IMPACTS OF DIABATIC PHYSICS PARAMETERIZATION SCHEMES ON MESOSCALE HEAVY RAINFALL SHORT-RANGE SIMULATION

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ABSTRACT

Based on the non-hydrostatic version of Mesoscale Model version 5 (MM5) and the data sets of four heavy rainfall scenarios occurring in August 2001 in China, this paper investigates the impacts of diabatic physical processes on predictions of dynamic and thermodynamic elements of heavy rainfall in China, deeply analyzes the effects of convective schemes on mesoscale heavy rain simulations and discusses the feasibility of using model physics perturbations in ensemble simulation of heavy rain. The results show that diabatic physical processes have little impact on the short-range prediction of geopotential height. However, planetary boundary layer schemes and convective schemes have significant influence on moisture divergence flux, vertical velocity, and unstable stratification, which are the three basic conditions of torrential rain. The forecast deviations in different convection schemes increase rapidly in the first 12 h time periods of simulation and the deviation structures are well correlated to that of sub-grid-scale rainfall, while in the later periods of simulation with less correlation. Diabatic physical processes influence the structure and evolution of the simulations. For the rain storm events with a homogeneous thermal environmental condition in China, the numerical model ensembles could be created by perturbing the planetary parameterization scheme and convective parameterization.

Key words: heavy rain, numerical prediction, diabatic physics, ensemble prediction

I. INTRODUCTION

Heavy rainfall is one of the most serious natural disasters in China. Through the great efforts of China's scientists, significant progresses have been made in analyses, forecast and basic theoretical research and practices (Tao 1980; IAP 1998). In recent years numerical prediction became one of the major tools (Li et al. 1997; Cui et al. 1999) for prediction on heavy rainfall. Extensive applications of various diabatic physics parameterization schemes in models greatly improved the heavy rainfall numerical prediction. Cumulus convection process is one of the most important wet physical processes in the model. The common cumulus convection parameterization schemes include Betts-Miller (Betts 1986; Betts and Miller 1986) Anthes-Kuo (Anthes 1977), Arakawa-Schubert (Arakawa and Schubert 1974), Fritsch-Chappell (Fritsch and Chappell 1980a; 1980b), Kain-Fritsch (Kain and Fritsch 1990), and Grell schemes (Grell 1993). The primary characteristics of these schemes are that the convective movement will be triggered when the model atmosphere satisfies a set of parameters, with which the schemes define the convective triggering function under certain close assumptions. By using various diabatic physics parameterization schemes, the model can simulate in a more realistic way the internal structure and the variance features of mesoscale system, in particular mesoscale convection system (MCS) (Zhang 1998).

China is a region of monsoon climate, where heavy rainfall occurs in the cumulus and stratocumulus hybrid clouds. The cumulus convection parameterization schemes mentioned above are primarily based on the study of the occurrence and development of cumulus convection in areas outside China. Many scholars in China have studied and improved the cumulus convection parameterization under the situation of China, and achieved quite good forecast results (e. g. Yan 1983; Chen and Qian 1992; Research Group 1996; Chen 1997; Liu 1998). We also notice, however, that different schemes have different predictions in respect to when and where the heavy rain occurs and the strength of the heavy rainfall due to the variant definition of convection parameterization. Many scholars at home and abroad made comparative analysis on these schemes, finding that none scheme has overwhelming advantages over others (Pan et al. 2002; Wang et al. 2001; Gu 1999). In addition, initial condition errors, model errors and other diabatic physics parameterization schemes add to the uncertainty of occurring time, location and area for heavy rainfall and restrain the further improvement of accuracy in heavy rain prediction.

In the recent couple of years, ensemble prediction was tried to solve the uncertainty of numerical prediction on heavy rainfall. Stensrud et al. (2001) used the method of model perturbation with various physics on the ensemble prediction test of strong convective weather. They find that the ensemble prediction using the various physics is effective in the heavy rainfall in homogeneous thermal field. Compared with the ensemble prediction of initial condition perturbation, however, the ensemble prediction of model perturbation lacks sound theoretical bases. As the environmental thermal field is homogeneous in the heavy rain process in China, deep and thorough analysis must be made first on the characteristics and ways of the effects of diabatic physical process on the heavy rain numerical prediction in China if the model perturbation is applied to the ensemble prediction of heavy rainfall. Most of the researches on cumulus convection parameterization in China focus more on the examination of influence of rainfall prediction while less on the effects of environmental dynamic and thermal fields. However, since the precipitation is controlled by dynamic and thermal fields, analysis of the effects of diabatic physical process on the environmental dynamic and thermal fields has great significance in understanding the intrinsic cause for the influence of various parameterization on the rainfall prediction. This article focuses on the impact of diabatic physical process schemes, in particular, the cumulus convection parameterization process on dynamic and thermal predictions of heavy rainfall in China with deep analysis of the effect of convective parameterization schemes on mesoscale heavy rain predictions. This is essential for study of ensemble prediction in heavy rain with the method of model perturbation. The article is divided into six parts: the second and third parts introduce the experiment scenarios and model. The fourth part presents the comparison of the impact of diabatic physical processes on the environmental dynamic field. The fifth part analyzes the impact of convection parameterization schemes on the structure and change features of mesoscale dynamic and thermal fields based on the case of extremely heavy rain occurring in Shanghai from August 5 to August 6, 2001. The sixth part discusses the ways of impact of different parameterization schemes on models. The final part is the summary.

II. STUDY CASES

As China is a vast country under the influence of monsoon, the weather systems in which heavy rain develops vary from region to region. To analyze more thoroughly the impact of the diabatic physical processes on different regions and types of heavy rain, the article chooses the most important four heavy rain scenarios in August 2001 (Abulimiti 2001). namely, "8. 5" Heavy Rain in Shanghai, "8. 18" Heavy Rain in Upper Reaches of the Yangtze River and Northern China, "8. 24" Heavy Rain in the South to the Yangtze River, "8. 29" Heavy Rain in Hainan and South China. The four cases have different weather systems. From August 5 to 6, under the influence of the tropic low pressure, heavy rain occurred in the eastern part of the South of the Yangtze River, where Shanghai saw the maximum precipitation of 294 mm, the biggest one since 1949. The heavy rain process from August 18 to 19 was the strongest one in northern China in 2001, of which the weather system includes trough of low pressure in westerlies and cold front. The heavy rain on August 24 to 25 mainly took place in the southern region to the Yangtze River, with the impact system of shear line. The heavy rain on August 29 to 30 occurred in South China with tropical storm Fitow as its impact system. For example, the coastal area of South China suffered extremely heavy tropical rain, which in Hainan amounted to 460 to 933 mm. As is shown, the four heavy rain scenarios have different impact systems, triggering mechanisms and raining regions. They can be taken as typical examples.

III. EXPERIMENT MODEL AND THE CONVECTION PARAMETERIZATION SCHEMES

1. *Description of Model System*

The model chosen for use in this study is a non-hydrostatic version of the Pennsylvania State University-National Center for Atmoshperic Research (PSU-NCAR) Mesoscale Model version 5 (MM5) with full physical processes and a two-way interactive grid-nesting procedure (Grell et al. 1994). All model simulations have 23 vertical sigma levels, with the spacing of sigma levels reduced near the ground surface to better simulate the evolution of the planetary boundary layer (PBL). The simulation domains in the fourth and fifth parts of the article have slight difference, and the parameters of horizontal grid spacing of the domains will be described in these two parts. The time separation scheme will be used in the calculating of the model. As for the lateral condition, the initial data of the model are created by blending the global analysis data of National Meteorological

Center (T106L19) with eastern Asia surface and rawinsonde data using the approach of Cressman's gradual correction method of banana weighted coefficient analysis. These blended analyses are also used to provide the model boundary conditions at 12-h intervals.

Since the year 2000 the Numerical Weather Prediction Division of National Meteorological Center has put the non-hydrostatic MM5V3 into quasi-operation on SW- I computer that was developed independently by China. The diabatic physical processes of that model are selected on the basis of careful comparison and analysis. Therefore, the physical process of the controlling simulations in this article is the same as in trial operation. These include Dudhia ice phase scheme (Dudhia 1989) used in the resoluble-scale precipitation; Anthes-Kuo (Anthes 1977) cumulus convection parameterization scheme in coarse grid domain, Grell cumulus convection parameterization scheme (Grell 1993) in inner grid domain, Hong-Pan high resolution planetary boundary layer parameterization scheme (Hong and Pan 1996) and Dudhia radiation schemes (Dudhia 1989).

2. *The Convection Parameterization Schemes*

As this article focuses on studying the impact of different cumulus convection parameterization schemes on heavy rain forecast, these schemes used in the experiment cited in this article are described hereby first.

Anthes-Kuo scheme is a parameterization one on assumptions of the presence of grid-scale moisture convergence. There are several convection triggering standards for Anthes-Kuo scheme: 1) the moisture convergence (M_t) in one grid air column is greater than 3.0×10^{-7}kg m^{-2} s^{-1}; 2) checking the unstable convection energy, the thickness of the cloud ($\Delta\sigma \geqslant 0.3$) and effective buoyant energy to see whether they satisfy the conditions of the convection occurrence. If the convection occurs, then calculate the convection precipitation, normalized vertical profile functions of thermodynamic structure $N_h(\sigma)$, $N_m(\sigma)$, and moisture divergence vertical eddy flux $V_{qf}(\sigma)$.

Betts-Miller (BM) wet convective adjustment scheme depends on the assumption of quasi-equilibrium between the cloud field and the large-scale forcing, believing that the presence of cumulus convection makes the thermal structure of model change from the non-balance thermal reference profile to quasi-balance. Though the scheme cannot describe thoroughly the inter-influence between the cumulus convections and environmental forcing field, it can still yield good temperature and moisture structure on the basis of numerous observation data.

Grell Scheme is a simplified Arakawa-Schubert parameterized one on single cloud model. Quasi-equilibrium assumption used in Arakawa-Schubert scheme is also adopted as the closed condition in Grell Scheme. In the Grell Scheme, the cloud is described to be two steady-state circulation caused by updrafts and downdrafts. There is no direct mixing between cloudy air and environmental air except at the top and the bottom of the circulation. Air mass flux is constant with height, and there is no entrainment or detrainment along the cloud edges. Precipitation rate is a function of low atmospheric average wind shear in the model. The scheme also includes the cooling effect of moist convection downdrafts. The feedback to large-scale thermodynamic fields is completely decided by the compensative air mass fluxes and detainment at cloud top and bottom.

Similar to Fritsch-Chappell Scheme, Kain-Fritsch (Fritsch and Chappell 1980) is a type of buoyant energy cloud scheme that takes into consideration the entrainment of updrafts and detainment of downdrafts in the cloud. As for the close conditions, the occurrence of the convection and the changes of the environment are determined by the convective available position energy (CAPE) and effective buoyant energy. The convection activities allow the effective buoyant energy to be depleted within a limited time interval τ. The cloud model of Kain-Fritsch is mass-conversed, allowing the cloud edge and the environment to affect each other and taking into consideration the micro-physical process of cloud water icing, in which the cloud changes from the saturated liquid water to cloudy ice.

IV. THE RELATIVE IMPORTANCE OF DIABATIC PHYSICS FOR HEAVY-RAIN NUMERICAL SIMULATION

1. *Simulated Domain*

A two-dimensional nested domain shown in Fig. 1 is designed for the four scenarios. The coarse grid domain of the model is Asian area, whose central longitude, latitude, horizontal grid spacing and number of grid points are 42.5°N, 95°E, 45 km and 136×169, respectively. The fine mesh grid domain of the model covers the eastern region of China, whose horizontal grid spacing and number of grid points are 18 km and 169×169. The above-mentioned control model is used to simulate the four scenarios. The time for the integral initial field is 1200 Z, August 5, 1200 Z, August 17, 1200 Z, August 23, 1200 Z, August 28, respectively, with total 48 hours of integration. Figure 2 shows the precipitation distribution comparison of the 48-hour observation and model forecast among the four cases. As shown in the figure, all of the scenarios are simulated quite well by the

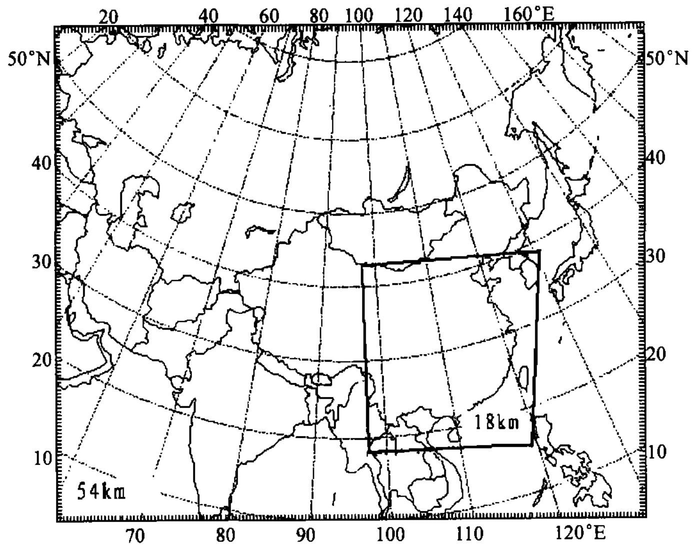


Fig. 1. Model domain for four scenarios. Coarse grid domain of the model is Asian area, whose central longitude, latitude, horizontal grid spacing and number of grid points are 42.5°N, 95°E, 45 km and 136×169 respectively.

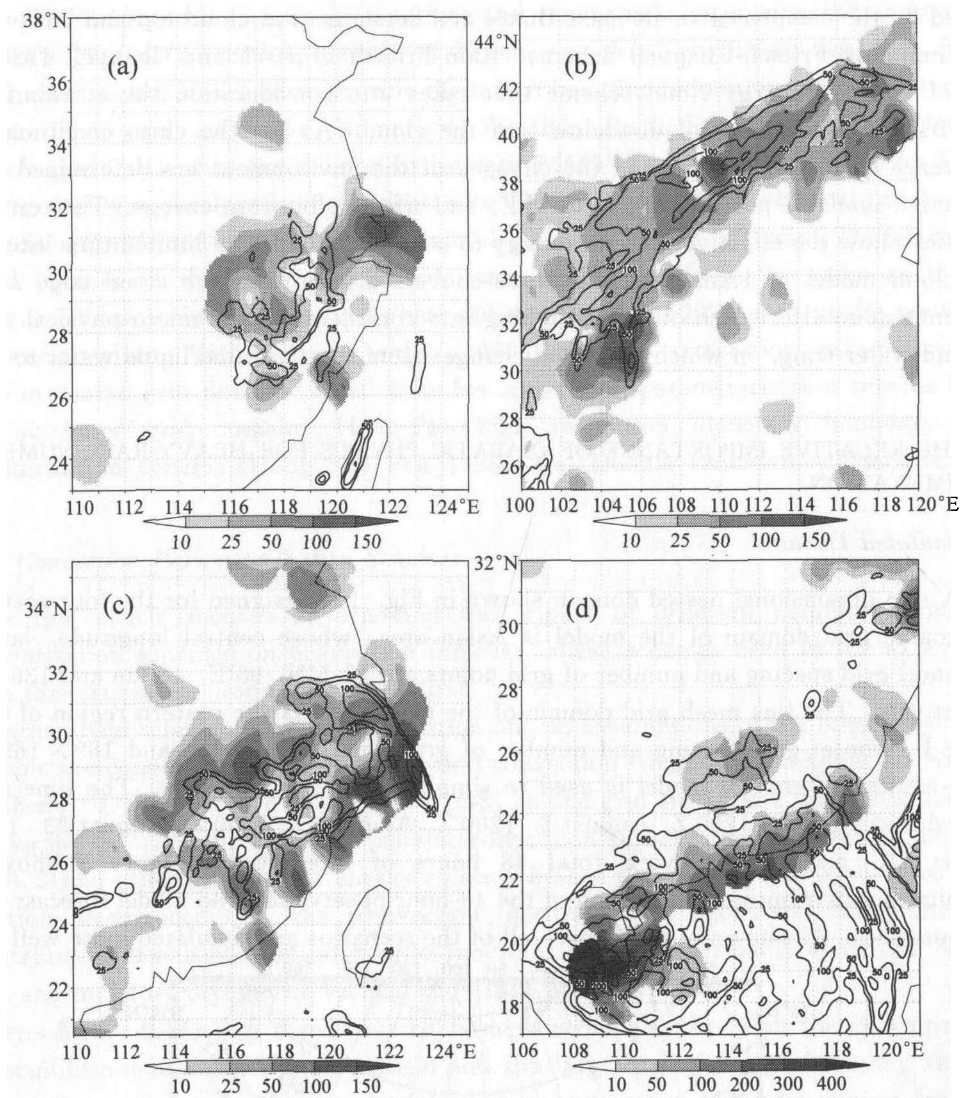


Fig. 2. 48 h precipitation observations (shaded) and prediction (contour) (unit: mm) : (a) 1200 Z Aug. 4—1200 Z Aug. 6, (b) 1200 Z Aug. 17—1200 Z Aug. 19, (c) 1200 Z Aug. 23—1200 Z Aug. 25, and (d) 1200 Z Aug. 28—1200 Z Aug. 30.

control model in terms of the location and strength of heavy rainfall except that the main heavy rain area of "8. 5" case deviates Shanghai City. The following analysis and statistic calculation are based on the model output results of the fine mesh domain.

2. *The Design of Test Scheme and Statistic Parameters*

Six sensitivity test schemes (see Table 1) are designed for the second nested domain to study the impact of different diabatic physical processes, in particular, the convection parameterization schemes on heavy rain numerical prediction. The first is the control simulation of the model. The impacts of different diabatic physical processes on heavy rainfall prediction are studied in Tests 1, 2, 3 while the impacts of different convective parameterization schemes on heavy rain prediction are studied in Tests 4, 5, 6. Test 7 studies the impact of the explicit scheme on the heavy rain forecast.

Table 1. The Design and Purpose of the Test

Test name	Explicit precipitation (Dudhia)	convective	PBL (Hong-Pan)	Radiation (Dudhia)	Purpose
Control	on	GR	on	on	control prediction
Test 1	on	off	on	on	impacts of convective process
Test 2	on	GR	off	on	impacts of boundary process
Test 3	on	GR	on	off	impacts of radiation process
Test 4	on	AK	on	on	impacts of Anthes-Kuo
Test 5	on	KF	on	on	impacts of Kain-Fritsch
Test 6	on	BT	on	on	impact of Betts-Miller
Test 7	mixed ice phase	GR	on	on	impacts of explicit scheme

Note: on: selected, off: closed, GR: Grell scheme, AK: Anthes-Kuo scheme, BT: Betts-Miller scheme, KF: Kain-Fritsch scheme.

To evaluate quantitatively the impact of diabatic physical processes on heavy rain, we define S_x, the deviation between the prediction of the sensitivity test and control prediction as

$$S_x = \frac{\int_{EC}(x_{exp} - x_{cont})^2 dA}{\int_{EC} dA}, \tag{1}$$

where x_{cont} is the prediction variable of control test, x_{exp} is the prediction variable of the sensitivity test, EC is Eastern China. At the same time, to compare quantitatively the physical quantity of different dimensional values, such as the deviation of temperature and wind, we define the standardized deviation S_{x_nor}

$$S_{x\_nor} = \frac{\int_{EC}(x_{exp} - x_{cont})^2 dA}{\int_{EC}(x_{ana} - x_{cont})^2 dA},$$

where x_{ana} is the objective analysis value.

3. *Results Analysis*

Select component zonal wind U, meridional wind V, vertical speed W, temperature T, specific humidity Q, geopotential height H, moisture flux divergence A, divergence D and vorticity ζ on the levels of 200 hPa, 500 hPa and 850 hPa, calculate respectively their deviation and standardized deviation in Tests 1—6. Table 2 shows the average deviation value of accumulated precipitation prediction in the four scenarios at 48 h integration and the average value of the prediction standardized deviation of the above nine physical elements. It must be clarified that, due to the unsteady calculation, Test 2 of "8. 18" scenario failed to integrate for 48 hours. There are only three scenarios in Test 2 for statistics.

Table 2. The Average Deviation of 48 h Precipitation Predictions and Average Standardized Deviation of Physical Elements in Four Heavy Rain Scenarios

Test	R	U			V			W			T		
name	Height(hPa)	200	500	850	200	500	850	200	500	850	200	500	850
Test 1	45.5	0.39	0.33	0.53	0.42	0.49	0.36	**1.17**	**3.33**	**2.48**	0.28	0.34	0.26
Test 2	36.2	0.86	0.63	2.53	0.75	**1.19**	**1.49**	0.60	0.89	**1.57**	0.72	2.80	**3.36**
Test 3	28.0	0.72	0.52	1.02	0.47	0.70	0.53	0.61	0.78	**1.11**	0.52	0.90	**1.09**
Test 4	23.2	0.25	0.19	0.19	0.23	0.27	0.12	0.45	0.87	**1.04**	0.11	0.24	0.08
Test 5	28.1	0.41	0.34	0.47	0.34	0.32	0.30	0.92	0.94	**1.26**	0.57	0.37	0.26
Test 6	61.8	0.26	0.15	0.61	0.30	0.22	0.31	0.63	0.64	**1.18**	0.21	0.17	0.57
Test 7	11.2	0.28	0.24	0.57	0.28	0.30	0.37	0.82	**1.11**	**1.73**	0.13	0.20	0.61

Test	Q			H			A			D			ζ		
name	200	500	850	200	500	850	200	500	850	200	500	850	200	500	850
Test 1	0.38	0.53	0.52	0.02	0.05	0.03	**1.86**	**1.76**	**2.06**	**1.65**	**1.61**	**1.68**	**1.34**	**1.44**	**1.46**
Test 2	0.44	0.89	**1.54**	0.34	0.28	**1.60**	**1.22**	**1.26**	**1.53**	**1.26**	**1.47**	**1.61**	**1.62**	**1.30**	**2.07**
Test 3	0.48	0.69	0.89	0.06	0.08	0.11	**1.23**	**1.13**	**1.06**	**1.21**	**1.15**	**1.01**	**1.09**	**1.03**	**1.07**
Test 4	0.15	0.24	0.15	0.05	0.02	0.02	0.89	**1.05**	0.96	0.85	0.96	0.85	0.71	0.79	0.73
Test 5	0.61	0.47	0.50	0.02	0.10	0.03	**1.68**	0.99	**1.27**	**1.28**	0.94	**1.10**	**1.19**	0.84	**1.04**
Test 6	0.71	0.54	0.45	0.05	0.06	0.10	**1.40**	0.74	**1.15**	0.96	0.73	**1.01**	**1.01**	0.56	**1.10**
Test 7	0.29	0.42	0.46	0.03	0.03	0.06	**1.38**	**1.00**	**1.57**	**1.20**	0.99	**1.35**	**1.02**	0.92	**1.47**

Note: A: moisture flux divergence, D: divergence, ζ: vorticity; the figures underlined indicate that their standardized deviations are larger than 1.00.

The deviation of the total rainfall in Tests 1, 2 and 3 shows that different diabatic processes have different impacts on precipitation prediction. The scheme with the greatest impact is convection parameterization scheme, followed by planetary boundary layer scheme, and the last one the radiation scheme, each with the deviations of 45.5, 36.2 and 28.0 respectively. The standardized deviations of dynamic field and thermal field in Tests 1,2,3 show that the diabatic physical process parameterization has a big impact on vertical speed, moisture flux divergence, divergence, and vorticity but small impact on model variable U, V, T and Q. The standardized deviation of the former is greater than 1.0, while that of the latter is usually smaller than 1.0. More importantly, the standardized deviation of vertical speed is far greater than those of other physical elements, reaching 3.3 on 500 hPa level and moisture flux divergence on 850 hPa level 2.06. This shows that the convective parameterization scheme has great impact on physical elements that reflect directly the mesoscale structure of the model atmosphere, such as the vertical speed. The deviation of U, V, W, T, Q and H in Test 2 mainly occurs in the mid and lower layers of the model. Except W, the deviation values are usually greater than those in Test 1, and particularly the deviation value of T in low level is the biggest. This shows that, determined by the characteristics of the boundary layer scheme, the boundary layer has great effects on physical elements of the mid and lower levels in the test. It is also worth mentioning that, Tests 1, 2 and 3 have small impacts on height field. Except that of the lower level 850 hPa caused by boundary layer scheme, all of the standardized deviations are smaller than 0. 11, with that of the height field in Test 1 as the smallest and even the biggest is no more than 0. 05. Therefore, we can see that in the short-range numerical prediction, the diabatic physical process, especially the convection parameterization scheme has small impact on large-scale circulation, but big impact on mesoscale elements and structure such as precipitation, vertical speed, and divergence that are easier to reflect directly the characteristics of mesoscale and small-scale weather system. It shows that the diabatic physical process mainly influences the physical elements with mesoscale features in the heavy rainfall numerical prediction. And the cumulus convection parameterization and boundary layer scheme take more effects on these elements than radiation scheme.

The results of Tests 4, 5, 6 and 7 show that, the rainfall deviation caused by Test 7 is 11. 2, and greater than 20 for Tests 4, 5 and 6, even reaches 61. 8 in Test 6. This indicates that the rainfall prediction deviation caused by the variance of convective parameterization is obviously greater than the explicit scheme. Tests 4, 5, 6 and 7 have the same effect on the physical elements. The deviations of vertical speed, moisture flux divergence, divergence, and vorticity are usually greater than or almost equal to 1. 0 while those of U, V, T, Q and H are basically between 0. 2 to 0. 5, showing that the convective parameterization schemes mainly influence the mesoscale physical elements. It must be noticed that Betts-Miller scheme has the greatest impact on rainfall prediction deviation, with the total rainfall deviation amounting to 61. 8. The possible reason may be that the convective triggering principles of Betts-Miller are different from those of Anthes-Kuo and Kain-Fritsch schemes. Betts-Miller scheme adjusts the environmental temperature and humidity profiles to the reference atmosphere, but other schemes to the neutral atmosphere.

As mentioned earlier, the weather systems of four heavy rainfall processes selected in the test are different. To analyze the impact of convective parameterization schemes on heavy rainfall processes with different triggering system, Anthes-Kuo, Betts-Miller and Kain-Fritsch schemes are adopted for simulated tests in the four scenarios, and then prediction deviations of each simulated test and control test are calculated. Table 3 is the average values of precipitation forecast deviation and standardized deviation of thermal and dynamic elements on 500 hPa level. It has the following characteristics: 1) The deviations of height field for the four scenarios are very small, with the biggest one being 0. 16 for "8. 29" scenario and 0. 03 or so for the other three scenarios. This indicates that the impact of convective parameterization schemes on height field is very small; 2) The deviations of U, V, W, T and Q are smaller than those for the other three scenarios and the deviation of rainfall amount is smaller than that for "8. 24"and "8. 29" cases, but the deviations of moisture flux divergence and divergence field are almost equal to or greater than those of other three scenarios. This shows that the various convective parameterization schemes have relatively small impacts on heavy rainfall processes caused by the baroclinic instability. After careful examination of the prediction of raining region and strength of each scenario, it is found that the precipitation in fine mesh grid domain only accounts for

10% to 20% of total rainfall in "8. 18" case (see Table 3). This shows that the deviation of rainfall in "8. 18" case mainly originates from the variance of large-scale system.

Table 3. The Average Deviation of 48 h Rainfall and Average Standardized Deviation of 500 hPa Physical Elements in the Three Convective Parameterization Schemes

Test case	Total rainfall	*U*	*V*	*W*	*T*	*Q*	*H*	*A*	*D*	*ζ*
8. 5	27. 0	0. 25	0. 27	0. 92	0. 23	0. 55	0. 03	0. 86	0. 86	0. 77
8. 18	30. 0	0. 15	0. 24	0. 67	0. 16	0. 34	0. 04	**1. 06**	0. 90	0. 60
8. 24	35. 3	0. 30	0. 26	**1. 08**	0. 29	0. 43	0. 04	0. 82	0. 91	0. 92
8. 29	55. 3	0. 35	0. 42	**1. 05**	0. 39	0. 60	0. 16	**1. 06**	0. 96	0. 92

The results of above analysis indicate that, various convective parameterization schemes have relatively small impacts on the dynamic and thermal fields of the heavy rainfall process triggered by the baroclinic perturbation, but big impacts on the heavy processes in homogeneous thermal filed. The reason is that, during such heavy rainfall process, the large-scale system can provide constant large-scale vapor convergence and forced lift movement. Though the latent heat of vapor condensation can strengthen the large-scale system, it does not have decisive effects. In the heavy rainfall process of a homogeneous thermal field, the large-scale force is relatively weak and the convective parameterization has big impacts on rainfall amount. The differences in definition of convective triggering functions of convective parameterization schemes, the occurring time, locations of convection and response to large-scale systems cause greater impacts on the evolution and development of model atmosphere and great differences in forecast results. In heavy rainfall caused by baroclinic perturbation or heavy rainfall of homogeneous thermal field, the impacts of convective parameterization schemes on moisture flux divergence and divergence should not be ignored.

V. IMPACTS OF CONVECTION PARAMETERIZATION SCHEMES ON THE DEVIATION EVOLUTION AND STRUCTURE OF THE DYNAMIC AND THERMAL FIELD PREDICTION

"8. 5" Heavy Rainfall in Shanghai is one of the most famous heavy rainfall processes in 2001 and also the most severe rainfall process in Shanghai after 1949. It mainly took place during the night of August 5 and the early morning of August 6, with a maximum rainfall rate of 50 mm/h and the rainfall amount of over 250 mm in 24 hours. Figure 3 shows the rainfall observation in that heavy rain process.

To analyze the impact of convective parameterization schemes on heavy rainfall dynamic and thermal field more thoroughly, a two-dimensional nested domain shown in Fig. 4 is redesigned for "8. 5" Heavy Rainfall, whose coarse grid domain central longitude and latitude, horizontal grid spacing and grid number are 30°N, 117°E, 54 km and 101 × 101, respectively. The horizontal grid spacing and grid number of fine mesh domain are 18 km and 103 × 103. Given the same parameters and physical process as the control simulation in the former part, the different convective parameterization schemes are used for simulation test, including Grell, Anthes-Kuo, Kain-Fritsch, and Betts-Miller schemes. Considering the time efficiency of prediction, the initial integral time is set as

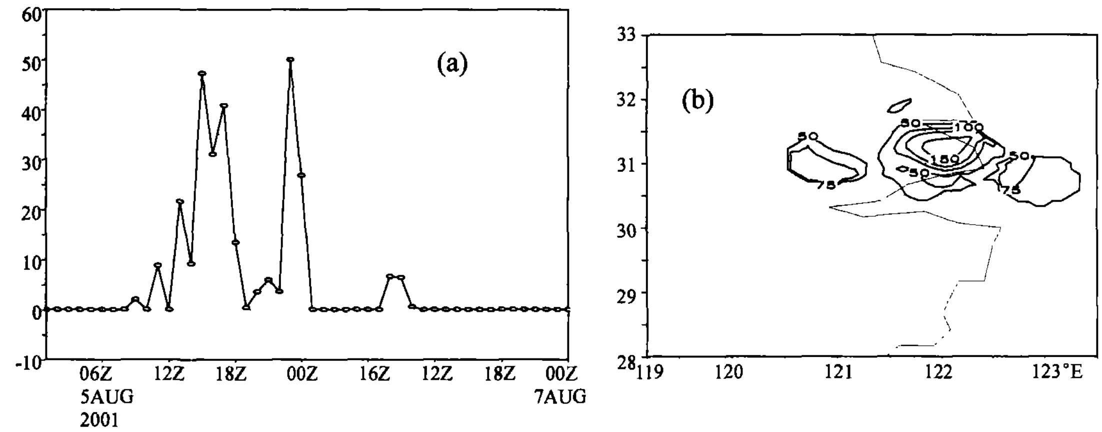


Fig. 3. (a) Hourly rainfall in Xujiahui Station of Shanghai from 0000 Z, August 5 to 1200 Z August 7; (b)observation of 24-h heavy rainfall from 0000 Z, August 5 to 0000 Z August 6 (unit: mm).

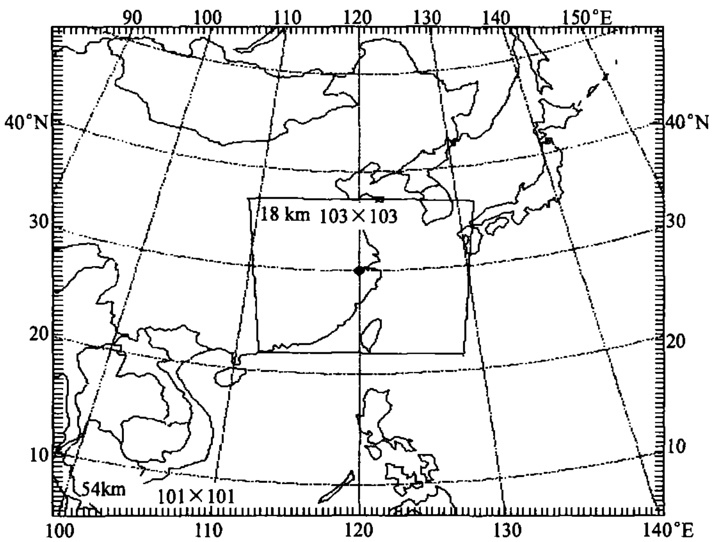


Fig. 4. Model domain for "8. 5" heavy rainfall in Shanghai with dark dot being the central point (• : the central point of model domain).

0000 Z August 5. Figure 5 shows the 24-h rainfall prediction and rainfall observation. In this figure, the four schemes simulate the dense rainfall in the east region of the south to the Yangtze River and have 100 mm rainfall centers. The positions of the raining centers, however, deviate significantly. Betts-Miller scheme predicts best, whose raining center is close to the observation value while Grell scheme deviates most, failing to predict the strong rainfall in Shanghai. The figures of hourly rainfall prediction of the four schemes (figure omitted) show that, the timing and strength of the sub-grid-scale rainfall by the different parameterization schemes are totally different, but the grid-scale rainfall is almost the same in the occurring time but different in strength.

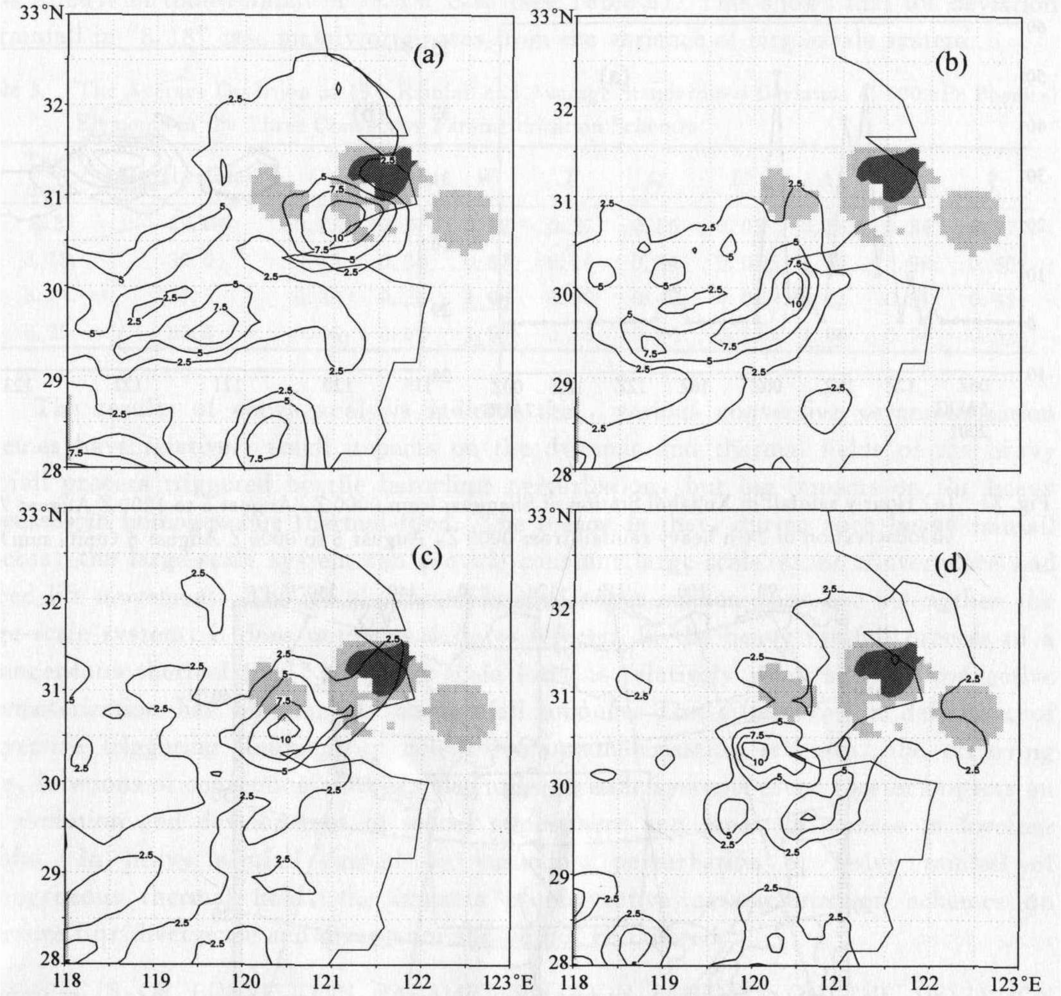
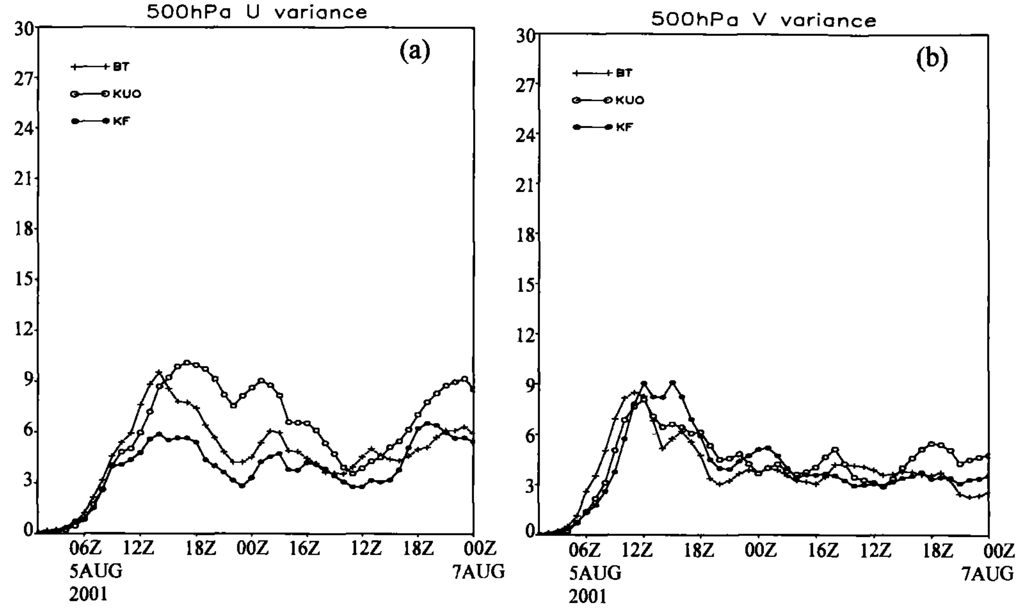


Fig. 5. 24 h accumulating rainfall prediction (contour, unit: mm) for the four convective parameterization schemes (a) Betts-Miller scheme, (b) Grell scheme (c) Kain-Fritsch scheme, and (d) Anthes-Kuo scheme (The light shadow reginon and the dark shadow region in the figure indicate the area with rainfall observation over 50 mm and over 100 mm, respectively.)

1. *Time Deviation Evolution Characteristics of the Prediction of Dynamic and Thermal Field*

Figure 6 shows hourly prediction deviation of 500 hPa dynamic field (U, V) and 850 hPa thermal field (T) simulated in Kuo, Kain-Fritsch, Betts-Miller and Grell schemes, respectively. As seen in the figure, the three schemes are similar in terms of dimensional and evolution characteristics of prediction deviation. The prediction deviations of T, U, V increase linearly in the first 12-h integrating, become saturated at about the 12th—18th hour and fall gradually after 12 hours. For example, the deviation of U in Betts-Miller scheme falls from 1 0 to 5 . After 1 2 hours of integrating , the prediction deviation gradually



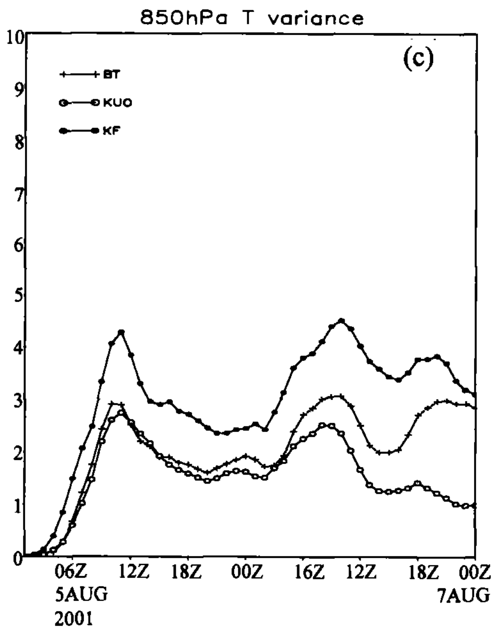


Fig. 6. Hourly predictions deviation of 500 hPa dynamic field (U, a; V, b) and 850 hPa thermal field (T, c) of Anthes-Kuo (abreviated as KUO), Kain-Fritsch (as KF), Betts-Miller (as BT) and Grell Schemes (Control simulation) for the simulated areas.

drops. In Betts-Miller scheme, for example, U deviation falls from 10 to 5. After 24 hours, the deviation oscillates. This shows that the prediction deviation produced by different parameterization schemes of models approaches saturated after 12 hours of accumulating, and this can also be applied to the changes of the dynamic and thermal fields of upper and low level atmosphere along with time. In comparison of the vertical distribution characteristics of dynamic and thermal fields (figure omitted), it is found that the deviation values of 200 hPa U, V are much greater than those of mid and lower levels, and the prediction deviations of three schemes and of KUO scheme are greater than 10 and even 50, respectively. The difference of temperature deviation value is lower than U and V, for after 12 hours of accumulating integral, the temperature deviations of the three schemes at 850 hPa, 500 hPa and 200 hPa are respectively between 3 to 6, between 1 to 2 and about 1. It shows that, as for dynamics factors, the convective parameterization scheme has more impacts on the high level atmosphere, however for thermal factors, more impacts on the low level atmosphere.

2. The Relationship of Prediction Field Deviation Structure and Precipitation of Sub-Grid-Scale

Choose Betts-Miller scheme which made a good prediction of the precipitation, and Grell which made a bad prediction. Using the sum of U and V absolute departure and T absolute departure to represent the absolute departure of dynamic field prediction and that of thermal field, respectively, we calculate the correlation coefficients between the absolute departure of dynamic and thermal fields of prediction at several pressure levels and the absolute departure of sub-grid-scale precipitation, correlation coefficients between the absolute departure of dynamic and thermal fields of prediction fields at several pressure levels and the absolute departure of grid-scale precipitation. Figure 7 shows the hourly correlation coefficient at 925 hPa. It can be seen that, as the integration time increases, the two kinds of coefficients tend to go down, and the coefficient of sub-grid-scale precipitation tends to decrease more obviously. In integration time of 1 h to 12 h, the coefficient between the departure of dynamic field prediction and that of sub-grid-scale precipitation is about 0. 4 and the other is only about 0. 2 (see Fig. 7a); The former is usually greater than 0. 4, with a maximum value greater than 0. 7. The latter is lower than 0. 4 (see Fig. 7b). This shows that before 12 hours of integrating, the horizontal structure of the sub-grid-scale precipitation and the departure of dynamic and thermal field prediction are rather the same and the areas where there is relatively heavy sub-grid-scale

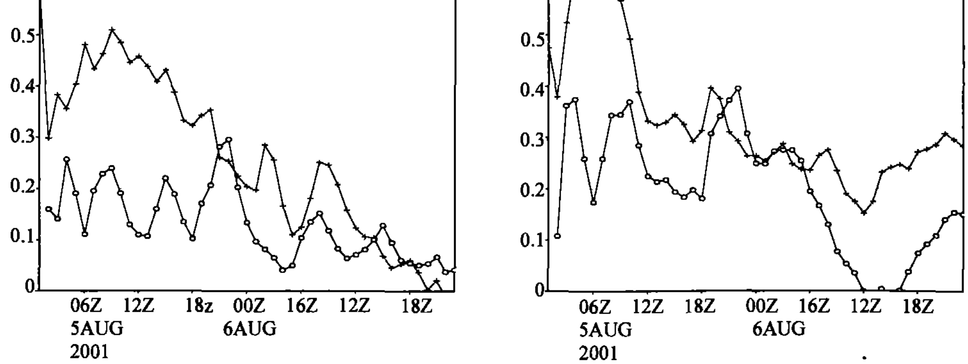


Fig. 7. Hourly coefficients of absolute deviation of prediction of 925 hPa in Betts-Miller and Grell schemes: (a) dynamic field, and (b) thermal field. (+: sub-grid-scale precipitation, o: grid-scale precipitation).

precipitation are also the areas with greater departure of dynamic and thermal field prediction. After 24 hours, the coefficient between precipitation of dynamic and thermal fields and that of sub-grid-scale drops to about 0. 2, the same as grid-scale coefficient. The possible reasons are that when the deviation of dynamic and thermal fields reaches a certain point, the "initial condition" of the integral used in the later integration in the model changes significantly, influencing the later prediction results. After comparison of the coefficients on all levels, it is found that their variance characteristics are similar to 925 hPa. On the whole, however, the coefficient of the lower layer is greater than that of the higher levels (figure omitted). Kuo and Kain-Fritsch's have similar structures of prediction deviation of dynamic and thermal fields as Betts-Miller's and need not explain again.

Figures 8 and 9 give the sum of the deviation of sub-grid-scale precipitation and the deviations of dynamic field U and V at 500 hPa level, and T deviation at 700 hPa level at the 2nd hour and 28th hour of integrating respectively between Kuo scheme and Grell scheme. The figure shows that at the 2 nd hour, the deviation distribution of convective

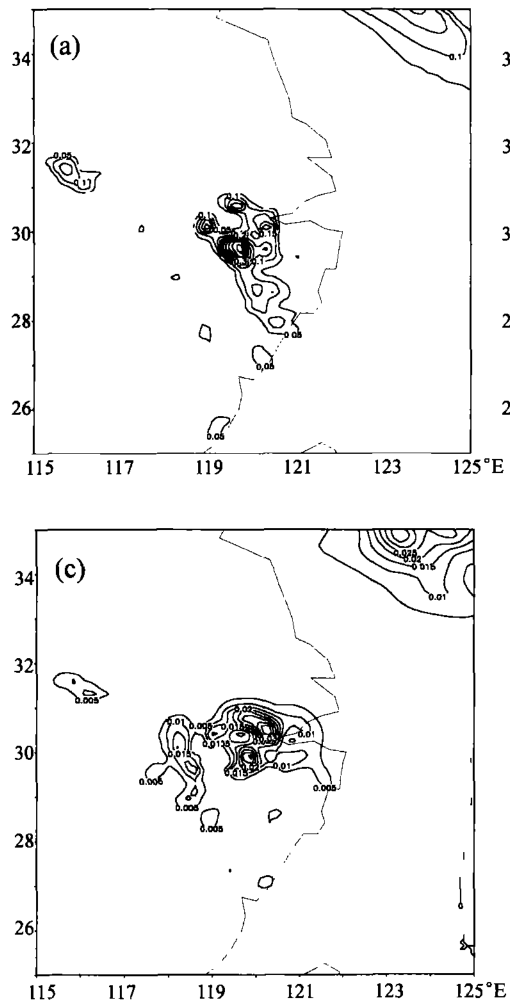


Fig. 8. The deviation (a) of sub-grid-scale precipitation, the sum of U and V's deviation of 500 hPa (b), and temperature T's deviation (c) of 700 hPa of Kuo and Grell schemes after 2 hours of integrating.

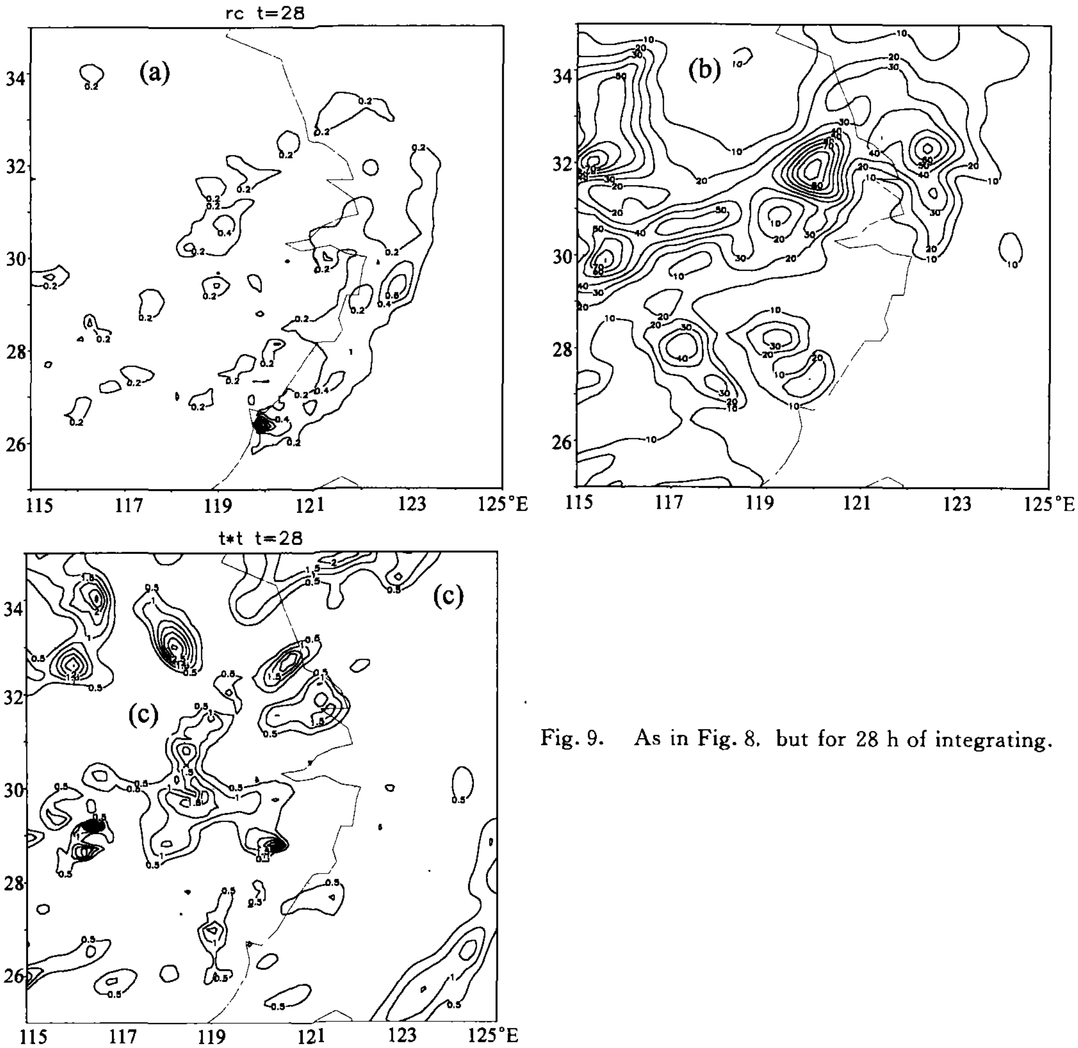


Fig. 9. As in Fig. 8. but for 28 h of integrating.

precipitation is similar to the deviation of U, V and T in terms of distribution area. The deviation of U, V and T with greater deviation of sub-grid-scale precipitation prediction is also in this area. At the 28th hour, the deviation of sub-grid-scale precipitation forms over the ocean at 120 to 123°E, but the deviation of U, V, and T relevant to this area is very small, mainly on the land at 30 to 33°E. This illustrates directly that the deviation area of the sub-grid-scale precipitation corresponds to that of U, V and T prediction well in the initial integrating time but not very well in later time.

3. *The Impact of Convective Parameterization Schemes on Mesoscale Circulation Structure*

The difference of convective parameterization schemes influences the structure of thermal and dynamic fields eventually. Figures 10 and 11 show the structures of longitudinal cross sections of the vorticity and potential pseudo-equivalent temperature of four schemes at 121°E and 28—33°N at heavy rainfall center after 24 hours of integrating. It can be seen that, the longitudinal structures of vorticity and potential pseudo-equivalent temperature are very different. In the figure of vorticity, the maximal vorticity centers of Betts-Miller and Anthes-Kuo schemes, are at 300 hPa (the higher level of troposphere), that of Kain-Fritsch scheme is at 500 hPa (the mid level of troposphere) and that of Grell scheme is at the lower level of troposphere. The lower levels of Betts-Miller scheme are all positive vorticity while those of other schemes have either positive or negative vorticity. At 30 to 31°N, the mid and lower levels of troposphere in Kuo scheme are of positive vorticity, but strongly negative appears in Grell scheme. The figure of potential pseudo-equivalent temperature shows that the greatest difference of temperature stratification occurs in the mid and lower levels of troposphere. The Kuo's is unstable geopotential

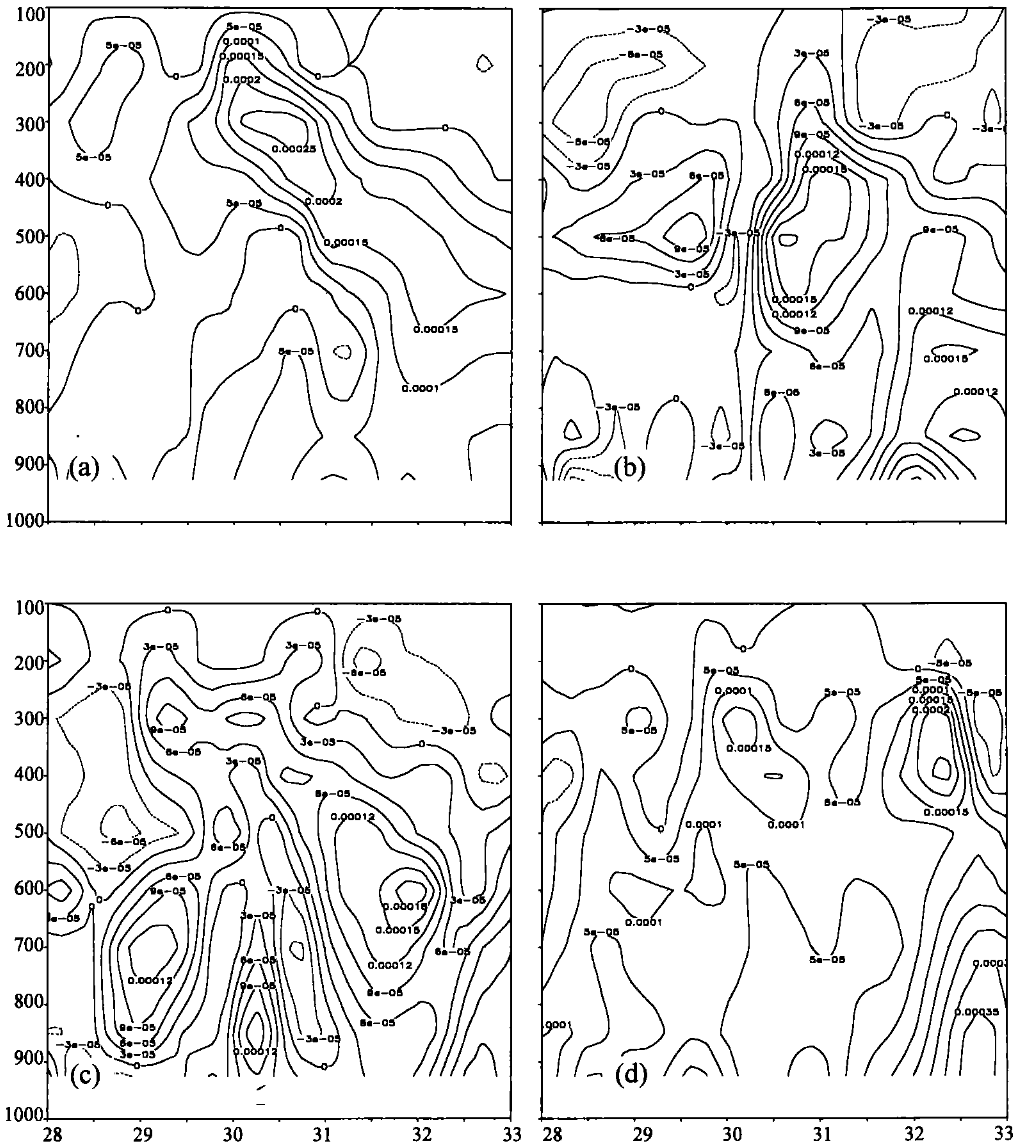


Fig. 10. Longitudinal cross sections of the vorticity of four schemes at 121°E after 24 hours of integrating: (a) Anthes-Kuo, (b) Kain-Fritsch, (c) Grell, and (d) Betts-Miller schemes (unit: s^{-1}).

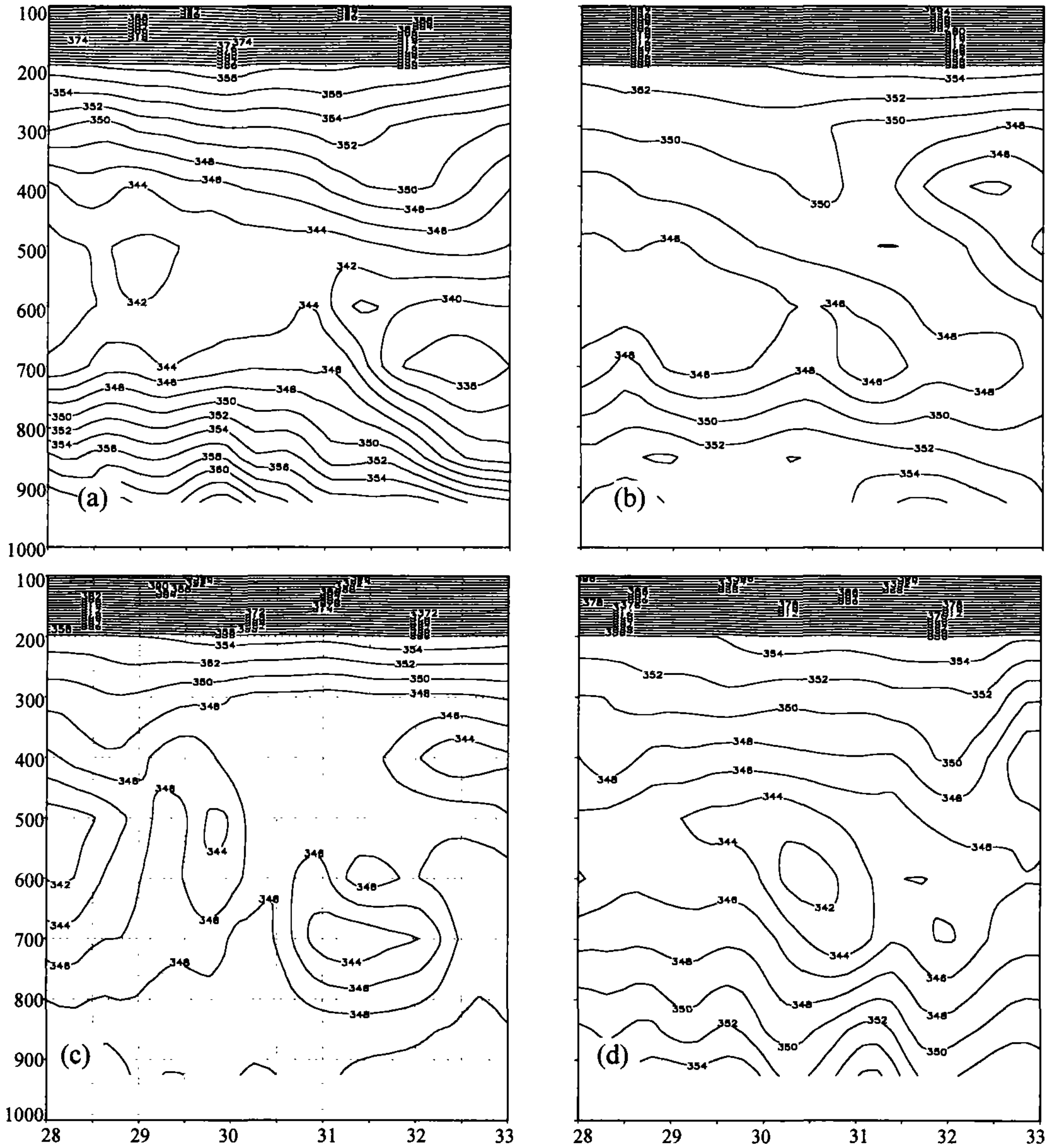


Fig. 11. As in Fig. 10, but for potential pseudo-equivalent temperature (unit: K).

stratification, whereas Grell's is approximately neutral and Kain-Fritsch's and Betts-Miller's are weakly unstable. Figures 10 and 11 illustrate that, thanks to the difference of convective parameterization schemes, the structure of thermal field and dynamic field at mid and lower levels of troposphere can be very different, the dynamic and thermal characteristics of initial values of later integration in the model have significant difference, and that difference will influence the result of the later model integration.

VI. DISCUSSION

There are three basic conditions for occurrence of heavy rainfall: vapor conditions, unstable stratification and vertical lift. The most important in vapor conditions is moisture flux divergence. In a large-scale environmental field, it is very difficult to find out where these favorable conditions will emerge. The studies of the four scenarios show that in short-range prediction the boundary layer scheme and cumulus convection parameterization scheme have small impact on large-scale circulation. However, the boundary layer scheme has great impact on thermal elements of lower level atmosphere and the cumulus convection parameterization scheme on moisture flux divergence and vertical speed, which are just the basic conditions of heavy rain. This shows that the two schemes have direct impact on the basic conditions for occurrence of heavy rainfall and their differences will result in significant difference in the locations and strength. Therefore, it can be regarded that in the numerical simulation of short-range heavy rainfall, the two schemes are two sensible factors that influence heavy rainfall simulation.

One of the reasons for inaccuracy of the heavy rainfall prediction is the inaccuracy of predicting the physics elements, such as moisture flux divergence and vertical speed that can reflect the mesoscale characteristics of heavy rainfall. The purpose of ensemble forecast for heavy rainfall is to reflect the uncertainty of these elements in numerical prediction. In this case, perturbing the elements that reflect the uncertainty of basic conditions for heavy rain can help construct successful ensemble prediction model and form a reasonable exhalation among the ensemble members. From the above study, it is found that the boundary layer and convective parameterization schemes have a big influence on physical elements that reflect the mesoscale structure of the heavy rainfall. The boundary layer scheme can reflect the uncertainty of unstable stratification prediction, for its difference has the greatest impact on thermal prediction. Reflecting the uncertainty of vapor conditions and vertical lift, the convective parameterization scheme influences most moisture flux divergence and vertical speed. Therefore, we can start with a boundary layer and convective parameterization schemes to construct the heavy rainfall ensemble prediction model of China.

There are two construction methods for ensemble prediction model. One is to blend different boundary layer and convective parameterization schemes and the other is to adjust the parameters of the schemes. The main reasons of prediction difference caused by convective parameterization schemes lie in definition of convective triggering function. Convective triggering function is a set of standard values of initial parameters. For example, Anthes-Kuo scheme in MM5V3 model is of vapor convergence scheme, for which there are three standards to trigger convection, i.e. the vertical integral of water-vapor flux divergence is greater than 3.0×10^{-7} kg m^{-2} s^{-1}, the positive buoyant energy under the top of the cloud is greater than negative buoyant energy, and the cumulus height must be higher than $\delta=0.3$ ($\delta=(P-P_t)/(P_S-P_t)$, the definition of vertical coordinate of MM5). Grell and Kain-Fritsch schemes are triggered by convective cloud height, whose principles are similar to that of Arakawa-Schubert. Grell scheme calculates the pressure difference between the maximum moist static energy and free convective height. The basic conditions for occurrence of convections are that cumulus thickness is greater than 150 hPa, and there must be ground moist downdrafts. Betts-Miller scheme is of convective adjustment on assumption of instantaneous balance, adjusting the thermal structure to quasi-balance structure. The difference of convective triggering function makes the location, time, and intensity of convection different, and influences the mesoscale characteristics and structure of atmosphere through feedback system. It can be seen that different schemes and parameter values can reflect the uncertainty of cumulus convection.

After model integrating for some time, the dynamic and thermal structures of prediction become significantly different due to the difference of parameterization schemes. As these differences are not caused by initial conditions, but by different parameterization schemes. Those not only infulence the physical elements that can reflect the mesoscale systematic characteristics in the model, but also influence the initial value of the integral of the model after some time indirectly, thus leading to different prediction results eventually. In this sense, different parameterization schemes can have impact not only on mesoscale system but also on the initial value of integral in the later time, bringing uncertainty to the heavy rainfall numerical simulation.

VII. SUMMARY

Using four heavy rainfall scenarios in 2001, this paper examines the impacts of diabatic physical processes on the dynamic and thermal fields of short-range heavy rainfall numerical prediction, studies thoroughly the effects of convective parameterization schemes on mesoscale heavy rainfall prediction and discusses the feasibility of heavy rainfall ensemble prediction in China with model perturbation method. The results and conclusions are as follows:

(1) In the short-range heavy rainfall numerical prediction, diabatic physical processes have small impacts on large-scale circulation and great impacts on physical elements that reflect the characteristics of heavy rainfall mesoscale circulation. On the other hand, cumulus convective process and boundary layer process have greater impacts on heavy rain prediction than radiation process does. The cumulus convection parameterization scheme has small impacts on heavy rain triggered by barocline system, great impacts on non-frontal system with weak gradient of large-scale thermal fields and the greatest impacts on rainfall, vertical speed, and moisture flux divergence. Boundary layer process has the greatest impact on the lower thermal field.

(2) The simulated test of "8. 5" Heavy Rainfall in Shanghai shows that, the deviations of dynamic and thermal field prediction in various convective parameterization schemes increase rapidly in the first 12 h integration, decreases in the 12 h to 18 h, and then oscillates in later time. In the initial time of integration, there is a good correlation between deviation structure of dynamic and thermal field and deviation structure of sub-grid-scale. They have similar horizontal structures. The impacts of convective parameterization schemes on U, V and T of higher and lower levels show that, there are greater impacts on U and V on higher levels than on lower levels, slightly greater impacts on T on lower level than on higher levels. After 12 h integration, the structure of dynamic field of the atmosphere in the model is significantly different from that of thermal fields, and the initial value of integral used in later integrating in the model is also different.

(3) The elements influenced by boundary layer and convective parameterization schemes are just the basic conditions for occurrence of heavy rainfall. This indicates that

the accuracy of numerical prediction on heavy rainfall is very sensible to boundary layer and convective parameterization schemes. The key to successful ensemble prediction is to find out those sensible elements that influence the accuracy of heavy rainfall prediction and to perturb them. It can be regarded that, in a homogeneous thermal field, the boundary layer and convective parameterization schemes can be applied in constructing ensemble prediction model. There are two construction methods for ensemble prediction model. One is to blend the different boundary layer and convective parameterization schemes and the other is to adjust the parameters of the schemes. In ensemble model, different boundary layer and cumulus parameterization schemes influence not only the mesoscale system of the model, but also the "integral's initial value" of the model, which reflects the uncertain influence of diabatic physical processes on heavy rainfall simulation.

(4) The heavy rainfall scenarios selected in this study are mainly short-range heavy rainfall cases. As for continuous heavy rainfall ones, such as those lasting for more than 2 to 3 days, the impact characteristics of diabatic physical processes on large-scale circulation need to be further studied.

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