A Numerical Study on Forecasting the Henan Extraordinarily Heavy Rainfall Event in August 1975①

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Received September 24, 1990; revised May 24, 1991

ABSTRACT

This study is essentially an experiment on the control experiment in the August 1975 catastrophe which was the heaviest rainfall in mainland China with a maximum 24–h rainfall of 1060.3 mm, and it significantly demonstrates that the limited area model can still skillfully give reasonable results even only the conventional data are available. For such a heavy rainfall event, a grid length of 90 km is too large while 45 km seems acceptable. Under these two grid sizes, the cumulus parameterization scheme is evidently superior to the explicit scheme since it restricts instabilities such as CISK to limited extent. The high resolution scheme for the boundary treatment does not improve forecasts significantly.

The experiments also revealed some interesting phenomena such as the forecast rainfall being too small while affecting synoptic system so deep as compared with observations. Another example is the severe deformation of synoptic systems both in initial conditions and forecast fields in the presence of complicated topography. Besides, the fixed boundary condition utilized in the experiments along with current domain coverage set some limitations to the model performances.

I. INTRODUCTION

An extremely heavy rainfall event occurred in the central–southern part of Henan Province during August 4–8, 1975 (hereafter abbreviated to 75–8 Heavy Rainfall). It was the heaviest rainfall in mainland China and produced a casualty just next to the strong earthquake in Tangshan area in 1976. So far, it holds the mainland China's records of rainfall amounts listed in Table 1 for the periods ranging from 20 min to 72–h (Committee of the Harness Huaihe River, 1979) where the 6–h value is the world record.

The rainfall amounts were not only very heavy but also locally and unevenly distributed in the event. Thus the rainfall amounts recorded are quite diverse, depending on the type and density of the observations. Listed in Table 2 are the maximum 24–h rainfall values recorded by different sites in the area of 112–115°E and 32–35°N, ending at 0000 GMT 8 August for which the precipitation was heaviest.

The value observed by hydrological stations is 1005.4 mm, about 4.7 times of that recorded by synoptic stations.

①The project is supported by the National Natural Science Foundation of China and State Meteorological Administration Typhoon Research Fund.

Table 1. The 75–8 Heavy Rainfall Amounts within Different Time Periods

Time Period	20	30	45	60	1	3	6	12	24	72	1	3
	(min)				(h)						(d)	
Rainfall (mm)	80.3	105.0	162.6	218.1	189.5	494.6	830.1	954.4	1060.3	1606.1	1005.4	1605.3
Site	Linzhuang		Xiachen		Laojun	Linzhuang						
	(all in Biyang County of Henan Province)											

Table 2. Daily Maximum Rainfall Amounts Recorded by Two Types of Stations and Numbers of Corresponding Stations (112°–115°E, 32°–35°N)

Type of Station	Numbers of Station	Value Recorded by the Two Types of Stations	
		Station Name	Rainfall (mm)
Synoptic Stations (including rawinsonde, radiowind and surface synoptic stations)	10	Zhumadian	215.5
Hydrological and Climatological Stations	244	Linzhuang	1005.4

Fig.1 depicts 24–h rainfall amounts observed by both types of stations, showing a greater difference between them. The four maximum values over 800 mm (1005.4 at Linzhuang, 999.0 mm at Guolin, 812.5 mm at Laojun, and 809.7 mm at Yanglou) were all recorded by hydrological stations. With rainfalls observed by both hydrological and climatological stations included, the area encircled by the 500 mm contour reaches 3,000 km^2 and that by the 200 mm contour is 11,000 km^2 in Fig.1. However, from those observed only by synoptic stations, the 500 mm contour is no longer present and the area surrounded by 200 mm contour is much smaller. The contours of 100 mm, encircling about 23,000 km^2, 50 mm and 25 mm encircle comparable areas no matter whether hydrological or climatological stations are included. Committee of Harness Huaihe River (1979) showed the rain data in terms of duration–depth–area at rainfall center. The averaged rain depth over 2,000 km^2 at the center

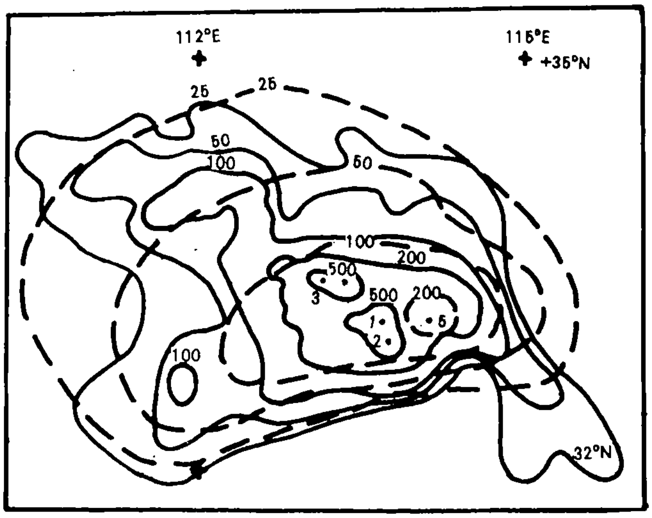

Fig.1. The 24–h observed rainfall (mm) ending at 0000 GMT 8, August 1975. Dashed lines are isopluvials based only on data of synoptic stations and solid ones with data of climatological and hydrological stations in addition. The five spots are: 1–Linzhuang, 2–Laojun, 3–Guolin, 4–Yanglou, 5–Zumadian, respectively.

reaches 680 mm while that over 8,000 km^2 is 470 mm. These two areas are roughly equivalent to the grid areas corresponding to the model resolution sizes of 45 km and 90 km respectively.

Naturally, this event of heavy rain received a lot of attentions from both meteorologists and hydrologists so that it was immediately surveyed from various angles. Only half a year after the event, 206 meteorologists from 26 institutions were organized to analyze the event from different points of view (Research Group on 75–8 Heavy Rainfall, 1977. In fact from then on, much research work on it has been carried out, and many papers and reports were published (Ding et al., 1980; Li et al., 1980; Cai et al., 1980; Ding et al., 1978; Beijing Group 75–8 Heavy Rainfall Cooperative Research, 1979; Zhao and Zhou, 1984).

The research work showed that this heavy rainfall event resulted from the 1975 Typhoon Nina. In effect, the event was composed of three episodes of rains which happened respectively on August 5, 6 and 7. These rain episodes had evident diurnal variation with heavy rains occurring between afternoon and late night, especially from early evening to middle night. Among the three episodes of rain, that on the 5th, locating 500 km north to the typhoon center, was caused by the peripheral easterly disturbance of the typhoon while those on 6th and 7th were directly associated with remains of the typhoon. Among many factors affecting the event, the main three are: (1) The long lived typhoon penetrated deep into Henan Province and lasted as long as 4 days in the continent; (2) Through the whole period of the event, there maintained a strong low level easterly jet from the ocean east of Japan to the north of typhoon; (3) There existed a favorable topography.

All the above work except Zhao and Zhou (1984) was completed in the end of 1970's, and conducted mainly large– or meso–scale synoptic analysis and preliminary diagnostics of this heavy rainfall event. The only numerical study by Zhao and Zhou (1984) put emphasis on demonstrating superiority of observed winds as initial conditions over calculated ones from the mass field. The rainfall simulated was quite different from the observed and several key problems were not included in experiments.

Therefore, the research on the "75–8 Heavy Rainfall" is quite far from adequate. Limited to the historical condition at that time, the detailed dynamic analysis and sophisticated numerical simulations were not performed.

The historical data show that 80% of the heaviest rainfall in the 15 coastal provinces of China resulted from landed typhoons, their remains or their peripheral disturbances (Cai, 1990). Thus, typhoon is the major weather system inducing extremely heavy rainfalls and severe flood disasters in the country. The "75–8 Heavy Rainfall" is just the most severe example of them. To understand, forecast and prevent these extremely heavy rainfalls better in the future, it is of great significance to study "75–8 Heavy Rainfall" in more detail. Because of this, a series of studies are underway on this heavy rainfall and this paper is the first one of the series.

The striking point of "75–8 Heavy Rainfall" is its record–breaking precipitation. Thus, the first thing to carry out is to simulate rainfall well compared with the observations. After that, more numerical experiments could be conducted in giving more reliable results. However, model–calculated precipitation is usually smaller than the observed and sometimes the difference is very evident (Zhao and Zhou, 1984). This under–prediction is also inevitable for the recent numerical study (Kuo et al. 1988). This shortcoming of numerical models should appear more evident in our case because of so large value of rainfall amount. Therefore, how to simulate the amount of this extremely heavy rainfall is a severe problem to tackle with. Considering this, in the current paper the experiments on various affecting factors are not yet conducted, concentrating only on the numerical model itself. The purpose of doing so is to choose a better scheme of control experiment to ensure future simulation of higher reliability.

II. MODEL AND EXPERIMENTAL SCHEMES

The model used in the paper was originally designed by Anthes and Warner (1978) and then developed and modified into the today's version called MM4 (Anthes et al. 1987). Now the MM4 has been installed on the DPS–7 by the Institute of Mesoscale Meteorology, Academy of Meteorological Science. It is a hydrostatic model written in σ coordinates where $\sigma = (p - p_t)/(P_s - p_t)$, P_s and P_t are the surface and model top (=100 hPa) pressures respectively. Vertically the atmosphere is divided into 10 layers whose σ values are 0.055, 0.165, 0.275, 0.385, 0.495, 0.605, 0.715, 0.825, 0.915 and 0.975. Computation domain is sized by 31×31 grid points spaced 90 (or 45) km apart and time step is 142 (or 71) seconds.

For the initial fields, 127 rawinsonde observations in eastern Asia at 10 levels (1000, 850, 700, 500, 400, 300, 250, 200, 150, and 100 hPa) are objectively analyzed to model grid points with successive correction scheme. 4 scans are applied in the successive correction. The first scan radius is 550 km and the successive radii are obtained by multiplying the previous one by a factor of 0.7 each time. Wind fields are adjusted such that the vertically average divergence vanishes. The boundary condition is fixed. Terrain heights in the model are obtained by interpolating the heights on 1×1 Lat. / Long. meshes from NCAR to model grid points.

The experiments conducted are listed in Table 3. Here the low resolution for boundary layer treatment (abbreviated to low in Table 3) refers to the bulk aerodynamic formula which considers heat, moisture and momentum exchanges between the surface and boundary layer. Using this treatment and Kuo–Anthes cumulus parameterization (abbreviated to K–A in Table 3), we tested the coarse (90 km) and fine (45 km) mesh (EX1, 2). The role of resolution is also tested in using explicit precipitation scheme (EX3, 4). The last experiment is designed for testing the effect of boundary layer treatment by using high resolution scheme (abbreviated to high in Table 3) (Zhang et al., 1982).

Table 3. Experimental Schemes, Forecasted Maximum 24–h Rainfall Amounts and Center Positions in Five Experiments as Compared with Observations from Two Types of Stations

EX. No.	Grid (km)	Cumulus Convection Scheme	Boundary Layer Resolution	Forecast Rainfall Center(mm)	Against Synoptic Station		Against All Station	
					A*(%)	B*(km)	A**(%)	B**(km)
1	90	K–A	Low	154	71 (154 / 216)	NNE 140	33 (154 / 470)	NNE 125
2	45	K–A	Low	291	135 (291 / 216)	NE 43	43 (291 / 680)	ENE 65
3	90	Explicit	Low	760	352 (760 / 216)	NW 340	162 (760 / 470)	NW 300
4	45	Explicit	Low	251	116 (251 / 216)	ENE 180	37 (251 / 680)	N 150
5	90	K–A	High	122	56 (122 / 216)	NNE 140	26 (122 / 470)	NNE 125

Note: A* refers to "Forecasted Rainfall / Observed Rainfall (216 mm)";

A** refers to "Forecasted Rainfall / Observed Grid Area–Mean Rainfall";

B*(B**) refers to "Location Error of Center" for A* (A**).

Integrations in all five experiments start at 0000 GMT 7 Aug. and last for 24 hours within which the daily rainfall of 1005.4 mm and other three rainfall centers over 800 mm are observed (Fig. 1). Such a large amount rainfall at four sites within one day is very rare indeed.

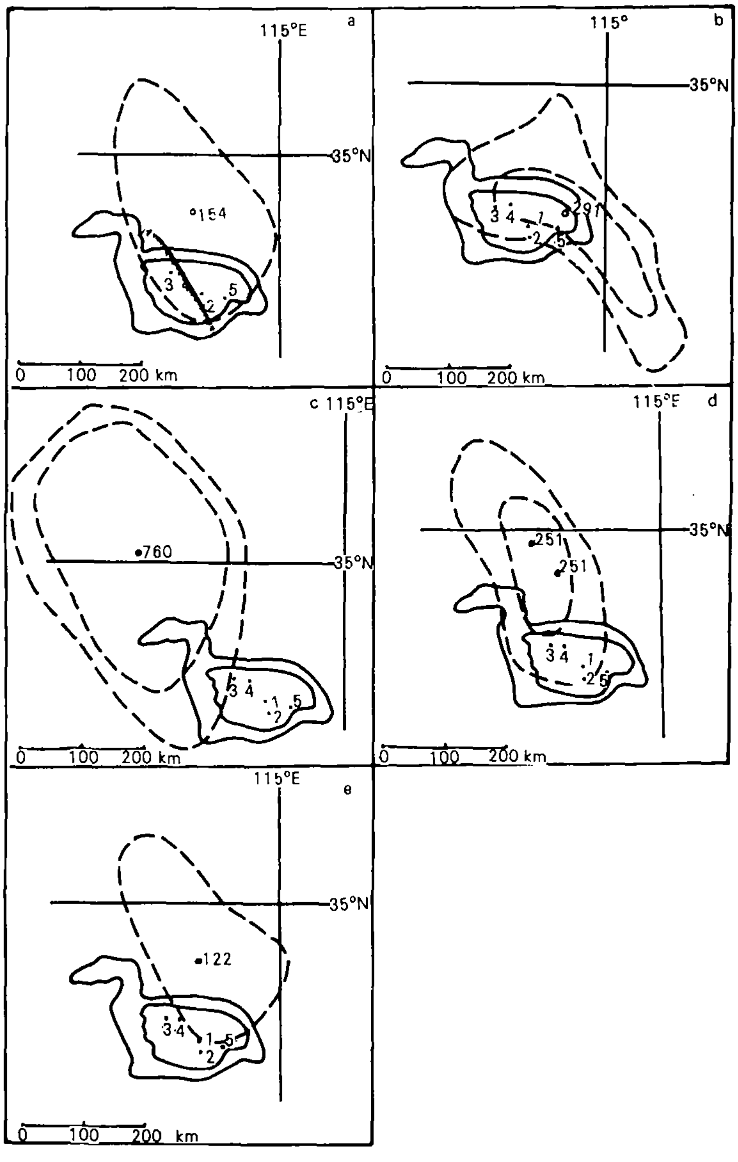

Fig.2. Model forecasted 24–h rainfall (mm) (dashed) ending at 0000 GMT 8, Aug. 1975, in experiments EX1, 2, 3, 4, and 5 and observed 24–h rainfall (solid) corresponding to a, b, c, d, and e. Drawn only for isopluvials of 100 and 200 mm. Open circles stand for the positions for forecasted maximum rainfall denoted by the number to the right. Small spots are the five observed maxima: 1. Linzhuang, 1005.4 mm, 2. Laojun, 812.5 mm, 3. Guolin, 999.0 mm, 4. Yanglou, 809.7 mm, 5. Zhumadian, 215.5 mm.

III. RESULTS OF EXPERIMENTS

1. 24–h *rainfall prediction*

Fig. 2 compares 24–h rainfall predicted in the five experiments with the observed in the identical period. Listed in Table 3 are the resultant comparisons.

Conventionally, only point rainfall observed at synoptic stations is used to be compared with model forecasts. In this way, 215.5 mm recorded maximum at Zhumadian (Table 2) is compared with forecasts as listed in Table 3. It is found in the table that predicted rainfall is quite close to the observed with 29% under–forecast and about 140 km center locating error to the NNE in the coarse experiment (EX1) and with 35% over–forecast and 43 km to the NE in the fine mesh experiment (EX2). However, the model–forecast rainfall represents the average over a grid area of the model rather than at a point. At the same time, the severity of disaster depends more on the average rain depth over an area.Thus for such extreme rains as "75–8 Heavy Rainfall", the rainfall amount at a point is less representative whereas the average rain depth over an area is better. Therefore, listed in Table 3 are also the comparisons with average rain depth over an area of grid sizes. This table shows that EX1, 2, 4, 5 forecast rainfall quite reasonably where EX2 is the best with the minimum location error of 65 km and 57% under–prediction for average rain depth. These figures demonstrate the model ability in forecasting the catastrophe even though the conventional data are available only, and this result is encouraging.

As far as the role of grid length concerned, the result of 45 km grid is somehow better than 90 km, but at the higher expense of computer resources.Therefore, limited to existing computer resources and economical condition, the cumulus parameterization with 90 km grid length is an acceptable option.

Comparing the results from EX1, 2 with EX3, 4 shows that cumulus parameterization is better in giving more reasonable rainfall forecast. This result agrees with that obtained by Zhang (1988). This may be due to the so–called CISK–like instability, a kind of positive feedback process. The process is not controlled in the explicit scheme, producing unbounded growth of storms, whereas its growth is restricted to some extent in the cumulus parameterization scheme. The "out of control" is most evident in EX3 although its maximum rainfall seems close to the actual (1005.4). The location error or bias, the distance between the predicted and observed rainfall centers, is the largest in EX3. In addition, the position and strength of synoptic systems forecasted in EX3 are distorted greater compared with observations. Another factor responsible for the failure in EX3 may arise from the coarse mesh (90 km). Although in the past some investigators succeeded in using explicit scheme with large grid lengths, e.g., Ross (1982) simulating a frontogenesis with a grid length of 61.5 km and Wang (1987) simulating a SW vortex (a kind of intermediate vortex in the sorthwest China) with a grid of 96.5 km, there were more authors failed. It is believed that even if grid length reduces to about 10 km, a cumulus parameterization is still necessary (Zhang, 1988). In our case the explicit scheme is acceptable when grid length decreases to 45 km even though it is much worse for 90 km.

Rainfall forecast in EX5 is no better than its control, EX1, while the former uses a much more sophiscated boundary layer treatment, the high resolution scheme. This implies that the effectiveness of a superior scheme is limited to the initial data which are only 850 hPa and the surface in our case although the treating approach is improved. This may also imply the fact that for strong convective storms upper–level forcing plays a more important role than lower level forcing (Cai et al., 1990).

Table 3 shows larger forecast error in rain centers for EX1, 3, 4, and 5.The analysis on rainfall center movement (not shown) at intervals of 3–h shows that most of the rainfall centers moved toward the north in all the four experiments except EX2 in which the 3–h rainfall centers moved more or less around the remains of 1975 Typhoon Nina producing greater rainfall among all experiments. In this period of time the mesoscale systems and rain center observed indeed moved within the surroundings of the typhoon remains. Therefore, EX2 gives the greater rainfall and smallest location bias among the all.

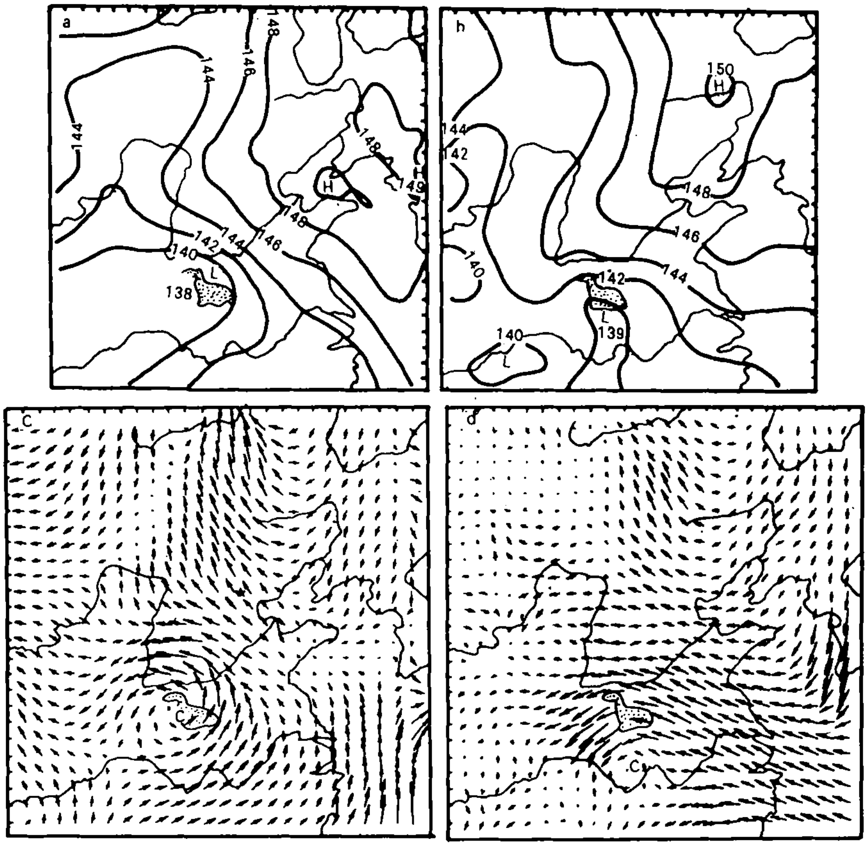

Fig.3. The 850 hPa height (a) and wind barb (c) for 12–h forecast for EX1 verifying at 1200 GMT 7 Aug. 1975, and the corresponding observed 850 hPa height (b) and wind barb (d). Dotted area is the rainy area exceeding 100 mm / 24–h.

2. *Synoptic system forecast*

As mentioned earlier, EX2 gives the best synoptic system forecast.However, with 31 × 31 grid points and a grid length of 45 km, its domain has a coverage of 1,822,500 km^2, limited to the computer storage, and it is too small to present synoptic systems completely. To discuss roles played by all synoptic systems more clearly, without being severely affected by boundary conditions, the following results presented are from EX1 covering a domain four times as large as EX2. To save space, only the 12–h forecast validated at 1200 GMT 7 August will be presented and compared with observations since this point is in time closest to the maximum 3–h rainfall occurring at 0900–1600 GMT 7 August.

Figs. 3a and 3b show the 12–h forecasted and observed 850 hPa heights, demonstrating a general similarity between them, e.g., a strong resemblance of the high located east of the middle and lower reaches of the Huanghe River and of the low pressure area from the Great Bend of the Huanghe River to the Changjiang River and Huaihe River basins. However, the trough in middle and upper reaches of the Changjiang River is forecasted opening to the southwest instead of to the south as observed. The remains of the 1975 Typhoon Nina were located initially at 150 km northwest of Wuhan (not shown) and 12–h after it was weakened

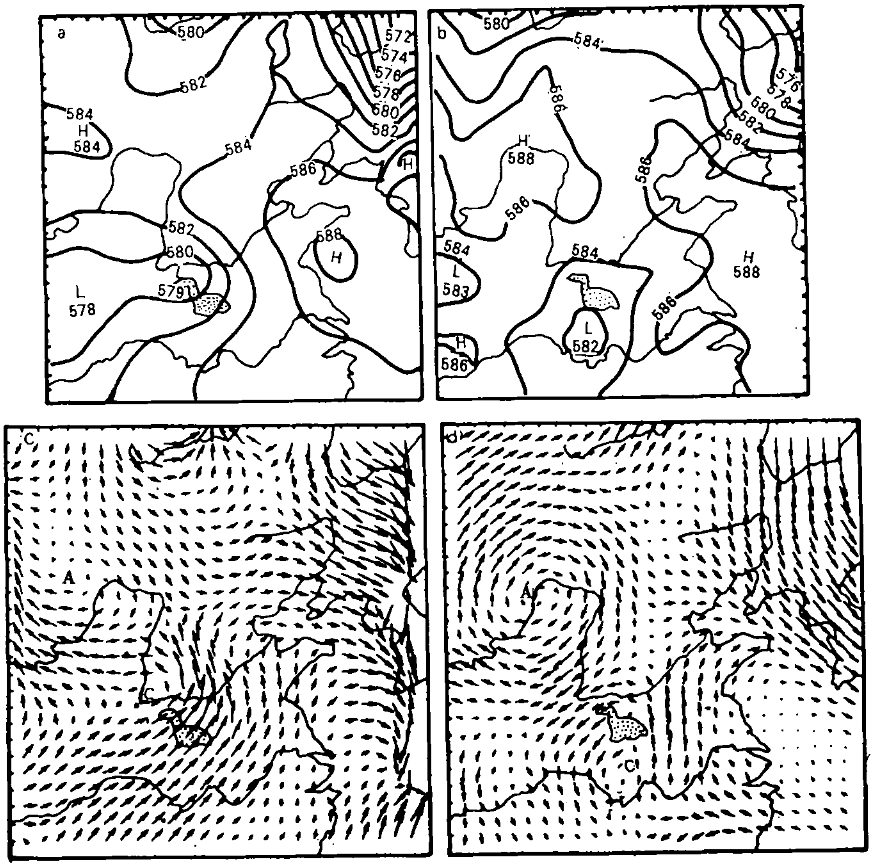

Fig.4. As in Fig.3, but for 500 hPa.

to a trough. This evaluation is correctly predicted although the strength forecasted is 10 m lower at the center than that observed.

In wind fields, the vortex of the remains of the typhoon close to the heavy rain area, is present in both the charts forecasted and observed (Figs. 3c, 3d). But the vortex predicted moves northward whereas it was observed almost stationary in reality, which gives a 250 km northward bias from the vortex and consequently of the rainfall center (Fig. 2a). The strength of the vortex forecasted is deeper than the observed, their vorticity centers are 15.7 and 11.2×10^{-5} s, respectively. In addition, the forecasted flow patterns differ somehow from the observed near boundary areas and in southeastern corner.

On the 24–h forecast chart, the trough at 850 hPa deepens further by 10 m but it was filled by 10 m in reality. Therefore, the trough predicted is 20 m lower than that observed. The position of the cyclone center in the trough was then 300 km bias to the north (figures not shown).

In EX2, the position of cyclone center at 850 hPa predicted is 90 km to the ENE at 12–h and 90 km to the NE at 24–h compared with the actuals, showing that the position bias does not increase with time because the predicted cyclone center shifts around the rainy area. Comparing with EX1, the prediction of cyclone position is better but its intensity is not, 60 m lower than the observed (figures not shown).

Figs. 4a and 4b give the forecasted and observed 500 hPa heights at 12–h. It is found on the figures that the highs at Bohai and Huanghai seas are realistically predicted whereas the high in the Great Band of the Hanghe River is more shallow and to the west as compared with the observed despite of the forecasted deepening for other systems. The low pressure center in the trough zone close to the heavy rainfall area is to the north by 300 km and deeper by 30 m at 12–h than observations. At 24–h (figures not shown), the deviation develops further with 400 km north and 40 m deeper respectively. As for the air–flow field, the 12–h predicted vortex in Fig.4c is 400 km NNE compared with observations (Fig.4d), corresponding to the vorticity 18.1 and 6.0×10^{-5} s respectively. Again, flow patterns at the four lateral boundaries are predicted worse.

In EX2, the forecasted 500 hPa height at 12–h is similar to 850 hPa with a clear closed vortex center, but with a smaller position error of 180 km and a greater height bias by 50 m. By 24–h, the trough orientation in the east–west direction is close in position to observations but its low center is 200 km to the ENE and 60 m lower in strength. Similar to 850 hPa, the predicted low pressure systems relevant to the heavy rainfall in EX2 are better in position and deeper in strength than EX1.

At 200 hPa, a astonishing point of 12–h prediction is that an anticyclone with diameter of 200 km is generated aloft over the rain area while the maximum rain intensity is reached. To the north of the new anticyclone, there exists a strong southwesterly outflow, very close the observation despite a 100 km NW bias for the anticyclone center (not shown). This reflects the effect of latent heat release on the flow patterns, as discussed in detail in the previous work (Cai et al., 1980).

In combination of weather systems and rainfall amounts, predictions discussed above reveals such a fact that the former is considerably stronger than, but the latter much smaller than observations. Even in EX2 the rainfall prediction is closest to the observation, only the positions of weather system are realistically forecasted, but the strength of systems is much over–predicted. One could easily imagine that if the forecasted rainfall is heavier, closer to the observed, the strength of systems would be much more unrealistically deep, that is, the improvement on rainfall forecast is at the expense of inaccuracy in system strength. Since most of rainfall results from convection this contradiction may imply that the model needs a more effective rain–producing cumulus parameterization or some other improving approaches.

In addition, realistically forecasted systems are only limited to the central part of the model domain while those at boundaries, especially at the west one with complicated topography, are unrealistic. This deficiency is also clearly seen even as earlier back as in initial conditions. Thus, it is necessary to enlarge the domain and improve initialization techniques.

Also, in all experiments forecasted rain areas and vortex systems are more or less biased to the north and the reason for this remains to be clarified.

IV. DISCUSSION AND CONCLUSION

As a numerical study, the first experiment is normally the control one and this paper serves essentially as experiments on the control. The experiments conducted show that even for such an extremely heavy rain as the "75–8 Heavy Rainfall", the limited area model can still skillfully give reasonable results only with the conventional data, this is a very interesting point.

For such heavy rainfall event, a grid length of 90 km is too big while 45 km seems acceptable. Under these two grid sizes, the cumulus parameterization scheme is evidently superior to the explicit scheme since it restricts the CISK–like instability. The high resolution scheme for the boundary layer does not improve forecasts clearly.

The experiments also reveal some interesting phenomena e.g., the forecasted rainfall is too small while affecting weather systems are so deep as compared with observations. Another example is the severe deformation existing not only in forecasts but also in initial conditions when complicated topography is involved. Besides, the fixed boundary condition utilized in the experiments and the current domain coverage set some limitations on the model performance.

This study is quite preliminary owing to the limited computer resources and it is planned to pursue the simulation by comprehensive experiments with a much more power computer in the future.

REFERENCES

Anthes, R. A. (1977), A cumulus parameterization scheme utilizing a one dimensional cloud model, *Mon. Wea. Rev.*, **105** (3), 270–286.

Anthes, R. A. and T. T. Warner (1978), Development of hydrodynamic models suitable for air pollution and other meso–meteorological studies, *Mon. Wea. Rev.*, **106** (8), 1045–1078.

Anthes, R. A., E.Y. Hsie and Y.H. Kuo (1987), Description of the Penn State / NCAR mesoscale model version 4 (MM4), NCAR Tech. Note, NCAR / TN–282–STR, 66pp.

Beijing Group on" 75.8" Heavy Rainfall Coopeative Research (1979), The dynamic analysis of 75.8 Henan excessively heavy rainfall *Acta Meteorologica Sinica*, (in Chinese), **37** (4), 45–55.

Cai Zeyi, Ding Yihui and Li Jishun (1980), The study of the excessively heavy rainfall in Henan Province early in August 1975, *The Collected works on heavy rain and severe convective storms* (3), (in Chinese), (9), 46–59.

Cai Zeyi and Li Jishun (1990), A comparative analysis of severe convective heavy rain and frontal heavy rain during the Meiyu peviod, *Journal of Nanjing Institute of Meteorolgy*, (in Chinese), **13** (4), 544–548.

Cai Zeyi (1990), The disaster of typhoon in China. "*The natural disaster in China*", (in Chinese, will be translated in English), Press of Academic Books and Magazines, 103–116.

Committee of Harness the Huaihe River, (1979), *Survey Reports on the Flood in August*, 1975. (in Chinese).

Ding Yihui, Cai Zeyi and Li Jishun (1978), Study of the excessively heavy rainfall in Henan Province early in August 1975, *Scientia Atmospherica Sinica*, (in Chinese), **2** (4), 276–289.

Ding Yihui, Cai Zeyi and Li Jishun (1980), The study of the excessively heavy rainfall in Henan Province early in August 1975 (1), *The Collected works on heavy rain and severe convective storms*, (in Chinese), (9), 5–38.

Kuo, Y. H., Linsheng Cheng and Jianwen Bao (1988), Numerial somulation of the 1981 sichuan flood, Part 1: Evolution of a mesoscale Southwest Vortex, *Mon. Wea. Rev.*, **116** (12), 2481–2504.

Li Jishun, Ding Yihui and Cai Zeyi (1980), The study of the excessively heavy rainfall in Henan Province early in August 1975 (2), *The Collected works on heavy rain and severe convective storms*, (in Chinese), (9), 39–45.

Research Group on "75.8 Heavy Rainfall" (1977), The Research Report on the Henan Extremely Heavy Rainfall in August, 1975. (in Chinese).

Ross, B. B. and I. Orlanski (1982), The evolution of a cold front, Part I: Numerical simulation, J. Atmos. Sci., 39 (2), 296–327.

Wang, B. and I. Orlanski (1987), Study of a heavy rain vortex formed over the eastern flank of the Tibetan Plateau, *Mon. Wea. Rev.*, **115** (7), 1370–1393.

Zhang, D. L. and R. A. Anthes (1982), A high–resolution model of the planetary boundary layer–sensitivity tests and comparisons with SESAME–79 data, *J. App. Met.*, **21** (11), 1594–1609.

Zhang, D. L. and E.Y. Hsie (1988), A comparison of explicit prediction of convective and stratiform precipitating weather systems with a meso–scale numerical model, Quart. J. R. Met. Soc. **114** (1), 31–60.

Zhao Sixiong and Zhou Xiaoping (1984), The effect of wind field disturbance on the forecast of rainfstorm formation, *Scientia Atmospherica Sinica*, (in Chinese), **2** (4), 276–289.