Yucheng, Xiayi and other places suffer from tornado. During 7.19, the heavy rainfall distribution has similar characteristics, observations on radar in Zhengzhou show that at 1800UTC on 18th, the heavy rainfall echo firstly develops near the shear line, and behaves scattered γ-scale convective systems (Figure 3b2).With the development of the vortex, the vortex rain belt structure of the gradually becomes clear. At 2145UTC, a strong and narrow echo band also appears in the southeast of the cyclone center (Figure b3), the strongest echo is 60dBz, and brings short-term heavy rain, local tornado to Pingdingshan, Xuchang and so on. At the same time in the northeast flow in the north of the cyclone center heavy rainfall echo also develops, leading to the heavy rain of 60.4mm / h in the west of Zhengzhou. At 2316UTC, the echo band in the southeast of the cyclone center weakens, the northeast air inflow area in its north becomes the concentrated areas of heavy

![Figure 2](image-url)
rainfall, the echo intensity is 55dBz (Figure 3b4), and rainfall intensity is 20 ~ 45mm / h. It is obvious that during the vortex rain belt formation and development of rain, the strong rainfall echo often develops in the inflow area in the southeast and north of rain belt, and the "narrow cold front rain belt" in the southeast of the vortex is main impact system causing strong convective weather, such as heavy rain, tornadoes, etc.

(Figure 3 at the end of the article)

4. Physic characteristics of the development of vortex
4.1 Structure of dynamic field

During the 7.17, the distribution of vorticity and divergence on 850hPa show that the positive vorticity reaches to the Huaihe River as a band NE-SW. At 0000UTC on 17th, the positive vorticity center is near 33°N, 113°E, in the north of which is the negative divergence center, with the central value of -4×10^-5 s^-1. Heavy rain occurs in the east of the positive vorticity center and near the negative divergence center. At 0600UTC, the positive vorticity band moves east, there are two positive vorticity centers near the vortex center and on the shear line, the remarkable area where the cold and warm air conflict, and the negative divergence area lie in the east of the positive vorticity band. The temporal evolution of the vertical dynamic field near the vortex center shows that the positive vorticity firstly develops on the lower and mid-layer from 1200 to 1800UTC on 16th, the maximum from 700hPa to 850hPa, which is in accordance with the analyses on the vortex evolution in 2.2 section, and the upper divergence layer lie on 2500hPa. From 1800UTC on 16th to 0000UTC on 17th, the vorticity maximum area descend to 850-900hPa, and the thickness of the upper divergence layer increases, which extends downward to 300hPa. About 0000UTC on 17th, the positive vorticity on 850hPa reaches maximum, that is 15×10^-5 s^-1, on the lower layer appears the significant negative divergence area, and the convergence on the boundary layer is obvious. Meanwhile, the upper divergence reaches maximum, the vertical ascending motion develops strongly, the ascending area extends to 200hPa, the area where the value of the vertical ascending velocity is ≤-1 Pa.s^-1, extends to 300hPa, and the central value is -1.2Pa.s^-1, near 450hPa. At 0600UTC, the upper divergence layer becomes thinner during descending and the thickness of the positive vorticity layer decreases. Although the obvious negative divergence layer appears in the middle of the convective layer, as the lower is divergence layer, the dynamic distribution is disadvantage to the development of the vertical ascending motion, and the vertical ascending velocity weakens apparently.

During the 7.19, at 1800UTC on 18th, the positive vorticity area is from the east of Sichuan to the north of Henna on 850hPa, SW-NE, the maximum positive center of which is near Pingdingshan, with the central value 18×10^-5 s^-1, where the meso-scale vortex forms and the heavy rain occurs. There are two negative divergence centers in the north and southwest of the vortex center, with central absolute value of 8×10^-5 s^-1 and heavy rain in the corresponding area. At 0000UTC on 19th, the positive vorticity center moves northeastward to the northeast of Henna, the vortex develops and strengthens further, the central vorticity is 32×10^-5 s^-1, and two negative divergence centers move northeast with it and strengthen, too. The temporal evolution of the vertical dynamic field near the vortex center (34°N, 112°E) shows that from 0600 to 1800UTC on 18th the positive vorticity area lies from 400hPa to 800hPa, the vorticity from 600hPa to 700hPa increases with time and reaches maximum of -14×10^-5 s^-1 at 1800UTC on 18th, when the strong convergence occurs near 850hPa, with the maximum absolute value of the negative divergence area 5×10^-5 s^-1, and there are upper divergence layers near 200hPa and 350hPa, with the maximum divergence 6×10^-5 s^-1 near 200hPa. Correspondingly, the vertical ascending motion develops rapidly, the ascending motion area extends from 900hPa to 200hPa, the area where the vertical ascending velocity is ≤-1 Pa.s^-1 lies on layers beneath 400hPa, and the absolute value maximum of the vertical ascending velocity is -1.4 Pa.s^-1, near 600hPa. Therefore, with the development of the positive vorticity on lower layer and the construction of the coupled dynamic mechanics between high-level divergence and low-level convergence, the vertical ascending motion develops significantly, which leads to heavy rain. At 0000UTC on 19th, with the northeast motion of the vortex, the positive vorticity decreases, the divergence characteristics of high-level divergence and low-level convergence disappears, and the vertical ascending motion weakens quickly. The vorticity variation above is according to the vortex evolution in 2.2 section.

Above all, the coupled dynamic structure between high-level divergence and low-level convergence near the center of vortex is in favor of the development of vertical ascending motion, which also benefits to the convergence and lifting of water vapor and forms heavy rain, and the deep vertical ascending motion leads to heavier rainfall.
4.2 Thermal and unstable conditions

The distribution of pseudo equivalent potential temperature ($\theta_{se}$) when the vortex on 850hPa forms during two heavy rain processes shows that at 0000UTC on 17th, the SW jet on 850hPa transports warm wet airflow to the north, and there is warm wet tongue northeastward near the vortex, which shows that the atmosphere in this region has the energy characteristics of high temperature and high humidity, as fig. 5a1. In vertical direction along 113ºE, the $\theta_{se}$ high contour is convex upward under 700hPa near the vortex center 32 $\sim$ 33ºN, $\theta_{se}$ decreased as altitude increased, and the atmosphere is convective unstable. The $\theta_{se}$ low contour is convex southward from 500 to 650hPa, $\theta_{se}$ contours are intensive in the north of the vortex center, and the energy front is significant, as fig. 5a2. The dry cold air moving southward in the north of front superimposing on the warm wet air moving northward below it , is advantaged to the development of convective instability, that means, as long as the ascending motion develops in this area the release of convective instability energy can be triggered and heavy rain generates. According to figure 5a2, the vertical ascending motion develops in and over the convective unstable area. The corresponding analyses on MPV shows that the MPV near the vortex center is <0, moisture symmetric unstable, the main contributors on 850hPa is MPV1 (baroclinic term), with center value -0.6PVU, and MPV2 (positive items) is from -0.2 to 0PVU, as Figure 6a3, therefore, the convective instability is main feature in the lower atmosphere and is the important background condition for heavy rainfall. At 0600UTC, SW jet becomes narrow, strengthens and extends northward, the vortex center enters energy front from the high energy tongue, as figure 5b1, and in the vertical direction, energy front is steep from 500 to 900hPa, the vertical ascending motion develops in front of the neutral convective energy front at 33 $\sim$ 34ºN, as figure 5b2. In this region, MPV on low and mid layer is <0, symmetric unstable, the area with MPV1<0 is from 800 to 900hPa, the area with MPV2<0 is expanded from 700hPa to 800hPa, compared with the previous range, and the absolute maximum is 1.2PVU, when the conditional symmetric instability is the main features.

The thermal structure over heavy rain area during 7.19 process is a little different from 7.17. At 1800UTC on 18th, along Huang River is a SW-NE energy front, the vortex forms in the south of the front near the warm wet tongue, and SW jet is significant with maximum velocity of 20m/s as figure 6a1, which provides beneficial dynamic and energy condition to the development of vortex and the generation of heavy rain. In the vertical direction along 113ºE, as figure 6a2, the high $\theta_{se}$ area is mainly under 850hPa, the convective unstable layer is shallow, in the north of the vortex center 34 $\sim$ 35 º N is the energy front, under 400hPa $\theta_{se}$ contours are intensive and steep, showing neutral or weak convective unstable, and the vertical upward motion develops mainly in the region. The analyses on MPV show that at 1800UTC on 18th(Fig. 6a3) MPV on low and mid layer is <0, moisture symmetric unstable, from 700 to 850hPa MPV1 is <0, and under 800hPa MPV1 is >0 and MPV2 is <0 with maximum absolute value 0.9PVU, where the conditional symmetric instability is dominant, that is, the baroclinic instability is the main feature of the lower atmosphere, and once the lower baroclinic unstable energy is triggered, slantwise vorticity will develop and local convection will generate. At 0000UTC on 19th, SW jet strengthens further, meanwhile, the north jet appears in the north of the vortex center, the $\theta_{se}$ contours are more intensive, and under the push of the warm wet airflow, the vortex center moves to the middle of the energy front(Fig. 6b1), accordingly, the vertical ascending motion...
develops in the middle and south of the energy front (Fig. 6b2), where MPV < 0, MPV1 > 0, atmosphere is conditional symmetric unstable, MPV2 is main contributor to MPV, and its absolute value is greater than 1PVU, as figure 6b3.

It is obvious that the energy front is the characteristics of two processes. During 7.17 the vortex forms in high energy tongue and develops on the south of the energy front, convective instability and conditional symmetric instability co-exist, convective instability is main feature of the atmosphere, and rainfall intensity of the process is relatively large. During 7.19 process, the vortex forms in the south of the energy front and develops in the middle of the front, conditional symmetric instability is main feature, and rainfall intensity is weak.

5. Diagnosis and analyses on vorticity budget

The regional average of each term in vorticity equation is calculated inside the vortex developing region, that is 32 ~ 34°N, 113 ~ 114.5 °N, in 7.17 process and 33 ~ 35.5 °N, 112 ~ 115 °E, in 7.19 process, and the vorticity budget on each layer inside this region is diagnosed in order to further review the vertical development features of vortex.

Without considering friction and cumulus effect on the vertical transportation of vorticity, p coordinates vorticity balance equation is that.

\[
\frac{\partial \zeta}{\partial t} = \left[ \frac{\partial \zeta}{\partial x} + \gamma \frac{\partial \zeta}{\partial y} + \frac{\partial \psi}{\partial y} \right] - \alpha - \frac{\partial}{\partial x} \left( \frac{\partial \zeta}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\partial \zeta}{\partial y} \right) - \frac{\partial}{\partial x} \left( \frac{\partial \psi}{\partial y} \right) + \frac{\partial}{\partial y} \left( \frac{\partial \psi}{\partial x} \right)
\]

Where f is Coriolis force, \( \zeta \) the relative vorticity. The left of the equation is the local variation of the relative vorticity, the first term of the right is side of advection of the absolute vorticity, the second term is the vertical advection of the relative vorticity, the third is the local variation of relative vorticity caused by divergence, and the fourth term is tilt.

During the development of the vortex on July 17th, the local change of vorticity in the whole layer shows an increasing trend, which shows two peaks at 1800UTC on 16th, located near 500hPa and 850hPa, mainly caused by vertical transportation while other items having little effect (Figure 7a1). At 0000UTC on 17th, the vertical transportation is still the main contributor for the vorticity increase, while the tilt is counteractive (Figure 7a2). At 0600UTC, in the lower troposphere, all terms except the horizontal advection have positive contribution to the increase of vorticity, in which the vertical transportation is most distinct (Figure 7a3). During 7.19 the local variation of vorticity in the vertical direction shows a single peak structure (Fig. 7b1 ~ b3). At 1200UTC on 18th, positive vorticity increases firstly near 500hPa, for which the vertical transportation and divergence terms are the main positive contributors. At 1800UTC on 18th, the whole layer vorticity increases significantly, the local variation near 650hPa is largest, reaching \( 3.9 \times 10^3 \text{s}^{-2} \), the vertical transportation is still dominant, whose variation is in accordance with analyses in 2.2, that is, the vortex firstly weaken and then strengthens, and the contribution of the divergence term to the vorticity increase is on low and middle layer. At 0000UTC on 19th, the local variation of vorticity decreases obviously. To sum up, the local variation of vorticity during two processes present this characteristics that is the peak is transported from high layer to lower layer, and the vertical transportation is main contributor to the vorticity increase, which is caused by the uneven distribution of the horizontal vorticity in the vertical direction leading by jet and strong vertical wind shear and the development of the horizontal vorticity in the vertical direction by heating up from the condensation of the latent heat during large precipitation process.

6. Conclusions

The causes on two heavy rain processes from July 16th to 19th in 2010 are analysed. It is found that the meso-scale vortex developed along the wind shear on the edge of SH is the main affect system for two processes and several conclusions are acquired as follows:

1) The interaction between the warm wet air flow on the edge of SH and the cold air spreading south benefits the formation of meso-scale vorticity; while the southward warm wet air on the edge of Typhoon in a far distance and SH provide abundant water vapor for heavy rain.

2) The strong convergence between the strong northeast flow and the SW jet on mid and low layer is beneficial for the formation and development of the vortex, and the strong southwest flow on the edge of the SH conducts vortex to move northeastward. During 7.17 process, the vortex lies mainly on the mid and low layer, while during 7.19 process, the development of the vortex is relatively complex, that is, the vortex is deep.

3) The southerly flow convergence zone in the southeast of the Sc and the east to northeast flow inflow area in the north of the cyclone are regions where the short-term heavy rain is concentrated. Accordingly, the radar data present the formation and development of the vortex rain belt during two processes. The "narrow Cold front rain belt" in its southeast is the main system
causing severe convective weather (heavy rain, tornadoes, etc.).

(4) The coupled dynamic structure between high-level divergence and low-level convergence near the mesoscale vortex is in favor of the development of vertical ascending motion, thus it is beneficial to the convergence and lifting of water vapor, and heavy rain forms. Deep vertical ascending motion will result in strong rain intensity.

(5) Energy front is the characteristics of two processes. During 7.17 the vortex forms in high energy tongue and develops on the south of the energy front, convective instability and conditional symmetric instability co-exist, convective instability is main feature of the atmosphere, and the rainfall intensity is relatively strong. During 7.19 process, the vortex forms in the south of the energy front and develops in the middle of the front, conditional symmetric instability is main feature, and it’s rainfall intensity is weak.

(6) The diagnosis of the vorticity budget show that the local variation of vorticity during two processes present the characteristics that is the peak is transported from high layer to lower layer, the vertical transportation is main contributor to the vorticity increase, and the divergence term plays a second role for the increase of local vorticity on lower troposphere.

7. References


Figure 3. Traverse route of surface mesocyclone, characters of short-time heavy rainfall and Radar reflectivity products at typical time on 17 and 19 July 2010 (UTC)

(a1 and b1 respectively represent the traverse route of surface cyclone and the distribution of the short-time heavy rainfall at 0200UTC on 17 and 2200UTC on 18; a2~4 and b2~4 are radar reflectivity products at typical time)

(green shaded area: the distribution of short-time heavy rainfall;
*black vector stream: predominant streamline on surface)
Figure 5. Thermal field structure during 7.17, 2010

a1: 850hPa horizontal wind field (shaded area: \( V \geq 12 \text{ m/s} \)) + 6σe (black solid line, the same below) at 0000UTC on 17; a2 and a3 are vertical through the distribution (along 113.5°E) respectively relative humidity (shaded area: \( RH \geq 80\% \)) + 6σe + vertical speed (red dotted line)MPV1 (shaded area: MPV1 ≤ 0) + MPV2

b1. b2. b3 are same above, just at 0600UTC, sections along the 114°E
Figure 6. Thermal field structure (the same as in Figure 5) during 7.19, 2010; a1, a2, a3 are at 1800UTC on July 18, the sections along 113° E; b1, b2, b3 are at 0000UTC on July 19, the sections along 114° E.
Figure 7 The regional averages of items in the vorticity equation on 17 July 2010 (32°−34°N, 113°−114.5°E) and on 19 July 2010 (33°−35.5°N, 112°−115°E) changes with height.
(a1: 1800UTC on 16; a2: 0000UTC on 17; a3: 0600UTC on 17;
b1: 1200UTC on 18; b2: 1800UTC on 18; b3: 0000UTC on 19)