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THE LIMITATION OF CLOUD-BASE MASS FLUX IN CUMULUS PARAMETERIZATION AND ITS APPLICATION IN A HIGH-RESOLUTION MODEL

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Abstract: A large area of unrealized precipitation is produced with the standard convective parameterization scheme in a high-resolution model, while subgrid-scale convection that cannot be explicitly resolved is omitted without convective parameterization. A modified version of the convection scheme with limited mass flux at cloud base is introduced into a south-China regional high-resolution model to alleviate these problems. A strong convection case and a weak convection case are selected to analyze the influence of limited cloud-base mass flux on precipitation forecast. The sensitivity of different limitation on mass flux at cloud base is also discussed. It is found that using instability energy closure for Simplified Arakawa- Schubert Scheme will produce better precipitation forecast than the primary closure based on quasi-equilibrium assumption. The influence of the convection scheme is dependent on the upper limit of mass flux at cloud base. The total rain amount is not so sensitive to the limitation of mass flux in the strong convection case as in the weak one. From the comparison of two different methods for limiting the cloud-base mass flux, it is found that shutting down the cumulus parameterization scheme completely when the cloud-base mass flux exceeds a given limitation is more suitable for the forecast of precipitation.

Key words: cumulus parameterization; high-resolution model; mass flux at cloud base
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1 INTRODUCTION

With the enhancement of computation capabilities, the resolution of numerical weather prediction (NWP) has been increased and the prediction capabilities have also been improved accordingly, especially in the short-range nowcasting of severe local rainfall. In the past 10 plus years, a number of operational numerical prediction centers (e.g. Meteorological Office of United Kingdom (Met Office), Japan Meteorological Agency (JMA) and German National Weather Agency (DWD)) have increased their horizontal resolution of limited-area models to less than 5 km and models with the grid interval at about 1 km have become the mainstream of its kind (Roberts[1]; Narita and Ohmori[2]; Steppeler et al.[3]). In these high-resolution models, many of the mesoscale and fine-scale systems are explicitly resolved and forecast that would have been processed implicitly in models with coarser resolution. Because of the explicit resolving of some convective systems that would be expressed implicitly with cumulus parameterization schemes and the advantages resulting from higher resolution (e.g. finer description of the terrain), people hope for more accurate forecast of precipitation. As shown in a number of studies, some large-scale convective systems, such as severe thunderstorms, mesoscale convective systems and squalls, can be simulated more reasonably if done with high-resolution models that are at grid intervals of 1 to 4 km and able to express convective systems explicitly (Weisman et al.[4]; Romero et al.[5]; Speer

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and Leslie[6]; Done et al.[7]).

For medium- and large-scale NWP models with grid intervals of 10^1 to 10^2 km, it is necessary to describe, using convective parameterization, the effect of subgrid scale convection motion, which cannot be resolved by models, on the large-scale circulation (Jia et al.[8]; Ho et al.[9]). For high-resolution models with grid intervals of less than 10 km, however, it is conventionally held that microphysical processes can predict convective processes almost all explicitly and makes it unnecessary to introduce the schemes for convective parameterization for this purpose. Using a 4-km operational model of the Met Office, Roberts[10] showed in a study that using no convective parameterization schemes is the best choice if the scale of a convective system is large enough to be resolved by models. It also pointed out that on one hand, completely shutting down such physical schemes will increase the intensity of precipitation and bring about much unrealized grid rainstorm when simulating the fine-scale, scattered convective systems that can only be partially resolved, and when conventional convective parameterization schemes are directly used, on the other, they will interact with model dynamics unrealistically to cause widespread false rain bands[1]. In order to introduce parameterization schemes in high-resolution models while avoiding consequential problems, Roberts suggested a convective parameterization scheme, which is suitable for the high-resolution models with grid intervals at 1 to 4 km, by limiting the mass flux at cloud base. Such scheme is selectively used in parameterizing the subgrid scale convective processes that have relatively small mass flux at cloud base and cannot be resolved by models explicitly. For the convection that can be explicitly resolved by models, explicit forecasting can all be done with microphysics.

The aim of this study is as follows. First, a 3-km regional high-resolution model for the region of south China, currently used at the Guangzhou Institute of Tropical and Marine Meteorology, China Meteorological Administration (GITMM-CMA), is incorporated with a convective parameterization scheme that limits the mass flux at cloud base. Second, case simulation is carried out to test whether it can improve the model forecast of precipitation and examine the model sensitivity to varying limitations of mass flux at cloud base.

2 INTRODUCTION TO MODEL AND CONFIGURATION OF PARAMETERS

A thousand-meter-scale model for south China used in this study is a non-hydrostatic, fully elastic model that is based on the GRAPES-meso system. Employing a semi-implicit, semi-Lagragian time-dependent advection scheme and mesh design featuring longitude-latitude grids, the model is configured with the Arakawa-C mesh in the horizontal and the Charney-Philips vertical-layer stratification in the vertical, with the model height adopting terrain-following coordinates. Its physical processes include explicit precipitation through cloud microphysics, sub-grid scale cumulus convection parameterization, longwave and shortwave radiation, land surface processes and boundary-layer processes. At present, the model is being used at GITMM-CMA in its operational refined regional forecasting for the area of south China.

In the model, the initial longitude/latitude is 104°E/17°N, the interval of grids is 0.03°, and the number of horizontal grids is 433×601. Vertically stratified to 55 layers, the model top is set at 28 km and the time step is given 30 s. The following physical processes are included: Simplified Arakawa- Schubert Scheme (SAS) as the cumulus parameterization scheme, WSM6 as the microphysical process, rrtm as the longwave radiation scheme, Dudhia as the shortwave radiation, Slab as the land surface process scheme, and MRF as the boundary-layer scheme. The initial and lateral conditions of the model are provided by a European Center for Medium-Range Forecast analysis field and its forecast field.

3 INTRODUCTION TO CONVECTIVE PARAMETERIZATION SCHEME

In the current operational forecast with the high-resolution model for the area of south China, the SAS is used. It is the SAS proposed by Arakawa et al.[11]. The scheme is made up of complicated interactions between cumulus clusters and large-scale forcings, which include adiabatic heating of updraft in clouds and the offset effect of the entrainment and mixing of ambient air on the latent heat due to condensation, moistening and heating resulting from compensating downdraft of the ambient air triggered by ascending cumulus, and the effect of detrainment and evaporation of liquid-state water near the cloud top on the cooling and moistening of the ambient air. Grell et al.[12] put forward a simple conceptual model by simplifying the scheme; the in-cloud circulation is kept stable due to two branches of air motion, ascending and descending, and only the clouds with deepest convection are included to replace the original cloud spectra. It is how the SAS scheme is formulated. Though much simpler than its older version, the SAS scheme has been shown in a lot of experiments to have simulations much close to those obtained with the original scheme that is much more complicated and costs immense computation. Pen et al.[13] were the first scientists who applied the SAS scheme into the operational forecasting with the MRF model, which showed that the SAS scheme is better than the previous case using the Kuo's scheme. On the basis of SAS, Han et al.[14] has improved much on a number of aspects.

4 LIMITATION OF CLOUD-BASE MASS FLUX

At present, the SAS convective parameterization scheme is still mainly used in mesoscale models with relative coarse resolution because it is incapable of resolving scales of the convective system. When used in high-resolution models, the scheme must be modified so that it reasonably describes the feedbacks arising from the subgrid scale convection processes unresolved by the model without influencing the explicit forecasting of relatively large convective systems resolvable by model microphysics.

Conducting experiments to limit cloud-base mass flux in the operational forecast of Met Office using a convective parameterization scheme with mass flux limitations, Roberts et al.[10] discovered that the modification can efficiently improve the precipitation forecast of high-resolution models. In the scheme of Gregory and Rowntree[15], the convective available potential energy (CAPE) is the atmosphere can be directly used to control and adjust the generation and development of cumulus convection and to describe the feedback of cumulus convection to the ambient field. When the convection is triggered, the CAPE is all consumed withinτ, a characteristic duration, putting the atmosphere back to the medium state. Following this assumption of closure, the cloud-base mass flux M can be obtained.

$$M=\text{CAPE}/\tau \quad (1)$$

In the original scheme, τ is assumed to be constant (30 min), which means that the larger the model instable energy, the stronger the convection (i.e. the greater the mass flux will be), regardless whether or not its scale can be explicitly resolved by model. As shown in the experiment, such assumption will, if the model resolution is high, result in widespread unrealized precipitation in unstable areas and restrain the development of some convective systems resolvable by model. To alleviate the adversary, the size of the spatial scale of convective clouds is assumed to be proportional to the intensity of the instability energy of the ambient field; the higher the latter, the easier it is for it to be resolved by model[1]. Based on this assumption, τ, a characteristic temporal scale, is designed that is associated with CAPE:

$$\tau=\frac{t}{c}\times\text{CAPE}+t\times\exp-(\frac{\text{CAPE}}{c}) \quad (2)$$

in which t and c are adjustable parameters. It is known from Fig.1a that Eq.(2) shows that τ increases exponentially with the growth of instability energy when CAPE is small but it is linearly connected with the instability energy when CAPE is large. It is shown in Fig.1b that the application of τ, a closure time scale, in Eq.(1) will lead to rapid growth of cloud-base mass flux with the instability energy within a small range of CAPE, and as CAPE increases gradually, the mass flux is usually restrained within a specific range, thus resulting in significant reduction of the effect from the convection parameterization scheme for large-scale convective systems, which have large instability energy. Without taking into account other possible factors that may affect the scale of convection, such assumption is with some drawbacks but it succeeds in capturing the main characteristics as follows: while shallow convection on small scales usually happens in the area with relative small amount of instability energy, mesoscale convection on medium scales usually takes place in the area with relatively large amount of instability energy.

Different from the Gregory scheme (Gregory and Rowntree[15]), the SAS is still the scheme that uses the quasi-equilibrium closure assumption, which is put forward by Arakawa et al.[11], to determine the mass flux at cloud base M:

$$\frac{A'-A}{dt}=\frac{A''-A}{m_b dt}M \quad (3)$$

in which A' is the cloud work function obtained with the thermodynamic field forced by large-scale advection, and A'' is the one determined with the thermodynamic field modified with unit of cloud-base mass flux $m_b dt$. As the quasi-equilibrium assumption is no longer suitable for high-resolution models (Fritsch and Chappell[16]) and for the ease of comparing with the work of Roberts, the way by which the SAS scheme is closed is first modified (Grell and Devenyi[17]):

$$-\frac{A}{\tau}=\frac{A''-A}{m_b dt}M \quad (4)$$

It is known from Eq.(4) that the SAS scheme is similar to the Gregory scheme when its closure assumption is modified: the model instability energy A is released, in the form of convection, within a characteristic time scale.

Next, the modified SAS scheme is experimented with limitations of the mass flux and its effect on the forecast of precipitation is tested through the thousand-meter-magnitude model for south China. A total of two methods are designed to limit the mass flux.

(1) Following the method of Roberts and other scientists, we changed τ, the time scale of Eq.(4), to:

$$\tau=\frac{t}{c}\times A+t\times\exp-(\frac{A}{c}) \quad (5)$$

and then limited the mass flux by selecting different *t* and *c*.

(2) In the scheme, we directly set an upper limit Xmb_{max} for the mass flux. When *M* is higher than the limit, the model is considered to be able to resolve the convective system. Then, the convective parameterization is shut down and the explicit forecast is conducted all with the microphysical scheme. When *M* is lower than the limit, the forecast is run using the modified SAS scheme as shown in Eq.(4).

The main difference between the two limiting methods is as follows. When the mass flux is large, the first method set limits only to the cumulus parameterization scheme, i.e. requires that the mass flux must be lower than the upper limit (by satisfying Eqs.(4) and (5)). For the second method, the limit is set without convective parameterization. The effect of the difference on the model precipitation forecast will be discussed in the following text.

5 DESIGN OF EXPERIMENT

Three sets of experiments were designed for comparison in this study (See Table 1). (1) Two closure assumptions of the SAS scheme were compared to determine whether the new closure assumption can improve the precipitation forecast by high-resolution models. (2) Two methods of mass flux limitation were compared to determine which one yields better precipitation forecast. (3) The sensitivity of different mass flux limitations was studied to the precipitation forecast to choose a reasonable and appropriate upper limit for the mass flux in routine forecasting operation.

For each group of the experiments, results from two different real cases were used for verification. Case 1 is a squall process that took place on April 25, 2012 in the area of south China. Being a typical severe convection case, the model started forecasting at 00:00 (Beijing Time, the same below) April 25. The case was chosen mainly because of the large error that will be caused by the use of primitive parameterization schemes for convection processes generally resolvable by model, and in contrast, such negative influence can be significantly reduced by limiting the mass flux at cloud base. Case 2 is a local, scattered process of weak convection in the area of Guangdong on July 8, 2012. The model started the forecasting of this typical weak convection at 00:00 July 8. The case was chosen to show that it is necessary to use the parameterization scheme to reflect better the effect of weak convection systems that is difficult to resolve even for a high-resolution model.

6 ANALYSIS OF RESULTS

6.1 *Modification of closure conditions in the SAS scheme*

It is known from the discussion in section 4 that the quasi-equilibrium assumption of the SAS scheme is no longer suitable for high-resolution models. For the ease of comparing with the result of Robert, we first modified the closure scheme of the SAS to make it similar to the closure assumption of the Gregory scheme. In other words, instability energy is released within a given adjustment time of τ through convective motion (Test-2). To avoid the spin-up effect at model cold start, this work chooses for comparison and discussion the 6-h accumulated forecast rainfall during Hour 6 to 12 in the two cases. In Test-2, τ is set at 30 min. Fig.2 gives a comparison between the forecast and observed rainfall under the two closure assumptions. It is known from the distribution of the observed rainfall in Case 1 that there is a rainband of more than 10 mm in central Guangdong, whose intensity and location are well simulated by the model. While there are a number of weak rain zones that distribute unevenly in the rainband under the quasi-equilibrium closure assumption (Fig.2b), the intensity distribution of the rainband becomes more even and closer to the observation when the closure conditions are modified (Fig.2c). As is shown in Fig.2d to 2f, the modification of the closure assumption does not have significant effect on Case 2.

According to Lord and Arakawa[18], the instability energy consumed by a unit of cloud-base mass flux depends on the internal nature of the cumulus so that the rate of consuming instability energy for a given type of cloud is generally a constant. Following the quasi-equilibrium assumption, the generating rate caused large-scale forcings (including the advection, radiative parameterization and boundary layer processes) is equal to the consuming rate caused by cumulus convection, for the instability energy. It can then be assumed that the cloud work function, caused by large-scale forcings within the adjusting time of convection, does not change with time. The quasi-equilibrium assumption is found to be sound in statistical studies using observations from the tropics and subtropics, thus making it possible for the large-scale forcing term A' to be replaced approximately by the climatological mean A'_0 when it is used in carrying out the closure. Such assumption is reasonable for large-scale models (with grid intervals greater than 50 km) so that the SAS scheme used in the GRAPES model has also made use of this conclusion. For high-resolution models, however, such assumption is unacceptable because large-scale forcings of subgrid convection usually come from medium- and fine-scale convective systems resolvable by model. When the large-scale forcing is assumed to be constant, it also indicate that the rapid and time-dependent change of medium- and fine-scale convective systems will be neglected to result in significant deviation in the intensity of convective systems triggered by the convective parameterization scheme. It mainly accounts for the inhomogeneous rainband intensity as shown in Fig.2b. By assuming that instability energy can be released through convective motion within a period of time, the inhomogeneous distribution of simulated precipitation with the original SAS scheme can be improved. For some scattered and small-scale weak convective systems, however, such modification does not have significant effect on the simulation due to small mass flux at cloud base (Fig.2d-2f). In general, the application of the assumption of instability energy release in closing the SAS parameterization scheme yields more reasonable precipitation forecast. In the experiments that follow, we will use the SAS scheme with changes to the closure scheme.

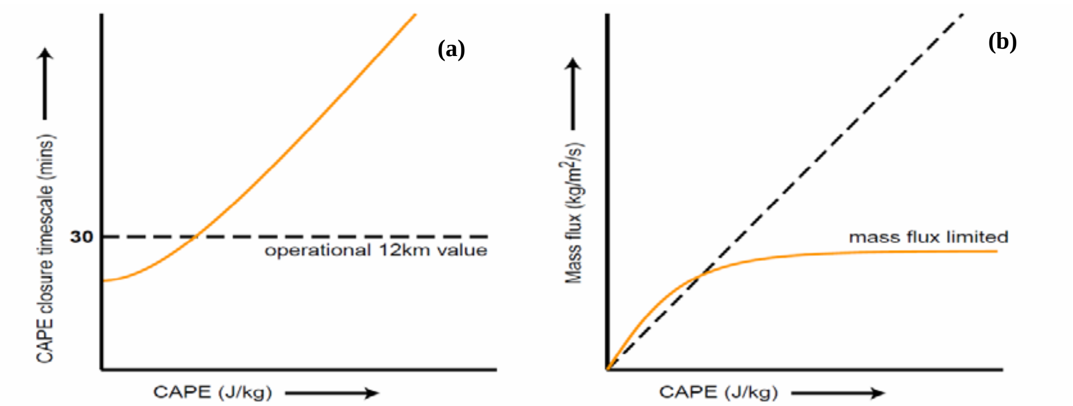

Figure 1. Modification of the closure time scale of CAPE (a) and its effect on the mass flux at cloud base (b)[10].

Table 1. Design of experimental schemes.

Control	Name of Exp.	Design of scheme
CNTL1	Test-1	Quasi-equilibrium closure scheme (old)
	Test-2	Modified closure scheme
CNTL 2	Test-3	First method to limit mass flux
	Test-4	Second method to limit mass flux
CNTL 3	Test-5	Xmb_{max}=0.5
	Test-6	Xmb_{max}=0.7
	Test-7	Xmb_{max}=1.0
	Test-8	Xmb_{max}=1.5

6.2 *Comparisons of the two methods of limiting mass flux*

Based on the modified closure assumption of the SAS parameterization scheme, this section will further compare the effect of the two ways of limiting the mass flux on the precipitation forecast. Using a Met Office model with 4-km resolution to conduct sensitivity experiments in which the mass flux is limited in the cumulus parameterization scheme, Roberts[10] showed that precipitation that is close to the observation can be obtained when c=1200 and t=10 are taken in Eq.(2). Applying Eq.(5) in limiting mass flux, this study also employs the same setting of parameters. For the second method of limitation, the maximum cloud-base mass flux Xmb_{max} will be set at 0.8, whose sensitivity test will be shown in section 6.3.

Figure 3 gives the model-predicted accumulative rainfall amount for Hour 6 to 12 by limiting the mass flux in the two different cases. For Case 1 (Fig.3a and 3b), the distribution of precipitation is closer to the observation after the limitation as compared to the original scheme. The results are generally consistent with the two methods of flux limitation. The cause is presented as follows. As Case 1 is a case of severe convection on relatively large scale, the role of convective parameterization will have little influence on the model forecast if the mass flux is limited at cloud base. Model-forecast precipitation is mainly from microphysics so that the simulation will not be changed much even the parameterization scheme is limited in either way. For Case 2, the difference in precipitation forecast is quite large with the two limiting methods (Fig.3c and 3d). With the first scheme of mass flux, there will be many and scattered small-scale areas of rainfall in Guangdong and Guangxi, very different from the observation. With the second scheme of mass flux, however, the scale of the rainfall areas is a little larger than that of the first scheme and the amount of rainfall is also closer to the observation. It indicates that precipitation forecast can be more reasonable if the mass flux scheme proposed in this work is used in weak convective systems on relatively small scales. As shown in the discussion of section 4, the main difference between the two limiting schemes is that when the forecast mass flux at cloud base is larger than a given upper limit, the first scheme still allows for adjustment to model variables against a preset maximum value while the second scheme shuts down the parameterization completely.

As a result, when the mass flux is limited for cases of weak convection using the first scheme, the parameterization scheme will report large amount of unrealized convective precipitation in areas with large instability energy if the preset maximum cloud-base mass flux is too large, and if the prescribed upper limit of mass flux is too small, it will restrain more than it should in the parameterization the description of the weak convective motion on some subgrid scales to lead to the appearance of many areas of unreasonable, scattered precipitation in model forecast (Fig.3c). It is obvious that the use of the second scheme is capable of preventing the parameterization from producing unrealized precipitation in areas with highly instability energy and thus making it possible to set reasonable limits to the mass flux at cloud base.

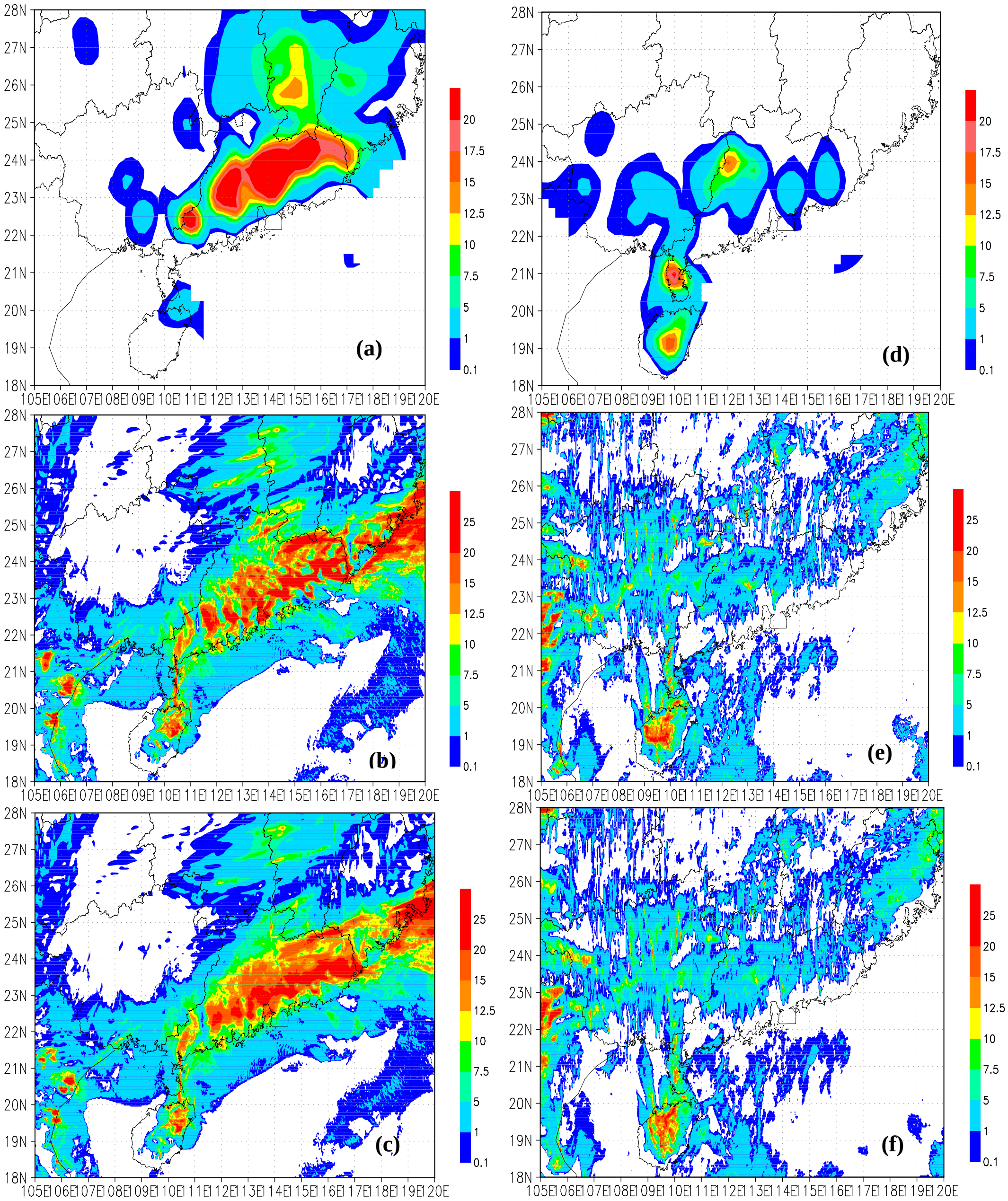

Figure 2. Comparisons of the forecast and observed 6-hour accumulated precipitation of the two real cases with different closure schemes. (a): observations of Case 1; (b): Test-1 of Case 1; (c): Test 2 of Case 1; (d): observations of Case 2; (e): Test-1 of Case 2; (f): Test 2 of Case 2.

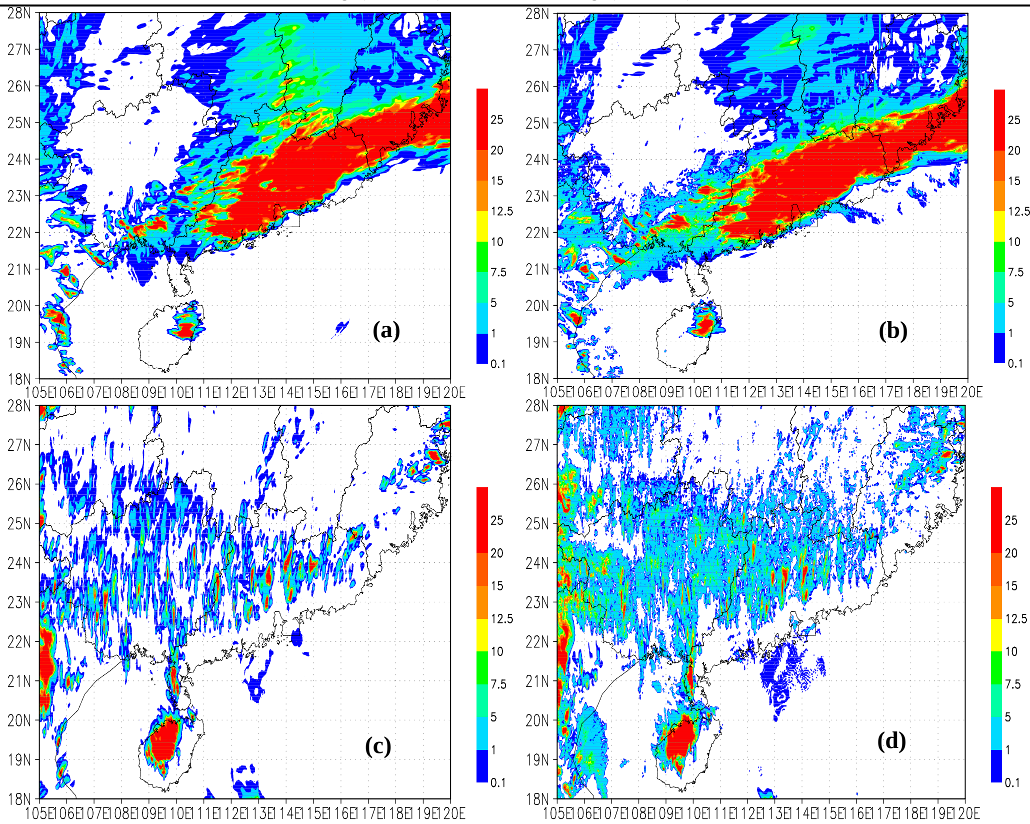

Figure 3. Effect of two mass flux limiting schemes on the forecast of Hour 6 to 12 accumulated precipitation. (a): Test-3 of Case 1; (b): Test-4 of Case 1; (c): Test-3 of Case 2; (d): Test-4 of Case 2.

6.3 *Sensitivity tests with different limitation of mass flux at cloud base*

In order to examine the sensitivity of limiting parameters to model forecast and determine appropriate limiting conditions that can be used in model forecast, the current section chooses four different upper limits of Xmb_{max} for the two cases, 1.5, 1.0, 0.8 and 0.5, and compares the corresponding results of accumulated rainfall forecast from Hour 6 to Hour 12. Fig.4 gives the forecast result of Case 1. With the increasing reduction of the flux limit, the effect of convective parameterization gets weaker and weaker, the unrealized precipitation over the ocean surface becomes smaller, and the forecast result also gets closer to the one obtained with microphysics only.

It shows that limiting the mass flux at cloud base can adjust the effect of convective parameterization on precipitation forecast significantly, especially so from the result of Case 2 (Fig.5). It is attributable to the fact that as many of the subgrid convective processes cannot be resolved well by model when the convection is weak, they need to be parameterized before being incorporated into model forecast. The effect on precipitation forecast will be more obvious if the mass flux is limited accordingly in the parameterization. For convective systems with large scales, however, they can be well identified by model microphysics while being little subject to convective parameterization itself. The result of precipitation forecast, therefore, is not sensitive to the limitation of mass flux at cloud base that varies within a specific range.

In terms of the ratio of hourly accumulated rainfall amount with regionally averaged cumulus parameterization to the total rainfall amount (Fig.6), the forecast results of the two cases are very sensitive to the limitation of the mass flux. It should be noted that the ratio of the rainfall amount with parameterization decreases gradually with the duration of forecast in Case 1 but generally remains unchanged or increases slightly in Case 2. It mainly results from the development and variation of convective systems. It is known from related radar echoes (figure omitted) that the intensity of convective systems in Case 1 keeps strengthening with the increase of forecast duration such that the proportion of the microphysics is getting larger and larger while the effect of cumulus parameterization is getting weaker and weaker; the small-scale, weak convective systems in Case 2 do not strengthen gradually to become large-scale, intense convective systems, keeping the convective parameterization an important factor in the forecast.

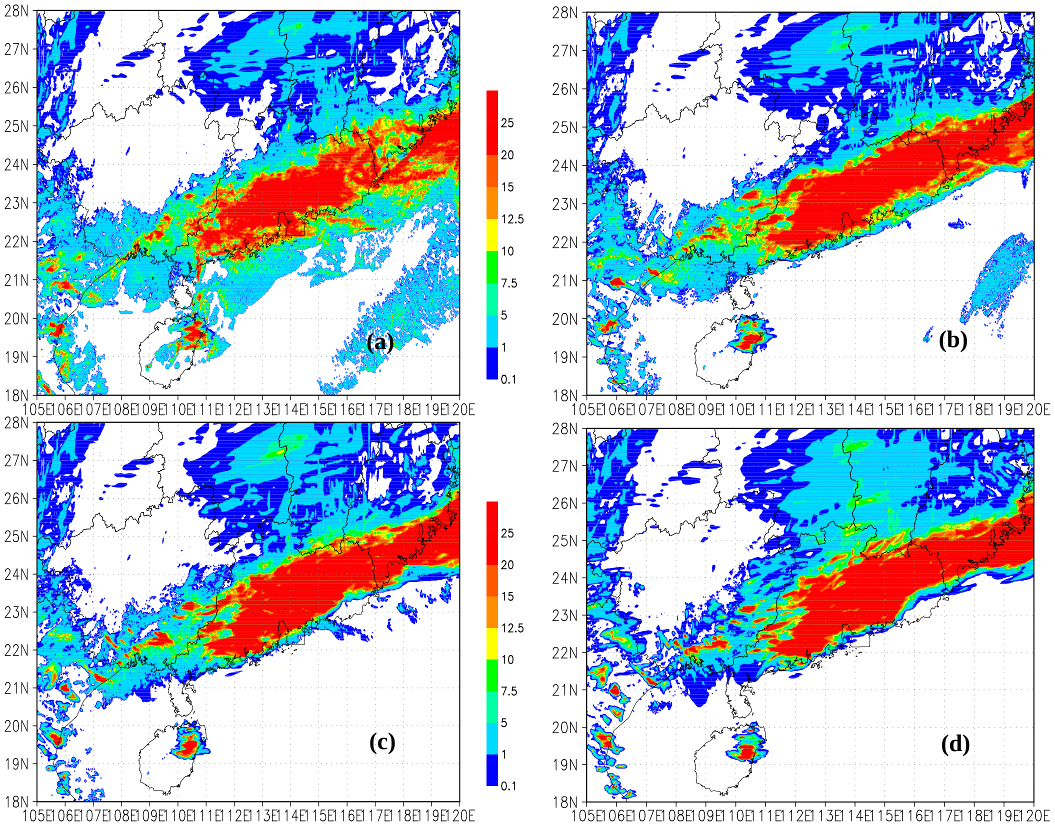

Figure 4. Precipitation determined when the mass flux takes different values in Case 1. (a): Xmb_{max}=1.5; (b): Xmb_{max}=1.0; (c): Xmb_{max}=0.8; (d): Xmb_{max}=0.5.

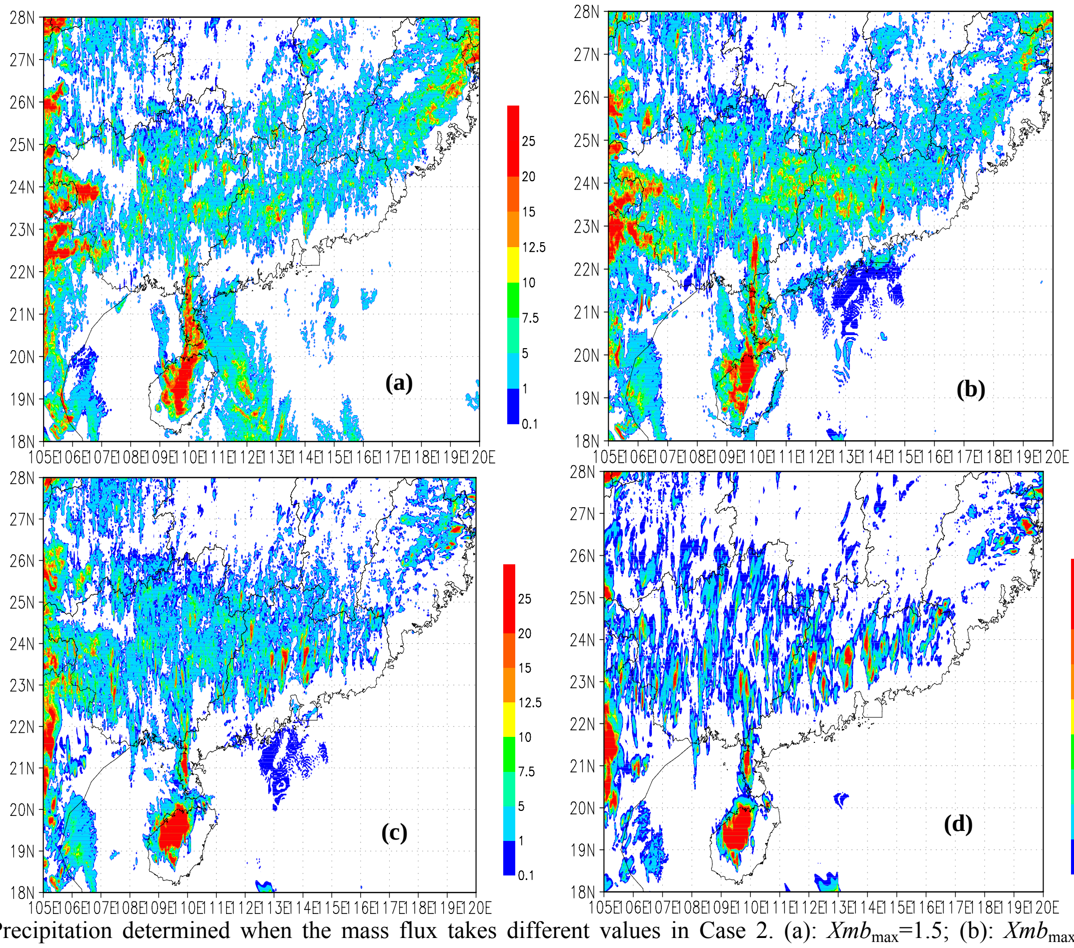

Figure 5. Precipitation determined when the mass flux takes different values in Case 2. (a): Xmb_{max}=1.5; (b): Xmb_{max}=1.0; (c): Xmb_{max}=0.8; (d): Xmb_{max}=0.5.

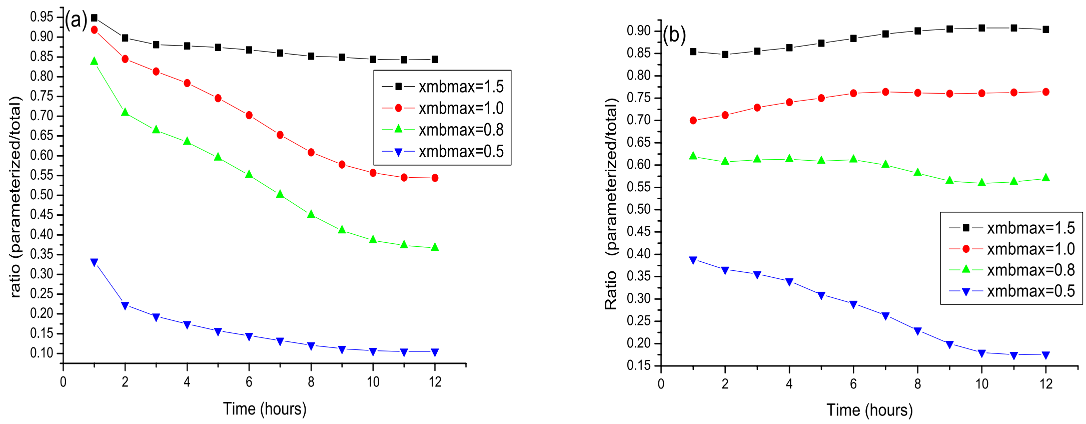

Figure 6. Proportion of precipitation with parameterization under different conditions of mass flux at cloud base in the total amount of precipitation. (a): Case 1; (b): Case 2.

For Case 1, the regionally averaged total amount of rainfall is not sensitive to the limitation of the mass flux (Fig.7a) because reasonable precipitation can be obtained if either the implicit forecast, which uses cumulus parameterization schemes, or the explicit forecast, which uses microphysics, is conducted for convective systems with large instability energy and large scales. For Case 2, on the contrary, in which the instability energy is both weak and of small scales, the difference in the total amount of rainfall is significant as it is determined under different restraints of the mass flux. Then, with the increase of the upper limit of the flux, more subgrid-scale convection is included in the model through the scheme of cumulus parameterization and the model-forecast rainfall amount will also increase as a result.

6.4 *Analysis of the unrealized convective precipitation induced by parameterization*

By comparing the forecast with the precipitation data from TRMM satellite (Fig.8a), we found that the precipitation forecast over the ocean in Case 1 (Fig.8b) is unrealized, which is all due to the parameterization (Fig.8c). As shown in Roberts et al.[1], such realistic precipitation is mainly caused by a positive feedback mechanism resulting from the interactions between the parameterization scheme and model dynamics on the grid scale. Its main principle can be described with Fig.9c and 9d[10]: a low-level cold air mass, caused by earlier convective motion, converges and raises the air in front of it to strengthen the instability energy and trigger the convective parameterization scheme. Then, once the convection is set off, it cools the low-level air, keeping the cold air mass propagate forward and trigger convection in the area ahead at the next point of time. The convective system thus moves forward gradually and the instability energy, caused by such mechanism, keeps accumulating and strengthening, eventually leading to the appearance of large-scale, unrealized rainbands. Fig.9b shows the cross sections of temperature and vertical velocity drawn in the *X-Y* direction along the rainband over the sea surface for Fig.9a. The base of a low-level ascending airflow area is corresponding to an area of low temperature, which is much similar to the mechanism described above.

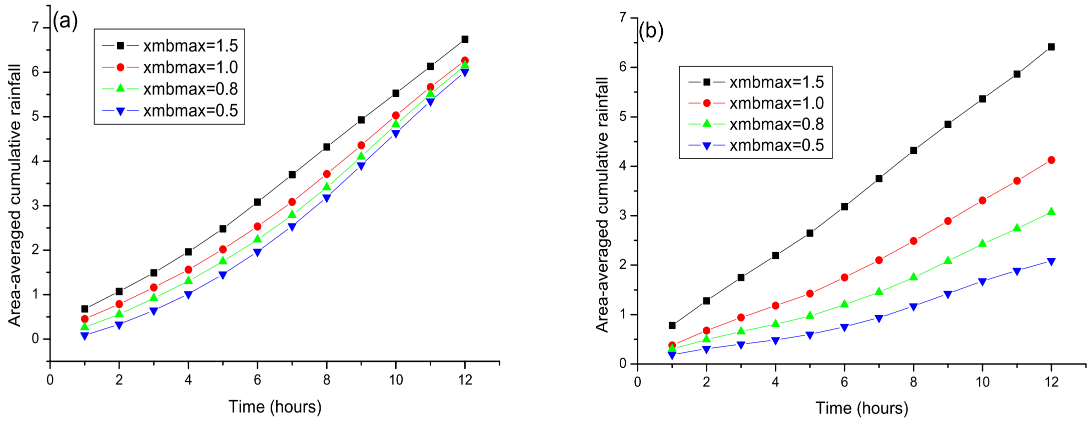

Figure 7. Total mean amount of precipitation determined with different restraints of the mass flux. (a): Case 1; (b): Case 2.

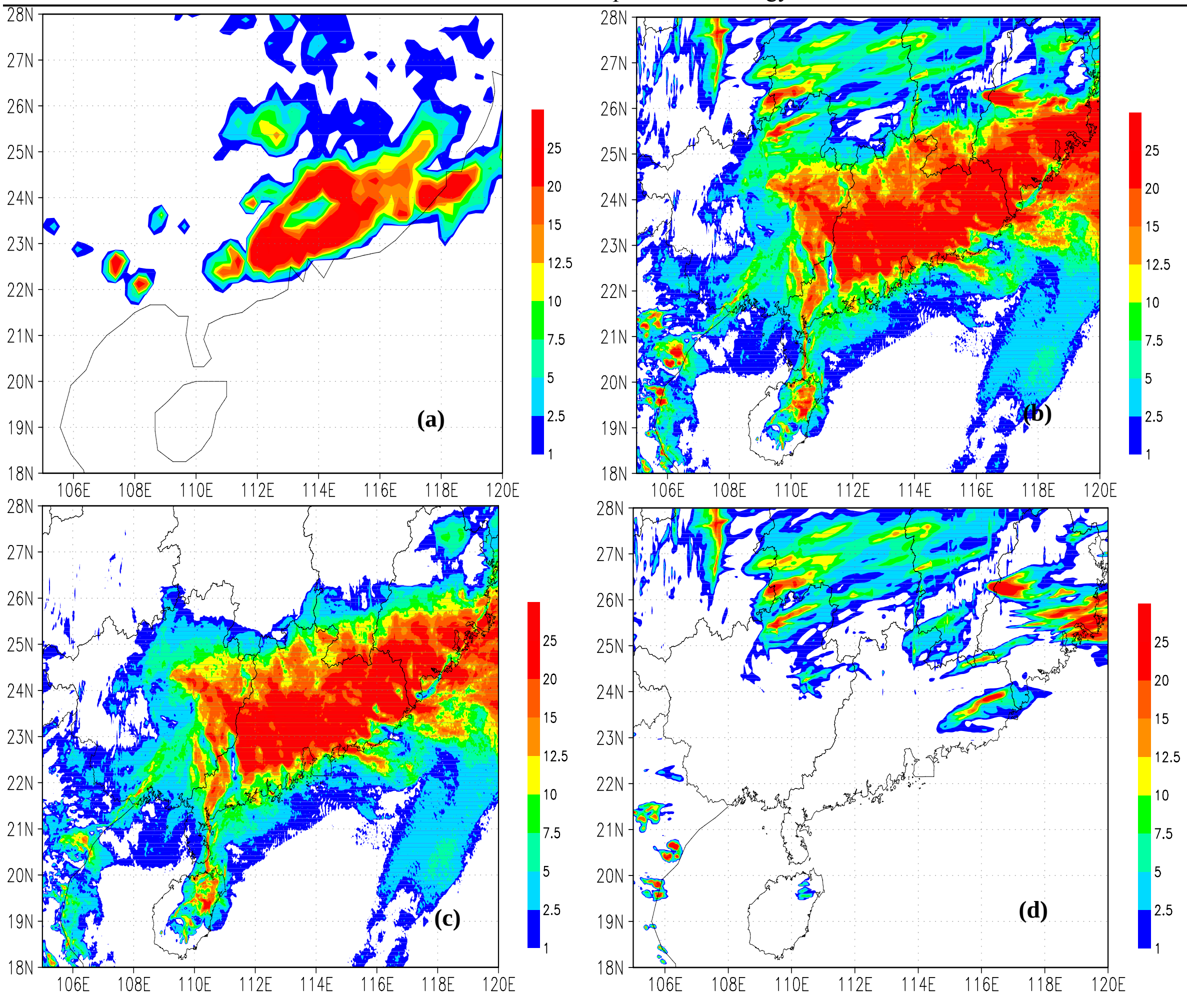

Figure 8. Comparisons of the accumulative rainfall amount for the first 12 hours between the observations and the forecasts determined with the three sets of experiments for Case 1. (a): Observations from TRMM satellite; (b): Precipitation forecast by Test-2 of Case 1; (c): Convective precipitation forecast by Test-2 of Case 1; (d): Microphysical precipitation forecast by Test-2 of Case 1.

7 CONCLUSIONS

For some subgrid convective processes that cannot be resolved explicitly by high-resolution models, this work introduces cumulus parameterization schemes with limited mass flux at cloud base to describe their effect on model forecasts. By simulating and comparing cases of strong and weak convection, this work studies the limitation of mass flux on precipitation forecast and discusses the sensitivity of different mass flux limitations on forecast results.

(1) For high-resolution models with grid intervals less than 10 km, the SAS convective parameterization scheme is closed with assumption of instability energy release in order to have more reasonable precipitation forecast than with quasi-equilibrium assumption.

(2) It is known from the 6-hour accumulative precipitation forecast that direct use of the primitive convective parameterization scheme will cause widespread unrealized rainbands in some areas while forecasting with the microphysical scheme only will neglect some subgrid convective processes that cannot be resolved by model. With the introduction of cumulus parameterization schemes with limitations on the mass flux, more reasonable forecasts can be obtained. With the increase of the upper limit of the mass flux, the parameterization scheme will have increasing influence on the model precipitation forecast. Under limitation conditions within a specific range, the forecasts of total rainfall amount by severe convective systems are not sensitive to different limitations and the proportion of precipitation with parameterization will be getting smaller with the strengthening of the systems, while the forecasts of small-scale weak convection are very sensitive to such limitations.

(3) It is found from comparisons of the two methods of mass flux limitation that unrealized precipitation, caused by convective parameterization, can be avoided more efficiently if the scheme is shut down for relatively large mass flux.

The use of cumulus parameterization schemes with mass flux limitation in high-resolution models can better describe the effect of some small-scale subgrid convective activities so as to improve the model forecast of weak convective precipitation effectively. However, as this work presents results from case analysis only and model initial fields are determined directly by interpolating analysis fields with coarser resolutions without corresponding assimilation, the precipitation forecast obtained in this way is much different from the observation. In the future research, it is necessary to take more account of the effect of data assimilation on forecast results.

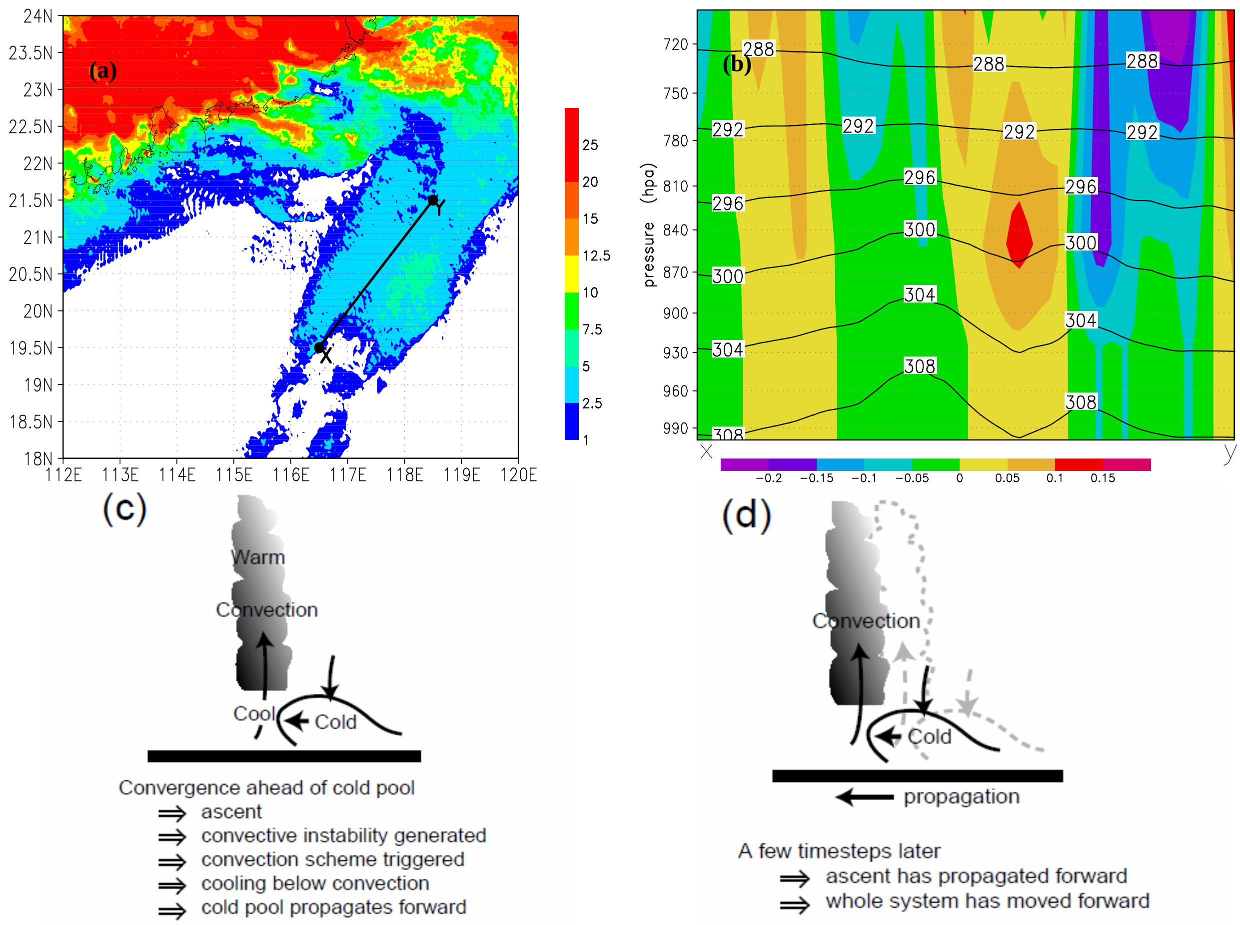

Figure 9. Unrealized precipitation caused by interactions between convective parameterization and model dynamics. (a): Precipitation of Case 1 determined by the control experiment for the first 6 hours where *X* and *Y* stand for the unrealized rainbands over the sea surface due to convective parameterization; (b): Vertical cross sections in the *X-Y* direction of Fig.9a where the shading indicates the vertical velocity and the contour stands for the temperature; (c & d): Schematic illustration of the mechanism by which convection rainbands are generated in the *X-Y* direction (Roberts[10]).

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