CHARACTERISTICS OF MESOSCALE FLOOD-MAKING TORRENTIAL RAIN SYSTEM SIMULATED BY HIGH RESOLUTION LIMITED AREA MODEL—NUMERICAL SIMULATION OF A HEAVY RAIN PROCESS DURING MEIYU SEASON IN 1991*

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ABSTRACT

An experimental work on the transplant of high resolution limited area model (HIRLAM) is firstly introduced into China. For the implementation, first of all is to adjust a new geographical coordination and to remove the instability caused by the Tibetan Plateau, the roof of the world. Then, we have applied this model to simulate a flood-making torrential rain process which occurred in the Changjiang-Huaihe River Valley in July 1991. That revealed the formation, development and movement of a mesoscale heavy rain system which had made a disastrous flood event in the middle and lower reaches of Changjiang River Valley.

The result encourages us to use the HIRLAM for the researches on the Meiyu belt, the salient feature of precipitation of East Asia, and the numerical prediction of heavy rains in China.

Key words: heavy rain of Meiyu, high resolution, mesoscale

I. INTRODUCTION

Severe Meiyu torrential rains and disastrous floods occurred in the Changjiang-Huaihe River Valley during May to July 1991, which had made a tremendous lost of property over 60 billion Yuans, the most serious disaster event due to flood economically since the foundation of new China. The extensive and long duration of Meiyu is a most salient precipitation feature in China and in the eastern Asia as well, which often brings heavy rains directly affected by the mesoscale heavy rain/flood systems, and is developed by the mesoscale systems interacted with the synoptic weather systems. Therefore, Meiyu heavy rain is usually more extensive and longer than the heavy rains formed by common strong convection. By historical records in China, the areal mean precipitation within successive 10 days over 10 000 km of 1050 mm (Zhan et al. 1983) occurred in the Qingjiang Valley, a tributary of Changjiang River by Meiyu heavy rains. Because Meiyu heavy rain is usually mixed

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within the synoptic rain belt, it is not easily detectable by the conventional synoptic weather analysis and/or numerical prediction models.

The mesoscale numerical simulation of a Meiyu heavy rain process occurring in the Changjiang-Huaihe River Valley in 1991 is performed by high resolution limited area model (HIRLAM) in the present work. The main content includes some modifications of HIRLAM in order to transplant it into China, and to reveal the characteristics of Meiyu heavy rain system.

II. SOME MODIFICATION OF ORIGINAL HIRLAM

The high resolution limited area model (HIRLAM) numerical weather prediction system (Gustafsson 1993) is jointly designed by experts from nine European countries and has been put into operation in five countries. HIRLAM is more adaptable for the detail analysis of thick atmospheric phenomena and for better revelation and prediction of mesoscale heavy rain. The model has a detailed division both in horizontal and vertical directions, and has an all-round consideration of various meteorological processes, such as radiation, turbulent exchange, surface physics, and precipitation process, etc. Usually the direct absorption of solar radiation is not to be considered in other limited area model, but in HIRLAM, the short wave and long wave radiation dispersion and reflection of cloud are to be considered in detail. For the surface physical processes of three layers underground, the influence of soil temperature and moisture variations on atmospheric process, radiation and precipitation, and the influence of surface friction, reflection, surface temperature and moisture distribution, land-sea deviation on atmospheric and surface heat, momentum and vapour exchange are considered also. The precipitation prediction is commonly a critical problem involved in various models in the world. To strengthen the precipitation prediction, besides the parametric method, a kind of explicit scheme is considered, i.e. consider the water vapour in cloud as an independent variable. For operational propose, the areal and vertical subdivision can be adjusted arbitrarily. It can be subdivided into 31 sublayers vertically and as close as 4 km grid space can be taken in horizontal direction. And for the use of data from other model, a set of programmes is introduced, in which the nested gird can be calculated nonsynchronously (Gustafsson 1993). The result of the model operational used in Denmark shows that the evaluation of prediction is evidently higher than that of ECMWF. Therefore, we believe that to introduce this model into China is practically beneficial. But this model had never been used in the lower and middle latitudes of East Asia, and especially, we are not certain of the performance of the model in prediction and smooth operation, practically when involved with the Tibetan Plateau—the roof of the world, in the upper reaches of Changjiang River Valley.

1. *Elimination of Topographic Error due to the Tibetan Plateau*

The topographic effects of the Tibetan Plateau on the weather system of China are very significant. It is so called the roof of the world, situated in the southwest of Asia, and is on the upper stream of weather circulation of China. But it is rather handicapped not only to get the real information in time but also for its huge volume and higher altitude. When we first introduce HIRLAM into this region, we found that instability of calculation

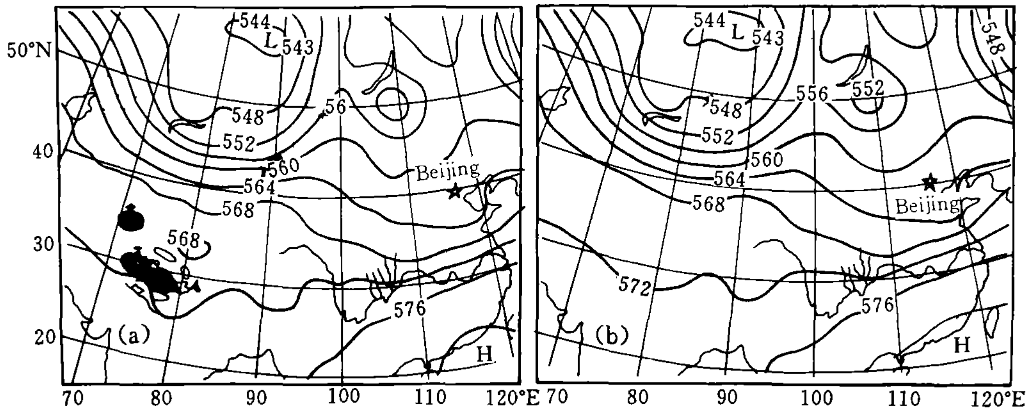


Fig. 1. Potential hight of 500 hPa before modification (a) and after modification (b).

occurred owing to the higher relief of the plateau as the dark areas illustrated in Fig. 1a; especially, it is very remarkable in the finer grid model. Through several operations and calculations, some errors are found out in the original scheme of design, i. e., very low value of surface pressure could be occurred where the altitude is higher than 5500 m, and hence, all of the vertical interpolations related to this value would fail. The original model can be smoothly operated in Europe because the altitudes are mostly lower than 5500 m. Authors had made some modifications as shown in the following initial fields and the errors produced by the higher topography are eliminated (Fig. 1b). The procedure of the calculation of surface pressure is as follows.

Let the vertical distribution of temperature near the surface be

$$T_v = B\ln P + C,$$

where B and C are two constants which are obtained by least square. And to integrate static function

$$\Phi_*^{ec} - \Phi_s^{hir} = -\int_{\hat{P}_s^{hir}}^{P_s^{ec}} R_d T_v \mathrm{d}\ln P,$$

superscript "ec" is ECMWF value and/or any other value different with HIRLAM; "hir" is HIRLAM value. Subscript "s" is surface value, $\hat{P}_s^{hir}$ is the estimation of P_s^{hir}. "$*$" is the value next to Φ_s^{hir}; and

$$\Phi_*^{ec} > \Phi_s^{hir},$$

when $B \neq 0$

$$\ln\hat{P}_s^{hir} = \frac{-C + \sqrt{C^2 + BIB(\ln P_*^{ec})^2 + 2C\ln P_*^{ec} + 2(\Phi_*^{ec} - \Phi_s^{hir})/R}}{B},$$

when $B = 0$

$$\ln\hat{P}_s^{hir} = \ln P_*^{ec} + (\Phi_*^{ec} - \Phi_s^{hir})/RC.$$

Each model layer coordinate is defined by $\hat{P}_s^{hir}$ and then, interpolate the ECMWF data onto each model layer and finally, correct $\hat{P}_s^{hir}$ value. The principle is that the calculated ECMWF and HIRLAM atmosphere from surface to P_l should be balanced, i. e., the thickness difference of $\Phi^{ec}(P_l) - \hat{\Phi}^{hir}(P_l)$ should be reduced to the surface pressure of HIRLAM

$$P_s^{hir} = \hat{P}_s^{hir} \exp\left(\frac{\Phi^{ec}(P_l) - \hat{\Phi}^{hir}(P_l)}{RT_{VN}^{hir}}\right),$$

where T_{VN}^{hir} is the virtual temperature of the lowermost layer of the model.

According to the relief of the topography. P_l must be higher than the highest mountain in the model. Therefore, in order to get a smooth operation, set the P_l to be 300 hPa, because the highest altitude of the Tibetan Plateau is commonly over 6000 m.

2. *Rotated Spherical Coordinate*

The rotated spherical coordinate is a new method adopted in the changeable limited area model. Particularly in the higher latitude, it can help avoid the contraction of longitudes that makes a greater distortion of grid points, and the North Pole is not necessary at the top of the figure. Figure 2 shows the transformation of the coordinate.

Let $\boldsymbol{n}$ on the X-Z plane, and the radius of earth be 1.

$$\boldsymbol{n} = (\cos\lambda_{np}\cos\Phi_{np},\ 0,\ \sin\Phi_{np}),$$

$\boldsymbol{c}$ is a point on the earth, and its longitude and latitude is (λ, Φ) respectively. In the new coordinate, $\boldsymbol{c}$ is (λ', Φ')

$$\boldsymbol{c} = (\cos\lambda\cos\Phi,\ \sin\lambda\cos\Phi,\ \sin\Phi).$$

$\boldsymbol{d} = (0, -1, 0)$, pointed to the counter direction of Y axis.

$$\Phi' = \pi/2 - \arccos\ (\cos\lambda\cos\Phi\cos\lambda_{np}\cos\Phi_{np} + \sin\Phi\sin\Phi_{np}),$$

$$\lambda' = \arccos\left|\frac{\cos\Phi_{np}\sin\Phi + \sin\Phi_{np}\cos\lambda\cos\Phi}{\cos\Phi'}\right|.$$

According to the method, we choose 72—120°E, and 20—40°N as the simulation area, which includes the whole area of Tibetan Plateau and the Changjiang River Valley.

After the modification and correction of the original model, HIRLAM can be

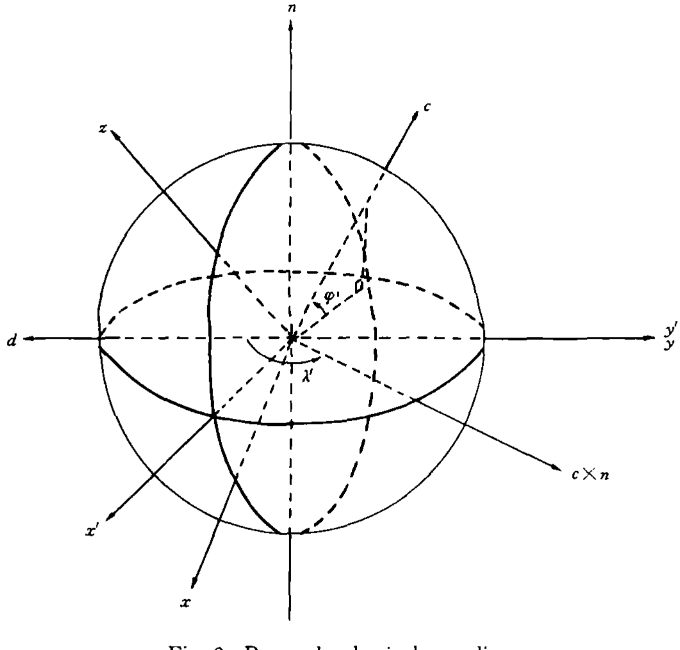


Fig. 2. Rotated spherical coordinate.

successfully operated in the Tibetan Plateau and the Changjiang River Valley, and a series weather systems are well simulated in these areas. Besides, various atmo-physical diagnostic fields related to the formation and development of Meiyu rains are added, such as vorticity, divergence, stability, low level jet, and various cross-sections are obtained.

By the calculation, the model has a higher ability to reveal the characteristic features of mesoscale heavy rain system and more accurately to predict either the trend or the order of magnitude of the system (Zhu 1995). Therefore, we introduce the HIRLAM to simulate a Meiyu heavy rain process that had made a disastrous flood event in the Changjiang-Huaihe Rivers Valley in 1991.

III. METHOD AND DATA

The modified HIRLAM is utilized for the simulation on the Meiyu heavy rains during 4—7, July 1991 in the Changjiang and Huihe Rivers Valley. The whole process is calculated by two periods: July 4, 0000 UTC to 6, 0000 UTC and 6, 0000 UTC to 7, 0000 UTC. The prediction model is primitive equation model and comprehensive physical parameterization is considered also. The integration area as shown in Fig. 4, is 194×110 grid points ($0.25^\circ\times0.25^\circ$), and 31 layers. The explicit scheme is used for precipitation, and every six-hour analysis of ECMWF for the boundary fields. In order to make a smooth operation, the six order Raymond filter is adopted here, which is more efficient to filter the short wave. The initial fields are produced by data assimilation, and global multiple optimal interpolation is adopted for the objective analysis. In order to get initial fields which keep the optimum mesoscale features and least errors in the first step of operation, the digital filter scheme which was developed by Huang et al. (1994) is used here.

For the calculation of parametric physical processes, some other background data, friction coefficient of surface, reflectance, vegetation, surface temperature and moisture distributions, deviation of land and sea are preliminarily calculated from the global climate data; the topographic relief is transferred from $10'\times10'$ data; and the highest relief of Tibetan Plateau can be calculated up to 6000 m.

IV. RESULT AND DISCUSSION

1. *General Circulation*

A typical Meiyu front occurred during 4—7, July 1991. The front stretched from the northwest Pacific toward the east side of Tibetan Plateau along 30°N. By the south side of the front, a strong subtropical high stretched from the East China Sea toward the inland of China. And by its west side, the warm and moist air with high vapour content from the Bengal and South China Sea transferred successively by southwest low level jet toward the Changjiang-Huaihe Rivers Valley. By the northern side, a blocked high was situated in the middle and higher latitudes; the cold air separated and moved southward continuously from the westerlies low trough and confronted with the warm and moist air over the Changjiang-Huaihe Rivers Valley where the middle latitude diabatic belt is also found. Meanwhile, a number of weather systems are favourable for the precipitation. Most of them are of synoptic scale, but the heavy rain/flood systems are formed by the interaction of multiple scale of weather systems and the majority of the rain/flood systems are of mesoscale. The simulation indicates (as shown later) that a mesoscale heavy rain system began to form at 0000 UTC, 5 July, nearby Yichang, in the upper reaches of Changjiang River Valley, and thereafter, it enhanced continuously and moved eastward. Eventually, a heavy rain/flood process occurred in the middle and lower reaches of Changjiang River Valley on 6, July. The 24 hour precipitation up to 256 mm was observed at Huangshan station and a disastrous flood event happened at Huangshan Mountain region.

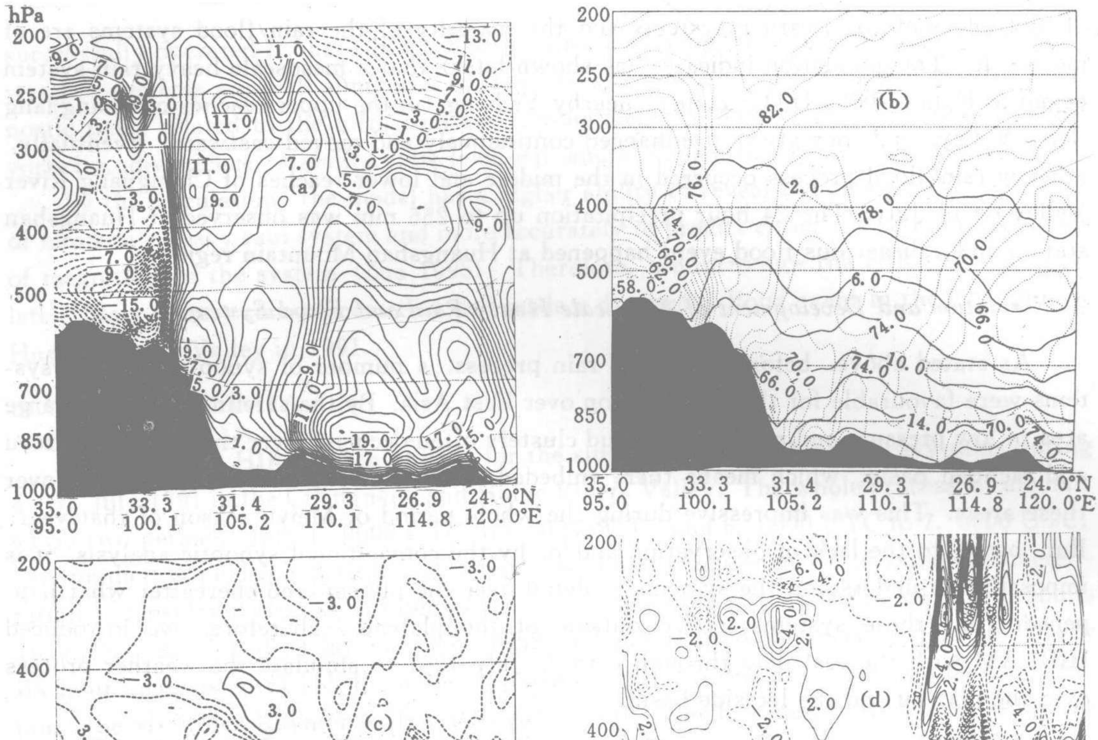
2. *Formation and Development of Mesoscale Heavy Rain and Flood System*

As stated above, before the heavy rain process, a number of synoptic weather systems were favourable for the precipitation over East Asia. By the satellite images, a large area of low pressure and mixed type cloud clusters often occurred over the Tibetan Plateau and Sichuan Basin, which means there embeded a lot of strong convective systems over these areas. This was impressive during the whole period of Meiyu season of that year. But, owing to the lack of observation and/or by the conventional synoptic analysis, it is impossible to understand the systems in detail over the plateau and thereafter what happened while these systems moved outside of the plateau. Therefore, we introduced HIRLAM with the real data through 4 to 7, July 1991 to simulate the weather process over the plateau and the lee-side basin.

(1) *Formation of vortices over Tibetan Plateau and Sichuan Basin*

The simulation shows that there are a lot of small vortices over the Tibetan Plateau and the neighboring Yunnan-Guizhou Plateau; therefore, the low level flow fields are rather fragmentary. These vortices are mainly due to strong solar radiation in summer on the plateaus. The scales of them are usually under 100 km, and so they are not easy to be detected by synoptic analysis.

As shown in sequential temperature profiles (figures ignored), isotherms clearly curve upward over the plateaus and the temperature at lower layer of plateaus is higher than that of the corresponding layer beside the plateaus. These vortices in the lower layer are with warm centers, and $\partial\theta_e/\partial p$ also shows very remarkable moist instability in the lower layer. And a diurnal variation is shown in sequential profiles. As Ding (1994) pointed out, a lot of vortices over the plateaus are mostly formed by the influence of solar radiation; and/or by the uplifting of the topography, and mostly produced in the central and west parts of the plateaus, only few of which can move outside of the plateaus. In the simulation (Fig. 4), there are a lot of vortices which are corresponding to the thick and mixed type clusters of cloud. As shown in Figs. 3d—3e, the magnitudes of divergence and vertical velocity over the plateaus are in great contrast with that in the Sichuan Basin. That also shows the role of the specific underlying conditions in maintaining these vortices. When these vortices moving outside of the plateaus, owing to the loss of necessary underlying conditions, vorticity will usually be weakened. They can exist unless they are driven by another stronger system or maintained a longer duration and/or combined with other low systems outside of the plateaus.



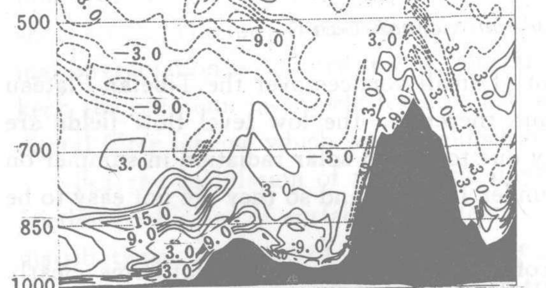


Fig. 3. Cross-sections of variables at 12 UTC, 4 (c) and 00 UTC, 5 July 1991 (a, b, d and e): (a) wind field normal to the profile, solid lines indicate inward (m s^{-1}), the dashed outward (m s^{-1}); (b) profile of water vapour, solid lines q (g kg^{-1}), the dashed θ_e (K); (c) profile of moist instability, solid lines $\frac{\partial\theta_e}{\partial p} > 0$ (K Pa^{-1}), the dashed $\frac{\partial\theta_e}{\partial p} < 0$ (K Pa^{-1}); (d) profile of divergence, solid lines div. >0 (10^5 s^{-1}), the dashed div. <0 (10^5 s^{-1}); (e) profile of vertical velocity, solid lines $\frac{dp}{dt} < 0$ (Pa s^{-1}), the dashed $\frac{dp}{dt} > 0$ (Pa s^{-1}).

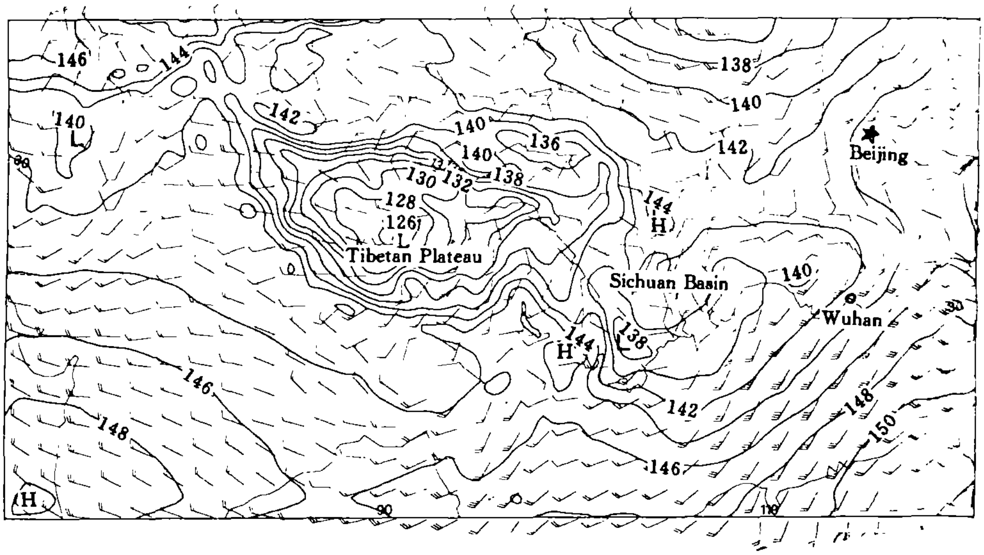


Fig. 4. Potential height and wind field of 850 hPa 1200 UTC, 5 July 1991 (unit: dagpm).

The vortices over the Sichuan Basin, namely southwest vortices, are different in property with former ones. By the simulation, the isotherms are not curved upward over the basin. Besides, the magnitudes of divergence and vertical velocity over the basin are very similar to Figs. 3d and 3e. That means the formation of vortices over the basin is different from that over the plateaus. Vortices over the basin are mainly due to the roundflow of the southern branch of westerlies, surface friction and the lee-side trough of overflow. Kuo (1986) has demonstrated by the numerical experiments with or without Yunnan-Guizhou Plateau, but under the influences of roundflow, vortices will be formed over the basin. Therefore, the formations of vortices over Tibetan Plateau and Sichuan Basin are different. But where the heavy rain/flood system will develop, and which system is of more importance are rather difficult to be decided by the forecasters.

(2) *Formation, development and precipitation of mesoscale heavy rain and flood system*

In the initial stage, 0000 UTC, 4 July, the 500 hPa high level trough separated from the Lake Balkhash is moving southward to the plateau. And the front of the trough drives a plateau vortex moving eastward. At 0000 UTC, 5. July, this trough moves out of the plateau and the vortex combines with the low level vortex of the Sichuan Basin. By the comparison of relative vorticities of the vortexes before and after moving outside of the plateau (figures ignored), owing to the loss of original underlying conditions of the plateau, the magnitude weakens clearly. In the meanwhile, a high level trough moves into the basin and combines with the southern branch monsoon trough, and then, a low level vortex over the basin develops and its range is doubled. Moreover, when high level trough superimposes with the southern branch monsoon trough, the warm advection in front of the high level trough has triggered and strengthened the low level southwest jet in front of the southern branch trough. A southerly flow is formed, south of 30°N, between 90—110°E, on 850 hPa, which makes the low level jet enhanced. In the same time, to the north of 30°N, a weak easterly occurred. A shear zone between the southerlies and the easterlies, therefore, results in an ideal convergent area. Yichang is situated in the central part of this convergence. As shown in profiles (Figs. 3a—3e) through the centre, a very strong low level jet is shown in Fig. 3a at the southern side of Daba Mountain, at 0000 UTC, 5, July. The magnitude of the centre is up to 20 m/s. The main vapour belt is situated at the left side of low level jet outside of the basin. The moist instability profile curved ($\partial\theta_e/\partial p>0$ Fig. 3c) also shows that low level thick moist instable layer is located nearby the low level jet but not in the basin centre. Therefore, when westerlies trough moves in, it triggers the development of instability. Moreover, due to the uplifting of Daba Mountain, in Figs. 3d and 3e, a quite strong centre of convergence and vertical motion begins to form at the windward side of Daba Mountain. And then, in the sea level map (omitted), an induced new closed mesoscale vortex is shown in Yichang area, at 0000 UTC, 5, July, with a horizontal scale of only 100 km, which is even not closed on 850 hPa level. By Figs. 3d and 3e, it can be seen that convergence is only up to 850 hPa and then become divergence at 700 hPa. The maximum vertical motion only occurs between 850—700 hPa, which means that the convergence is rather thin and shallow. Precipitation strengthens in Yichang district with the occurrence of vortex and hence large energy is gained from the release of latent heat. A heavy rain/flood system is formed and a closed system can be seen at 850 hPa 12 hours later (Fig. 4). Its horizontal scale shown on 850 hPa is only of 100—200 km.

3. *Movement of Mesoscale Heavy Rain/Flood System*

It can be seen in the wind field (Fig. 4) that Meiyu front becomes a long wind shear line with the appearance of high level trough. It is about several thousand kilometers long, from 100°E to 120°E, along 30°N, and the mesoscale heavy rain/flood system occurred. From the relative vorticity field on 850 hPa (Fig. 5), there is an east-westward zone of

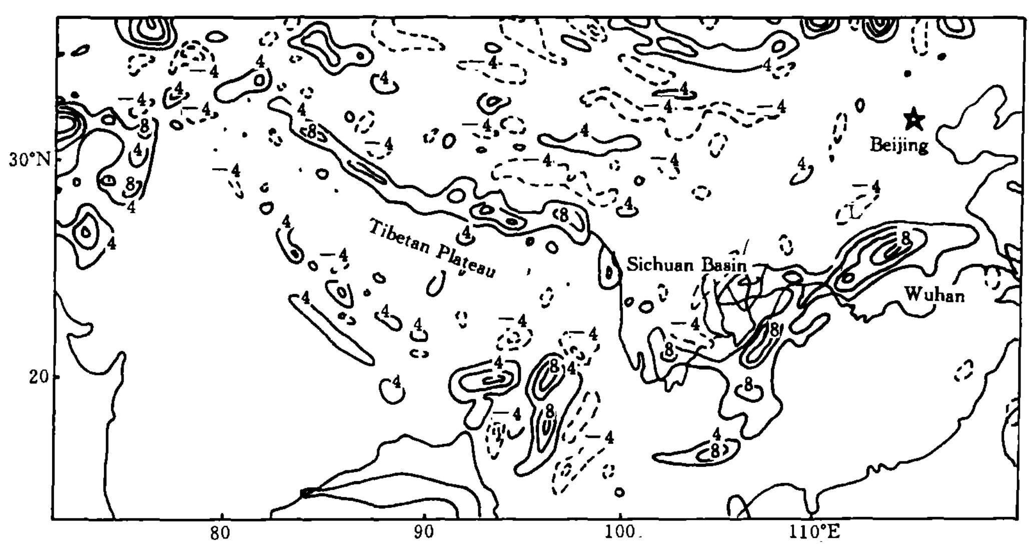


Fig. 5. 850 hPa relative vorticity, 1800 UTC, 5, July, 1991.

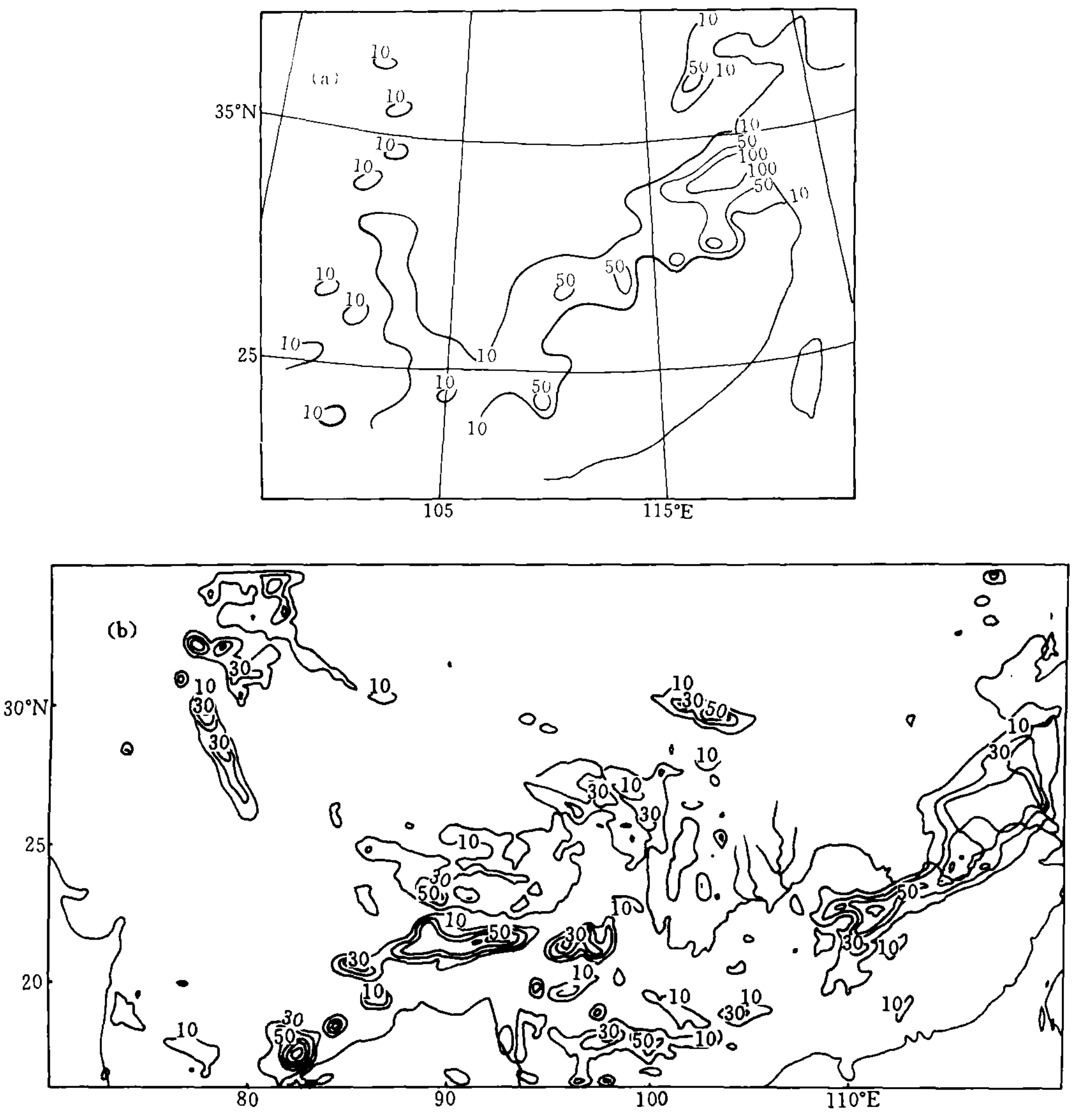


Fig. 6. 24 hour rainfall 6. July. 1991: (a) real; (b) simulated.

positive vorticity. The former shear zone in which the heavy rain/flood system was formed stretches eastward with the eastward moving of high level trough. The area is continuously enlarged, but is always consistent with the shear line. That means, the successive Meiyu heavy rains with the mesoscale systems continuously regain the energy from the large scale weather systems, especially where Meiyu front occurred in the summer of Changjiang River Valley. The wind shear line and the positive vorticity zone can be utilized to estimate the Meiyu front, practically under 700 hPa which is rather difficult to define in summer.

Comparison of simulation precipitation with the real data is shown in Fig. 6; the main precipitation areas are quite concordant; and some heavy rain centers are also similar. Although the simulated rainfall in Huangshan Mountain region does not reach the observed value, an extra-heavy rainfall over 100 mm is obtained.

V. CONCLUSION

By introducing modified HIRLAM, a variety of weather systems over the Tibetan Plateau and Changjiang-Huaihe Rivers Valley can be simulated in detail. And by the simulation the vortices over the plateaus are different from those over the Sichuan Basin. A newly induced mesoscale vortex forms nearby Yichang, and reveals the influences of the low level jet, high level trough in westerlies, and vortices over the Sichuan Basin on the induced vortex. In the initial stage, the horizontal and vertical scale of vortex is quite small, and it becomes a heavy rain/flood system 24 hours later. When v rious weather systems occurred in the plateau and in its eastern region, it is difficult to define the accurate occurrence of this newly formed mesoscale system by conventional synoptic analysis or numerical prediction. Therefore, it is beneficial to improve the prediction of time and location of heavy rain, if the development and movement of newly formed mesoscale system can be detected earlier. The high resolution in revealing two kinds of vortices over the plateau and the basin also helps us to understand the formation, development of the heavy rains further.

This work is a preliminary study, and more case-study and detail research of heavy rains are needed.

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