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The Analysis of the Asymmetric Precipitation Caused by the No.10 Tropical Cyclone "Damrey" in 2012 Based on Observation and Numerical Simulation

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Abstract

The No.10 tropical cyclone "Damrey" in 2012 is the first landing typhoon on the north of the Yangtze River after 1949. After its landing, Damrey showed an obvious asymmetric structure and precipitation. Using the ERA-interim reanalysis data from the European Centre for Medium-Range Weather Forecasting (ECMWF), the study simulated the whole process of Damrey from pre-landing to extinct by using WRF model. Based on the model result and FY-2E satellite data and observation data, the study analysis the causes of the asymmetric structure of Damrey. It is found that the descending motion is strong on the west and south sides of the typhoon, they blocked the southwest water vapor transport. So the development of convective cloud system was hindered, and the wind shear on the west and south sides on the typhoon was stronger than on the east and north. It caused the result of the precipitation on the east and north sides of typhoon much more than on the west and south. Q-vector, upper level jets and other factors are also analyzed in this study.

Keywords

Typhoon Damrey, Asymmetric Structure, Q-Vector, WRF Model

1. Introduction

Tropical cyclones (TC) are mainly generated on the ocean surface of tropical low-latitude regions. When tropical cyclones land in coastal areas of my country, severe winds, heavy rains, storm surges and other disasters often occur, causing economic losses to affected areas, hindering economic development and even

Threats to shipping safety and people's lives. There are mainly three moving paths of tropical cyclones that have a greater impact on the coastal areas and even inland areas of my country: northward path, northwest path and westward path (Zhu et al., 2007). Among them, tropical cyclones with a northward path will affect the northern coastal areas of my country (Zhou et al., 2007). They are located in the north of the Yangtze River in the middle latitudes. Although the frequency of typhoons affected by typhoons is much lower than the frequency of typhoons in the coastal areas of South China and East China, after 2000, the frequency has risen. During the 64 years from 1949 to 2012, a total of 17 typhoons made landfall, including those that transformed into extratropical cyclones after landfall, and entered the Bohai Sea north of 37˚N. Among them, there were 5 typhoons after 2000. Asymmetry is one of the characteristics of tropical cyclone circulation precipitation, especially after a tropical cyclone makes landfall (Chen & Meng, 2001). The reasons for the asymmetric precipitation distribution after typhoon landfall are quite complicated. According to the research of many scholars (Rogers et al., 2003), the distribution of typhoon asymmetric net water drop area and the appearance of asymmetric structure include topography, changes in the properties of the underlying surface during the landing period, the movement of the typhoon, and the interaction between the typhoon and the surrounding airflow. And other factors. The research results of many scholars (Cangialosi, 2004) show that the intensity and distribution of typhoon rainfall will be significantly changed due to mechanisms such as surface friction and terrain uplift. In addition to the influence of changes in the underlying surface, the influence of factors such as atmospheric environmental fields cannot be ignored. The asymmetric structure formed by the typhoon will bring challenges to the forecast of heavy rain and strong winds, and also increase the uncertainty of the forecast. Therefore, the key to establishing the idea of rainstorm and gale forecast is to study which factors cause the structural changes of typhoons. Many experts and scholars (Tao et al., 1994; Yuan et al., 2009; Lv et al., 2009; Zhu et al., 2010; Zhou et al., 2011) have done certain analysis and research on the asymmetric structure and characteristics of landfall typhoons in East China and South my country, as well as the causes, and have achieved some results. The number of typhoons that make landfall in the northern coastal areas of the north is less, so there are fewer studies of such typhoons. Chen & Ding (1979) and Zhang et al. (1975) found through statistical analysis that the speed of typhoons tends to increase after landing on the southeast coast of my country. Wei et al. (2003) concluded that when the main precipitation area is located on the right (left) side of the typhoon's advancing direction, it will accelerate (decelerate) the typhoon's movement and promote the occurrence of heavy precipitation. Li et al. (2017) and Shi et al. (2017) analyzed long-distance precipitation caused by typhoons and similar typhoon paths. Qian et al. (2010) analyzed the distribution characteristics of typhoon precipitation, and discussed the relationship between the variation of typhoon structure and the occurrence of heavy rain. He et al.

(2006) concluded after analyzing the 2005 No. 9 typhoon "Masha" that the asymmetric distribution of the thermal field and the typhoon circulation field after the typhoon landed was the key to the asymmetric distribution of the rainstorm area, and the 500 hPa etc. The strong upward movement of the pressure surface often causes torrential rain in this area. Di et al. (2008) simulated and analyzed through numerical models and concluded that the intrusion of cold air at the bottom is the key factor leading to the structural change of "Masha". Wang et al. (2007) explained the relationship between the asymmetric distribution of the rainstorm area of typhoon "Masha" and the asymmetric structure of the cloud system, the unconventional distribution of thermal field, water vapor condition and dynamic field near the typhoon center, and the intrusion of cold air relation. Earlier scholars (Merrill, 1988; Demaria, 1996; Frank & Ritchie, 2001) found that vertical wind shear has a great impact on the occurrence and development of tropical cyclones, the distribution of typhoon precipitation and the distribution of vertical velocity near the typhoon center. Each typhoon is different, and the precipitation area after landfall is also different. Therefore, it is necessary to analyze each typhoon in depth to find out the similarities and differences, in order to contribute to the forecast of typhoon precipitation.

After typhoon Damrey made landfall in the coastal areas of northern Jiangsu on August 2nd, 2012, its moving speed was greatly reduced, especially on August 3rd, Damrey moved slowly in Shandong for a period of time, almost at The stagnant state, the asymmetric structure of the typhoon and the slow moving speed have brought a huge impact on Shandong. The torrential rain and strong wind brought by Typhoon Damrey caused serious losses to Shandong's fishery, forestry, and agricultural production, and the affected population in the province reached more than 6 million (Shi et al., 2014).

This study uses the European Centre for Medium-Range Weather Forecast (ECMWF) ERA-interim reanalysis data and the FY-2E satellite data to analyze in detail the asymmetric structure characteristics and causes of Damrey after the landfall. Based on the observational facts, the wind and rain distribution characteristics of the typhoon after landfall were revealed, and the asymmetry of the typhoon Damrey was analyzed from the aspects of circulation background, mesoscale structure, water vapor transport, vertical velocity, vertical wind shear, and Q-vector divergence. The structure is analyzed, hoping to provide a reference for the forecast of typhoon rainstorms and typhoon movement in the middle and high latitudes in the future, landing and going north to the north of the Yangtze River to the northeast of North China.

2. Data and Methods

2.1. Data

The observation data used in this study are the reanalysis data (ERA-interim) of the European Centre for Medium-Range Weather Forecasts (ECMWF) from August 2 to August 4, 2012, with a spatial resolution of 1.5˚ × 1.5˚ and a temporal resolution of 6 hours. The IR1 infrared channel cloud image, water vapor image, visible light cloud image and color composite image of the FY-2E satellite from August 2 to 3, 2012. The time used in this article is Beijing time.

2.2. WRF Model Brief

The WRF (Weather Research Forecast) model system is a new generation of mesoscale forecast models and assimilation systems jointly developed by the meteorological community in the United States. The WRF model is a fully compressible, nonhydrostatic model (with a hydrostatic option). Its vertical coordinate is a terrain-following hydrostatic pressure coordinate. The grid staggering is the Arakawa C-grid. The model uses the Runge-Kutta 2nd and 3rd order time integration schemes and 2nd to 6th order advection schemes in both horizontal and vertical directions. It uses a time-split small step for acoustic and gravity-wave modes. The dynamics conserves scalar variables.

3. Results and Analysis

3.1. Case Brief

Typhoon Damrey formed in the higher latitudes of the Northwest Pacific Ocean at 20:00 on July 28, 2012, and then moved to the northwest. At 08:00 on July 31, Damrey strengthened into a severe tropical storm. At 02:00 on August 1, it intensified into a typhoon. At 21:30 on August 2, Damrey landed on the coast of Chenjiagang Town, Xiangshui County, Jiangsu Province. At the time of landing, the central pressure of the typhoon was 965 hPa, and the maximum wind speed in the center was 35 m/s. After landing, Damrey moved northwestwards into Shandong Province. On August 3, Damrey moved slowly in Shandong, and its intensity weakened to a tropical storm. At 06:00 on the 3rd, Damrey was still in Shandong, and the direction of movement turned to the northeast. At 18:00 on the 3rd, Damrey moved to the northeast and entered the Bohai Sea. The intensity quickly weakened to a tropical depression, and died in the Bohai Sea.

After Damrey made landfall, from 20:00 on August 2 to 08:00 on August 4, heavy rains to heavy rains occurred in areas such as central and eastern Shandong, northeastern Hebei, and central and southern Liaoning, which are located on the east and north sides of the typhoon center. In the Shandong region, there are 119 observation stations with precipitation exceeding 100 mm, and the largest precipitation occurred at Shatou Station in Binzhou, with a precipitation of 288.8 mm. **Figure 1** shows the path and process rainfall of this typhoon Damrey (statistical time: from 17:00 on August 2, 2012 to 17:00 on August 3, 2012).

It can be seen from the wind field after Damrey landed (**Figure 2**) that there are obvious cyclonic circulations on the isobaric surfaces of 500 hPa and 850 hPa, and the wind speed on the east and north sides of the cyclone center is significantly higher than that on the west and south sides of the center. It shows obvious asymmetric distribution characteristics. The strong winds on the east and north sides brought sufficient water vapor to the cyclone, and at the same

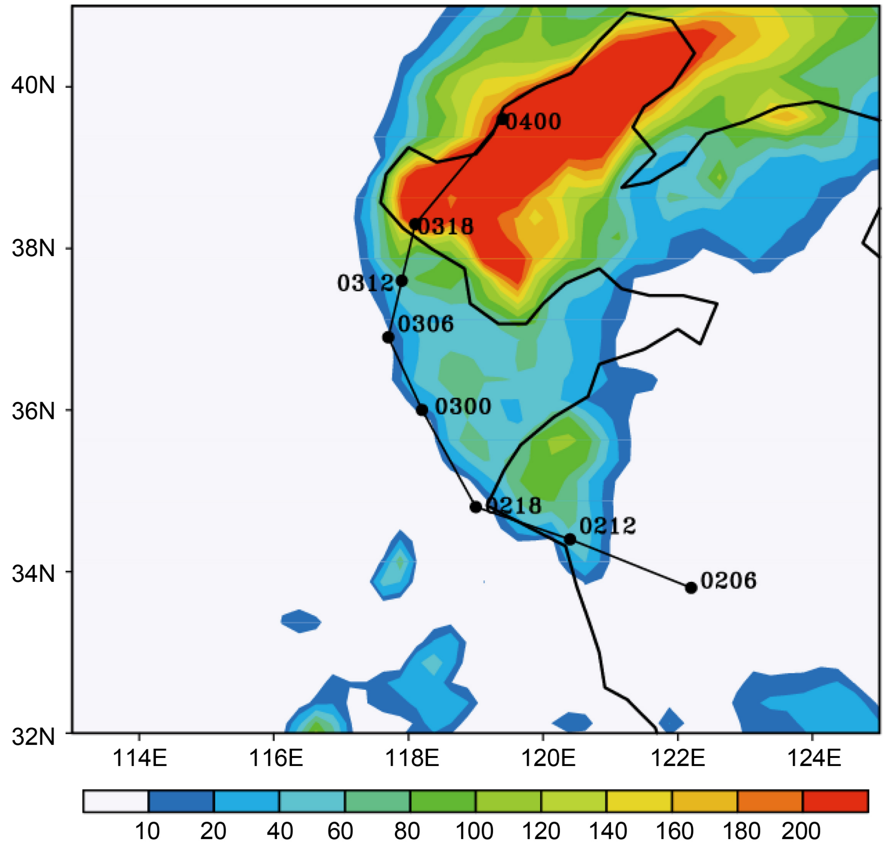

Figure 1. The movement path and process rainfall of Typhoon Damrey. (The black line represents the moving path of the typhoon, "0206" represents 06:00 on August 2nd, 2012, and so on; the shadow represents the process rainfall).

time, it could lead to the enhancement of instability and promote the accumulation and release of unstable energy, which had an important impact on the occurrence of heavy precipitation on the east and north sides of the typhoon.

The typhoon Damrey is characterized by its small scale (with a radius of less than 200 km), high latitude of formation, and slow movement in Shandong. At the same time, Typhoon Sula (No. 1209) in low latitudes made landfall in Fujian Province at almost the same time. The most notable feature of typhoon Damrey is the asymmetric precipitation of the typhoon. The main precipitation area of the typhoon appears on the right side of the typhoon's moving path, northeast of the typhoon center.

3.2. Circulation Characteristics

Before Typhoon Damrey made landfall, while moving to the northwest, the 588 dagpm line on the 500 hPa isobaric surface of the western Pacific subtropical high kept moving little. Southeastern block distribution. Typhoon Damrey is on the periphery of the subtropical high and moves along the edge of the subtropical high. After the typhoon Damrey made landfall on the night of August 2, the subtropical high retreated significantly to the east, and at the same time, the typhoon trough at 850 hPa deepened significantly.

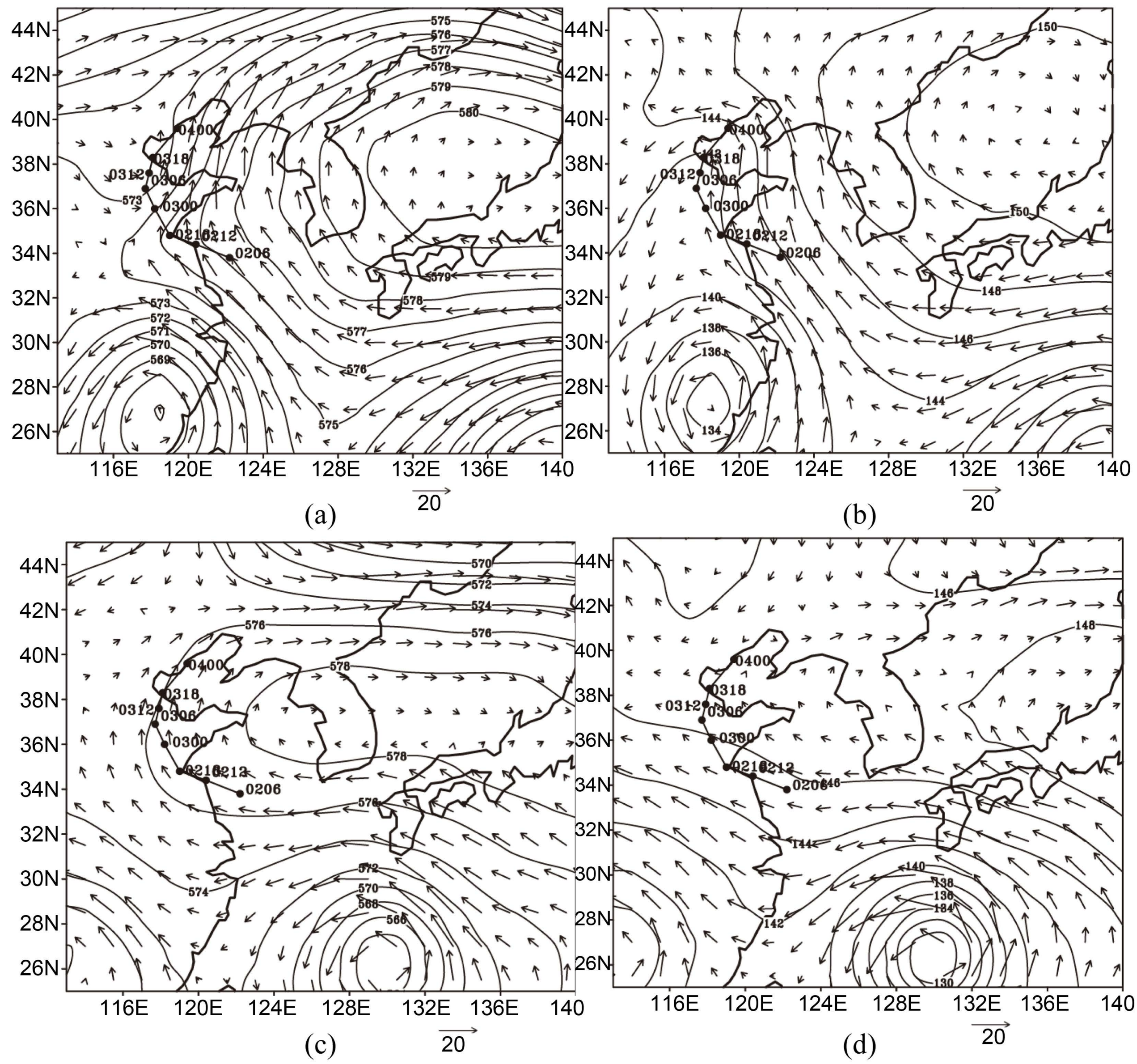

Figure 2. Wind field and height field. ((a). 06:00 on August 3, 2012 500 hPa; (b). 06:00 on August 3, 2012, 850 hPa; (c). 18:00 on August 4, 2012, 500 hPa; (d). 18:00 on August 4, 2012, 850 hPa).

At 06:00 on August 3rd, typhoon Damrey moved to Shandong, and the 588 dagpm line at 500 hPa was still located in the east of Shandong Peninsula. At the same time, there is a shallow trough in the westerly belt at 500 hPa in the Hetao area. The cold air brought by the westerly belt has not yet affected the typhoon circulation. There is no obvious temperature gradient in the Shandong area. At this time, the baroclinicity at 500 hPa in the Shandong Peninsula is not strong. However, at 850 hPa, the typhoon is still in the south of the ridge line of the subtropical high, but a clear temperature gradient has appeared, indicating that the bottom layer has cold air intrusion, and the typhoon will begin to degenerate in the future. At the same time, there is an obvious low-level jet in the eastern coastal area of China. From the eastern coastal area of China to the central

Shandong area, the wind speed of 850 hPa is above 14 m/s. This jet provides a rich source of water vapor for Shandong. On August 4th, Typhoon Damrey left Shandong and gradually weakened, and the subtropical high obviously strengthened its westward extension. At 18:00 on the 4th, the deputy high regained control of Shandong, extending to the east and west of the mountain.

3.3. Vertical Motion Distributions

By analyzing the asymmetric structure of Damrey and the vertical movement around Damrey, we can better understand the causes of the asymmetric wind and rain distribution after Damrey landed.

From 12:00 on August 2, 2012 to 18:00 on August 3, 2012, the Q-vector divergence field of the 400 - 200 hPa pressure layer (**Figure 3**) can be found that obvious asymmetric structures can be seen on both sides of the path of typhoon Damrey. At 12:00 on the 2nd, typhoon Damrey was on the ocean in eastern Jiangsu, my country. At this time, there was a weak convergence area of Q-vector between the junction of Shandong Province and Hebei Province in the northwest of the typhoon to the southwestern Bohai Sea and the Shandong

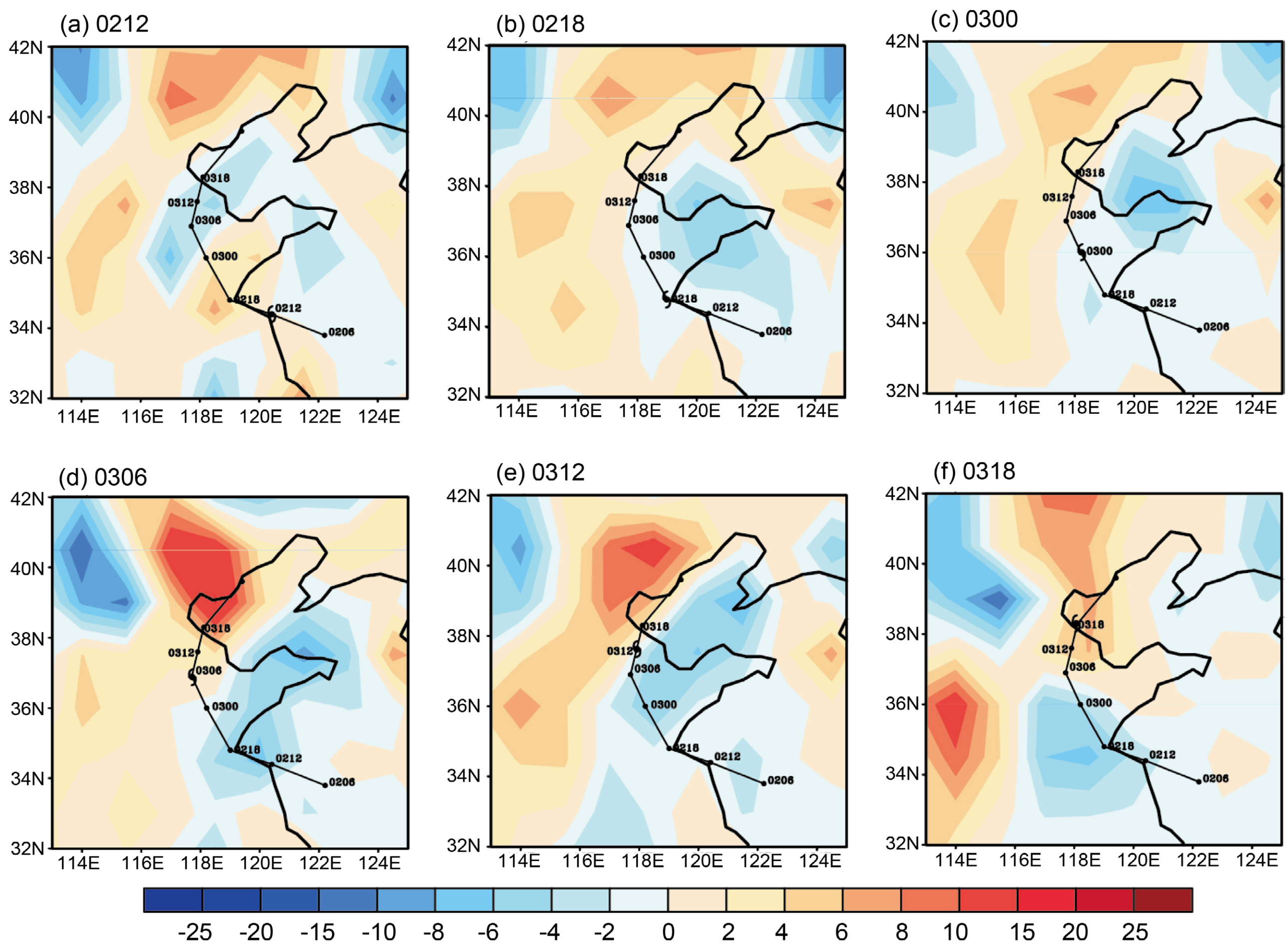

Figure 3. The Q-vector divergence field at 400 - 200 hPa from 12:00 on August 2nd to 18:00 on August 3rd, 2012. (The black line represents the typhoon path, the shading represents the Q-vector divergence).

Peninsula in the northeast. On the west side of the typhoon, there is a divergence area of the Q-vector in the western part of Shandong and the northeastern part of Henan.

At 18:00 on the 2nd, the Q-vector convergence area in the northwest of the typhoon disappeared and turned into a Q-vector divergence area. The Q-vector convergence area in the northeast direction expanded while the intensity increased. At this time, the western side of the typhoon was completely transformed into a Q-vector. In the divergence area, the sea areas around Shandong, East Shandong and Shandong Peninsula are controlled by the convergence area of Q-vector, and the intensity of the convergence area of Q-vector is slightly larger than that of the divergence area. At 06:00 on the 3rd, the strong center of Q-vector divergence appeared in the northwest to north direction of the typhoon, and the intensity of the Q-vector convergence area on the east side of the typhoon increased slightly, and the southward development affected northern Jiangsu and Anhui. At 12:00 on the 3rd, the intensity of the Q-vector divergence zone and the convergence zone both weakened and the range was reduced. By 18:00 on the 3rd, the area near the typhoon was completely controlled by the divergence area of the Q-vector, and the convergence area of the Q-vector moved out of Shandong and moved to the northern part of the three provinces of Henan, Anhui, and Jiangsu.

Looking back at the whole process, it can be found that from 12:00 on the 2nd day before the landfall of typhoon Damrey until it weakened into a tropical depression, there has always been asymmetric distribution of the Q-vector on both sides of the typhoon, and there has always been a convergence area of the Q-vector on the east side of the typhoon. There is always a Q-vector divergence zone on the west side of the typhoon, that is, there is always upward movement on the east side of the typhoon, and there is always a sinking movement on the west side of the typhoon. The forcing effect of the Q-vector, which stimulates the upward movement, is an important factor leading to the asymmetric distribution of typhoon precipitation.

3.4. Upper Jet Stream

From the 200 hPa isobaric wind field from 12:00 on August 2, 2012 to 18:00 on August 3rd, 2012 (**Figure 4**), it can be found that the 200 hPa isobaric surface is 8 - 10 latitudes north of typhoon Damrey in northeastern my country. There is an obvious high-altitude jet area on the upper. Typhoon Damrey is always on the right side of the 200 hPa high-altitude jet inlet area. On the right side of the high-altitude jet, the air at the edge of the high-altitude jet accelerates due to friction, resulting in cyclonic curvature. The upper-level divergence enhances the lower-level ascending movement and makes the convective movement in Shandong more vigorous.

At 12:00 on the 2nd, the 200 hPa isobaric jet was in a southwest-northeast trend. From 12:00 on the 2nd to 18:00 on the 3rd, the 200 hPa high-altitude jet

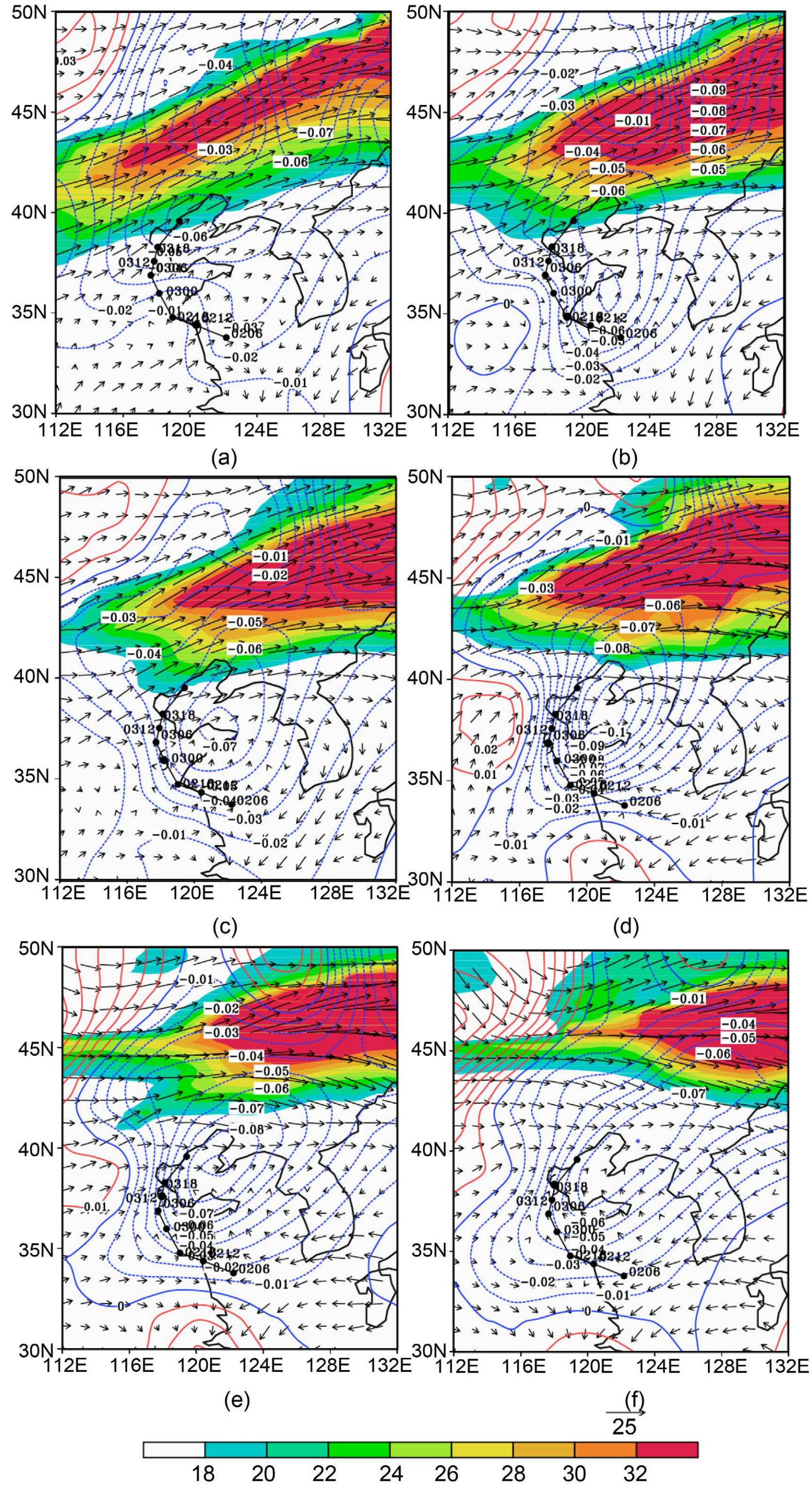

Figure 4. The 200 hPa wind field from 12:00 on August 2nd to 18:00 on August 3rd, ω and typhoon path calculated by the Q-vector. (Panel a is at 12:00 on the 2nd, and b is at 18:00 on the 2nd. By analogy, f is 18:00 on the 3rd. The shaded area represents the 200 hPa jet stream, the black line represents the typhoon path, the dashed contour line represents the vertical velocity ω (unit: Pa/s) calculated by the Q-vector, and the arrow represents the Q-vector).

moved to the northeast, from the southwest-northeast trend to a west-to-east jet, and its intensity Significantly intensified, and the maximum wind area increased significantly. From 18:00 on the 2nd, the width of the jet stream axis increased from about 1 latitude at 12:00 on the 2nd to about 3rd latitude, and the width of the jet stream axis remained until 18:00 on the 3rd. The east side of the typhoon center is always on the right side of the 200 hPa high-altitude jet inlet area, and the suction effect of high-altitude divergence provides favorable strengthening and maintaining conditions for the convergence and upward movement of the low-level.

Combining with the vertical velocity of the inverse calculation of the Q-vector, it can be found that there is always an upward motion center on the right side of the jet stream inlet area, on the east side of the typhoon path, and near the Bohai Sea. On the other hand, the west side of the typhoon track is always located at the rear of the high-altitude jet inlet area, with little divergence, weak upward movement, and even a sinking movement center.

Combined with the analysis of Q-vector divergence, high-altitude jet and vertical motion, it can be found that the Q-vector divergence accurately reflects the distribution of vertical motion. The asymmetric distribution of vertical motion is one of the important reasons for the asymmetric precipitation of typhoon Damrey.

3.5. Water Vapor Transports

After typhoon Damrey landed and affected Shandong, another typhoon "Sura" existed in the south of the Yangtze River in my country at the same time, which created a very stable water vapor transport channel in eastern my country. From the water vapor flux divergence at 06:00 and 18:00 on August 3, 2012 (Figure 5),

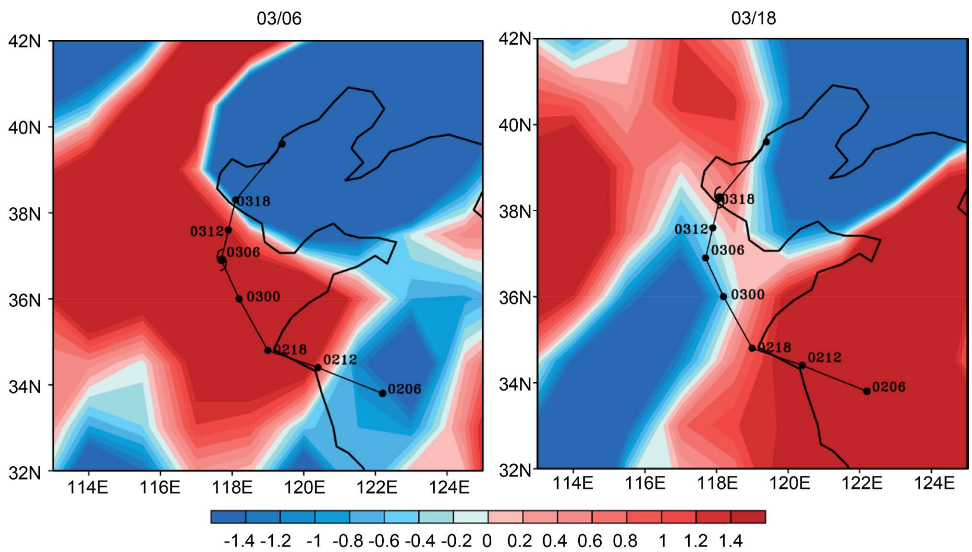

Figure 5. The water vapor flux divergence of the whole layer (1000 hPa - 100 hPa) at 06:00 and 18:00 on August 3, 2012. (The black line represents the actual observed typhoon path; the shading represents the water vapor flux divergence, in the unit of 10^{-5} g/s·m^2·hPa).

it can be found that there was a water vapor convergence near typhoon Damrey, and the water vapor convergence at 06:00 was higher than that at 18:00. Stronger strength and greater range.

Water vapor is an important factor to promote the development of typhoons, maintain the structure of typhoons, and cause typhoon precipitation. Through the FY-2E water vapor map (omitted), we can intuitively understand the water vapor transport and its changes in the periphery of typhoon Damrey, and we can also understand the cause of the asymmetric structure of Damrey from another perspective.

Based on the above analysis, it can be found that while the cloud system on the north side of the Damrey's center is developing vigorously, the water vapor supply to the west and south of the typhoon center is cut off, resulting in the formation of the Damrey's asymmetric structure.

4. Conclusions and Discussion

The No. 10 typhoon Damrey in 2012 is a tropical cyclone with small scale, high intensity, high latitude, and relatively complete structure. The most prominent feature of typhoon Damrey is that the precipitation is distributed asymmetrically from east to west after landfall. The scale and intensity of precipitation on the east side are much larger than those on the west side of the typhoon track.

Through the analysis and study of satellite cloud images, satellite water vapor images, WRF model simulation, Q-vector and observation data, the reasons for the asymmetric precipitation after the landfall of Damrey can be summarized as follows.

The model successfully simulated the entire process of typhoon Damrey from before landfall to its demise, and simulated the typhoon path well. The simulated cyclone path and central pressure changes were in good agreement with the actual observation data. The simulated precipitation distribution and precipitation intensity are in good agreement with the actual observations. The simulation results also well reflect the asymmetric structure and asymmetric precipitation distribution of this process.

Through the analysis of the weather situation, after the typhoon made landfall, the 588 dagpm line on the 500 hPa isobaric surface has been maintained near Japan Island, and the short-wave trough in the Hetao area transported cold air to the lower layers of the typhoon area. At the same time, the east side of the typhoon center is always located on the right side of the entrance area of the low-altitude and high-altitude jets, and the convergence and upward movement are strong. The vertical wind shear on the east and north sides of the typhoon is small, and there is always a large value area of wind shear on the west side of the typhoon produce. From the vertical velocity map, it can be found that there is a large-scale sinking motion on the west side of the typhoon center, while the sinking motion on the east side of the typhoon center is located in the middle layer and has a small range. And the range of this deep ascending motion extends from 2 to 4 longitude. From extent to intensity, the rising motion east of the typhoon center was more intense than that west of the center.

Judging from the distribution of Q-vector divergence, from before the landfall of Damrey to its demise, the east side of the typhoon center was always the Q-vector divergence convergence area. Due to the forcing effect of the Q-vector, the development and maintenance of the upward movement were stimulated. The west side of the typhoon is always controlled by the divergence area of the Q-vector divergence, and the sinking motion is obvious. The Q-vector convergence area remained near Shandong until the typhoon died out.

Based on the above analysis, the cause of the asymmetric precipitation of typhoon Damrey and the process of generating the asymmetric structure can be obtained.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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