MODIFIED MASS FLUX CUMULUS CONVECTIVE PARAMETERIZATION SCHEME AND ITS SIMULATION EXPERIMENT—PART I: MASS FLUX SCHEME AND ITS SIMULATION OF THE 1991 FLOOD EVENT*

LIU Yiming (刘一鸣) and *DING Yihui* (丁一汇)

National Climate Center, Beijing 100081

Received September 5, 2001

ABSTRACT

Based on the existing cumulus convective parameterization schemes, a mass flux scheme (MFS) for cumulus convective parameterization has been successfully developed by reference to the work of Chen et al. (1996). The MFS is a comprehensive scheme. In MFS, not only the importance of the large-scale moisture convergence is taken into account, but also it includes the cumulus updrafts and downdrafts, cumulus-induced subsidence in the environmental air, entrainment, detrainment and evaporation. The interaction between the cumulus and the environment is described by using a one-dimensional bulk model. At the same time the scheme includes the penetrative and shallow convections.

The MFS has been successfully incorporated into the regional climate model RegCM2 developed by NCAR. The new model has been applied to simulate summer monsoon characteristics and their variations of heavy rainfall process in the Changjiang-Huaihe River Basins for three months from May to July 1991. The results show that the new model can successfully simulate this rainfall prolonged process. By comparising the model outputs of RegCM2, using the Kuo scheme and the MFS, it is found that the MFS is better in simulating the surface temperature, rainfall position and amount, and rainfall duration.

Key words: cumulus convection, mass flux scheme (MFS), regional climate model

I. INTRODUCTION

Cumulus convection process is one of the most important diabatic heating processes in the numerical models. Since mid 1950s various cumulus parameterizations have been developed. The existing cumulus convective parameterization schemes can be divided into two kinds: shallow cumulus convective parameterization scheme and deep cumulus convective parameterization scheme (Chen 1997). The shallow cumulus convection can only bring about the change in the vertical distribution of temperature and humidity in the air column from cloud bottom to cloud top, but can not produce the net release of latent heating and convective precipitation. The deep cumulus convective process can cause not

* Supported by "National Key Program for Developing Basic Sciences" G1998040900 and the National Natural Science Foundation of China (No. 49794030).

only the change in the vertical distribution of temperature and humidity in the air column from cloud bottom to cloud top, but also the net release of latent heating and convective precipitation. There is more extensive research about the deep cumulus convective parameterizations than the shallow cumulus convective parameterizations. The deep cumulus convective parameterization schemes can be divided into four kinds: convective adjusting scheme (Manabe et al. 1965; Betts 1986; Betts and Miller 1986), Kuo-type scheme (Kuo 1965; 1974; Anthes 1977; Geleyn 1985), mass flux scheme (Arakawa and Schubert 1974; Arakawa and Chen 1987) and mesoscale model cumulus parameterization scheme (Kreitzberg and Perkey 1977; Fritsch and Chappell 1980a; 1980b; Frank 1984).

In convective adjusting schemes humidity and temperature are firstly forecasted after taking out the condensation and then adjusted in order to avoid the supersaturation. The precipitation is often underestimated and the heating level is always too low in the convective adjusting parameterizations. This kind of scheme is often used in general circulation models (GCMs) because of the small amount of calculation.

In Kuo-type schemes convection is assumed to develop in the area where there is deep conditional unstable layer and there is large-scale convergence in the lower levels. The cumulus will change the temperature and humidity in the environmental air through lateral mixing heating and moistening after it is formed. Part of the net converge water vapor in the cloud column will be condensed into precipitation. The other will moisten the environmental air. One of the main differences between the different versions of this kind of scheme is the choice of moistening factor "b". The main strongpoint of Kuo-type schemes is to determine the cumulus scale heating and moisture flux directly through the large-scale variable and need not consider the dynamical processes (such as entrainment, detrainment and downdraft) and the cloud microphysical process. The Kuo-type scheme is often used in the operational prediction model.

The Arakawa-Schubert (A-S) scheme is characterized by the focus on the relationship between cumulus and large-scale environment. It is one kind of spectral model. The clouds of different scales are in coexistence at the same time. In this scheme the main reason for formation of the heating distributing in the large-scale environment is the convection-induced downdrafts among the cumulus ensemble. The effect of A-S scheme is the best in the prediction of large-scale and meso-scale processes because of its detailed moist physical processes. But it is generally used in the research because of the large amount of calculation.

The above three schemes are often used in coarse-mesh models. For mesoscale model the cumulus parameterization scheme needs to describe the interaction between cumulus and mesoscale environment and the interaction between cumulus and large-scale system. The cloud model is a little complicated because the cloud microphysical process and water vapor phase change process are considered in the model. The most popular parameterization in mesoscale model is the Fritsch-Chappell scheme.

From the 1970s, especially after the 1980s, the development in all kinds of cumulus parameterization schemes is very rapid (Liu 1998), such as Betts-Miller scheme in 1986 and Tiedtke scheme in 1989. In this paper, on the basis of the research by Chen et al. (1996), the mass flux scheme (MFS) is simplified from ECMWF Tiedtke scheme and is put into the second generation Regional Climate Model (RegCM2/NCAR) in order to simulate the summer regional climate character in the monsoon region in China. The study is structured as follows. In Section II the mass flux cumulus parameterization scheme is described. A brief description of the model (Section III) is followed by the experimental design (Section IV). The simulation of excessively severe flood in China in 1991 is described in Section V, with a concluding discussion in Section VI.

II. SIMPLIFIED ECMWF MASS FLUX CUMULUS PARAMETERIZATION SCHEME

1. *Large-Scale Budget Equations*

Considering the bulk properties of the cloud ensemble, the large-scale budget equations (Chen et al. 1996; Tiedtke 1989) for heat and moisture are

$$\frac{\partial S}{\partial t}+\boldsymbol{V}\cdot\nabla S+\omega\frac{\partial S}{\partial p}=\frac{\partial}{\partial p}[M_uS_u+M_dS_d-(M_u+M_d)S]+ L(c_u-e_d-\tilde{e}_l-\tilde{e}_p)+Q_R, \quad (1)$$

$$\frac{\partial q}{\partial t}+\boldsymbol{V}\cdot\nabla q+\omega\frac{\partial q}{\partial p}=\frac{\partial}{\partial p}[M_uq_u+M_dq_d-(M_u+M_d)q]- (c_u-e_d-\tilde{e}_l-\tilde{e}_p), \quad (2)$$

where S is the dry static energy, q the specific humidity, $\boldsymbol{V}$ the horizontal velocity, ω the vertical velocity and Q_R the radiative heating. M_u, M_d, c_u and e_d are the net contributions from all clouds to the upward mass flux, downward mass flux, condensation and evaporation, respectively, and S_u, S_d, q_u and q_d are the weighted averages of S and q from all updrafts and downdrafts. $-(M_u+M_d)$ is cumulus-induced subsidence in the environmental air. $\tilde{e}_l$ is the evaporation of cloud air that has been detrained into the environment and $\tilde{e}_p$ is the evaporation of precipitation in the unsaturated subcloud layer. The cumulus convective rainfall is

$$P_c=\frac{1}{g}\int_{P_T}^{P_B}(G_p-e_d-\tilde{e}_p)\mathrm{d}p, \quad (3)$$

where G_p is the conversion from cloud water into precipitation, P_T, P_B are the pressure at cloud top and cloud base, respectively.

2. *Cumulus Updrafts*

The updraft of the cloud ensemble is assumed to be in a steady state. Then the bulk equations for mass, heat, moisture and cloud water content are

$$\frac{\partial M_u}{\partial p}=D_u-E_u, \quad (4)$$

$$\frac{\partial (M_uS_u)}{\partial p}=D_uS_u-E_uS-Lc_u, \quad (5)$$

$$\frac{\partial (M_uq_u)}{\partial p}=D_uq_u-E_uq+c_u, \quad (6)$$

$$\frac{\partial (M_ul)}{\partial p}=D_ul+G_p-c_u, \quad (7)$$

where D_u and E_u are the rates of mass detrainment and entrainment per unit length in updrafts, l is the cloud liquid water content. Cloud air is assumed to be saturated.

Entrainment of mass into convective plumes is assumed to occur through turbulence exchange of mass through cloud edges ($E_u^{(1)}$) and through organized inflow associated with large-scale convergence ($E_u^{(2)}$). Detrainment of mass from cloud entity is made through turbulent exchange ($D_u^{(1)}$) and organized outflow ($D_u^{(2)}$) at cloud top:

$$E_u = E_u^{(1)} + E_u^{(2)}, \tag{8}$$

$$D_u = D_u^{(1)} + D_u^{(2)}. \tag{9}$$

3. *Cumulus Downdrafts*

Downdrafts are considered to be associated with convective precipitation from the updrafts and originated from cloud air influenced by the injection of environmental air. The equations for mass, dry static energy and moisture content are

$$\frac{\partial M_d}{\partial p} = D_d - E_d, \tag{10}$$

$$\frac{\partial (M_d S_d)}{\partial p} = D_d S_d - E_d S - Le_d, \tag{11}$$

$$\frac{\partial (M_d q_d)}{\partial p} = D_d q_d - E_d q + e_d, \tag{12}$$

where D_d and E_d are the rates of mass detrainment and entrainment per unit length in downdrafts.

4. *Penetrative Convection*

In this study penetrative convection and shallow convection are both considered. For the penetrative convection and shallow convection, the cloud model is same, but with different hypothesis and parameters. Many diagnostic studies show that penetrative convection predominantly occurs in disturbed situations and strongly depends on low-level synoptic scale convergence. The injection of mass into the clouds through their base is determined by imposing a moisture balance for the subcloud layer such that the moisture content is maintained in the presence of large-scale transports, turbulent transports and convection transports. According to the cloud model the closure hypothesis is

$$[M_u(q_u - q) + M_d(q_d - q)]_B = -\int_{P_B}^{P_S}\left[\nabla \cdot (qV) + \frac{\partial (\omega q)}{\partial p}\right]dp + E_S, \tag{13}$$

where P_S, P_B are the pressure at surface and cloud base respectively. This hypothesis brings the quasi-steady state for the subcloud layer moisture content.

The organized entrainment is only considered in the lower part of the cloud layer where large-scale convergence is encountered and is directly proportional to the large-scale moisture convergence as

$$E_u^{(2)} = -\frac{1}{q}\left[\nabla \cdot (qV) + \frac{\partial (\omega q)}{\partial p}\right]. \tag{14}$$

The organized detrainment only happens near the cloud top

$$D_u^{(2)} = \frac{(M_u)_{k+1/2}}{\Delta p}. \tag{15}$$

The penetrative cumulus is one kind of cumulus with convective precipitation. The conversion from cloud droplets to raindrops is assumed to be proportional to the liquid cloud water content.

5. *Shallow Convection*

The shallow convection predominantly occurs in the absence of large-scale convergent flow. Many studies show that the net upward moisture flux at cloud base level is nearly equal to the turbulent moisture flux at the surface. As this implies a quasi-steady moisture balance, we shall apply the same moisture budget Eq. (13) as for penetrative convection. The difference, however, is that the moisture supply to cumulus clouds is now largely through surface evaporation as the contributions from large-scale convergence are either small or even negative.

The scheme presented here ignores the effect of very small cumuli which in large numbers detrain immediately above cloud base, but tentatively accounts for the effects of overshooting cumuli (Tiedtke 1989). The overshooting effects of the shallow cumulus are considered in the scheme. The shallow cloud air shall be only partly detrained into the environment within the cloud top layer; the remaining fraction shall intrude into the next layer above and be detrained there. Then the detrainment rate through the organized outflow is

$$D_u^{(2)} = (1-\beta)\frac{(M_u)_{k+1/2}}{\Delta p}, \qquad \text{at} \quad k_{\text{top}} \tag{16}$$

$$D_u^{(2)} = \beta\frac{(M_u)_{k+1/2}}{\Delta p}, \qquad \text{at} \quad k_{\text{top}}-1 \tag{17}$$

where β means the intensity of overshooting effects. The shallow convection has no precipitation.

III. MODEL DESCRIPTION

The model used in this paper is the second generation Regional Climate Model (RegCM2/NCAR)(Giorgi et al. 1993a; 1993b). Liu et al. (1996), Zhao et al. (1997) and Luo and Zhao(1997) made a lot of descriptions and summaries about the RegCM2 and its regional climate simulations. The performance of the RegCM2 is accomplished with the general circulation model (such as CCM2) or assimilation analysis providing the initial and lateral boundary conditions to drive RegCM2. Then the simulation of RegCM2 will be made in the chosen research region in order to explore the more accurate and detailed characters of the regional climate under the large-scale background. The nesting method is one way nesting, that is, the GCM model provides the initial and lateral boundary conditions to RegCM2, but the simulative results of the RegCM2 will not be fed back to the general circulation model. A lot of simulative researches have been done with the improvement and development of RegCM2 in NCAR. The researches of Liu et al. (1994), and Luo and Zhao (1997) show that RegCM2 has the simulative ability of regional climate character and can have better simulations in many aspects than general circulation models with coarse mesh. On the other hand, the simulative studies (Giorgi 1991; Giorgi and Marinucci 1991; Ding et al. 1998) of the physical process parameterizations in RegCM2 show that RegCM2 is very sensitive to the parameterization schemes. Up to now the treatment of physical processes in the model is still very weak, so it is very important for improving the simulative quality of regional climate model with refinement of the treatment of the physical processes.

IV. EXPERIMENTAL DESIGN

There are two kinds of convection parameterization schemes in RegCM2, Kuo scheme and Grell scheme. Now the MFS is put into the RegCM2 and used as the third choice. In order to test the simulative ability of MFS for cumulus convective process, the same case is chosen for Kuo scheme and MFS scheme to simulate, analyze and compare.

There is a catastrophic flood in Changjing-Huaihe River Basin (hereafter referred to as Jianghuai) in China during the summer, 1991 (Ding 1993). It becomes one of the most famous Meiyu cases in the recent 40 years in China with its large amount of precipitation, long lasting duration, and serious damage to economy and human life. It happens in Jianghuai during the Meiyu season. The main character is that the Meiyu comes early and lasts long, the period of rainstorm is concentrated, the intensity of rainstorm is large, and the positions of rain areas almost have no any change. This disaster event provides a good opportunity to examine the simulative ability of RegCM2 to grasp the regional climate character of heavy rainfall in China.

The initial and lateral boundary conditions are provided by the Pacific Northwest National Laboratory (PNNL) of USA from ECMWF-TOGAII datasets. The lateral boundary conditions are updated at 12-h intervals with relaxation, exponential technique. The SST is updated with the lateral boundary conditions. The SST is interpolated at 12-h intervals from the observed monthly mean SST of $2°\times 2°$. The simulative period is May 1 to July 31, 1991. The time step is 120 s. The domain is the region of East Asia and the West Pacific, 100—150°E, 10—45°N. The central point is at 120°E, 30°N. The horizontal resolution is 60 km. There are 65 grid points in the north-south direction and 85 in the west-east direction. There are 23 levels in the vertical direction, 6 levels below 850 hPa and 6 levels above 300 hPa. The top level in the model is at 10 hPa. There is an 18-layer buffer zone on the sides. The elevation and vegetation data are derived from a global 10 min data set. There are 18 kinds of vegetations. The research region includes part of the Tibetan Plateau, with the highest elevation of 5200 m. The main vegetations of the underlying surface in the domain are grassland, tropical and subtropical forest, deciduous forest, coniferous forest, desert, savanna and agricultural land.

The physical process parameterization schemes in the regional model include the CCM2 radiation transfer scheme, the Hotslag planet boundary layer scheme, the BATS, and the non-explicit scheme for the large-scale precipitation process.

Two simulations with different cumulus parameterization schemes (Kuo and MFS) are made with the same domain, period, time step and same other physical process parameterization schemes. Next part is directed to the analysis of the simulative results.

V. SIMULATIVE RESULTS

The 3-month integral of RegCM2 with MFS shows that it is successful to transplant the MFS scheme into the RegCM2 initially. The simulative results will be compared with the reanalysis data firstly. Then the simulation will be compared with the simulation of RegCM2 with Kuo scheme.

1. *Comparison of Circulation in Lower and Middle Layer between Simulation and Observed Data*

The simulation of RegCM2 with MFS is basically consistent with the ECMWF analysis in the lower and middle layer. The RegCM2 with MFS can depict the regional climate character in the domain in detail. The monthly mean wind at 850 hPa in May—July 1991 from ECMWF analysis is indicated in Fig. 1. The simulations of monthly mean wind and moisture at 850 hPa are shown in Fig. 2 and Fig. 3 respectively. In May there was a depression in Southwest China, with the strong southerly wind at its eastern side. The strong southwest monsoon dominated East China and Southeast China. The coastal region in Southeast China is controlled by the strong southwesterlies in the outer region of the West Pacific subtropical high. It is consistent with analysis of the earlier first northward jump of the West Pacific subtropical high, and the main convergence in the lower layer in Southwest China, Jianghuai and its northern portion. There is a moist tongue from Indochina Peninsula to East China. This situation is consistent with the

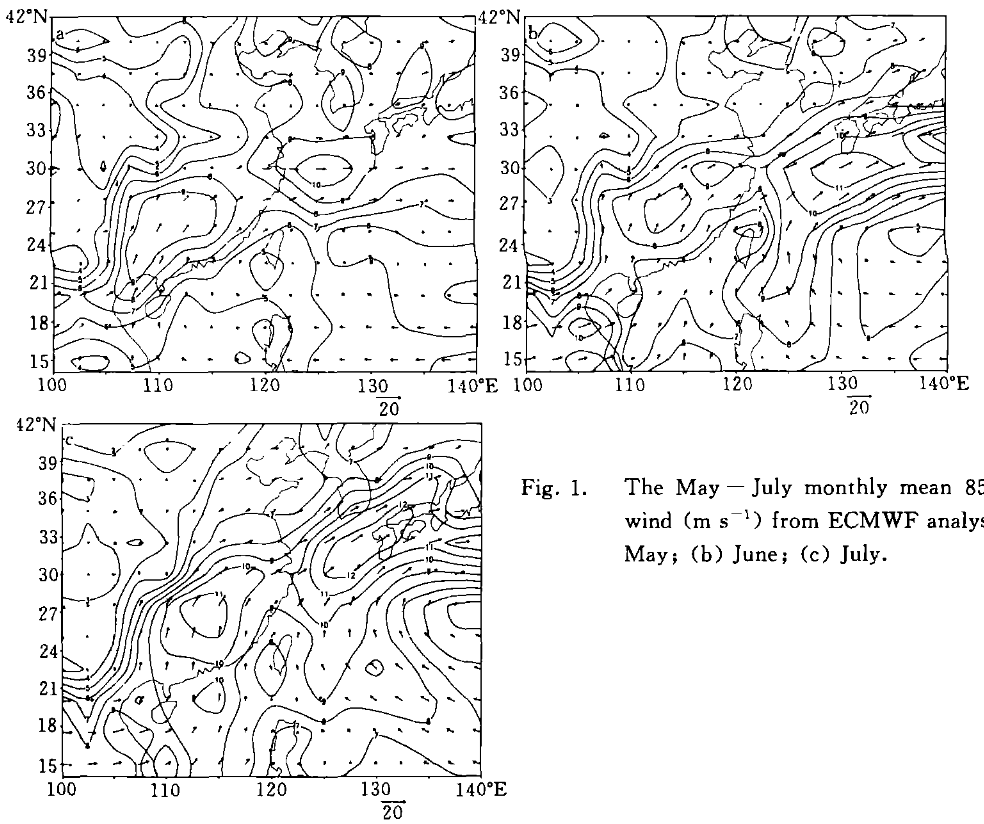


Fig. 1. The May — July monthly mean 850 hPa wind (m s^{-1}) from ECMWF analysis (a) May; (b) June; (c) July.

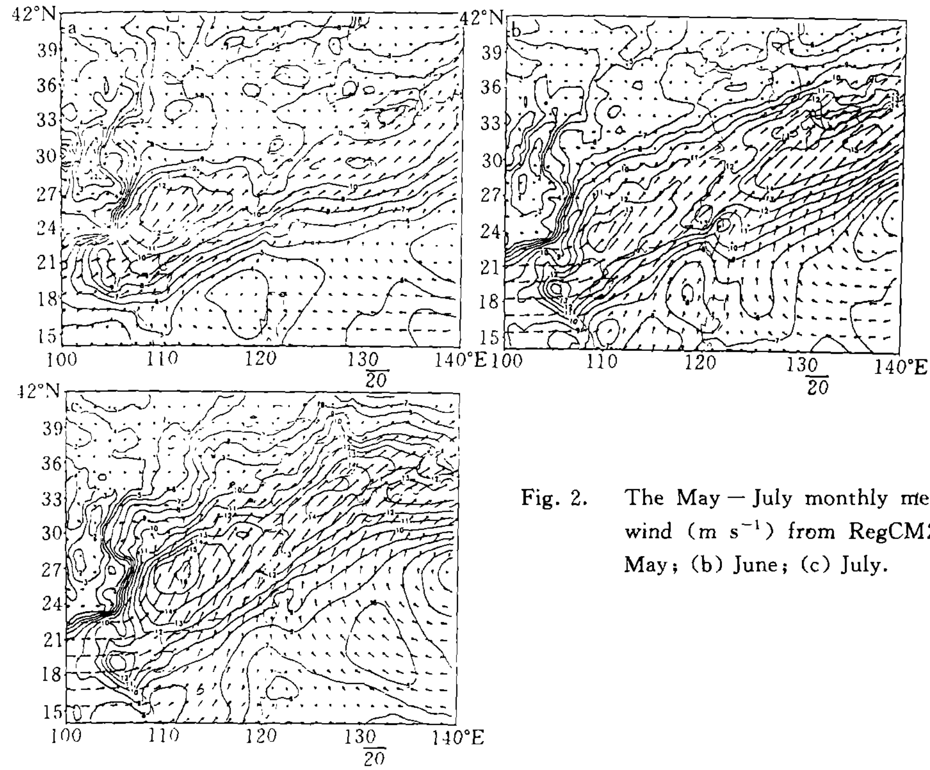


Fig. 2. The May — July monthly mean 850 hPa wind (m s^{-1}) from RegCM2/MFS (a) May; (b) June; (c) July.

observation that the rain season begins in this region in May and no heavy rainfall in South China. There was obvious change in the simulation in June compared with the simulation in May. The southerlies decreased from Southwest China to the western part of North China. The southwest monsoon still dominated Southeast China and East China, with decreased intensity and more extensive area. The specific humidity is obviously increased in South China and Jianghuai. This simulation corresponds to the observed heavy precipitation in East China and Southwest China. Until July the southwest monsoon obviously moved northward to the Bohai Sea. It is in line with the observed second northward jump of the West Pacific subtropical high. During July the specific humidity was increased greatly in north. The long-lasting heavy rainfall process was ended in Jianghuai and the main rain belt moved northward. From the circulation at 500 hPa, it is very obviously shown that the southwest monsoon prevails and moves northward and the West Pacific subtropical high moves northward.

Above all, the RegCM2 with MFS not only can simulate the large-scale circulation, the abnormity in the East Asian circulation, and the East Asian summer monsoon activities during May—July, 1991, but also can reveal the fine regional climate character.

2. *The Comparison of Surface Elements Simulated by RegCM2/MFS and RegCM2/Kuo*

Precipitation and surface air temperature are the main elements in the regional climate simulation and prediction. The observed and simulated precipitation amount in June, 1991 is shown in Fig. 4. The observed precipitation is drawn from the 132 stations rainfall in

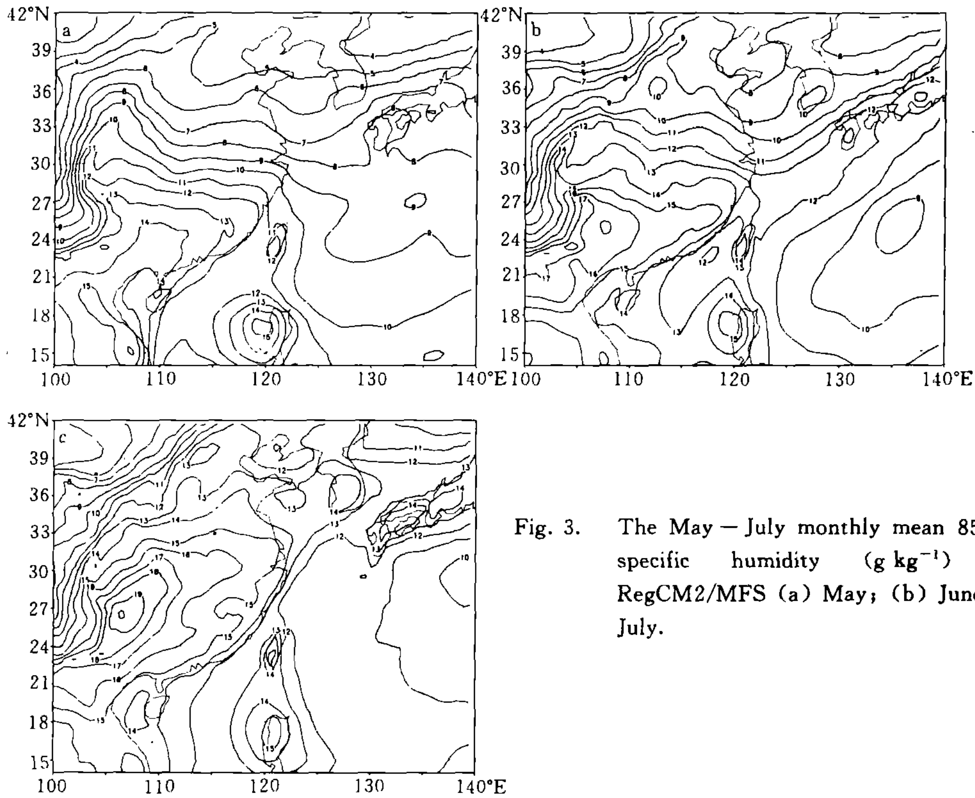
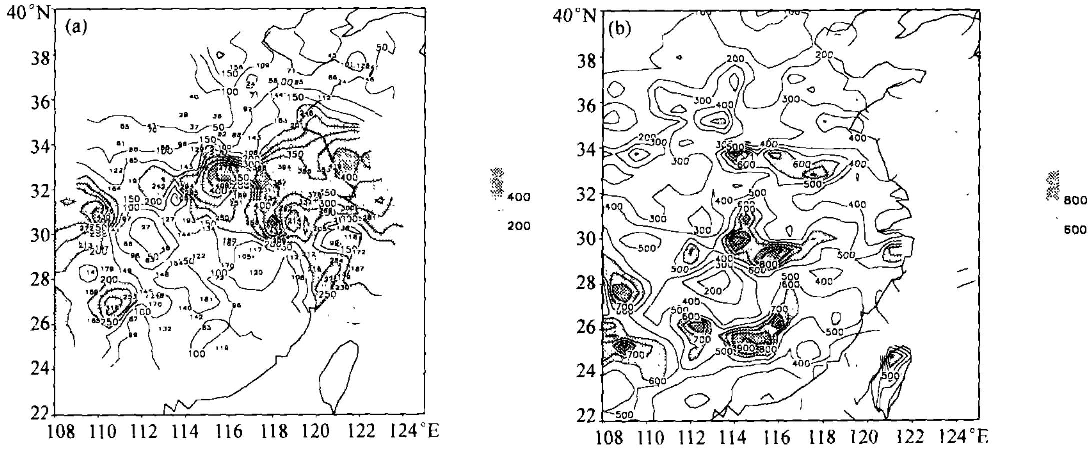


Fig. 3. The May — July monthly mean 850 hPa specific humidity ($g\ kg^{-1}$) from RegCM2/MFS (a) May; (b) June; (c) July.

Jianghuai. The observed rain belt is oriented with east-west direction along 30 — 34°N. There are two heavy rainfall areas, one near 33°N, with the isohyet line of 400 mm located at 116°E, 33°N, and the maximum of 478 mm, the other located at 110°E, 31°N with the maximum of 430 mm. The total precipitation amounts simulated by Kuo and MFS are greater than the observed. The rainfall area simulated by RegCM2/Kuo is quite scattered over South China and East China. The rainfall area simulated by RegCM2/MFS can reflect the observed main rainfall area in East China. The over-simulated precipitation amount is related with the physical process parameterization, initial and lateral boundary conditions and error in the model. The centers with abnormal heavy precipitation amount are the "grid-point storms".

The daily observed and simulated precipitation averaged over Jianghuai region (28—34°N, 114—122°E) is shown in Fig. 5. The thick solid line is the observation, the dashed line is the simulation of RegCM2 with Kuo, and the thin solid line is the simulation of RegCM2 with MFS. The 1991 Meiyu process of Jianghuai consists of three episodes of excessively heavy rain. The first rain episode (May 18—26) is called early Meiyu, and the second (June 2—19) and the third (June 30—July 13) are the typical Meiyu. By means of comparison between the observation and the simulations, we can see that the daily precipitation amounts simulated by Kuo and MFS are greater than the observation. The two schemes can simulate the variation of rain episodes with time and reflect the three rain episodes. But there is an unrealistic episode between the first and the second episode



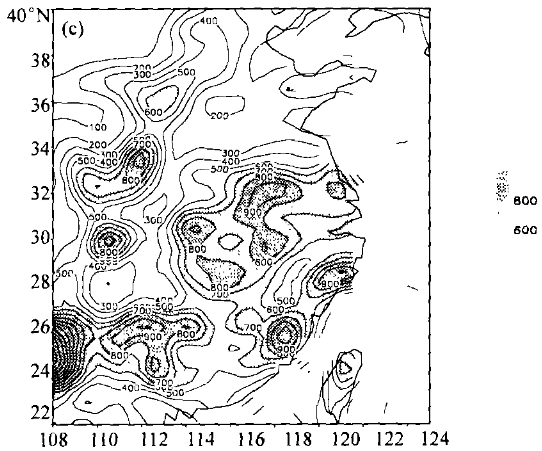


Fig. 4. Precipitation amount (mm) in June, 1991. (a) observation, (b) Kuo, and (c) MFS.

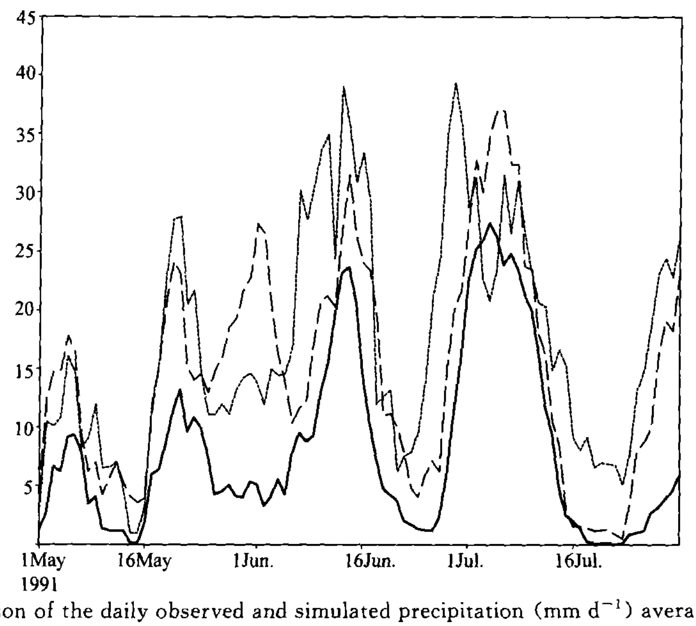


Fig. 5. A comparison of the daily observed and simulated precipitation (mm d^{-1}) averaged over region (28—34°N, 114—122°E) during May—July, 1991. Thick solid line stands for observation, dashed line stands for Kuo and thin solid line stands for MFS, respectively.

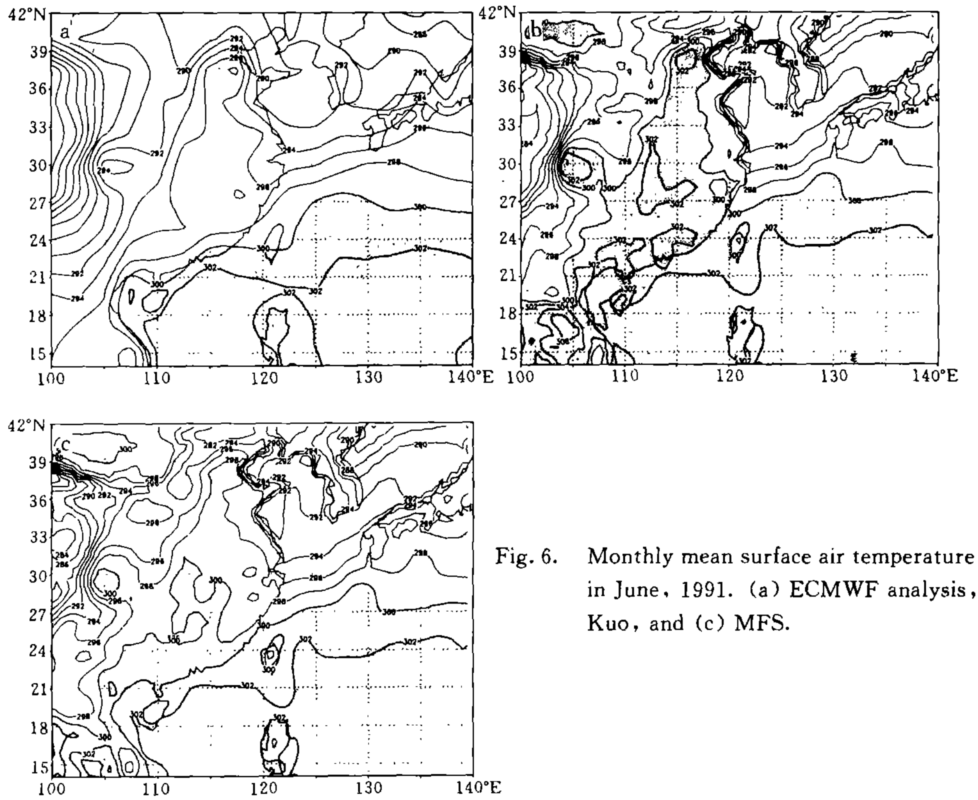


Fig. 6. Monthly mean surface air temperature (K) in June, 1991. (a) ECMWF analysis, (b) Kuo, and (c) MFS.

simulated by Kuo. The RegCM2 with MFS can clearly reproduce the three rain episodes and two intervals (May 27—June 1 and June 20—29).

The analyzed and simulated monthly mean surface air temperature is shown in Fig. 6. In June 1991, there is a warm tongue of 296 K in Jianghuai. The simulations over theocean are very close to the analysis, but there is obvious error over land. The simulation by Kuo scheme is 5—6 K higher than analysis with the warm center of 302 K in Jianghuai and Shichuan Province, 2—3 K higher in South China, and 8—10 K higher in Indochina Peninsula with a warm center of 306 K. The simulation of MFS is about 4—6 K higher than the analysis in Indochina Peninsula and 2—4 K higher in Jianghuai. It means that the simulation of RegCM2 with MFS is better than the simulation of RegCM2 with Kuo in surface air temperature.

VI. SUMMARY

A simplified mass flux cumulus parameterization scheme (MFS) is transplanted into RegCM2 and is used to simulate the regional climate character of summer heavy rainfall in China during May—July, 1991 with the following results obtained.

(1) MFS is a comprehensive scheme of Kuo-type scheme and Arakawa-Schubert scheme. In MFS, the cumulus updrafts, cumulus downdrafts, cumulus-induced subsidence in the environmental air, entrainment, detrainment and evaporation are

considered. The interaction between the cumulus and the environment is described by using a one-dimensional bulk model. The penetrative convection and shallow convection are included in the same model. The overshooting effect of shallow cumulus and the interaction between cloud layer and subcloud layer are also considered in the scheme.

(2) MFS is transplanted into RegCM2 and a 3-month integral is made successfully. This means that the performance is stable and successful. The simulation of RegCM2 with MFS is consistent with the ECMWF analysis. The RegCM2 with MFS can simulate the abnormity of East Asian circulation, reflect the course of East Asian summer monsoon, and depict the regional climate character and variation. It can simulate the early northward jump of West Pacific subtropical high over 20°N in May, the direct influence of southwest monsoon on the Jianghuai region and the early beginning of Meiyu. From June to the first dekad in July it can depict the position of West Pacific subtropical high which is a little farther southward than the normal, the long-persistent Meiyu circulation, and the long Meiyu period because of the southwest monsoon dominating in Jianghuai. It can reproduce the obvious northward jump of southwest monsoon and the ending of Meiyu in July. The fact that the simulation can grasp the spatial and temporal distributions of heavy rainfall episodes in Jianghuai shows that the RegCM2 with MFS has the simulative ability of regional climate character and variation. The common shortage in the simulations of Kuo and MFS is the over-simulated precipitation amount. It may be caused by the over-simulated non-convective precipitation amount. It will be tested in the future.

(3) By comparing the simulation of MFS with that of Kuo, we can find that the mass flux cumulus parameterization scheme can improve the simulation of surface air temperature. It can decrease the error of simulated surface air temperature over Indochina Peninsula, South China, Jianghuai and North China. The simulation of rainfall area with MFS is very close to the observation. From examination of the three rain episodes and two gap episodes in between, the simulation of MFS is better than that of Kuo scheme.

Acknowledgments: We thank Prof. TAO Shiyan, Prof. WU Guoxiong, Prof. WANG Shaowu, Prof. LIU Shida, Prof. XIE An and Prof. LI Weijing for their advice and encouragement, Prof. F. Giorgi for providing the RegCM2 and Prof. ZHAO Zongci for providing the data.

REFERENCES

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

Arakawa, A. and Chen, J. M. (1987), Closure assumptions in the cumulus parameterization problem, Short- and Medium-Range Numerical Weather Predicition, T. Matsuno, Ed., *J. Meteor. Soc. Japan*, Special Volume, 107—131.

Arakawa, A. and Schubert, W. H. (1974), Interaction of a cumulus cloud ensemble with the large scale environment, Part I, *J. Atmos. Sci.*, **31**: 674—701.

Betts, A. K. (1986), A new convective adjustment scheme, Part I: Observational and theoretical basis, *Quart. J. R. Meteor. Soc.*, **112**: 677—691.

Betts, A. K. and Miller, M. J. (1986), A new convective adjustment scheme, Part II: Single column tests using GATE wave, BOMEX, and arctic air-mass data sets, *Quart. J. R. Met. Soc.*, **112**: 693—709.

Chen Bomin et al. (1996), Forecasting experiments of modified ECMWF mass flux cumulus parameterization scheme, *Plateau Meteor.* **15**: 37—47 (in Chinese).

Chen Dehui (1997), A review on the cumulus convective parameterization, *Quart. J. Applied Meteor.*, **8**: 69—77 (in Chinese).

Ding Yihui (1993), Research on the 1991 heavy precipitation over the Yangtze River, China Meteor. Press, Beijing, 255pp (in Chinese).

Ding Yihui, Zhang Jing and Zhao Zongci (1998), An improved land-surface processes model and its simulation experiment, Part 2: Land-surface processes model (LPM—ZD) and its coupled simulation experiment with regional climate model, *Acta Metero. Sinica*, **56**: 385—400 (in Chinese).

Frank, W. M. (1984), A cumulus parameterization scheme incorporating subgrid scale convective forcing, The 15th Technical Conference on Hurricanes and Tropical Meteorology *A. M. S.*, 183—190.

Fritsch, J. M. and Chappell, C. F. (1980a), Numerical prediction of convectively driven mesoscale pressure systems, Part I: Convective parameterization, *J. Atmos. Sci.*, **37**: 1722—1733.

Fritsch, J. M. and Chappell, C. F. (1980b), Numerical prediction of convectively driven mesoscale pressure systems, Part II: Mesoscale model, *J. Atmos. Sci.*, **37**: 1734—1762.

Geleyn, J. F. (1985), On a simple, parameter-free partition between moistening and precipitation in the Kuo scheme, *Mon. Wea. Rev.*, **113**: 405—408.

Giorgi, F. (1991), Sensitivity of simulated summertime precipitation over the western United States to different physics parameterizations, *Mon. Wea Rev.*, **119**: 2870—2888.

Giorgi, F. and Marinucci, M. R. (1991), Validation of a regional atmospheric model over Europe: Sensitivity of wintertime and summertime simulations to selected physics parameterizations and lower boundary conditions, *Q. J. Roy. Meteor. Soc.*, **117**: 1171—1206.

Giorgi, F. et al. (1993a), Development of a Second-Generation Regional Climate Model (RegCM2), Part I: Boundary-layer and radiative transfer processes, *Mon. Wea. Rev.*, **121**: 2794—2813.

Giorgi, F. et al. (1993b), Development of a Second-Generation Regional Climate Model (RegCM2), Part II: Convective processes and assimilation of lateral boundary conditions, *Mon. Wea. Rev.*, **121**: 2814—2832.

Kreitzberg, C. W. and Perkey, D. J. (1977), Release of potential instability, Part II: The mechanism of convective/mesoscale interaction, *J. Atmos. Sci.*, **34**: 1569—1595.

Kuo, H. L. (1965), On formation and intensification of tropical cyclones through latent hear release by cumulus convection, *J. Atmos. Sci.*, **22**: 40—63.

Kuo, H. L. (1974), Further studies of the parameterization of the influencee of cumulus convection on large scale flow, *J. Atmos. Sci.*, **31**: 1232—1240.

Liu Yiming (1998), Application of cumulus parameterization schemes in China, *Acta. Meteor. Sinica*, **56**: 247—255 (in Chinese).

Liu Yongqiang, Ding Yihui and Zhao Zongci (1996), Regional climate modeling of anomalous rainfall along Yangtze and Huaihe Rivers in 1991, *Investigations on Short-Term Climate Forecast Models in China*, Ed. By Zhao Zongci, China Meteor. Press, Beijing, pp. 106—120 (in Chinese).

Liu Yongqiang, Filippo Giorgi and Warren M. (1994), Washington, Simulation of summer monsoon climate over East Asia with an NCAR regional climate model, *Mon. Wea. Rev.*, **122**: 2331—2348.

Luo Yong and Zhao Zongci (1997), Numerical simulation of East Asian regional climate with NCAR RegCM2, *Quart. J. Applied Meteor.*, **8**: 124—133 (in Chinese).

Manabe, S. et al. (1965), Simulated climatology of a general circulation model with a hydrological cycle, *Mon. Wea. Rev.*, **93**: 769—798.

Tiedtke, M. (1989), A comprehensive mass flux scheme for cumulus parameterization in large-scale schemes, *Mon. Wea. Rev.*, **117**: 1779—1800.

Zhao Zongci, Luo Yong et al. (1997), Simulations of summer monsoon over East Asia: Intercomparisons of three regional climate models, **8**: 116—123 (in Chinese).