# A Comparative Study of the Numerical Simulation of the 1998 Summer Flood in China by Two Kinds of Cumulus Convective Parameterized Methods

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## ABSTRACT

The NCC T63L20 model of the National Climate Center, China Meteorological Administration is employed to simulate the 1998 summer flood, which mainly occurred in the region of the Yangtze River and Northeast China. For this study, two kinds of cumulus convection parameterized schemes are employed in this model respectively. The simulations show that the Gregory parameterized scheme, which is still used in the United Kingdom Meteorological Office routine model, simulates more reasonable rainfall amount and distribution compared to the Kuo-type scheme. Moreover, the Gregory scheme better simulates the tendency of general circulation than the Kuo-type scheme. On the whole, the Gregory scheme provides a good simulation of the main features of the seasonal precipitation and general circulation in China, although the simulated result still exhibits some departures from the observations.

**Key words:** cumulus convection; numerical simulation; parameterized scheme; the heavy flood

## 1. Introduction

During the summer of 1998, the heaviest flood since 1954 occurred in the region of the Yangtze River valleys. In addition, the regions of the Nenjiang River and Songhua River valleys were affected. In the spring of 1998, the National Climate Center of the China Meteorology Administration began to forecast the short-term climate in China using the T63120 model in which the Kuo-type cumulus convection scheme was utilized. The main feature of the simulation was that it showed more precipitation would exist in the Yangtze River valley and the most precipitation would be located in the region of Guangdong, Guangxi, and Fujian Provinces, which would be 20 percent greater than normal. Furthermore, it showed the drought would exist in North China. It could be seen from the post-analysis that the heavy flood in the Yangtze River and Nenjiang River valleys was not well simulated and that the simulated rainfall in the precipitation cell was less than the observed data, thus indicating obvious systemic errors. In addition, the prediction for the summer precipitation in China gave more rainfall in the north of China and less rainfall in the south compared to a normal year. And this prediction differed form the observed data also. From the above analysis, the conclusion can be drawn that the original T63 model, which employs the Kuo-type scheme, cannot accurately simulate the precipitation in China and needs to be improved.

Specifically, the cumulus convection scheme needs to be examined and modified in order to improve the precipitation simulation of this model. Cumulus parameterization is an indispensable non-adiabatic physical process. It has a great influence on precipitation, especially heavy precipitation, and on the large-scale general circulation. The research on cumulus parameterization can be traced back to the 1950s (Smagorinsky, 1956). In the 1960s, Mintz and Arakawa (1965), and Manabe (1965) successively developed dry and moist convection adjustment schemes about large-scale stratification instability. At the same time, Ooyama (1964) and Kuo (1965) brought forward a Kuo-type scheme, which centers on large-scale vapor convergence. In the 1970s, Arakawa and Schubert (1974) designed a kind of cloud mass spectrum scheme, which introduces and calculates vapor mass flux and considers the mutual effect between cumulus mass and the large-scale environment. In the late 1980s, the study of cumulus convection made progress and some synthetic mass flux schemes appeared including the

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schemes of Gregory and Rowntree (1990), Albrecht et al. (1986), Bougeault (1985), and Tiedtke (1989).

The Gregory parameterized scheme is a synthetic mass flux scheme. It not only includes a clear physical picture which can reflect the mutual effect between cumulus mass and the large-scale environment, but also considers the influence upon the large-scale vapor convergence. From the viewpoint of theory, it should provide a better simulation than a Kuo-type scheme. In order to test this conclusion, this paper employs the Gregory parameterized scheme in the T63L20 model (NCC) and comparative tests are made to simulate the multiple-month flood in the summer of 1998. The conclusion is supported by the test results. This paper consists of four parts: (i) introduction and background of the Gregory parameterized scheme; (ii) the basic concepts about the two kinds of cumulus parameterized schemes; (iii) the comparison of the two simulated results; and (iv) discussions and conclusions.

## 2. Background and comparison of the two kinds of parameterization schemes

### 2.1 *The Kuo-type cumulus convection scheme*

#### 2.1.1 *Deep convection parameterized scheme*

The modified Kuo-type cumulus convection scheme (Kuo, 1974) was originally used in the ECMWF (Europe an Centre for Medium-Range Weather Forecasts) model. In this scheme, the amount and distribution of latent heat, which is produced by deep cumulus convection, are calculated by the vapor convergence and the difference ($T_c - T_e$) between the temperature in the air and that in the environment. Additionally, the hypothesis of mass and vapor convergence is used in this scheme. Cumulus convection occurs in the level where there is a convergence of unstable stratification. The condensation height of the surface air is taken as the height of the cloud base, and the intersectant height between moist adiabatics and the environment curve is taken as the cloud top. During the scheme's procedure of cumulus development, the entrained air from the environment is neglected. When cumulus convection has developed, it changes the environmental temperature and humidity by its lateral diffusion heating and moistening. In the column, part of the net convergence vapor condenses into precipitation and the other part moistens the environmental air. Hence, the following two conditions are needed for the development of convection in this scheme. The first condition is the unstable stratification of atmosphere and the second is the existence of net vapor convergence in the column.

Here we define $Q_{\mathrm{AC}}$ as the amount of vapor convergence and $\beta$ is defined as the moistening factor. Thus part of the vapor convergence ($\beta Q_{\mathrm{AC}}$) is sustained in the cloud to moisten the environmental air and the other part ($(1-\beta)\,Q_{\mathrm{AC}}$) is taken as rainfall and heats the environmental air. The moistening factor $\beta$ is determined by the mean saturation difference, which can be expressed as relative humidity in the cloud. That is,

$$\beta = \left(1 - \frac{\displaystyle\int_{p_{\mathrm{top}}}^{p_{\mathrm{base}}} rh dp}{p_{\mathrm{base}} - p_{\mathrm{top}}}\right)^3 , \tag{1}$$

where $p_{\mathrm{base}}$ is the pressure of the cloud base and $p_{\mathrm{top}}$ is the pressure of the cloud top.

If we postulate that the moistening part of the vapor convergence is positive to the local saturation difference of the environment, then the humidity change after the cumulus convection has adjusted is defined as:

$$\Delta T = \frac{L/c_p(1-\beta)Q_{\mathrm{AC}}(T_c - T_e)}{\displaystyle\int_{p_{\mathrm{top}}}^{p_{\mathrm{base}}} (T_c - T_e)dp} . \tag{2}$$

On the other hand, the cumulus heating is related to the vertical distribution of temperature difference between the cloud and environment. The temperature change after the cumulus convection has adjusted is defined as:

$$(\Delta q)_{\mathrm{moist}} = \frac{\beta Q_{\mathrm{AC}}(q_s(T_e) - q_e)}{\displaystyle\int_{p_{\mathrm{top}}}^{p_{\mathrm{base}}} (T_c - T_e)dp} . \tag{3}$$

The temperature in the formula is calculated by tracing air plume ascent from the rising height. The plume ascends to the saturation level along the dry adiabatics, and then ascends along the moist adiabatic curve. The height of the cloud top is the level where the virtual temperature of the air plume equals that of the environment.

#### 2.1.2 *Shallow cumulus convection*

Shallow cumulus convection is defined as non-precipitation convection. Its convection level is thin and its height from the surface to the top of the cloud is less than 3 km. In general, shallow convection only causes a change in temperature and humidity vertical diffusion, but it does not cause the net latent heat exchange or convection rainfall. Shallow convection greatly affects the maintenance of the cloud level. At present, the two main kinds of shallow convection parameterized schemes are the convection adjustment scheme and the turbulent diffusion scheme. The shallow convection scheme utilized in the ECMWF T63 model is the turbulent diffusion scheme, as developed by Tiedtke (1983). This scheme employs the following two assumptions about the cumulus level: (i) the change of advection with time is very small; and (ii) the evaporation of liquid turbulence remains balanced with the condensation. The effect of shallow convection on the large-scale environment is illuminated by the turbulence flux of heat, vapor, and liquid water. The formula are written as

$$\left(\frac{\partial s}{\partial t}\right)_{\mathrm{cu}} = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial t}[\bar{\rho}(\overline{w's'} - L\overline{w'l'})] , \qquad (4)$$

$$\left(\frac{\partial q}{\partial t}\right)_{\mathrm{cu}} = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial t}[\bar{\rho}(\overline{w'q'} - L\overline{w'l'})] . \qquad (5)$$

### 2.2 *The Gregory cumulus convection scheme*

This is a penetrative convection scheme, applicable to moist convection of all types (shallow, deep, mid-level) and also to dry convection. In the Gregory scheme, a single cloud model is used to represent an ensemble of convective clouds, which differ from each other in characteristics and terminate at different levels. Thus the characteristics of a parcel calculated by the cloud model represent the averages over the entire ensemble.

The main principle of the Gregory cumulus convection scheme is as follows. For a column of atmosphere, working from the bottom upward, each layer of the model is tested until one is found, which, with a slight excess of buoyancy $s$ (0.2 K), is still buoyant by more than a lower limit $b$ (0.2 K) at the next layer after ascent, while taking the entrainment of environmental air into consideration. The convective process is then initiated. The parcel continues to rise until it is no longer buoyant after being lifted from layer $k$ to the next model layer $(k-1)$. The parcel ascent continues until the zero buoyancy level of an undiluted parcel from the starting layer of convection is reached or the convective mass flux falls below a minimum value.

The mathematical formulation of the modified Gregory scheme is described accurately in following formulas,

$$\frac{\partial M_p}{\partial \delta} = E - N - D , \qquad (6)$$

$$\frac{\partial \theta_p M_p}{\partial \delta} = (E\theta_E - N\theta_E - D\theta_R) + \frac{LQ}{c_p} , \qquad (7)$$

$$\frac{\partial q_p M_p}{\partial \delta} = (Eq_E - Nq_N - Dq_R) - Q , \qquad (8)$$

$$\frac{\partial l_p M_p}{\partial \delta} = (El_N - Dl_R) + Q - R_{\mathrm{p}} , \qquad (9)$$

where $M_p$ is cloud mass flux; $E$ is mixing entrainment rate; $D$ is forced detrainment rate; $N$ is mixing detrainment rate; $\theta_p$ is $\theta$ in cloudy air; $\theta_E$ is $\theta$ in environmental air; $\theta_N$ is $\theta$ on mixing detrainment; $\theta_R$ is $\theta$ on forced detrainment; $q_p$ is $q$ in cloudy air; $q_E$ is $q$ in environmental air; $q_N$ is $q$ on mixing detrainment; $q_R$ is $q$ on forced detrainment; $l_N$ is $l$ on mixing detrainment; $l_R$ is $l$ on forced detrainment; $Q$ is conversion of water vapor to liquid water and ice; $R_{\mathrm{p}}$ is precipitated liquid water and ice; and $c_p$ is specific heat.

In the above set of equations, the mass flux $M$ is not determined and thus the equation set is not closed. Hence an experience formula is utilized. It can be shown from the following formula that the initial convective mass flux is related to the stability in the troposphere.

$$M=10^{-3}C\{[(\theta_{p,v})_{k-1}-(\theta_{E,v})_{k-1} - b]/\Delta\delta_{k-1/2}\} , \qquad (10)$$

$$C = 3.33 \times 10^{-4} , \qquad (11)$$

where $\theta_{p,v}$ is $\theta_p$ vertical component and $\theta_{E,v}$ is $\theta_E$ vertical component.

### 2.3 *Comparison and analysis of the two schemes*

It was shown in the foregoing that the Kuo-type scheme employed in the original T63 model was the modified Kuo scheme (Kuo, 1974) and its modification mainly focuses on the determination of the moistening factor $\beta$, which is derived from the mean relative humidity of the whole level and vertical distribution heating function, which is derived from the saturation ratio difference of the column $(q_{\mathrm{s}}(T_{\mathrm{e}}) - q_{\mathrm{s}})$. In addition, the second iteration method is introduced to accurately compute the condensation. The mechanism of the Kuo-type scheme is the convergence of the vapor and it can be summed up in the following description.

In the low level of the troposphere, the large-scale convergence or friction can induce ascending motion in the top of the boundary layer. This ascending motion brings air from the lower level to the cumulus tower, or lets the mass of air and vapor continually flow in the cumulus tower. When the vapor condenses into water, the potential temperature in the cloud is obviously higher than in the environment on account of the release of latent heat, so such a cumulus tower is called a heat tower. Then, the turbulent lateral mixing between the cloud air and environmental air allows the sensible heat to move into the clear sky area all around and fulfill the cumulus heating to the large-scale environment.

The main advantage of the Kuo-type scheme is to only introduce the large-scale variables to directly determine the cumulus-scale heating and vapor flux. Moreover, it has other merits including a real heating profile, a sample physical course, a small computation requirement, and a clear physical basis. So this scheme was widely used in climate models and it was used in the ECMWF T63 model until May 1989. However, the Kuo-type scheme has obvious deficiencies. For example, the releasing buoyancy energy is artificially restricted and the meticulous effect between cloud groups as well as the microphysics in the cloud are not considered. But the main deficiency is found in the moistening factor $\beta$, which is difficult to determine accurately. In real atmosphere, the amount of precipitation exceeds the amount of vapor convergence in the lower troposphere, especially in the situation where the environmental air is close to saturation. Thus the result is that the predicted precipitation amount is obviously less than the observed data. Therefore, this scheme exhibits an obvious deficiency in the prediction of strong precipitation.

In this paper, the Gregory scheme is essentially a synthesis between the moist convection adjustment scheme and the Arakawa-Schubert mass flux scheme, and has an explicit physical mechanism. In convection, the abundant upward transport of mass exists in the cumulus cloud and it causes a mass sink to appear in the high level and the compensated subsidence air in the environment around the cumulus; thus two branches of air (dry ascending and moist subsidence air) exist between the cumulus tower and the environment. The convergence in the lower troposphere results in the air ascending. This moist air ascends in the cloud and begins to condense and releases the latent heat. However, the latent heat cannot increase the temperature of this ascending air, but counteracts its adiabatic expansion.

In other words, most of the condensation latent heat is used to strengthen the ascending motion of the air, and most of the latent heat energy is transformed into geopotential energy while a small amount of it is transformed into sensible heat. In addition, the detrainment of air from the cloud causes the liquid water in the cloud to be transported to the environment and the water evaporation in the environment directly causes cooling. From the analysis of the bulk effect of the sensible heat and the detrainment of liquid water, it can be seen that the cumulus tower has a direct cooling effect on the environment. Nevertheless, when the moist air ascends to the high level, it spreads all around and a compensative sink is produced around the cumulus. This elevated temperature effect even exceeds the above evaporation cooling and thus the cumulus tower effect on the environment is still one of heating.

The advantage of the Gregory scheme is that it can describe the real mutual effect between the cumulus cloud and the environment, and the cloud microphysics course including the ascending, the sink, the compensative sink, the entrainment, the detrainment, and the evaporation. The Gregory scheme can deduce the real vertical profiles of apparent heat source and apparent moisture sink. Furthermore, it is simpler than the Arakawa-Schubert scheme in calculation and avoids computing the cloud spectrum. The Gregory scheme is not only suitable for different convective depths in moist convection, is but also suitable for the dry convection process. This scheme economizes computing time and its physical mechanism is explicit and clear. Its closure hypotheses about deep convection and shallow convection are approximately the same. The only difference is that deep convection occurs in areas where there is an unstable stratification and a strong convergence of vapor in lower levels, but the vapor for shallow convection is supplied via surface evaporation.

The deficiency of the Gregory scheme is the lack of an elaborate description of different cloud types and its physical process is too simplified to describe. For example, aerosols affect precipitation by defining a critical thickness variable.

## 3. Comparative simulation experiments

### 3.1 *The prediction model and simulated examples*

The short-term climate prediction model NCC T63L20 was developed from the middle term forecast model ECMWF T63. In calculation, the semi-implicit time integration scheme is employed and in the vertical direction, the $p-\delta$ hybrid coordinate is utilized. The grid spacing in the horizontal direction is 1.875 Gaussian latitudes and there are 19 layers in the vertical direction. In this model, the large orographic effect is considered and more integral physical processes are included.

In this paper, the weather field of 31 May 1998 is taken as the initial field and the sea surface temperature field is chosen as the observed data. For the experiment, the two different cumulus convection schemes are employed in the model respectively to simulate the summer flood in 1998, and the simulated result is compared with the observed data.

### 3.2 *Observed station precipitation data and comparison with simulated results*

Figure 1 shows the precipitation field from 160 stations in China for the summer of 1998, and certain precipitation features can be seen. There are a few precipitation centers which are located in the northeast of China, Yangtze River valley, Sichuan Province, and parts of Guangdong and Guangxi Provinces. The precipitation amounts in the above areas are about 700–900 mm and the maximum value exceeds 1000 mm. However in most parts of the north, the precipitation amount is less than 200 mm.

Figure 2 shows the 160-station precipitation field as simulated by the Kuo-type scheme. The maximum precipitation occurs in the north of Sichuan and the south of Guansu Provinces. Compared with the observed data, the position is further north. In South China and Sichuan Province, the precipitation amount is comparatively large but the position is still displaced to the north. The main error is that the simulated precipitation amount in the north of China is comparatively large and in the Yangtze River valley, the

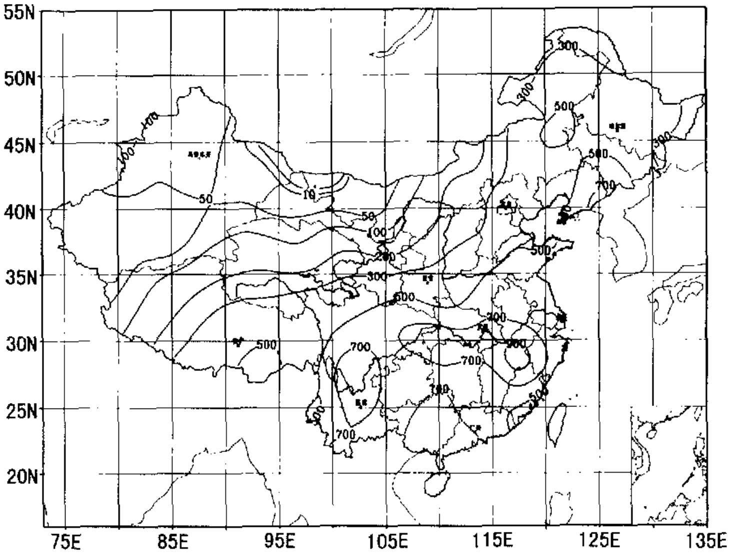


Fig. 1. The observed precipitation field over China from 160 stations in the summer of 1998.

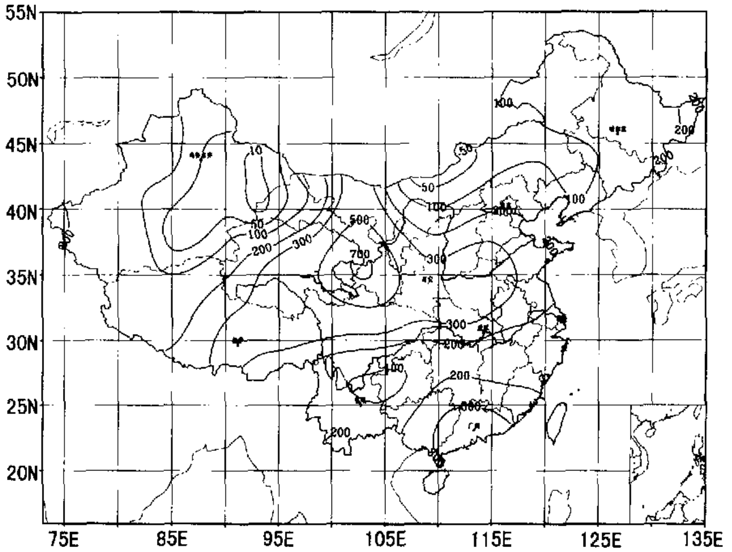


Fig. 2. The simulated precipitation field over China from 160 stations in the summer of 1998 by the Kuo-type scheme.

amount is comparatively small versus the observed data.

Figure 3 shows the 160-station precipitation field as simulated by the Gregory scheme. There are a few precipitation centers, which are located in the northeast of China, Sichuan province, Yangtze River valley and South China areas. The simulated precipitation field generally conforms to the observed data, but some discrepancies exist. The precipitation center in Sichuan province is displaced northward and the precipitation amount in the Yangtze River valley is small. From the analysis of precipitation amount, the simulated result generally conforms to the observed data.

It can be seen from the above analysis that the precipitation field simulated by the Gregory scheme conforms more to the observed data than the Kuo-type scheme does. However, the simulated precipitation field under the Gregory scheme still has systemic errors although the scheme obviously improves the prediction accuracy.

### 3.3 *Simulation of general current circulation under the two schemes*

The general tendency of air circulation over the European continent can be seen from the observed 500 hPa monthly mean height field (Fig. 4). In the middle or high latitudes of the continent, there are two roughs and one ridge in July, and this tendency of the current is the typical two blocking highs pattern, which benefits the summer precipitation in China. The Ural high develops more strongly than in a normal year and becomes a deep weather system. The Ω-type blocking high appears in the area. In the area of 60°N latitude and 120°W 120°E, there is a wide trough. In the low latitude area, the western Pacific subtropical high begins to weaken and is divided into two centers, which are located in the area between 110° 120°E, and to the east of 130°E respectively. The ridge of the western Pacific subtropical high reaches to the 15°N area nearby.

It can be seen from the simulated 500 hPa monthly mean height field under the Gregory scheme that in July, there are two troughs and one ridge in the middle or high latitude area. The Ural High is simulated but its strength is weak. The Okhotsk high is simulated weakly and does not form into the Ω-type. In the area of 60°N latitude and 120°W 130°E, there is a wide trough. In the low latitude area, the West Pacific Subtropical High is divided into two centers, which are located in the area between 110°-160°E and to the east of 170°E respectively.

At the same time, the simulation of the 500-hPa monthly mean height field under the Kuo-type scheme is made (Fig. 6). In the middle or high latitudes of the European continent at the 500-hPa height is a west wind area and the air current tendency is latitude type.

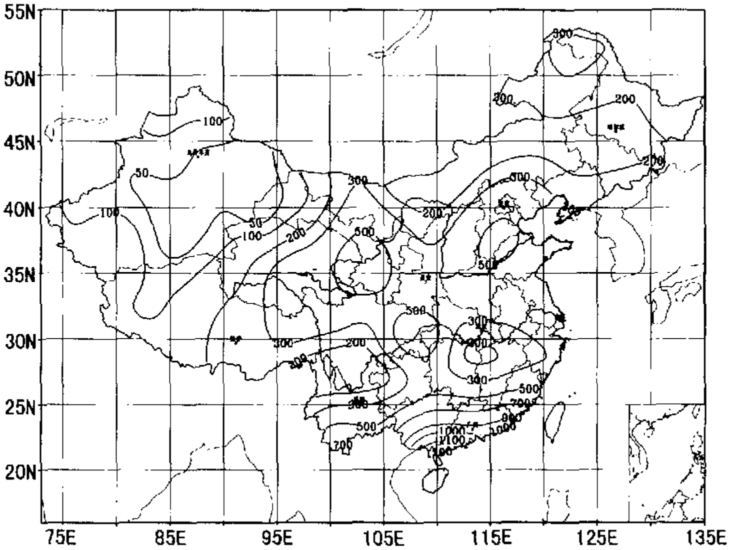
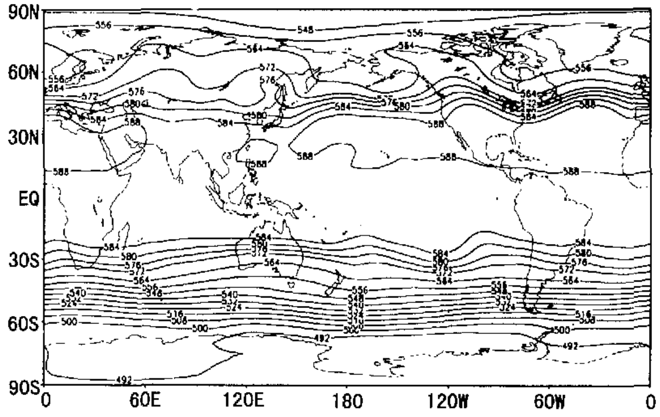
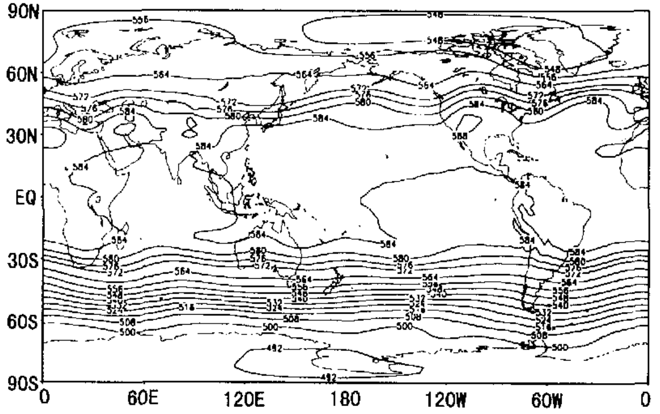


**Fig. 3.** The simulated precipitation field over China from 160 stations in the summer of 1998 by the Gregory scheme.

(a) Observed



(b) Kuo-type scheme



(c) Gregory scheme

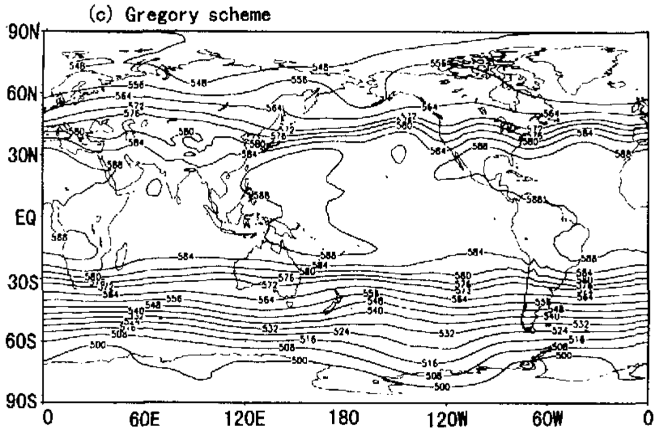


**Fig. 4.** The July 1998 500 hPa monthly mean height field: (a) Observed field from NCEP data, (b) simulated field under the Kuo-type scheme, and (c) simulated field under the Gregory scheme.

In the low latitude area, the western Pacific subtropical high is simulated to be weak and there is not a 588-gpm closure center.

It can be seen from the above-simulated results and the observed data that the simulated 500 hPa monthly mean height field under the Gregory scheme conforms more closely to the observed data than under the Kuo-type scheme. The model employing the Gregory scheme can not only simulate the two troughs and one ridge pattern, but also well simulates the position and strength of the western Pacific subtropical high.

## 4. Conclusion and discussion

This paper chooses the flood which occurred in the Yangtze River and Nenjiang River valleys during the summer of 1998 as an example to compare and test the efficiency of the Kuo-type and Gregory cumulus parameterized schemes.

It can be shown from the comparative test that the simulated precipitation field under the Gregory scheme is better than under the Kuo-type scheme because the former can simulate more rational precipitation areas and predict more rainfall in the Yangtze River and Nenjiang River valleys than in a normal year. Moreover, the precipitation amount forecasted by the model under the Gregory scheme conforms to the observed data. Nevertheless, the scheme still contains systematic errors and it can be seen from the simulation that the precipitation scope and amount in the Yangtze River valley is smaller than the observed data. The main reason for this is that the main precipitation cloud is a kind of mixed cloud, which consists of cumulus and stratus clouds during the period of Meiyu. This shows that the storm rainfall or torrential rain is mainly caused by this mixed cloud. In the Meiyu frontal zone, the precipitation cloud is of this mixed type also. Due to this mixed cloud being deep stratus embedded with convective cumulus, the convective cumulus can improve the precipitation rate of the stratus by the scatter effect, and the wide and moist stratus can prolong the life of the cumulus. Thus, the simulated situation of stratus precipitation affects the total precipitation, then covers up the effects of improving the cumulus parameterized scheme to some extent. Perhaps this needs to be improved in further work.

The large-scale environment background field is simulated by the Gregory scheme and Kuo-type scheme respectively. It can be seen from the simulation that the result under the Gregory scheme is superior to that under the Kuo-type scheme. The general trend of the current and important large-scale system under the Gregory scheme is better simulated than under the Kuo-type scheme.

In conclusion, the model employing the Gregory scheme can improve the prediction of the precipitation field and large-scale background field. There are some reasons why the simulated result under the Gregory scheme is superior to that with under the Kuo-type scheme. The main reason is that the mechanism of the Kuo-type scheme is excessively simple and it is mainly suitable for the low latitude areas. In the low latitude areas, the cumulus cell and deep convective cloud are well related to the convergence in the low layer, especially the large-scale convergence. But in the middle or high latitude areas, the invocation and maintenance mechanism of cumulus cloud is very complicated due to air baroclinicity and stratification. In the cumulus invocation and maintenance process, the cumulus cloud continually exchanges energy and heat with the environment by the entrainment and detrainment of air.

Thus, the cumulus effect on the large-scale environment and the environmental restriction of the cumulus are mutual effects and feedback processes. This relationship is better described in the Gregory scheme, which describes this mutual effect between clouds and environment and includes the cumulus ascending and sinking activity, as well as entrainment, detrainment and evaporation. In the Gregory scheme, there are two edge currents of air, including moist ascending and dry sinking, between the cumulus tower and the environment, and the effect of the cumulus tower is directly cooling and indirectly heating. The research of Gray in 1973 confirms this view.

The other reason for its merit is that the Gregory scheme is suitable for different convection depths in moist convection and dry convection. It not only saves the computation amount, but also its physical mechanism is explicit and clear. In this scheme, the closure hypotheses of deep cumulus convection and shallow cumulus convection are similar. The difference is only that deep cumulus convection usually occurs in the area where there is unstable convection, strong convergence in the lower troposphere, and the vapor supply is ample. But the vapor of shallow cumulus convection is mainly supplied by surface evaporation, and the vapor supply from the convergence in the lower troposphere is small. This view has been proved by the diagnostic results of large scale observed data.

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# 两种不同积云参数化方案对1998年中国夏季洪涝灾害数值模拟的比较研究

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## 摘 要

利用国家气候中心的全球T63谱模式，以1998年夏季（6-8月）我国长江中下游和东北嫩江-松花江流域发生的特大洪水为试验个例，分别采取原来模式中的Kuo积云参数化方案和UKMO/unified的Gregory积云参数化方案进行了整个夏季的逐月降水预报的对比试验。结果表明：Gregory质量通量方案能给出较Kuo方案更加合理的降水落区，并且对降水量的预报也有显著的改进。此外，Gregory质量通量方案对大尺度环流背景场的预报也较Kuo方案好。从整个夏季的预报来看，Gregory参数化方案能较Kuo方案更好地模拟出1998年的降水的总体趋势，尽管Gregory方案模拟的降水与实况相比，仍然存在着系统性的误差，还需要进一步改进。

**关键词**：积云对流，数值模拟，参数化方案，洪水