

The Uncertainty of Mesoscale Numerical Prediction of Heavy Rain in South China and the Ensemble Simulations*

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ABSTRACT

In the context of non-hydrostatic MM5 version we have explored the impact of convective parameterization schemes on uncertainty in mesoscale numerical prediction of South China heavy rain and mesoscale heavy rainfall short-range ensemble simulation by using two kinds of physics perturbation methods through a heavy rain case occurring on June 8, 1998 in Guangdong and Fujian Provinces. The results show the physical process of impacts of convective schemes on heavy rainfall is that different latent heat of convective condensation produced by different convective schemes can make local temperature perturbation, leading to the difference of local vertical speed by the intrinsic dynamic and thermodynamic processes of atmosphere, and therefore, making difference of the timing, locations and strength of mesh scale and subgrid scale precipitation later. New precipitations become the new source of latent heat and temperature perturbation, which finally make the dynamic and thermodynamic structures different in the simulations. Two kinds of methods are used to construct different model version stochastically. The first one is using different convective parameterization and planetary boundary layer schemes, the second is adjusting different parameters of convective trigger functions in Grell scheme. The results indicate that the first ensemble simulations can provide more uncertainty information of location and strength of heavy rainfall than the second. The single determinate predictions of heavy rain are unstable; physics ensemble predictions can reflect the uncertainty of heavy rain, provide more useful guidance and have higher application value.

Physics ensembles suggest that model errors should be taken into consideration in the heavy rainfall ensembles. Although the method of using different parameters in Grell scheme could not produce good results, how to construct the perturbation model or adjust the parameter in one scheme according to the physical meaning of the parameter still needs further investigation. The limitation of the current study is that it is based on a single case and more cases will be addressed in the future researches.

Key words: South China heavy rain, convective parameterization schemes, uncertainties, ensemble simulations

1. Introduction

Heavy rain is a kind of severe natural calamity that influences South China. After decades of years of tests and theoretical exploration by Chinese scientists, significant progresses have been achieved in its prediction and basic theoretical studies (Huang, 1986; Xue, 1999; Zhou et al., 2003). Currently, the mesoscale numerical model has already been employed as one of the major tools in the prediction and research on heavy rain in South China, promoting considerably the accuracy of prediction.

Concerning the accuracy of mesoscale heavy rain-

fall prediction, however, there is still much to be desired for the numerical model. Three main factors influence the accuracy of the heavy rain prediction: model initial errors, model errors and the descriptive errors of diabatic physics in the model. The diabatic physics that accompany the turbulence, convective transmission, condensation and radiation have great significance for the occurrence and development of the mesoscale heavy rain. Parameterization schemes are used at large in the model to describe the diabatic physics. As one of the most important physics in the model, the cumulus convection has an immediate impact on the development and evolution of the cumulus

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convection of the model, so the cumulus convective parameterization scheme had been developed rapidly in recent decades of years. In the current numerical models, the cumulus convection schemes often used include Grell Scheme (Grell, 1993, 1994), Anthes-Kuo Scheme (Anthes, 1977), Betts-Miller Scheme (Betts, 1986), Arakawa-Schubert Scheme (Grell, 1994), Kain-Fritsch Scheme (Kain, 1990), etc. These schemes have following basic characteristics: under certain close presumptions, convection triggering function is defined with a set of planetary parameters (Kain, 1992). Only if the model atmosphere satisfies the parameters, can the convective movement in the model be triggered and the convective precipitation and large-scale feedback be calculated. The convective trigger function varies in different schemes. Even in the same scheme, the critical value of different convective trigger functions can be different. In China, many scholars made a lot of tests and research on different types of cumulus convective parameterization schemes. Most of them put the focus on the influence of parameterization schemes on precipitation. The results showed that on the whole these schemes could influence the timing, location and strength of the rain and make the heavy rain numerical prediction uncertain, although in a few cases the influence on the strong rainfall in North China was not obvious (Wang et al., 2001). At present, there are no absolute advantages of one over another (Gu, 1999; Wang et al., 1997). Chen et al. (2003) studied the influence of diabatic physics on the heavy rainfall dynamic and thermal fields. The convective parameterization schemes were found to affect most the vertical speed and moisture flux divergence that reflected the characteristics of the mesoscale movement and the planetary layer scheme to affect most the lower-layer thermal field. Nevertheless, we are not clear of the physics processes where the difference of cumulus convective parameterization schemes influences the uncertainty of heavy rainfall prediction. In order to gain a further understanding of the internal reasons for the uncertainty of numerical prediction in the different parameterization schemes, it is necessary to go to great lengths to make analysis.

Ensemble prediction is a new dynamic stochastic

prediction technology developed in recent years. Its basic principle is that, the initial field errors, model errors and highly non-linear chaotic features of the atmosphere add the uncertainty to the results of the numerical prediction results. Therefore, the numerical prediction should not be only determinable, but a probability prediction of dynamics. Since the late 1990s, some scholars have adopted different combination of parameterization schemes for the uncertainty of prediction caused by the model physics processes, studying the model-perturbed ensemble prediction methods of strong precipitation. For example, Stensrud et al. (2000), and Wang and Duan (2003) used different convective parameterization schemes and planetary boundary layer schemes to construct multi-model versions. These studies showed that the ensemble prediction has a better effect than a determinate prediction. Nevertheless, how can a more effective perturbation model be achieved through the study of uncertainty of prediction caused by the diabatic physics? Which factor can reflect the impact of the model error on the heavy rain prediction? Through a simulation test of a typical heavy rain in South China and comparison of the effects of two model perturbation ensemble prediction methods, this paper is designed to study in depth the above problems and provide theoretical evidence for mesoscale heavy rain ensemble prediction.

2. The “1998-06-08” strong rainfall process in South China

During the test period of heavy rainfall in South China, namely from the nighttime of 8 June to the daytime of June 9, 1998, a strong rainfall process occurred in Guangdong and Fujian Provinces and Guangxi Region. Figure 1 shows the 24-h observed precipitation in Guangdong and Fujian from 20 BT 8 June to 20 BT 9 June (Beijing time, below is the same). As is shown, the precipitation was distributed along the direction of northeast and southwest, covering most of the South China region. There were three strong rainfall centers. The strongest was located near Hong Kong with over 400 mm in the rainfall center, a record amount

for this area. The centers of the other two were in Fujian Province and Wuzhou Prefecture of Guangxi. The special scale of the precipitation indicated that this precipitation process had strong mesoscale features. From Hong Kong's hourly precipitation from 20 BT 8 June, to 20 BT 9 June 1998 (figure omitted), it was found that the heavy rainfall process consisted of three strong rainfalls. The first occurred from 04 BT to 09 BT 9 June, with the total precipitation of 163.4 mm in 5 hours, the second from 11 BT to 14 BT with the total precipitation of 13.2 mm in 3 hours, and the third 16 BT to 18 BT with the total precipitation of 101.00 mm in 2 hours. All these rainfalls lasted for 2 to 5 hours, with an obvious mesoscale feature for the precipitation time scale. Recently Chinese scholars such as Sun et al. (2002) and Sun and Zhao (2000) studied this case from perspective of numerical simulation and diagnostic analysis. They thought that the heavy rainfall in Zhujiang River Delta was a warm-type heavy rainfall. The predictability of this kind of mesoscale heavy rain in South China should be studied further.

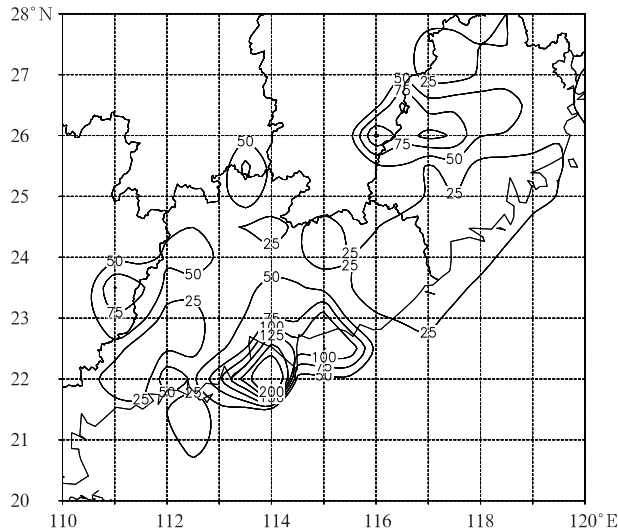


Fig.1. The observed 24-h precipitation (unit: mm) in Guangdong and Fujian from 20 BT 8 June to 20 BT 9 June, 1998.

3. Principles of the test model and four convection parameterization schemes

3.1 Description of the model configuration

The model chosen for use in this study is a

non-hydrostatic version of the Pennsylvania State University-National Center for Atmospheric Research (PSU-NCAR) Mesoscale Model version 5 (MM5) (Grell et al., 1994) with a two-dimensional nest domain. The coarse-grid domain of the model represents East Asia and the fine-mesh area South China (as shown in Fig.2). For the central points of the two areas, both longitude and latitude are 22.5°N, 114°E, the spacing grids are 54 and 18 km, the number of grid points are 101×101 and 103×103, and there are 24 vertical sigma levels (σ coordinate). The time splitting scheme will be used in calculating of the model. As for the lateral condition, the initial data of the model are created by blending the global analysis data from the National Meteorological Center of Beijing (T106L19) with eastern Asia surface and rawinsonde data using the approach of Cressman's gradual correction method of banana weighted coefficient analysis.

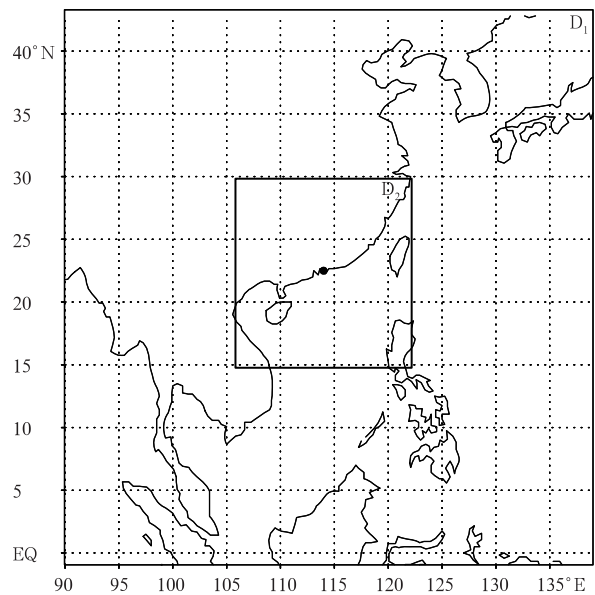


Fig.2. The simulation area of the model. D1: coarse grid domain; D2: fine grid domain.

Since the year 2000 the Numerical Weather Prediction Division of NMC of Beijing 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 resolvable-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). The time step in coarse domain is 120 s. In the simulations in part four and five, the physics are instead only in inner domain and are same as the control in coarse domain. The time for the integral initial field is 12 UTC, 6 June 1998 with total 48 hours of integration.

3.2 Description of the parameterization scheme

The purpose of the cumulus convection parameterization is to calculate the cumulus overall effect in convective precipitation, heating and humidity increase by use of large-scale variables. A parameterization scheme includes convective trigger conditions, close assumptions, precipitation efficiency and the feedback to the environment field. In the simulations in this paper, four cumulus convection parameterizations are employed (Grell, Anthes-Kuo, Betts-Miller, Kain-Fritsch). The principles and convective triggering process of these four schemes are detailedly described in Chen et al. (2004).

4. The impact of the cumulus convection parameterization schemes on the uncertainty of heavy rain prediction in South China

The high resolution model has revealed its capability of simulation and prediction in heavy rain in South China. Although the model can make reliable prediction on the emergence and changes of a rainfall process, the prediction errors are still great in timing, location, strength of the heavy rainfall. Previous studies show that heavy rain is sensitive to the diabatic physical process, particularly the cumulus convection parameterization schemes. Therefore, we will hereby discuss thoroughly how the difference of these schemes

in the model gives rise to the prediction uncertainty of heavy rainfall in South China.

4.1 The impact on the uncertainty of the rainfall prediction

With the control model described in the previous section, four simulation results are produced when the four schemes are integrated respectively for 48h in the fine-grid domain. Figure 3 shows the 24 h total precipitation prediction of the four convection parameterization schemes and the sub-grid precipitation ratio when the total precipitation is over 25 mm. As the shown in distribution of the total precipitation, the rain belt over 1 mm order predicted by the four schemes are similar, all crossing from northeast to southwest, indicating that the differences of the four schemes have a small influence on the large-scale rain belt. However, there are significant differences in terms of location and intensity of the raining center. For example, Grell and Betts-Miller Schemes have different heavy rainfall centers. In Grell Scheme, for instance, two heavy rainfall centers above 150 mm are predicted: one is located in 22.5°N, 116°E and the other in 24°N, 114.2°E. In Betts-Miller Scheme, no heavy rainfall center along the coast is predicted but one above 200 mm on the border between Guangdong and Guangxi is predicted. Another example is that the rain intensity of Grell Scheme is different from that of Anthes-Kuo Scheme. In Grell Scheme, the central isoline is 150 mm and there are two heavy rainfall centers while in Anthes-Kuo Scheme there is a large rainfall area at 50 mm in rain intensity but the maximum value of the rainfall center is obviously small, with a central isoline of 100 mm located near 24° to 25°N, 119°E. Figure 3 also shows that the ratios of sub-grid precipitation in these schemes are quite different. Anthes-Kuo Scheme has mainly sub-grid precipitation accounting for 90% of the total. In the other three schemes, the sub-grid precipitation accounts for the major share of the rainfall in the area to the south of 23°-24°N. For example, the ratio of sub-grid precipitation of Betts-Miller Scheme amounts to 90% of the total. While in the area to the north of 23°-24°N, grid-scale precipitation accounts for the major part and the ratio of sub-grid precipitation is lower than 30% on the whole. It is

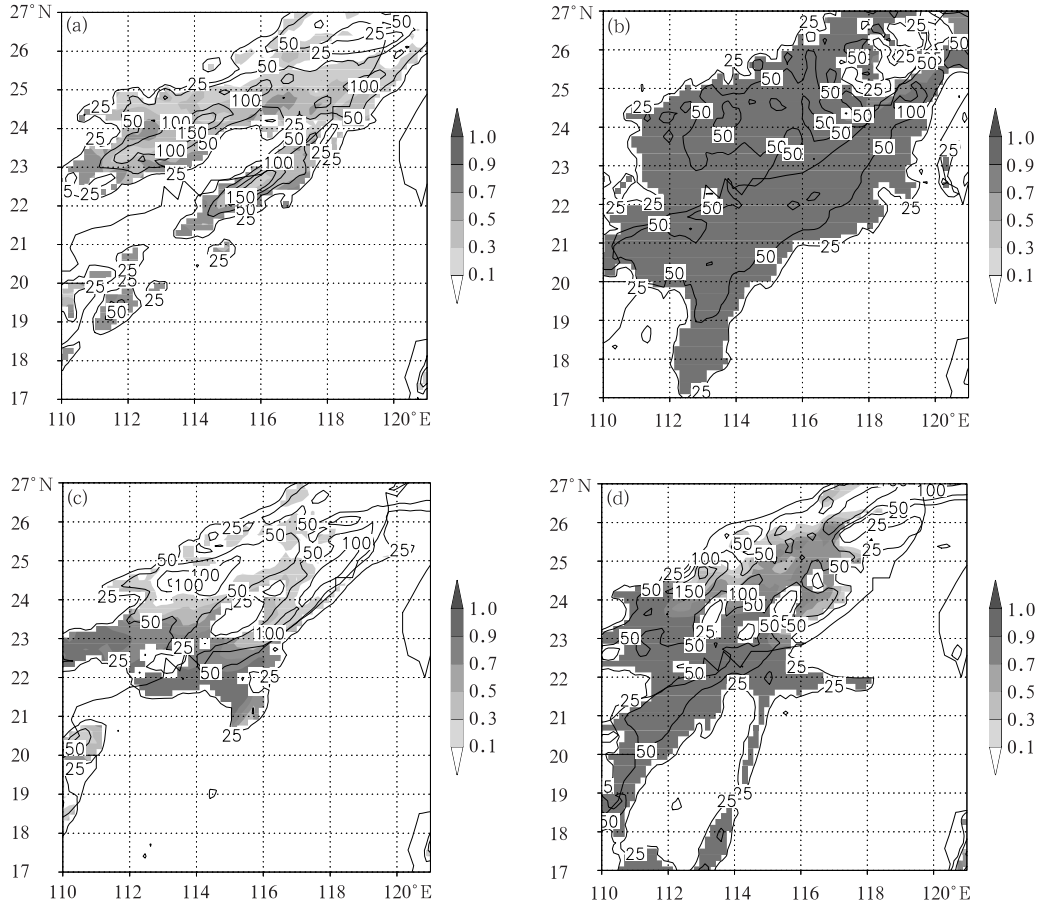


Fig.3. The 24 h total precipitation prediction of the four cumulus convection parameterization schemes (solid line:mm) and the sub-grid precipitation ratio when the total precipitation is over 25 mm (shaded area). (a) Grell Scheme, (b) Anthes-Kuo Scheme, (c) Kain-Fritsch Scheme, and (d) Betts-Miller Scheme.

found, after careful analysis of vertical distribution of pseudo-equivalent potential temperature (figure not shown), that at 24°N there is a weak cold wave near the ground level. To its north, $\partial\theta_{se}/\partial z$ at the middle and lower levels of the convection is equal to or higher than 0, a nearly neutral or stable stratification. To its south, $\partial\theta_{se}/\partial z < 0$ at the middle and lower level of the convection is a potential unstable stratification. At the same time, convective rainfall accounts for most of the precipitation and the proportion of the grid-scale to sub-grid scale precipitation near the wave is the same. Therefore, the weak cold wave may be the possible cause for the difference of precipitation distribution. It is also noticed that the ratios of sub-grid precipitation for Grell and Kain-Fritsch Schemes

also have some relations to the center of heavy rainfall. The precipitation near the center of strong rainfall is mainly the grid scale precipitation. At the strong rainfall center close to Hainan Island, the ratio of sub-grid scale precipitation is very low.

4.2 Physical processes producing the uncertainty of precipitation

Figure 4 shows the meridional section of the circulation, temperature, latent heat of convective condensation, the sub-grid precipitation and grid precipitation based on the four schemes integrated for 1 h along 114°E, where the rainfall center is located. It can represent the general situation when convection is triggered. It must be indicated that the latent heat of

condensation (unit: $^{\circ}\text{C}/\text{min}$) is not a cumulative value, but an instant one by the forecast time. Through comparison of Figs.3 and 4, it is found that at the early time of integrating, the precipitation of the four schemes is main of convection, but these schemes differ in convection location, region and heat-

ing layers of convective condensation. The convection in Betts-Miller Scheme, for example, occurs around 19° - 24°N , in Anthes-Kuo Scheme around 21° and 24° - 27°N , and in Grell and Kain-Fritsch Schemes around 25° - 26°N . The latent heat of convective condensation corresponds to convective precipitation domain.

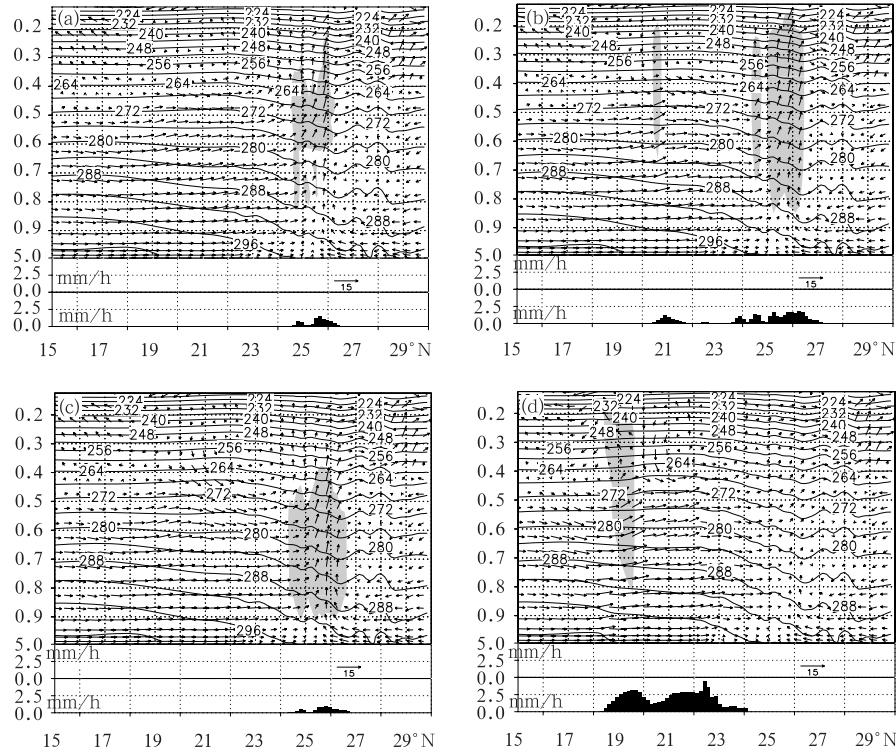


Fig.4. The meridional section along 114°E at 1 h integration of the meridional circulation ($v, w \times 50$), temperature (solid line, unit: K), latent heat of convective condensation (shaded area for $> 0.1 \text{ K min}^{-1}$), the sub-grid precipitation (unit: mm), and grid precipitation (unit: mm) of the four schemes. The vertical coordinate is σ . The histogram in the lowest part of the figure represents the sub-grid precipitation (mm h^{-1}) in the previous one hour, and in the middle part represents grid-scale precipitation (mm h^{-1}) in the previous one hour. (a) Grell Scheme, (b) Anthes-Kuo Scheme, (c) Kain-Fritsch Scheme, and (d) Betts-Miller Scheme.

Figure 5 shows the meridional section of the circulation, temperature, latent heat of convective condensation, the sub-grid precipitation and grid precipitation for the four schemes at 5-h integration along 114°E . It can be noticed firstly that great changes have taken place to precipitation, including precipitation location, the ratio of sub-grid precipitation to total rainfall. The precipitation in Grell and Kain-Fritsch Schemes is mainly grid-scaled, with the raining domain in Grell Scheme at 23° - 26°N and that in Kain-Fritsch

Scheme at 22° - 26°N . For Betts-Miller and Anthes-Kuo Schemes it is mainly sub-grid precipitation convective. Secondly, in comparison with the results of 1 h integration, the precipitation domain of these schemes by that time is more various than that at the 1-h integration. Even for the same scheme, the convective precipitation domain begins to differ from that at the initial phase of integration. For instance, the convective precipitation mainly takes place around 25° - 26°N when Grell Scheme integrates for 1-h, but after 5-h, it

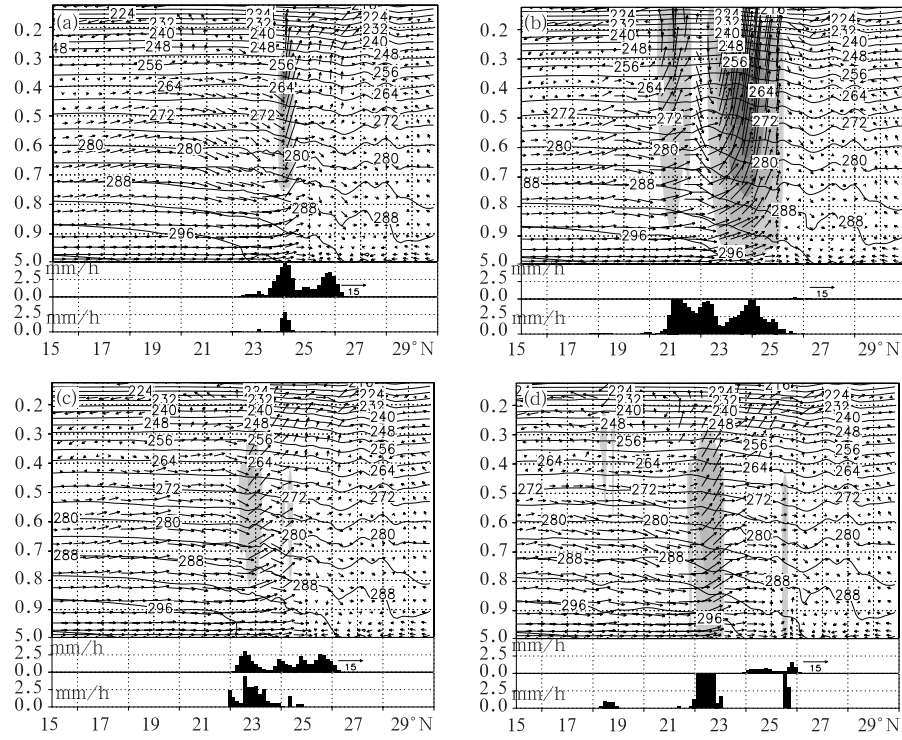


Fig.5. As in Fig.4 but for integration time of 5 h.

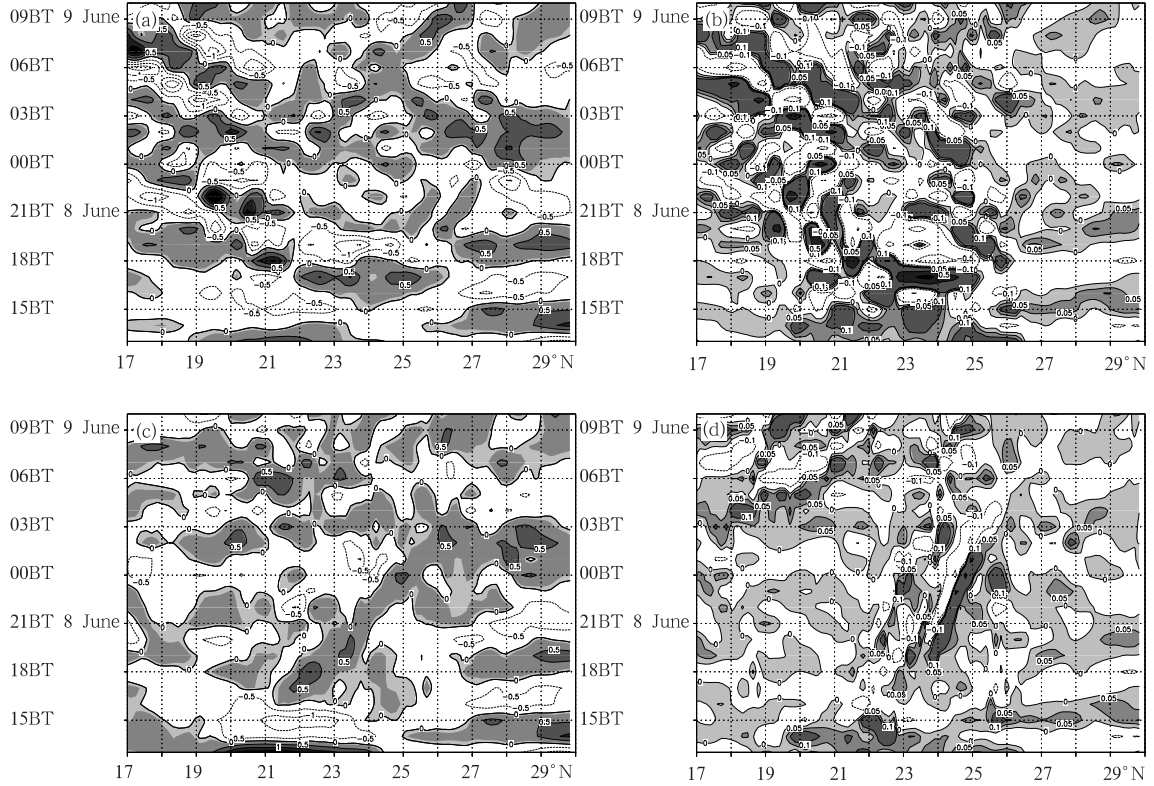


Fig.6. The hourly temperature variability (a, c, unit: K h^{-1}) and vertical acceleration (b, d, unit: m s^{-2}) at $\sigma=0.4$ level featured by considerable heating at 114°E in Anthes-Kuo and Betts-Miller Schemes shaded areas indicate areas with positive values.

occurs around 24°N. Another example is that in Betts-Miller Scheme, there appears an obvious convective precipitation area after 5 h of integration. From Figs.4 and 5, it can be found that as the time moves forward, the released latent heat of condensation caused by different convective precipitation brings about various temperature perturbations. In addition, with the difference of large-scale feedback of convection, the initial values such as temperature and humidity, used in the later integration of the model become different, causing the location and intensity of grid and sub-grid scale precipitation to vary, and furthermore, through the released latent heat making the spatial distribution of the perturbing source different.

How does the energy of the perturbation source diffuse to the atmosphere around? Figure 6 describes the hourly temperature variability and vertical acceleration at $\sigma=0.4$ level featured by considerable heating at 114°E in Anthes-Kuo and Betts-Miller Schemes. As shown in Fig.6, from 1 to 3 h, there is no much difference between the two schemes concerning the 1 h temperature variability and vertical acceleration. After 5 h of integrating, a large perturbation center emerges in both the schemes, and the temperature variability and vertical acceleration reach their maximum value. It is noticed that the two perturbation

centers have very different features in diffusing to the atmosphere. The temperature variability and vertical acceleration of Anthes-Kuo Scheme spread to the south and the positive temperature variability corresponds to an upward vertical acceleration. Different from that of Anthes-Kuo Scheme, the perturbation center of Betts-Miller does not spread to the south, but to the north and so does a strong positive acceleration. At the same time, it is also noticed that the transmission direction of the two schemes are opposite and mainly one-way. One possible reason for this is that the transmission of the temperature perturbation and vertical speed is related to gravity waves. Examination of the atmospheric stratification in the process (figure omitted) shows that the structures of the equivalent temperature stratification θ are on the north and south sides of 24°-25°N and 114°E. To the south of 24°N the mid and lower atmospheric levels are in unstable stratification, but to the north of 24°N they are in nearly neutral or stable stratification. Brunt-Vaisala frequency values of the north and south sides of 24°N are opposite, and hence the transmissions of the gravity wave are totally different. Another possible reason is that different convective parameterization schemes have different convection triggering mechanism. In Anthes-Kuo Scheme convection is

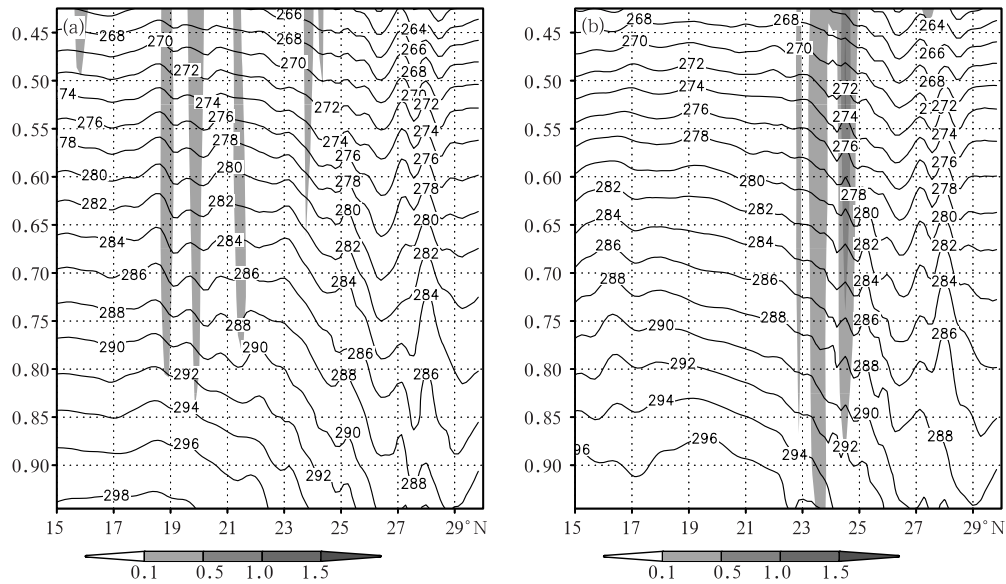


Fig.7. After 11 h of integration, the vertical cross section (σ : 0.4-0.95) of temperature (solid line: K) and vertical acceleration over 0.1 m s^{-2} (shaded area) at 114°E for Anthes-Kuo (a) and Betts-Miller (b) Schemes.

triggered by the large-scale moisture convergence while Betts-Miller Scheme is a wet-convection adjustment one. This indicates that there is an updraft movement in Anthes-Kuo Scheme before convection occurs and Betts-Miller Scheme is adjusted towards neutral atmosphere. The joint effects of the two factors give rise to such simulation results.

Figure 7 shows the vertical section of temperature and vertical acceleration $>0.1 \text{ m s}^{-1}$ at 114°E in Anthes-Kuo and Betts-Miller Schemes. As shown, the structures of the temperature perturbation in the two schemes after 11 h of integrating appear to be quite different. The range of temperature perturbation in Anthes-Kuo Scheme is larger than that of Betts-Miller's. Near 17°N Anthes-Kuo Scheme gives a cold trough but Betts-Miller Scheme gives a warm ridge stretching upward. At the same time, it can be seen that the domain and levels of the updraft movement in the two schemes are also different. Anthes-Kuo Scheme has a vast vertical lift domain while the vertical lift domain in Betts-Miller Scheme is concentrated in $23^\circ\text{--}25^\circ\text{N}$.

Generally speaking, the latent heat of convective condensation of the convective parameterization scheme causes the perturbation of local temperature. Changes of the air density near the perturbing source cause the air of relevant domain to expand and local convergence to diverge, leading to vertical speed to change and furthermore affect the timing, location and strength of grid scale and sub-grid scale precipitation in a thermodynamic process. New precipitation continues to form new perturbing source through the release of latent heat of condensation. Due to the difference of parameterization schemes and the transmission means of the energy of perturbing source, the dynamic and thermal structures of simulation atmosphere are also different.

5. Model perturbation ensemble prediction test

5.1 Scheme of perturbation models

5.1.1 The method of different physics

For heavy rain ensemble prediction, the key in

model perturbation is to perturb the factors sensitive to heavy rain prediction. Stensrend (2001) combined different diabatic physics into multiple model versions. The results show that when large-scale forcing is weak, the ensemble prediction produced by using model configurations with different model physical process parameterization scheme is more effective than initial perturbation ensemble prediction. The ECMWF (European Center of Medium-Range Weather Forecast) adds stochastic noise in diabatic physics, hence making the impact of physical process on the model stochastic. The above research of the paper shows that different convective parameterization schemes can cause the vertical speed of the integrating domain to change and affect the strength and position of the heavy rain prediction. With such understanding, this paper tested two model perturbation methods: one is created by combining the cumulus convective parameterization scheme and planetary boundary level scheme and the other is by perturbing the amplitude of major parameters in convective parameterization schemes.

Du (1997) pointed out that ensemble mean can improve the forecast, for it can achieve 90% of forecast effect with 8 ensemble members. Therefore, four cumulus convective parameterization schemes and two boundary level schemes are used randomly to construct 7 perturbation models. The cumulus convective parameterization schemes are Anthes-Kuo Scheme, Grell Scheme, Kain-Fritsch Scheme and Betts-Miller Scheme. The planetary boundary level schemes are MRF high resolution scheme developed by Hong and Pan (1996) and HRIR high resolution scheme by Zhang et al. (1982). The resolvable scale precipitation and radiation scheme is the same as the control prediction scheme. See Table 1 for the parameters of the 7 perturbation schemes. The first member is parameters of control prediction. All schemes are supposed to have the same prediction skills.

5.1.2 The method of the perturbation on convection parametric amplitude

With the second model perturbation method, 7 ensemble members are obtained through adjusting Grell Scheme parameterization amplitude. Table 2 reveals the disturbed values of 7 major parameters and

7 perturbed members of convection triggering function in Grell Scheme. The physical meanings of the 7 parameters are explained in the note. The first member is the parameter setting of control prediction, and in other members the parameters of the control prediction are perturbed between maximum and minimum value allowed by the scheme. For example, the amplitude of the most unstable level ranges in 50-250 hPa. The parameters are combined stochastically and all schemes are supposed to have the same prediction techniques.

Besides perturbing the major convection triggering parameters in Grell Scheme, tendency values of the temperature and humidity caused by the convection adjustment are also perturbed. The perturbation procedures are as follows: Produce first in grid

air columns the normally distributed stochastic number with an average value of zero. The temperature and humidity range from -0.5 to 0.5 and from -0.1 to 0.1 respectively. Then time stochastic number with the change value of temperature and humidity and the perturbation range is yielded. At last add the change value of temperature and humidity to the perturbed value of Grell Scheme, and the sum is taken as the final change value of temperature and humidity of the convection parameterization scheme. Perturb all the members in the same way. The initial value yielded with stochastic number is determined by the zonal wind speed on grids, thus guaranteeing all the produced stochastic numbers belong to different sequences and adding stochastic features of perturbation to the change value of temperature and humidity.

Table 1. The configuration of the first model-perturbation scheme

Ensemble member	Cumulus convective parameterization schemes	Boundary level schemes	Explicit precipitation scheme	Radiation scheme
1	Grell	MRF	Dudhia	Dudhia
2	Anthes-Kuo	MRF	Dudhia	Dudhia
3	Kain-Fritsch	MRF	Dudhia	Dudhia
4	Betts-Miller	MRF	Dudhia	Dudhia
5	Grell	HRIR	Dudhia	Dudhia
6	Anthes-Kuo	HRIR	Dudhia	Dudhia
7	Kain-Fritsch	HRIR	Dudhia	Dudhia

Table 2. The perturbation parameters of Grell Scheme

Ensemble member	Maximum allowed depth of stable layer (hPa)	Minimum convection cloud depth (hPa)	Minimum/maximum precipitation efficiency	Minimum/maximum detrainment efficiency of cloud air mass	Maximum cloud base height (σ)	Maximum depth of downdraft detrainment	Minimum/maximum convection cooling/heating rate ($K d^{-1}$)
1	50	150	0.2-0.8	0.3-0.9	0.4	75	-250-500
2	25	75	0.1-0.9	0.2-0.9	0.3	50	-250-450
3	50	225	0.1-0.9	0.2-0.9	0.5	100	-250-550
4	50	150	0.1-0.9	0.1-0.9	0.3	50	-250-450
5	65	200	0.3-0.7	0.2-0.8	0.4	50	-250-500
6	40	100	0.2-0.8	0.5-0.5	0.5	75	-250-550
7	75	75	0.3-0.7	0.5-0.5	0.3	100	-250-450

5.2 The result of ensemble prediction

At middle and high latitudes, the pattern field and the model variables can reflect effectively the development and evolution of Rossby Waves. Usually, 500 hPa height field can be used to calculate the reliability of medium-range ensemble prediction. At present there is no physical quantities commonly accepted to reflect the uncertainty of heavy rainfall prediction, because the model variables only play a con-

trol role, and they are difficult to reflect the structure and features of mesoscale circulation of the weather system, such as heavy rainfall. The development of the mesoscale weather is closely related to the gravity and inertia waves which are usually calculated with diagnostic variables such as divergence and vorticity. We believe that with the current observation and test techniques, the ground precipitation can directly reflect the evolution outcome of mesoscale motion. Hence the precipitation prediction will be used to test the

results of ensemble prediction.

5.2.1 The test method of ensemble prediction

Use the above two perturbation methods to produce ensemble prediction of the heavy rainfall process, in which initial conditions of models are completely identified, the initial time commences at 12 UTC 8

June 1998 for 48-h integration. Then calculate the ensemble prediction mean, precipitation probability over 50 mm, precipitation variance, and prediction skills including Threat Scores (T_S) and Bias Scores (B_S). To obtain grading T_S and B_S , first interpolate mode precipitation prediction field onto 129 intensified

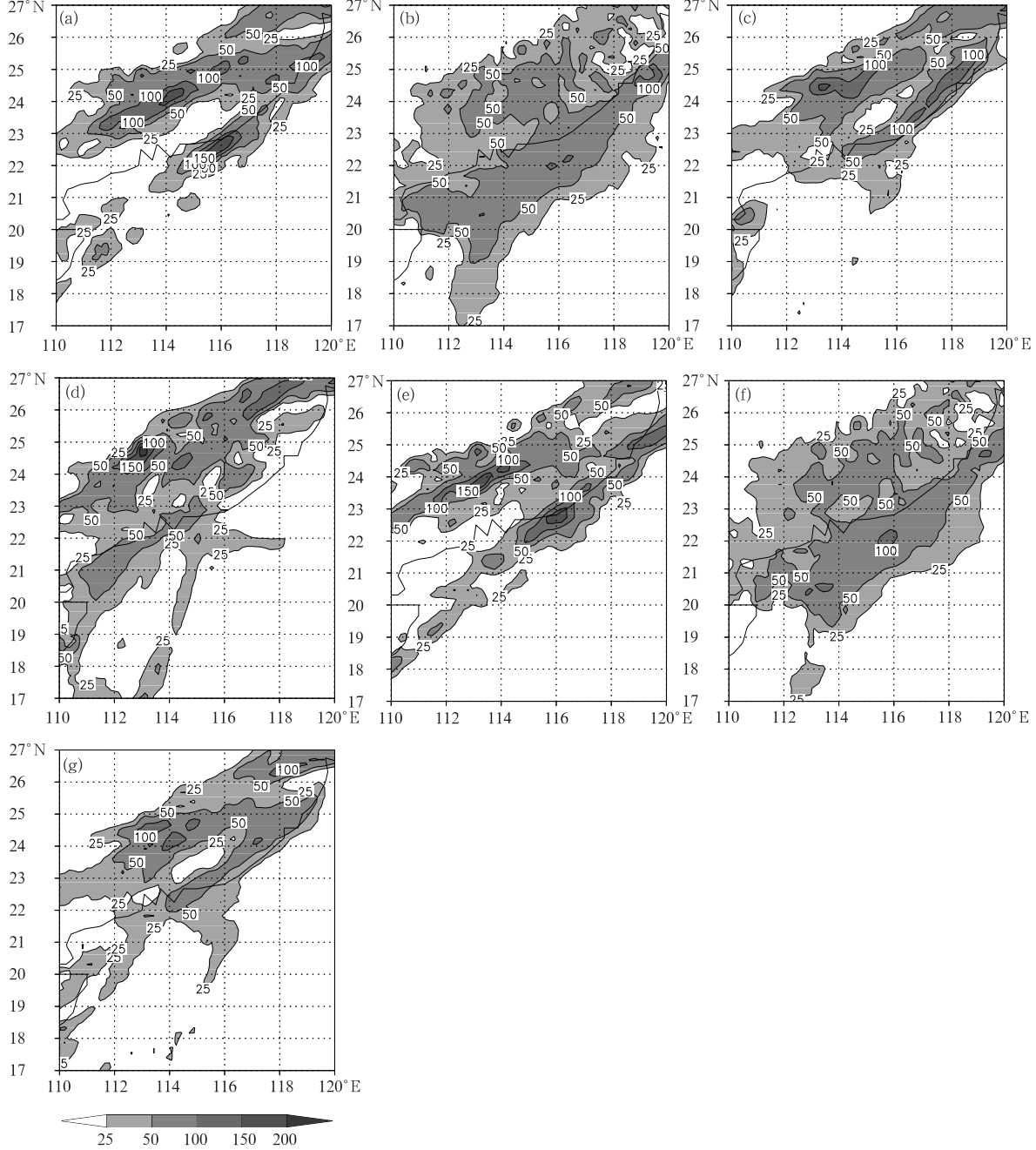


Fig.8. 24-h accumulative precipitation prediction of the 7 members in the first model perturbation method (unit: mm): (a) The control test, (b) to (g) correspond to ensemble members 2 to 7 respectively (unit: mm, see Table 1).

observation stations with bilinear interpolation and calculate every 6 hours the T_S and B_S values when precipitation reaches 1.00, 10, and 25 mm. T_S and B_S are defined as follows

$$T_S = \frac{N_a}{N_a + N_b + N_c}, \quad (1)$$

$$B_S = \frac{N_a + N_b}{N_a + N_c}, \quad (2)$$

where N_a is the number of stations that make correct estimate, N_b is the number of those that make over-estimate and N_c is the number of those that make under-estimate.

5.2.2 The results of ensemble prediction

Figure 8 illustrates the ensemble members' 24 h accumulative precipitation prediction in the first model perturbation method and Fig.8a the 24 h accumulative precipitation prediction derived by the control prediction. As is shown, the control test predicts that precipitation belt crosses from southwest to northeast with two strong rainfall centers with accumulative precipitation over 150 mm, and the location of strongest rainfall center between 24°N , 114°E and 22°N , 116°E . Compared with Fig.1, control model fails to predict the strong precipitation and the predicted rainfall center is still deviated from observations. It can also be seen that all the seven models predict that precipitation belt crosses from southwest to northeast, each, however with different rainfall center and intensity.

Figure 9 illustrates the 24-h accumulative precipitation means of ensemble members, precipitation probability over 50 mm, and ensemble prediction spread (namely mean square deviations of ensemble precipitations) of 7 members. In comparison of Figs.8a and 9, a raining area with the mean precipitation over 50 mm near Hong Kong can be seen in the chart of ensemble prediction mean. In the chart of precipitation probability over 50 mm, there appeared the highest probability center near Hong Kong with the maximum value of 0.7. The results of the ensemble prediction indicate that the probability of heavy rainfall near Hong Kong is high, showing considerable difference from the control prediction. If such results are taken for reference in forecasting, they will make a positive impact on prediction. A sign of the prediction reliability, the

mean square deviations show the spread of the ensemble members. The higher the spreads are, the lower the prediction reliability will be. In comparing Figs. 8a and 9, it is found that the location of maximum precipitation of the control prediction is identical to that of ensemble mean and that of precipitation probability over 50 mm, all near 24°N , 114.5°E . Nevertheless, the spread in accumulative precipitation prediction in this area is also the maximum, with the central value higher than 50 mm (the darkest part of Fig.9c). This indicates the great uncertainty in the precipitation prediction of this area and low prediction reliability. In actual process, this area is indeed not the maximum raining center. The small mean square deviation of accumulative precipitation prediction near Hong Kong shows that the reliability of prediction is high. These results indicate that the spread of ensemble prediction product can provide more indeterminate information of prediction.

In the second model perturbation method with which the amplitude of major convective triggering parameters is perturbed in Grell Scheme, the 24-h accumulative precipitation of 7 members shows that the locations of the major rain belt and strong rainfall center in the 7 members are very similar to those in the control test. The precipitation belt lies across from northeast to southwest, each with two strong rainfall centers and with some discrepant precipitation intensity at the center. Figure 10 displays the 24 h accumulated ensemble precipitation mean, precipitation probability over 50 mm, and ensemble prediction spread of 8 members for the second model perturbation method. As is shown, the ensemble mean and the horizontal distribution of precipitation probability over 50 mm are similar to those of the control prediction. The spread between ensemble members is also small. All these reveal that the ensemble prediction constructed with the second method seems not to reflect well the uncertainty in heavy rain prediction.

It can be seen from the above analysis that the ensemble prediction in different combination of parameterization schemes can provide more uncertain information of precipitation prediction. To know more about the impact of model perturbed ensemble on large-scale pattern field, the 48-h prediction noodle

chart of the 5880 m isohypse of 500 hPa height field, and the 14 m s^{-1} isotach on 850 hPa are analyzed (figure not shown). The results show that locations of the subtropical high ridge predicted in the 7 members are very close. Although there are some differences in 850 hPa isotach in some local areas, the location and domain of jets are also very close. The 500 hPa

large-scale pattern field and the 14 m s^{-1} isotach of 850 hPa nearly coincide; the variance among members is smaller than that in the first model. This shows that the ensemble prediction of these two model perturbation methods will not have a great impact on the large-scale circulation pattern.

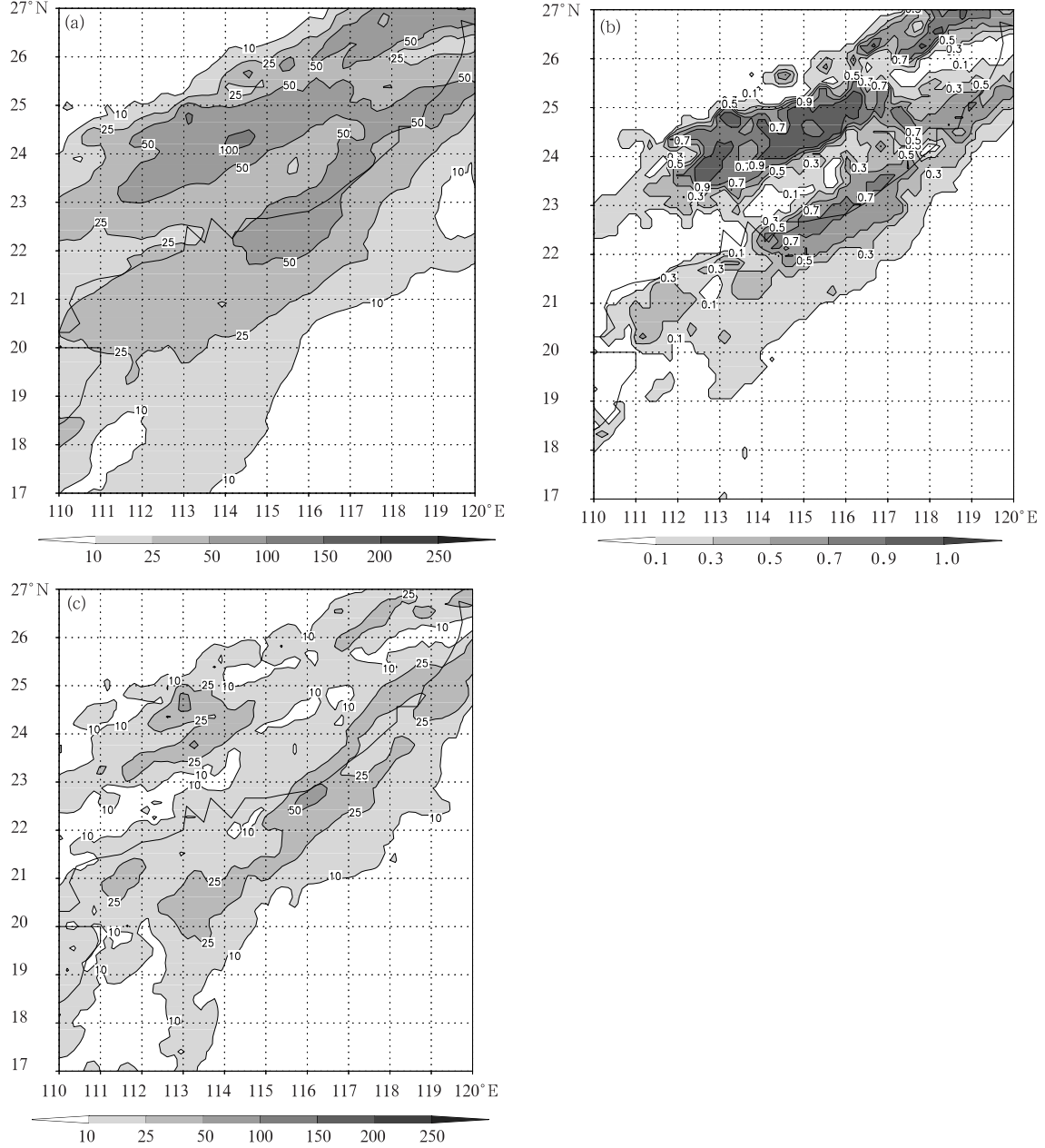


Fig.9. The result of accumulative precipitation ensemble prediction in the first model perturbation method: (a) the mean of ensemble precipitation (unit: mm), (b) precipitation probability over 50 mm, and (c) mean square deviation of precipitation.

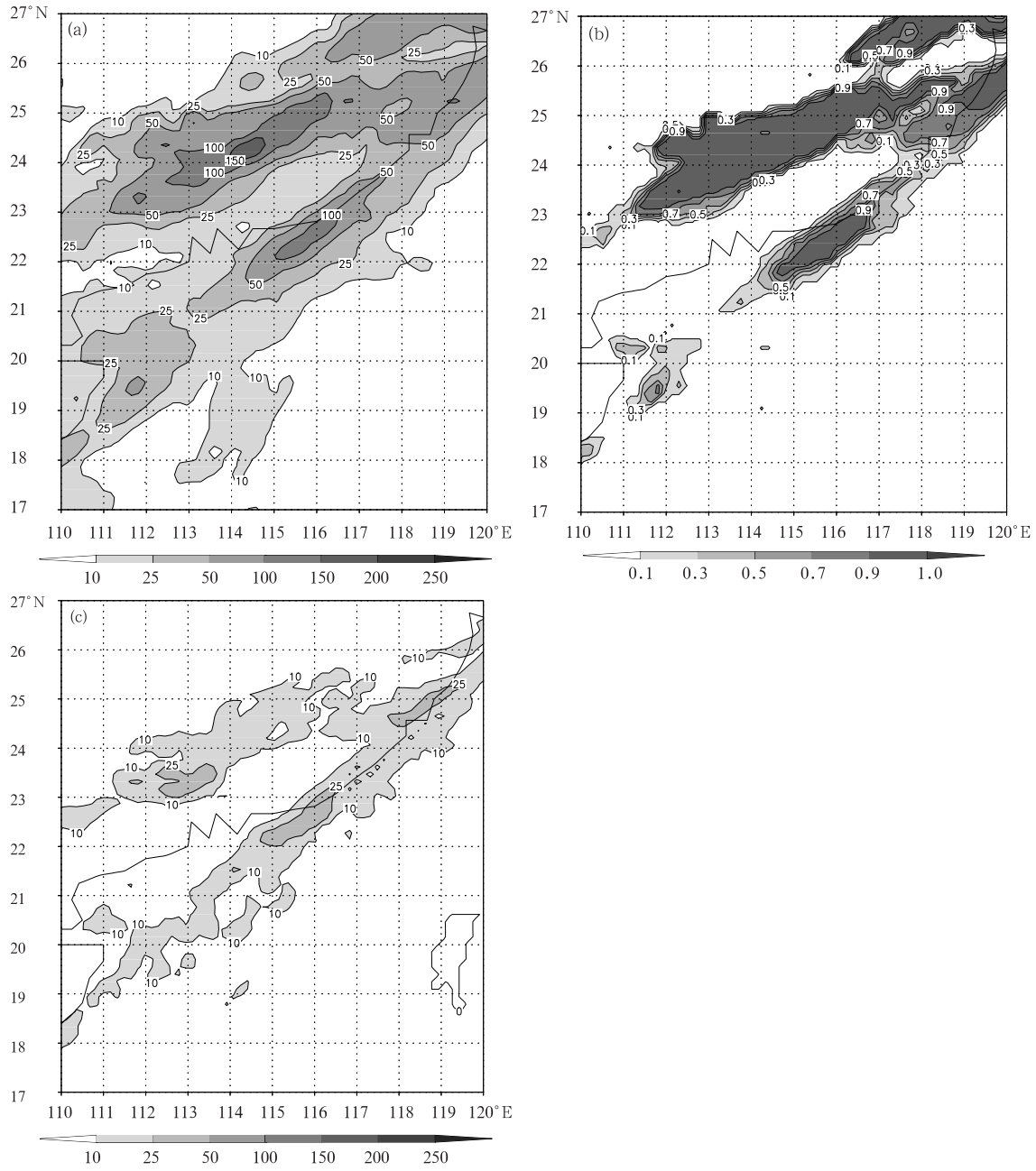


Fig.10. As in Fig.9, but for the second model perturbation method.

T_S and B_S are two statistical quantities used in testing the prediction of precipitation levels. T_S is a measure for the prediction accuracy of a certain precipitation level, arranging from 0 to 1. Zero means no prediction skills and one means 100% accuracy, without any over-estimate or under-estimate. B_S is a measure for the prediction deviation of a precipitation level. When $B > 1$, then the over-estimate prediction rate is higher than the under-estimate rate. It

is just opposite when $B < 1$. Figures 11 and 12 illustrate respectively the 6 h precipitation T_S and B_S of the 7 ensemble members and ensemble mean in the first model perturbation method when precipitation is over 1.0, 10.0 and 25.0 mm. As is shown, the T_S scores of ensemble mean at the three levels are higher than those of the most ensemble members, but still not the best. The B_S scores of ensemble mean with precipitation of 1.0 and 10.0 mm are higher than those of the

most ensemble members, but B_S scores of ensemble mean with precipitation over 25.0 mm is lower than that of the most ensemble members in most of the time, still not the lowest. When precipitation is over 25 mm, T_S and B_S scores show that ensemble mean is better than most of the ensemble members, which means on the whole the results of the ensemble prediction mean in the first model perturbation method are better than those of a single ensemble member. For the second method, T_S and B_S scores of each ensemble member and ensemble mean when precipitation is over 1.0, 10.0 and 25.0 mm are similar to the T_S and B_S curves of the control prediction in Figs.11 and 12 (figure not shown). T_S score of ensemble mean is lower than that of the first model perturbation method.

The analysis shows that in the unstable layers, the convective cloud calculated with Grell Scheme is usually much thicker than minimum required. In addition, unstable layers exist almost everywhere between

the layers of lifting condensation and free convection. The discrepancy of temperature perturbation domain and diffusion direction between members in the second model is much less than that in the first model (figure not shown). The local convergence and divergence are also similar to vertical motion among the members created by the second perturbation method, and therefore there is little difference between members and less reflection of uncertainty of ensemble prediction in heavy rain prediction.

The above results show that only perturbing the parameters may not be able to reflect the uncertainty of heavy rain. As the schemes with different physics have different definition of convection triggering function and feedback to the atmosphere, the spreads of prediction results are much greater. The first model perturbation method can reflect the uncertainty in the numerical prediction on heavy rain in South China more effectively than the second one.

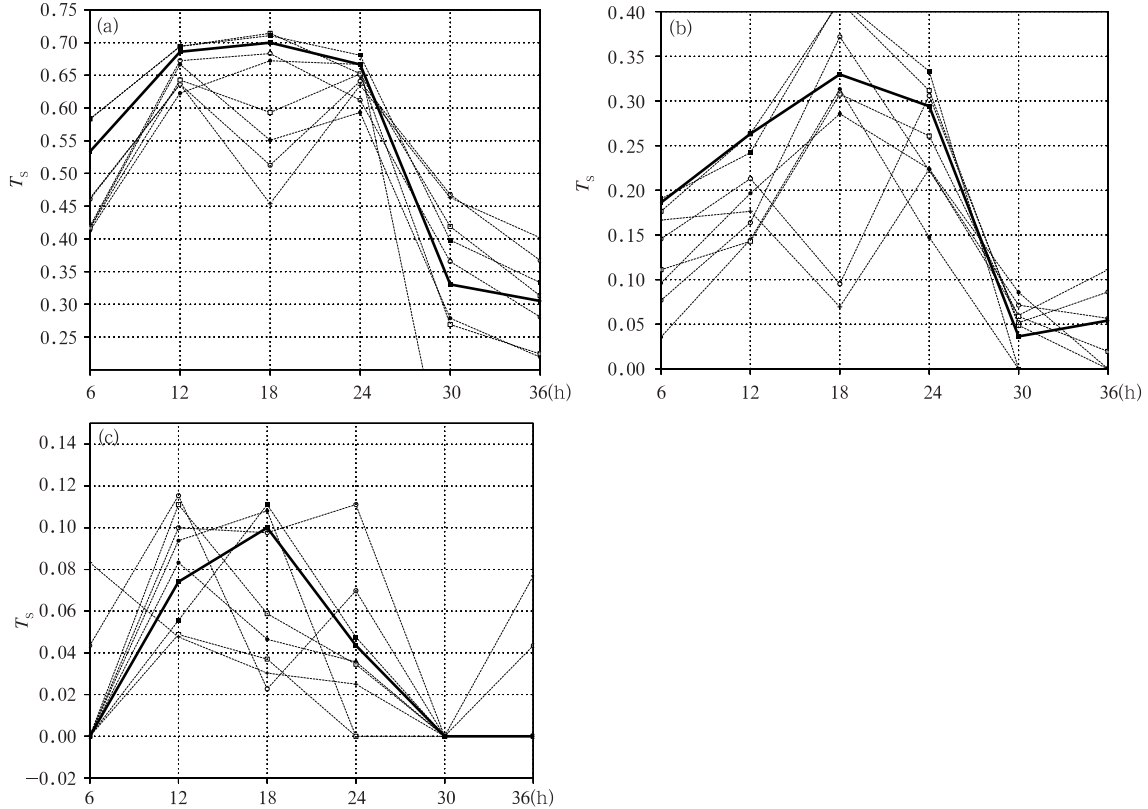


Fig.11. The 6 h T_S of categorical precipitation of the 7 ensemble members and ensemble mean (thick line) in Guangdong and Fujian Provinces with the first model perturbation method for (a) >1 mm, (b) >10 mm, and (c) >25 mm.

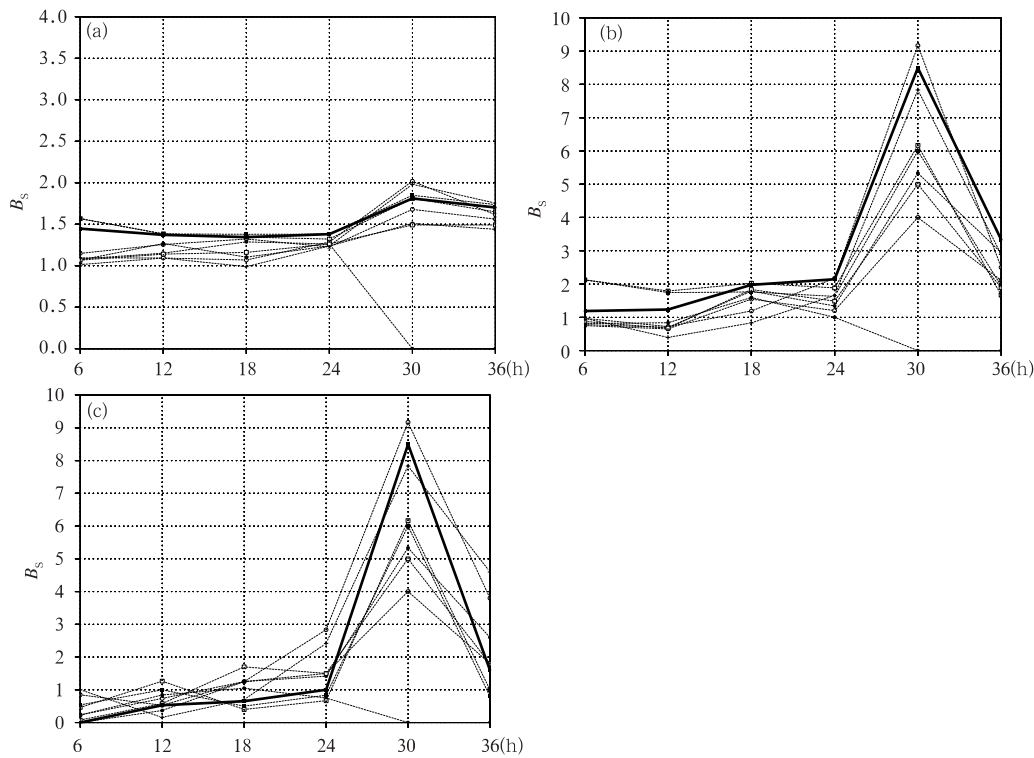


Fig.12. The 6 h B_s of categorical precipitation of the 7 ensemble members and ensemble mean (thick line) in Guangdong and Fujian Provinces in the first model perturbation method for (a) >1 mm, (b) >10 mm, and (c) >25 mm.

6. The conclusions and discussion

In this paper, a numerical test of a typical heavy rain in the warm area of South China was used to analyze the physics processes of the impact of different cumulus convection parameterization schemes on uncertainty of heavy rain simulation. At the same time, two model perturbation methods were tested, of which one is by combining stochastically the planetary layer boundary schemes and cumulus convection parameterization schemes and the other is by perturbing the amplitude of main parameters of Grell Scheme in the control prediction. Thereby we reach the following conclusions:

(1) The latent heat of convective condensation in the convection parameterization scheme causes the local temperature perturbation, leads to discrepancy of vertical velocity through the thermal and dynamic process in the atmosphere and affects the timing, location and intensity of the grid and sub-grid scale precip-

itation. The new precipitation gives rise to new perturbation source by releasing latent heat. The difference of the parameterization schemes and accordingly the difference in the means of diffusing the energy of the perturbation source eventually cause the difference of the dynamic and thermal structure of the simulated atmosphere.

(2) As the precipitation prediction is sensitive to convection parameterization schemes, the model perturbation ensemble prediction, a stochastic combination of various convection parameterization schemes and planetary layer boundary schemes can reflect the uncertainty of the raining region and the rainfall intensity that exists in the heavy rain prediction of the warm area in South China. However, only perturbing the amplitude of the parameters in the schemes seems insufficient for reflection of the uncertainty in prediction of heavy rain in South China by comparing the results of the two methods. Much more experiments and further researches are needed.

(3) More valuable guidance for “1998-06-08” heavy rainfall process in South China and uncertainty information for prediction on the rainfall area and intensity can be provided with the help of the ensemble products of model perturbation ensemble prediction formed by combination of various convection parameterization with planetary boundary level schemes, such as precipitation mean, probability of precipitation over 50 mm, and spread of precipitation. T_S scores of the ensemble mean are higher than those of the most members, but it is not the best. The ensemble mean of prediction of precipitation over 25 mm is better than that of the most members.

(4) In the area of low latitude, the diabatic physics parameterization schemes do not affect much the large-scale circulation pattern, but mainly the variables with strong mesoscale features, such as precipitation.

(5) The single determinate prediction is not stable in terms of the reliability of the heavy rain location and intensity, while the model perturbation ensemble can reflect the uncertainty of heavy rain prediction, providing more useful guidance and with higher application value.

(6) Model perturbation is efficient in constructing the heavy rainfall ensemble prediction. Adjusting parameters is also a means for constructing such prediction. Although this paper has not gained a satisfactory result of ensemble prediction by means of adjusting parameters, it does not mean that this method is useless, because there may lie two possible reasons for the result. First, the designed scheme cannot reflect well the physical meaning of the convection triggering process in the scheme; second, the physical meaning of the parameters in Grell Scheme cannot reflect the uncertainty of the convection parameterization schemes in heavy rain of South China. If another scheme were used, the results might be different. Hence, further research should be done on how to adjust, open or close the parameters according to their physical meanings. Meanwhile, as the above conclusions are based on a single case of heavy rain in South China, more cases should be investigated to find whether the conclusion

is applicable for other cases in South China.

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