A Numerical Simulation Study of Typhoon Rananim(0414)*

YU Zhenshou[1](余贞寿), XU Wenming[2](徐文明), JI Chunxiao[3](冀春晓), ZHAO Fang[1](赵 放), and LOU Liyin[1](楼丽银)

1 *Wenzhou Meteorological Bureau, Wenzhou* 325003

2 *Meteorological Observatory of He'nan Province, Zhengzhou* 450003

3 *Zhejiang Research Institute of Marine Meteorology, Hangzhou* 310002

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ABSTRACT

Using the high-resolution non-hydrostatic model ARPS (Advanced Regional Prediction System), the Typhoon Rananim (0414) was simulated by using the CINRAD Doppler radar data. The results before and after typhoon landfall show that model ARPS performs well to simulate the track, the variation of center pressure, as well as severe heavy rain of Rananim. Meanwhile, the simulated composite reflectivity was compared with the observed radar composite reflectivity. The numerical results reveal that the asymmetrical structure of Rananim plays an important role in its westward deflecting after landfall. The sensitivity simulation experiments of terrain effects on Rananim (0414) were also investigated, and the terrain of the southeastern China has important effects on Rananim turning right slightly of its track and increasing its intensity obviously, but when typhoon is far away from the coastline, the terrain only impacts slightly on the storm intensity during its landfall. The results show that topographic lifting contributes greatly to precipitation enhancement, and makes the distribution of precipitation more uneven.

Key words: ARPS, numerical simulation, Typhoon Rananim, heavy rain, terrain

1. Introduction

Rananim was originated at the night of August 8, 2004 over the ocean northeast of Luzon Island of the Philippines, and then deepened into a typhoon at 18:00 BT 10 August, when its center lay at 22.8°N, 126.9°E, with maximum winds of scale 12 near the center. It landed at 20:00 BT 12 August in Shitang Town of Wenling City in Zhejiang Province, with maximum winds over scale 12 near the center, moving westward through the south of Taizhou, the north of Wenzhou, and the north of Lishui in Zhejiang Province. At 21:00 BT 12 August, its center lay at 28.8°N, 119.2°E, with maximum winds of scale 11 near the center, then it weakened into a tropical storm in the wee hours of August 13, at 08:00 BT, its center lay in Quzhou City of Zhejiang Province with maximum winds of scale 9, and it weakened into a tropical depression by 18:00 BT 13 August.

Coming like a hundred of bricks, with large intensity and big destructive power, Rananim is the strongest typhoon landing in Zhejiang since 1956, veering westward obviously after landfall, bringing large amount of rainfall which distributes unevenly. For example, the rainfall is 916 mm at Feitou Station in Yueqing, 200-250 mm in coastal plain, and over 350 mm in hilly land, which has a relation with topography. Chen et al. (2002) have done numerical experimental research using the quasi-geostrophic barotropic vorticity equation model with topography and pointed out that topography can make typhoon turn westward. Much of work on the influences of Taiwan's terrain on typhoon has been done by Chinese scholars. Meng et al. (1998) and Luo and Chen (1995) thought that the terrain is one of the possible reasons that cause typhoon pathway's deflecting. Yang et al. (1996) simulated the complex changes when Typhoon Dot (No.9017) passed Taiwan Island using TCM-90 data and numerical method, and analyzed its reason and mechanism. By numerical research, Yang et al. (1996) proposed that the anomalous pathway of Typhoon Dot is the result of the development of Taiwan terrain-induced

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depression. Zheng et al. (1996) did numerical research for the enhancing influences of the coastal terrain in the southeast of China on typhoon (No.9017) rainstorm. Wang (1998) examined the influence of Taiwan terrain on typhoon (No.9608) rainstorm and indicated that the terrain of Taiwan hills made the cyclonic circulation in the southeast of the typhoon center converge and rise, thus enhancing the rainstorm by about six times. Chen et al. (2004) summarized the research for the landing tropical cyclones and pointed out that the forcing effect of the land mountains will increase the rainfall in the north of the center of typhoon landing in East China and will place the large-scale rain area mainly in the north of the center, making the asymmetric distribution of the rain area and rainfall in the south and north of the center. Niu et al. (2005) studied the influences of the terrain on typhoon (No.0216) precipitation and pointed out that topography effect makes rainfall increase in windside and decrease in leeside.

The terrain in the south of Zhejiang Province and north of Fujian Province is complex, and the range of the mountains there is similar to that in Taiwan Island, i.e., NE-SW oriented. What influence will the terrain impose on typhoon (No.0414)? This study plans to simulate the track and the distribution of wind and rainfall of typhoon first, and then performs sensitivity experiments on topography influences of the terrain in south of Zhejiang and north of Fujian on the track, intensity, and precipitation of Rananim.

2. Description of the model and simulation scheme

The model ARPS (Advanced Regional Prediction System) is a high-resolution non-hydrostatic regional forecasting system exploited by Center for Analysis and Prediction of Storms (CAPS) in American Oklahoma University (Xue et al., 1995). The ARPS is very suitable to the weather system on small scales ranging from regional-scales down to microscales (Xue et al., 2003), using the generalized terrain-following coordinate, Arakawa-C horizontal cross grid, and second-order leapfrog time integral scheme, including cloud microphysics, subgrid scale turbulence, and so on. It mainly consists of ARPSTRN, ARPSSFC, EXT2ARPS, ADAS, ARPS, ARPSPLT, etc. The ARPS Data Analysis System (ADAS) performs objective analysis by inputting the background, surface and rawinsonde observations, modifies the horizontal wind field, relative humidity field, and microphysical water vapor parameter field by ingesting radar and satellite data, starts up the complex cloud analysis model, and finally forms the initial field with high quality in dynamical harmony.

The regional center of the model lies at 28.0°N, 120.5°E, using two-way nested grid mesh. The horizontal grid sizes are 36 km and 12 km, respectively. The dimensions (x, y) are 121×121, and there are 121 meridional grids and 121 zonal grids, 35 layers in vertical, vertical resolution is 400 m, time integral step length is 18 seconds, and terrain resolution is 30″ (about 1 km), coming from EROS data center. Convective parameter scheme is Kain-Fritsch scheme, using explicit large-scale condensation dealing, boundary layer parameter scheme is Blackadar scheme, and lateral boundary is using the alterable time scheme including radiation.

The initial and lateral fields are $1° \times 1°$ AVN grid data from NCEP, with 6-h interval. The surface and rawinsonde observations, basic reflectivity from Wenzhou Doppler radar data, and radial wind speed are introduced into the model using ADAS system. The model starts to integrate from 00:00 UTC 12 August, then basic reflectivity from Wenzhou Doppler radar data and radial wind speed are introduced into the model to form new initial and lateral data using ADAS system, and next it integrates again for 30 h in total. The scanning area of the radar is that, azimuth from 0° to 360°, elevation from 0.5° to 19.5°, range is 230 km and resolution is 1 km. At last, the model results in the 12-km area studied in this paper are analyzed.

3. Analysis of the numerical simulated results

3.1 *The numerical simulation and tests of the track of Typhoon Rananim* (0414)

The track of typhoon is the key problem in typhoon prediction, since it is the basis of exact forecast

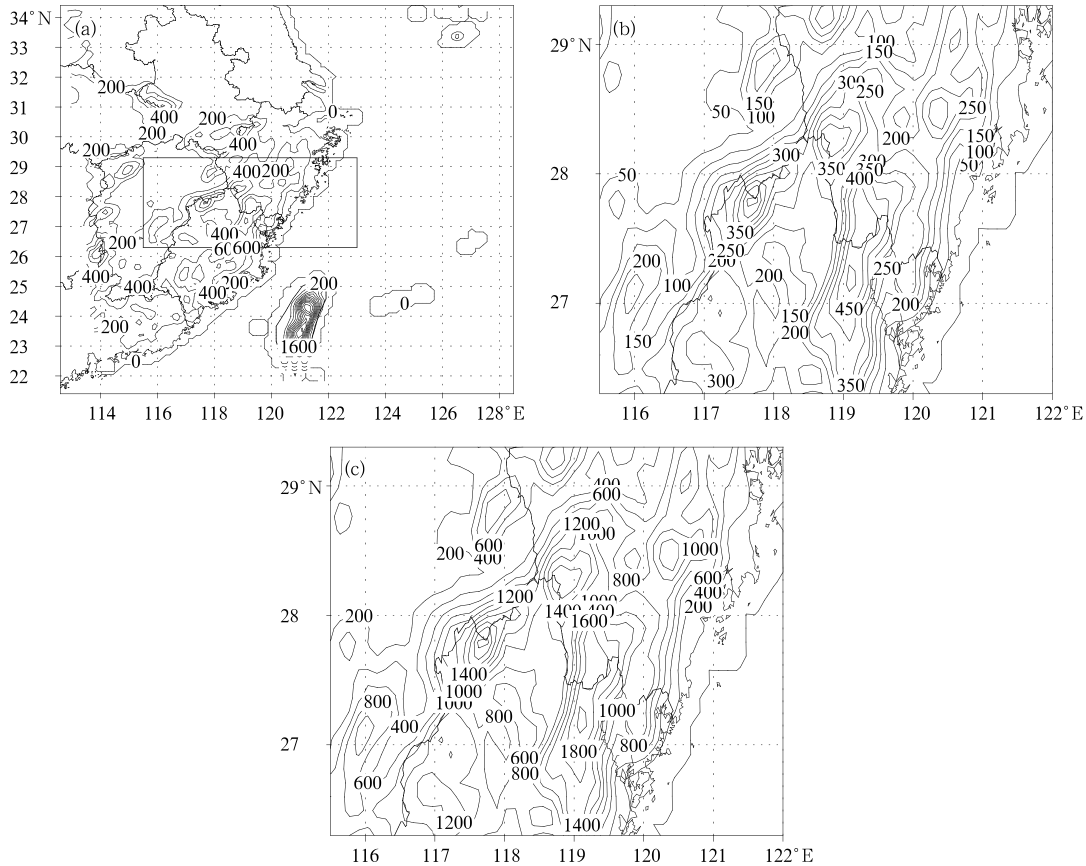

Fig.1. The domain and terrain of model tests for (a) the normal terrain, (b) the terrain of half terrain test (HT), and (c) the terrain of double terrain test (DT).

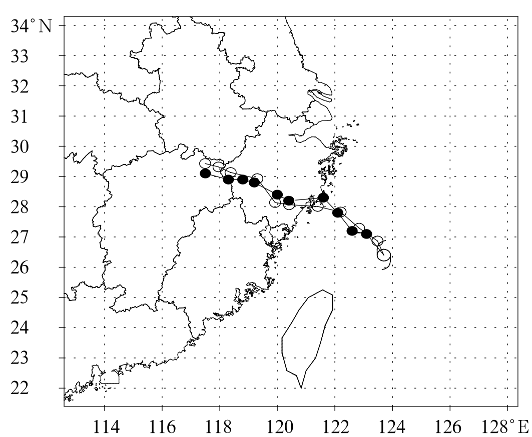

Fig.2. The simulated (blank circle) and observed (soild circle) tracks of Typhoon Rananim from NMC.

for typhoon rainstorm and gale wind. Figure 2 shows ARPS-simulated track for Typhoon Rananim (0414) and the objective location from NMC (National Meteorological Center). The simulated center position in the model is determined by the cyclonic center of the whole layer-averaged stream field. By comparing the simulated and objective results, it is known that the landing place is a little further south to the actual, but is very near to the objective one. The ARPS can simulate the westward veering after landfall in Yuhuan in Taizhou. After landfall, typhoon first shifts westward obviously, northwestward 6 h later, and west-northwestward. Compared with the track during 24 h after landing, the simulated track is very similar to it, and the maximum distance anomaly is about 50 km. Therefore, the ARPS model is successful in simulating the track of Typhoon Rananim (0414) in this paper.

3.2 *The numerical simulation and tests of the intensity of Typhoon Rananim* (0414)

The forecast of the pressure intensity in typhoon center is also of great importance, for it can be referred to as wind forecast. Figure 3 depicts the ARPS

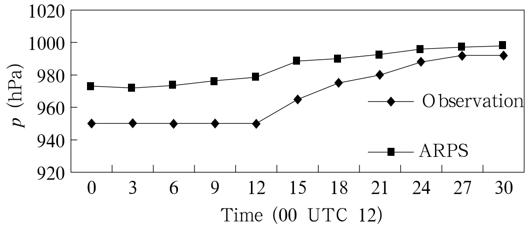

Fig.3. The simulated (dark square) and observed (dark rhomb) center intensity variations of Typhoon Ranamin.

simulated central pressure intensity variation and the actual observation from the NMC of Beijing. The simulated intensity variation is a little smaller before landfall, and the central pressure intensity weakens immediately after landfall, which is in agreement with the actual observation. But the simulation results before and after landfall are both weaker, which is related to the circumference condition that there is no human intervention in the experiment, i.e., the initial typhoon center position and central pressure have been corrected to the initial field, by means of Bogus technique. In sum, the ARPS is successful in simulating the variation of typhoon intensity.

3.3 *The numerical simulation and tests of the rainfall of Typhoon Rananim* (0414)

Figure 4 shows the simulated rainfall field every 6 h and the actual one in the corresponding time period. The rainfall center moves with typhoon, varies when the intensity changes, lies along the track or in the left and front of the typhoon every time period, and rainstorm falls in the northwest quadrant of the typhoon. For 0-6-h simulation (Fig.4a), typhoon center lies over sea, without heavy rain, and the maximum rainfall is merely 40 mm. For 6-12 h (Fig.4c), the area and intensity of rainfall over land increase gradually, when typhoon moves northwestward. In the simulated figure, the eye is clear, so is the spiral rain belt. There is a cyclonic eddy in the northwest quadrant, and a the heavy rain center in the southeast of Taizhou and in the north of Wenzhou which is similar to the actual observation, and the axis of rainfall distribution is corresponding to the terrain. For 12-18 h (Fig.4e), when typhoon landed for just a moment, it moves westward, its rainfall enhances, the center of the spiral belt moves onto the ground, and the heavy rain center in the southeast of Taizhou and in the north of Wenzhou enhances further. As typhoon moves westwards, the rain belt begins to expand to the southwest, and heavy rain centers appear in the southwest hills of Wenzhou, the south of Lishui, and the north of Fujian. Further contrast analysis indicates that the main rainfall time period of the rainstorm is in 6-18 h, when typhoon lands, bringing abundant water vapor, together with the interaction of terrain, land process and other factors, thus the rainfall intensity is very strong, and the precipitation time period is concentrated. The formation of the heavy rain center in the middle and southwest of Zhejiang is mainly contributed to this time period. The model simulated the intensity and position of precipitation during this period. For 18-24 h (Fig.4g), typhoon turns from westward to WNWward, and the precipitation in typhoon center is still obvious, although typhoon begins to weaken, and the spiral rain belt becomes asymmetric due to the influence from the underlying surface. For 24-30 h (Fig. 4i), because typhoon moves far away from the coastline and lasts for a long time, it fills up to reduce to a low depression, rainfall reduced obviously, but a heavy rain center still generates in the northeast of Fujian, the simulated center location is east to the actual observation and intensity smaller than the actual. In sum, the ARPS succeeded in simulating the characteristics of this typhoon precipitation process. That is to say, not only the simulated heavy rain center locations and the intensity are in accordance with the actual observation, but also the structural characteristics of the whole typhoon rain belt are simulated very well.

3.4 *The simulation and tests of the echo of typhoon*

Zhu et al. (2002a, b) pointed out that the distribution of surface weather stations and rainfall stations is uneven, in the meantime, there is a representative problem in the rainfall data, and thus the above problems affect the test of the simulated results. Radar data have even distribution characteristics, and its spatial resolution is higher than that of surface station, near to that of the mesoscale model. Therefore, using radar data as the standard of the test can avoid

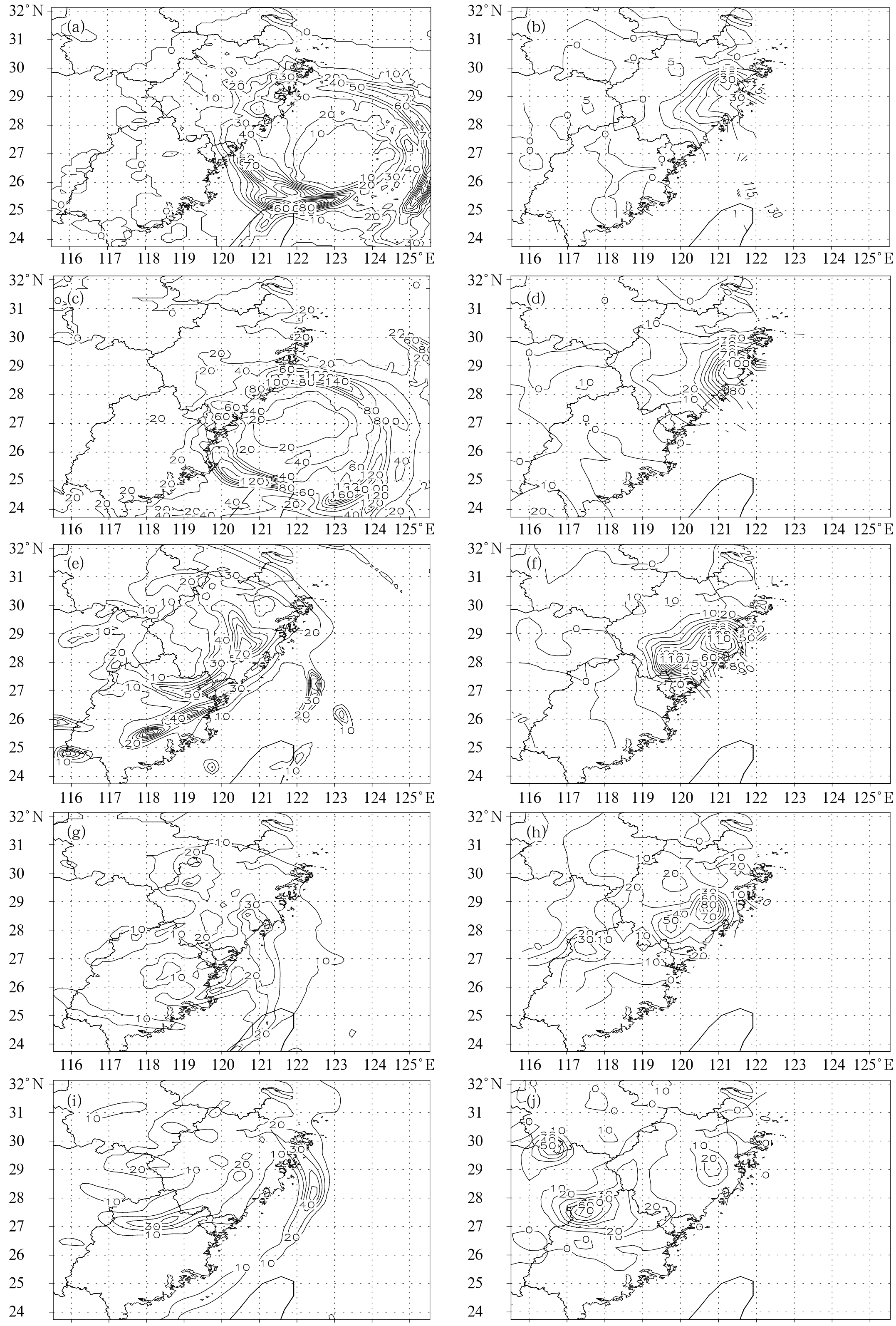

Fig.4. The 6-h accumulated precipitation simulated by the ARPS model (a, c, e, g, and i) and observed rainfall (b, d, f, h, and j) for (a), (b) 0-6 h; (c), (d) 6-12 h; (e), (f) 12-18 h; (g), (h) 18-24 h; and (i), (j) 24-30 h. Units: mm.

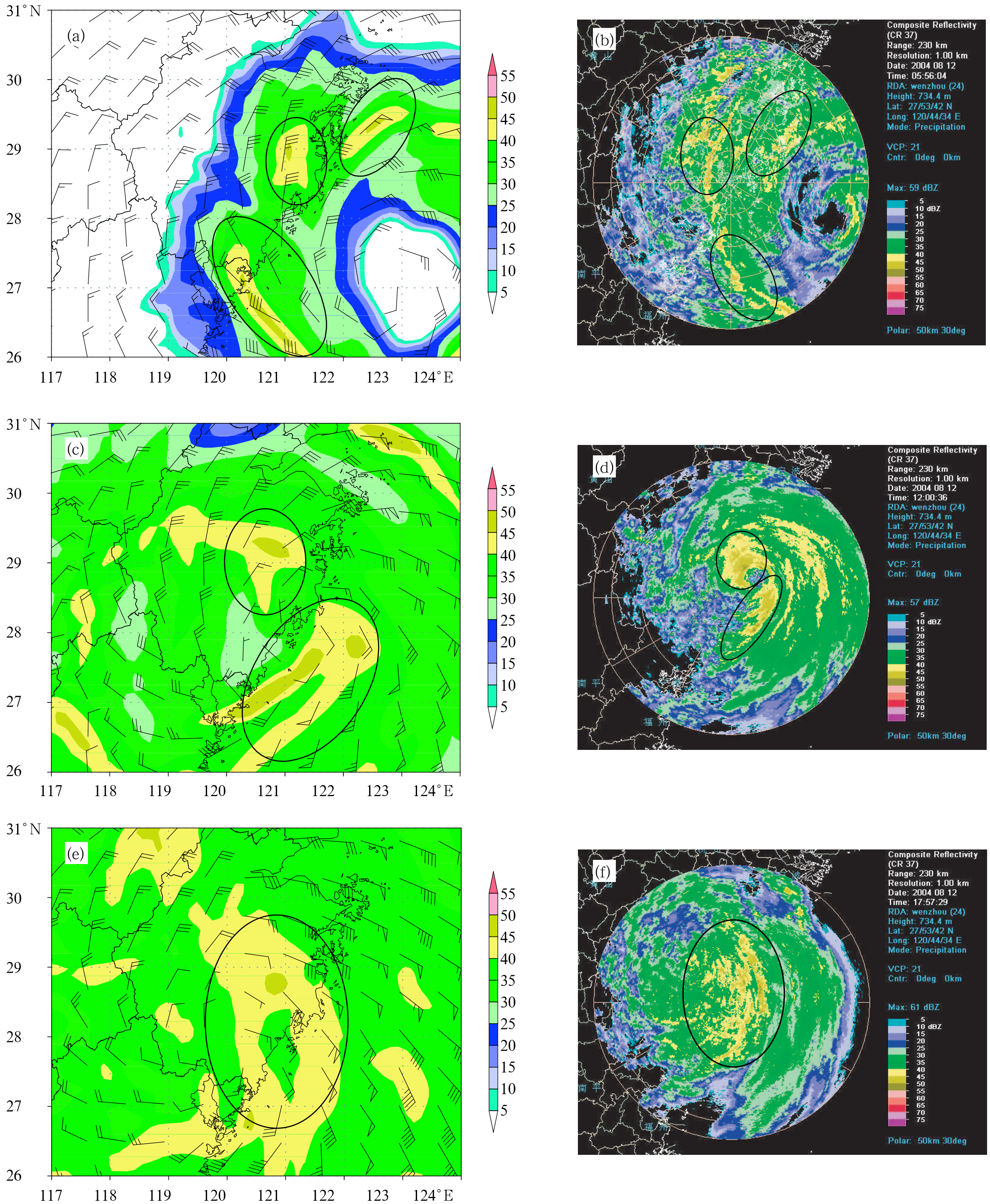

Fig.5. The composite reflectivity and surface wind fields simulated by the ARPS model at (a) 06:00 UTC 12 August, (c) 12:00 UTC12 August, (e) 18:00 UTC 12 August; and the composite reflectivity observed by Wenzhou radar at corresponding hours (b, d, and f), unit: dBz.

the uneven and representative problem of the rainfall data. In this paper, the composite reflectivity outputs from the model and the radar composite reflectivity are compared in order to test the simulated results. Since radar scans the volume every 6 min, we take the data nearest to the hour as the comparison data.

At 06:00 UTC 12 August (6 h before typhoon landing), when typhoon center lies over sea, the simulated echo (Fig.5a) has the circular structure, with obvious typhoon eye but without echo, and echo band with intensity >40 dBz in the spiral cloud belt is in the west of typhoon, which is consistent with the strong convective cell in the spiral belt, and similar to that of radar observation (Fig.5b). Over the ocean east of typhoon, the strong echo band turns to the south of Taiwan as typhoon moves. At 12:00 UTC 12 August, when typhoon lands, simulated echo (Fig.5c) looks like number "9", strong echo (>40 dBz) in the northwest quadrant of typhoon lies in Taiwan, and strong echo in the southeast quadrant lies over the ocean in the southeast of Zhejiang, which is in accordance with the observation (Fig.5d), but the simulated echo in the northeast quadrant is a little weaker than the observation. At 18:00 UTC 12 August, when typhoon has landed for 6 h, the simulated echo (Fig.5e) shows that the main body of the strong echo, which is located on the ocean southeast of Zhejiang during fall, moves to land, while typhoon moves inland, the distributing area of strong echo expands, and the echo intensity in the north of Wenzhou and in the southwest of Taizhou is greater than 45 dBz, which is very similar to the observed echo distribution (Fig.5f). In sum, not only in the intensity and formation but also in the distribution and moving mode, the simulated echo corresponds to the observed, and the strong echo accords with the heavy rain center, only the radar observed echo structure is more accurate. In conclusion, the composite reflectivity made from the water matter in the model atmosphere is an effective way to test the simulated results.

4. The sensitivity experiment of terrain effect on typhoon

4.1 *The design for the terrain sensitivity experiment*

The analyses above indicate that the ARPS in this paper can simulate the track before and after landfall and the precipitation of Typhoon Rananim (0414), which lays a foundation for the study of the effect of the terrain in the south of Zhejiang and in the north of Fujian on Typhoon Rananim (0414). In order to study terrain effect on typhoon, three groups of terrain experiments are designed. First, the control test (CTL for short) is the same as the numerical simulating test. Second, the terrain (HT for short) the south of Zhejiang and in the north of Fujian in the test is half of the actual terrain. Compared with the CTL, after $30''$ terrain is read in from the terrain dataset, the terrain altitude is reduced to half of the actual (Fig.2b), while other conditions are the same as CTL. Last, the terrain in the south of Zhejiang and the north of Fujian in the test is double of the actual terrain (DT for short). Compared with the CTL, after $30''$ terrain is read in from the terrain dataset, the terrain altitude increases to double of the actual (Fig.2c), while other conditions are the same as CTL.

4.2 *The terrain effect on typhoon's intensity and structure*

Figure 6a gives the variation of the disturbance pressure in typhoon center 3 h after typhoon's landfall. Three numerical tests are compared, the influences on typhoon intensity are not obvious, especially in HT and CTL, the distributions of the disturbance pressure are very consistent, and the simulated pressures in typhoon center in all tests are very similar, too. But 12 h after landfall, the variation of the disturbance pressure in typhoon center is obviously different. In CTL (Fig.6b), the disturbance pressure in typhoon center opens downwards like mushroom, as in HT, while in HT, the opening is bigger. In DT, the pressure intensity on middle and low layers of typhoon notably weakens, forming a closed center on middle and high layers, and the pressure in the front of typhoon weakens slowly, while in the back of typhoon it enhances fast. Therefore, after landfall, the farther away from the coastline, the terrain becomes higher and more complex, and the influences of the terrain on typhoon intensity are more obvious in the back than in the front. Figure 7 is the 500-hPa total wind speed 3 h after landfall, simulated by the numerical test. The wind speed in the northeast quadrant

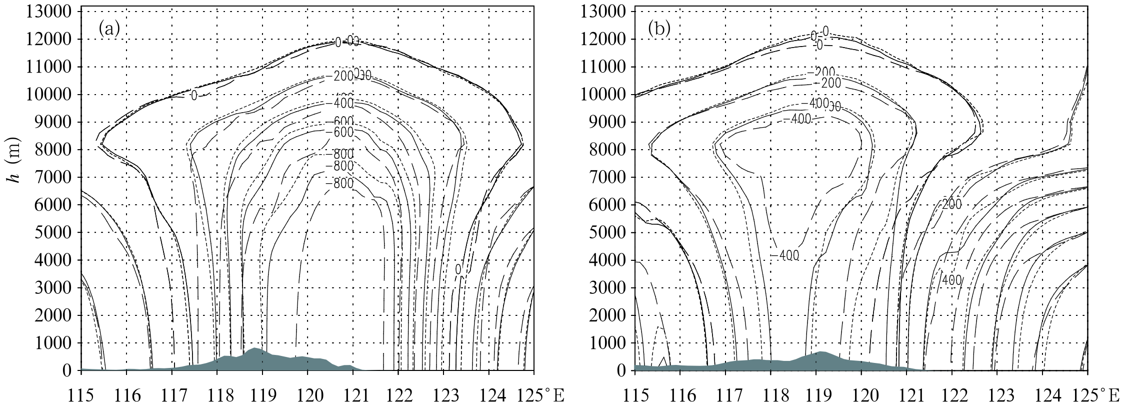

Fig.6. The altitude-longitude cross section of perturbation pressure (Pa) along typhoon center (short dashed line: HT, solid line: CTL, and long dashed line: DT). (a) 3 h after landfall and (b) 12 h after landfall.

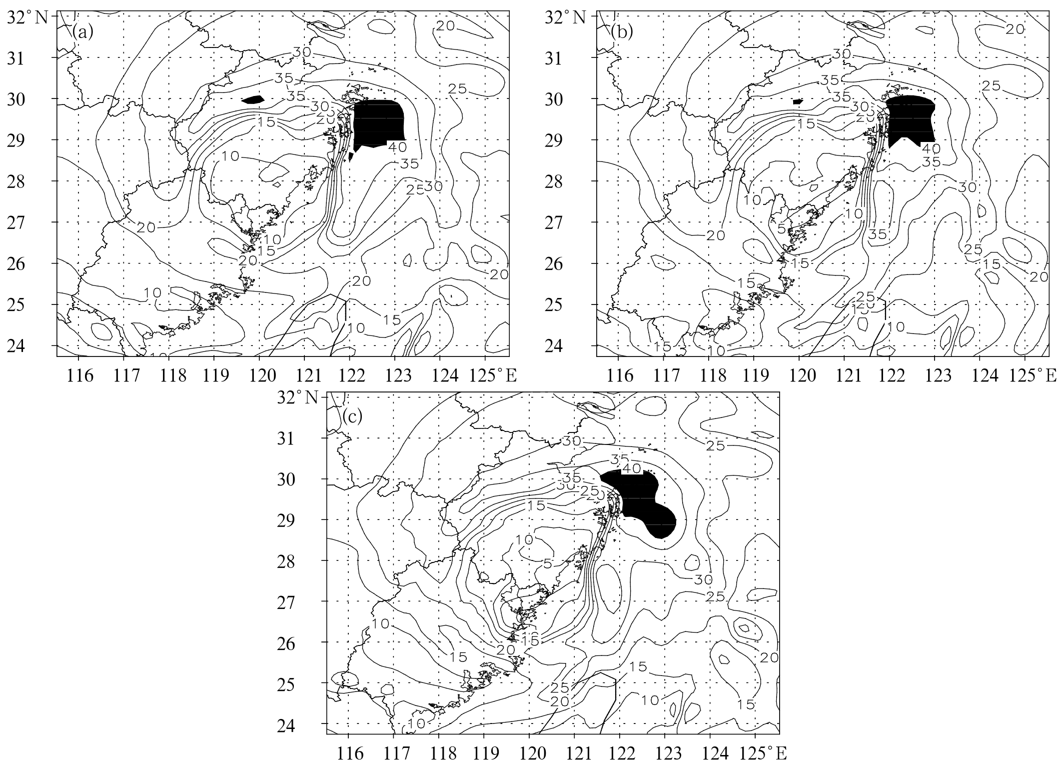

Fig.7. The simulated total wind speed (m s^{-1}) at 3 h after landfall (15:00 UTC). (a) HT, (b) CTL, and (c) DT. The value in shaded area is greater than 40 m s^{-1}.

is more than twice of that in the southwest quadrant, showing an elliptic distribution with NE-SW long axis. By comparing Figs.7a, 7b, and 7c, it is known that as the terrain uplifts, the wind speed in the northwest quadrant weakens obviously.

4.3 *The terrain effect on typhoon track*

The simulated typhoon tracks in these numerical experiments (Fig.8) show that the ARPS simulated landing location lies in the north of the actual position when the terrain is added, and the higher the terrain, the further north the landing location. And the westward track after landfall in Yuhuan in Taizhou is simulated, which is in agreement with the conclusion of Chen (1985), i.e., the terrain will make typhoon tracks rightward. By comparing the test results, the

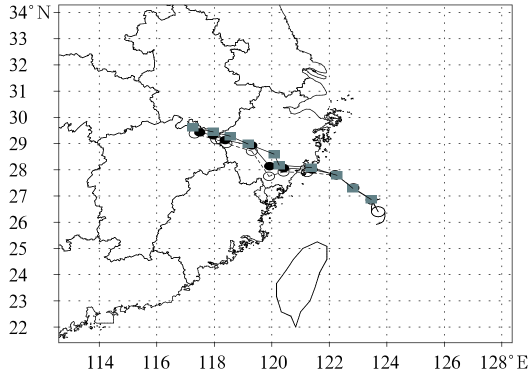

Fig.8. The simulated track of Typhoon Rananim (HT: blank circle; CTL: soild circle; DT: square).

terrain in south of Zhejiang and north of Fujian has an effect on the track of Typhoon Rananim, but the effect is not strong enough to change the westward pathway after landfall. Chen and Luo (1996) proposed that the asymmetric structure inside typhoon is often one of the factors that induce the abnormal movement of typhoon. Figure 9 depicts wind vector field at 850 and 500 hPa simulated by CTL test when typhoon is landing. Wind speed is the largest in the northeast quadrant and smallest in the southwest quadrant of typhoon center, and it is distributed asymmetrically about NE-SW direction. Numerical tests with dense observed data indicate that typhoon with asymmetric structure often moves westward. Therefore, the NE-SW asymmetric structure of typhoon itself is one of the important factors that induce the westward track after landfall. But the analyses on typhoon structure in the terrain tests indicate that because of the terrain effect, the wind speed in the northwest quadrant weakens, which is adverse to the westward movement of typhoon.

4.4 *The terrain effect on typhoon's rainfall*

Then the precipitation variation in the terrain test is analyzed. When the terrain is reduced to half, 12 h before landfall (Fig.10a), the rainfall in the heavy rain center in the southeast of Taizhou and in the north of Wenzhou decreases by more than 20 mm, and decreases by more than 30 mm 18 h after landfall (Fig.11a), and the rainfall of other heavy rain centers decreases in different degree, for example, the rainfall in the northwest of Fujian decreases by more than 30 mm. On the contrary, when the terrain is uplifted to double, the rainfall in the southeast of Taizhou and in the north of Wenzhou increases by more than 30 mm (Fig.10b), and increases by 30-60 mm 18 h after landfall (Fig.11b), and the rainfall in other heavy rain centers increases in different degree, for example, the rainfall in the northwest of Fujian increases by 30-60 mm. Figures 11a and 11b are compared, showing that the terrain makes precipitation distribute uneven, and many little precipitation centers occur after the terrain is double. In the terrain test area, the rainfall decreases in some places and increases in others, and compared with the terrain distribution (Fig.1), the rainfall in windward increases and in leeward decreases, which is in accordance with the research results of Niu et al. (2005). The variation of vertical velocity indicates that under the effects of terrain, when

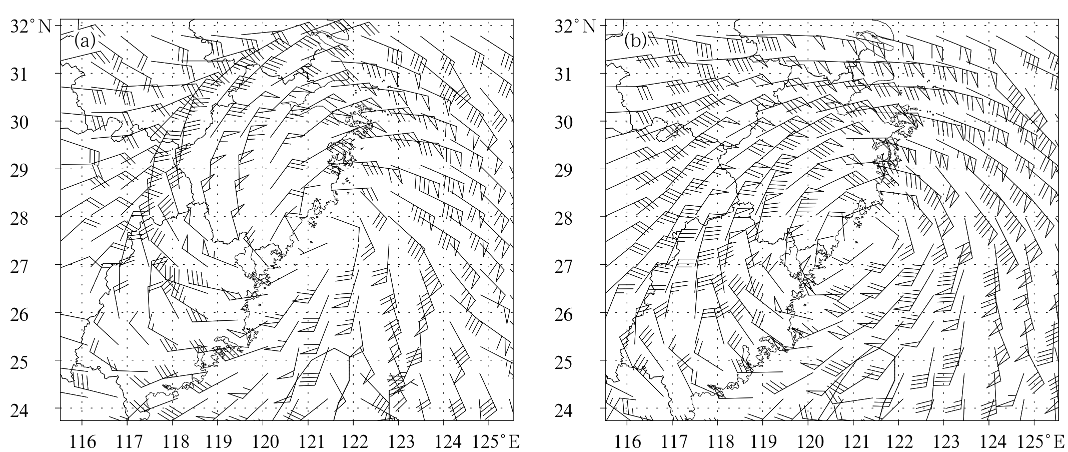

Fig.9. The wind vector field simulated by model at 850 hPa (a) and 500 hPa (b) during typhoon landfall (12:00 UTC).

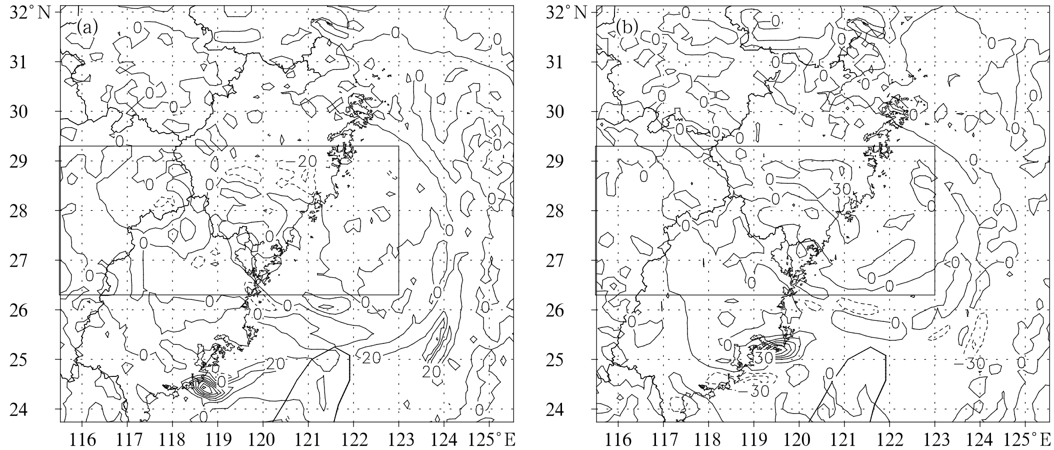

Fig.10. The 12-h precipitation difference before typhoon landfall. (a) HT minus CTL and (b) DT minus CTL (unit: mm).

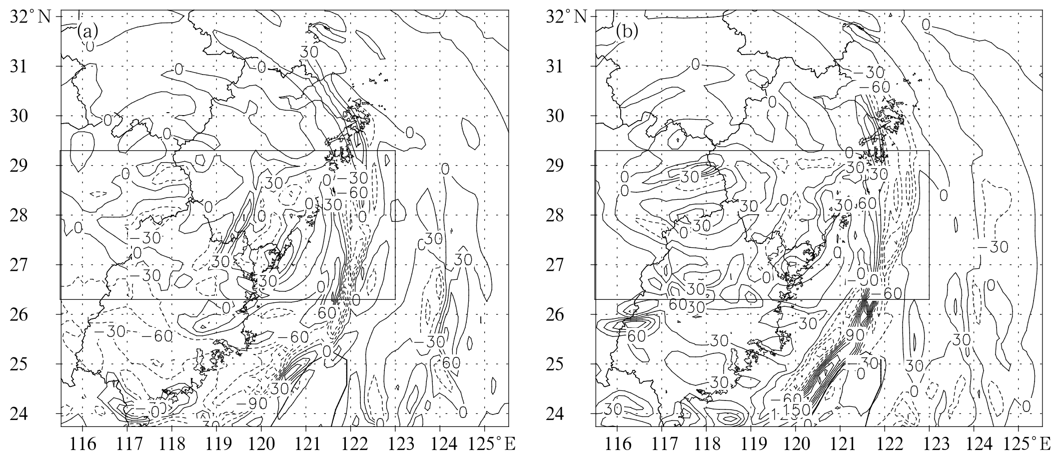

Fig.11. The 18 h precipitation difference after typhoon landfall. (a) HT minus CTL and (b) DT minus CTL (unit: mm).

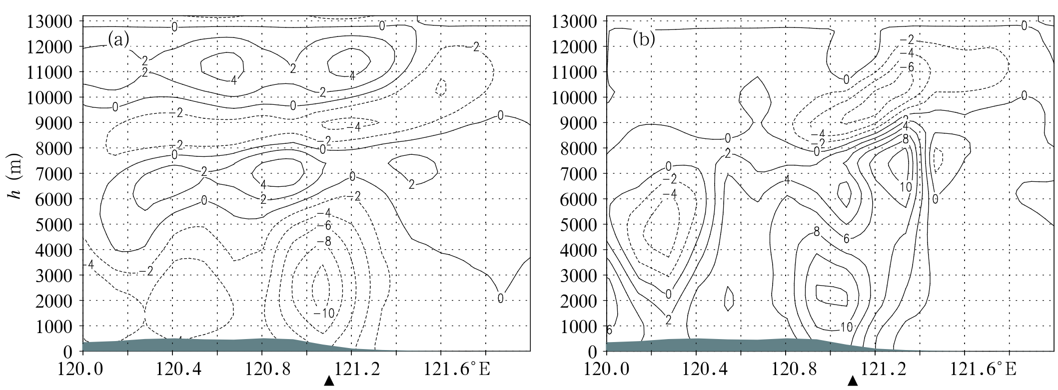

Fig.12. Simulated vertical velocity differences in the vertical section across Wenzhou-Taizhou rainstorm center during typhoon landfall for (a) HT minus CTL and (b) DT minus CTL. Triangles ▲ denote the location of rainstorm (unit: 10^{-2} m s^{-1}).

the terrain is double (Fig.12b), the vertical velocity on the middle and low layers over the rainstorm center enhances obviously, and weakens on the high layer, while when the terrain is half (Fig.12a), the vertical velocity on the middle and low layers over the rainstorm center weakens obviously, and on the high layer, the strong area alternates with the weak area, which is in general contrary with the situation before. And on the windward, the uplift effects of terrain is obvious, the convergence on the middle and low layers enhances, which is beneficial to the increase of rainstorm. Comparing the rainfall variation distributions before and after landfall, the terrain effect is stronger after landfall than before. During the whole simulation, half terrain will make the rainfall reduce by 1/3, and double terrain will make the rainfall increase by 1/3-1/2.

5. Concluding remarks

Using the ARPS model, the landing process of Typhoon Rananim is simulated for 30 h, the results are compared with the actual observation, the influence of terrain in the south of Zhejiang and north of Fujian on typhoon is studied in numerical tests, and several conclusions may be drawn as follows.

(1) The (CINRAD) Doppler radar data, used in ARPS, can simulate the track, intensity variation of Typhoon Rananim (0414), the rainfall, and distribution of rainstorm, thus providing high resolution data for the research of problems such as the reason of westward track, the rainstorm of typhoon, and so on. The comparison between the composite reflectivity made from the water mass in the simulated atmosphere and the radar composite reflectivity is an effective method to test the simulated results.

(2) Terrain sensitivity tests show that the influences of terrain in south of Zhejiang and north of Fujian on Typhoon Rananim intensity are small, but when typhoon moves inland, the influences become larger. The higher the terrain, the more obvious the weakening of typhoon intensity, when typhoon center passes by.

(3) Numerical test and terrain sensitivity test show that the asymmetric structure of typhoon is one important factor that induces the westward movement. The terrain in south of Zhejiang and north of Fujian makes the wind speed in the northwest quadrant weaken and makes the track veer westward, what is more, the higher the terrain, the more rightward the track. The possible mechanism about how the asymmetric structure of typhoon affects the track needs to be further studied.

(4) Terrain sensitivity tests show that though the terrain makes the central pressure weaken, the vertical speed in the middle and low layers over the rainstorm center enhances obviously. The terrain in south of Zhejiang and north of Fujian can enhance typhoon rainstorm, and the higher the terrain, the more uneven the rainfall distribution is.

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