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Impact of Different Cumulus Parameterizations on the Numerical Simulation of Rain over Southern China

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1. INTRODUCTION

Convective rain occurs over southern China mostly in late spring and summer time. It could be brought about by troughs of low pressure and tropical cyclones. Successful simulation of the rain occurrence by numerical weather prediction (NWP) models would benefit the day-to-day weather forecasting services.

At the Hong Kong Observatory (HKO), the operational NWP model suite consists of mesoscale model covering southern China with a spatial resolution of tens of kilometres, which is then nested downwards to microscale model over the region near Hong Kong with a spatial resolution of a couple of kilometres. Whereas convective development may be explicitly simulated in the latter model, cumulus parameterization would still be required in the mesoscale model. Moreover, due to limitation of computing power, it is still not practical to conduct operational simulation of rain occurrence over the whole southern China with explicit modelling of convective development. As a result, it is useful to examine the performance of the various cumulus parameterization schemes for numerical simulation with a spatial resolution in the order of 10 km.

In the present paper, the cumulus parameterization schemes of Regional Atmospheric Modelling System (RAMS) version 4.4 would be examined. In the original version of RAMS, only one cumulus parameterization scheme is available, namely, the Kuo scheme. Later on, the Kain–Fritsch (KF) scheme has also been implemented. Recently, there is also a modified version of KF scheme available in RAMS. At the same time, RAMS may be run without the cumulus parameterization scheme and with the turbulent mixing at the top of the cloud switched off. The performance of the various simulation methods was studied by considering two typical cases of heavy rain over southern China, one associated with a surface trough of low pressure and another brought about with the passage of a tropical cyclone.

2. PARAMETERIZATION SCHEMES

In the original version 4.4 of RAMS, only the Kuo scheme of cumulus parameterization is available. A review of Kuo scheme is given in Stensrud (2007). This scheme is one of the earliest proposed convective schemes and remains one of the most popular schemes for parameterizing cumulus convection. It is also computationally less demanding as compared with the other more modern schemes. In essence, Kuo scheme relates convective activity to total column moisture convergence. The precipitation rate PR is assumed to be related to:

$$PR = (1-b)M_t.$$

In the above formula, M_t is called moisture accession and represents the total moisture convergence into the vertical column from the surface to the top of the atmosphere, thus including the surface moisture flux. The parameter b defines the fraction of total moisture convergence that is stored in the atmosphere. As a result, $(1-b)$ defines the fraction that is precipitated and used to heat the atmosphere. The total heating that convection produces could thus be derived, giving the time rate of change of potential temperature. The vertical structure of the heating is assumed to be in a form that relaxes towards a moist adiabatic, often specified as originating in the boundary layer. The time over which the scheme adjusts the atmosphere to the assumed potential temperature profile depends upon M_t.

A review of the implementation of KF scheme in RAMS is given in Truong et al. (2009). This scheme has five main features: (a) trigger function – It decides when and where deep convection should occur. Beginning at the surface, updraft source layers are determined to include vertically adjacent model layers whose total depth is at least 50 hPa. The parcel is lifted to its lifting condensation level (LCL). A temperature perturbation is added to its temperature at LCL and a check is done to see if convection initiates; (b) moist convective updraft – Updraft mass flux at LCL is computed. The component loops from LCL to the cloud top. Within the loop, the component checks if the parcel is supersaturated, then the compensate is computed. Next, the component computes precipitation generated within the updraft, along with liquid and solid precipitation generated at the given model level as a function of the updraft velocity. The updraft entrainment and detrainment rates are also computed; (c) moist convective downdraft – Precipitation efficiency and downdraft entrainment rate are computed. The downdraft parcel evaporates water on its decent from the LCL. At each model level, this evaporated water is determined and the net generated precipitation is computed; (d) compensating circulation – After updraft and downdraft fluxes are determined, the scheme computes compensating mass flux so that the net vertical mass flux at any level is zero. The compensating mass flux is equal to the sum of entrainment and detrainment caused by updraft and downdraft; and finally (e) closure assumption – It is to remove (at least 90% of) CAPE over the convective time scale (30 minutes to 1 hour), which is defined as:

$$CAPE = \int_{LCL}^{CT} g \frac{T_u(z) - \bar{T}(z)}{\bar{T}(z)} dz$$

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where CT is the cloud top, T the virtual absolute temperature. The subscript "u" denotes the updraft variables, and the overbar denotes the grid-scale variables. g is the acceleration due to gravity.

A modified version of KF scheme has been implemented in RAMS (Truong, 2009). By considering pressure perturbation and buoyant force (PDB) for the updrafts, a new diagnostic equation is determined to compute the updraft velocity, closure assumption and trigger function. For instance, the closure assumption has been revised to be:

$$CAPE = \int_{LCL}^{CT} g \frac{T_u(z) - \overline{T}(z)}{\overline{T}(z)} [1 + PDB(z)] dz .$$

From the above equation, deep convection can be maintained with negative buoyancy provided that the vertical gradient of pressure perturbation is positive and large enough. Similar changes are made to the trigger function and the updraft velocity at LCL.

3. MODEL SETUP

The outer model is the Operational Regional Spectral Model (ORSM) of HKO with a spatial resolution of 20 km. It is nested directly with RAMS with a spatial resolution of 9 km. The cumulus parameterization schemes described in Section 2 are used in separate model runs. In addition, there are two model runs with the cumulus parameterization scheme switched off. In these two model runs, one is performed with the original setting of RAMS in which turbulent mixing at the top of the cloud is maintained. In the other model run, this turbulent mixing is switched off by setting a flag in the turbulence module of RAMS 4.4, as in Szeto and Chan (2006).

Turbulence is parameterized in the model based on a simplified second-order closure method that employs a prognostic turbulence kinetic energy (TKE) equation (Mellor and Yamada 1982). The shortwave and longwave radiation schemes (Chen and Cotton 1983) consider cloud effects in calculating the heating and cooling caused by radiative flux divergences.

4. TROPICAL CYCLONE CASE

The first case in this study is Typhoon Neoguri in April 2008. In the morning of 19 April 2008, Neoguri was located at about 300 km to the southwest of Hong Kong over the northern part of the South China Sea. It continued to move northeast and made landfall over western coast of Guangdong. After making landfall, it remained on a northeasterly track over the inland areas. Neoguri brought heavy rain to Hong Kong on its movement over inland Guangdong. Between 4 and 8 p.m. on that day (Hong Kong time = UTC + 8 hours), a total of 161.1 millimetres of rainfall were recorded at the HKO Headquarters. This necessitated the issuance of "black rainstorm warning" in Hong Kong, which means the occurrence of widespread heavy rain over the territory with an hourly rainfall of 70 mm or more.

The radar picture at 6 p.m. on 19 April 2008 is shown in Figure 1(a). Model simulation is performed starting at 06 UTC. The four-hour forecasts (10 UTC) of the various model runs are shown in Figures 1(b) to (f), corresponding to (i) cumulus parameterization switched off, and with cloud-top turbulent mixing; (ii) cumulus parameterization switched off, and with cloud-top mixing switched off as well; (iii) Kuo scheme; (iv) KF scheme; and (v) modified KF scheme, respectively. The five simulations forecast the rain band of the tropical cyclone reasonably well. However, in terms of the spatial extent of the rain band (particularly the occurrence of heavy rain over the Pearl River Estuary to the west of Hong Kong), the first three simulations appear to be better. Among these three, the switching off of cloud-top turbulent mixing appears to overestimate the rainfall intensity, with the instantaneous rainfall rate reaching 100 mm per hour (coloured red in Figure 1(c)).

5. MONSOON TROUGH CASE

In the morning of 29 May 2008, a trough of low pressure lingered over the southern coast of China, bringing heavy rain to the region. Between 9 and 11 a.m. on that day, more than 60 mm of rain was recorded at the HKO Headquarters in the urban area.

Model simulation is performed starting at 21 UTC, 28 May 2008 (5 a.m. the following day). The radar picture at 9 a.m., 29 May 2008 is shown in Figure 2(a). The four-hour simulation results of the various model runs are given in Figures 2(b) to (f) respectively, corresponding to the same selections of cumulus parameterization schemes and cloud-top turbulent mixing as in Figure 1 (as described in Section 4 above). It could be seen that, once again, the first three forecasts appear to be better, particularly in the forecasting of the occurrence of rain near the coast of Guangdong. Among them, the model run with the switching off of both cumulus parameterization and cloud-top turbulent mixing (Figure 2(c)) even forecasts the rain over and to the west of Hong Kong. On the other hand, the use of KF and modified version of KF (Figures 2(e) and (f)) appear to produce considerably less convective development along the coast. The reason about this requires further investigation.

6. CONCLUSIONS

Two typical cases of heavy rain over southern China are considered in this paper, namely, Typhoon Neoguri, and a trough of low pressure at surface. Three cumulus parameterization schemes in RAMS are considered, and model runs have also been performed without cumulus parameterization schemes and with/without the switching off of cloud-top turbulent mixing. The simulations are performed with a horizontal resolution of 9 km. Among the three parameterization schemes, the Kuo scheme appears to perform the best. Explicit simulation of convection (with the cumulus parameterization scheme switched off) also seems to work well in forecasting the development of rain band, even with a spatial resolution in the order of 10 km. In comparison with actual observations, the switching off of cloud-top turbulent mixing may produce convective development correctly at locations that could not be achieved with the other simulation methods, but the rainfall intensity may also be over-forecast at times.

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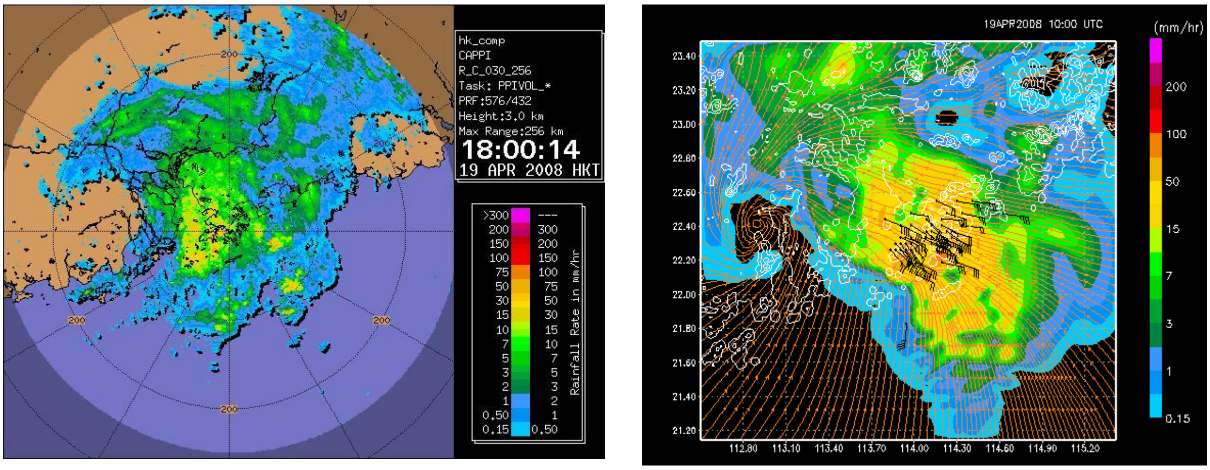
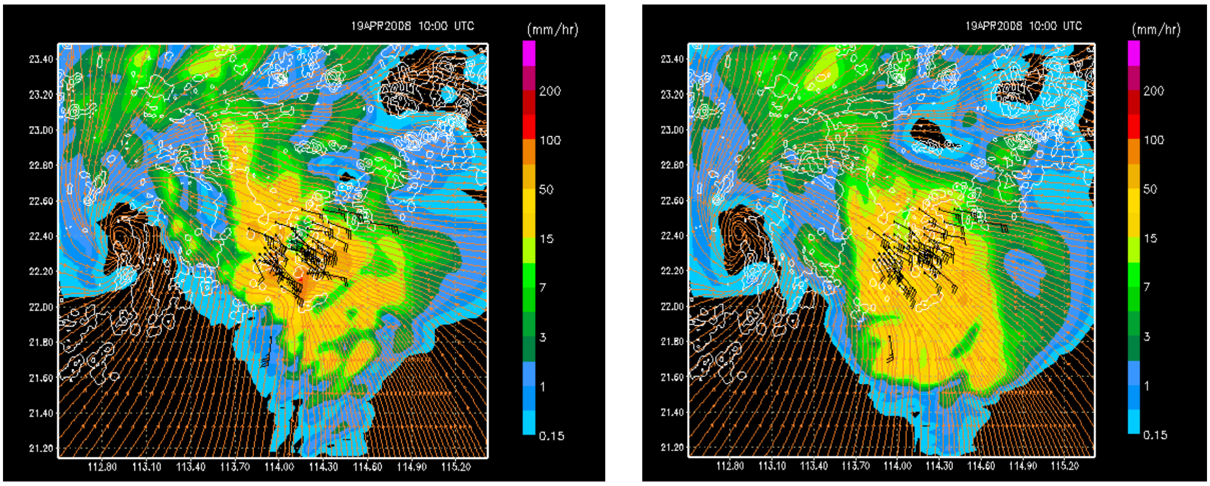


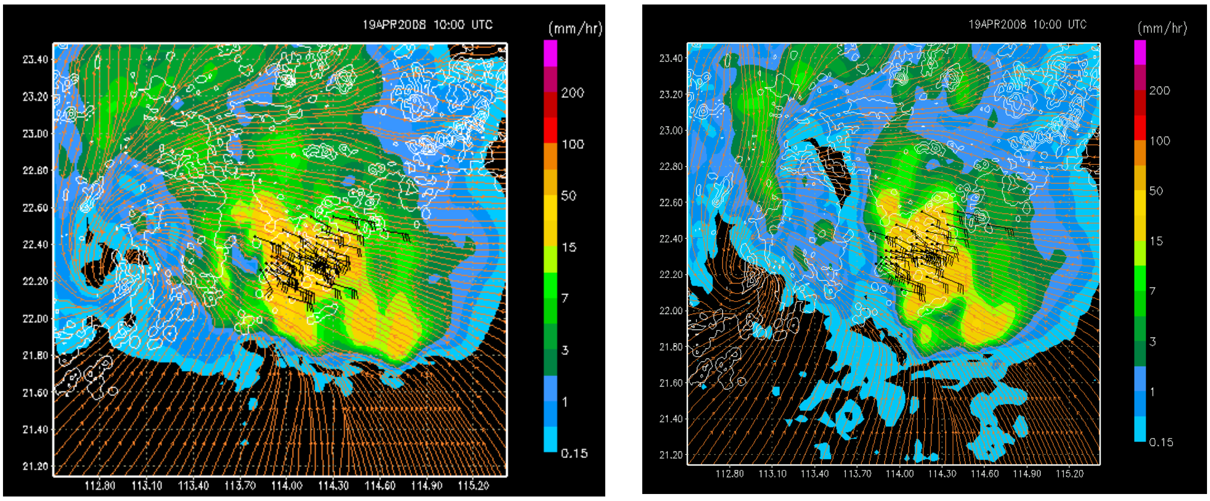
(a) radar picture

(b) cumulus parameterization switched off, and with cloud-top turbulent mixing



(c) cumulus parameterization switched off, and with cloud-top mixing switched off as well;

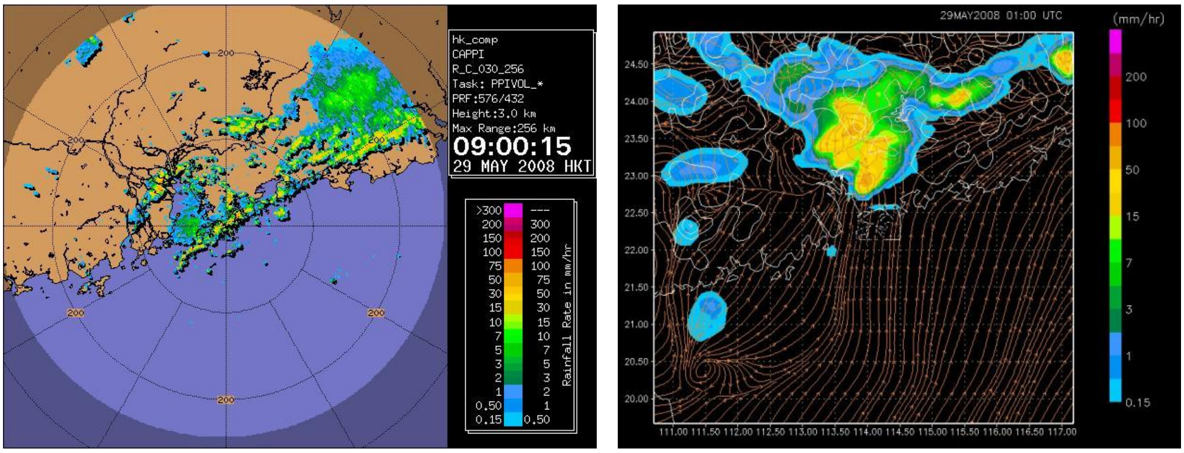
(d) Kuo scheme



(e) KF scheme

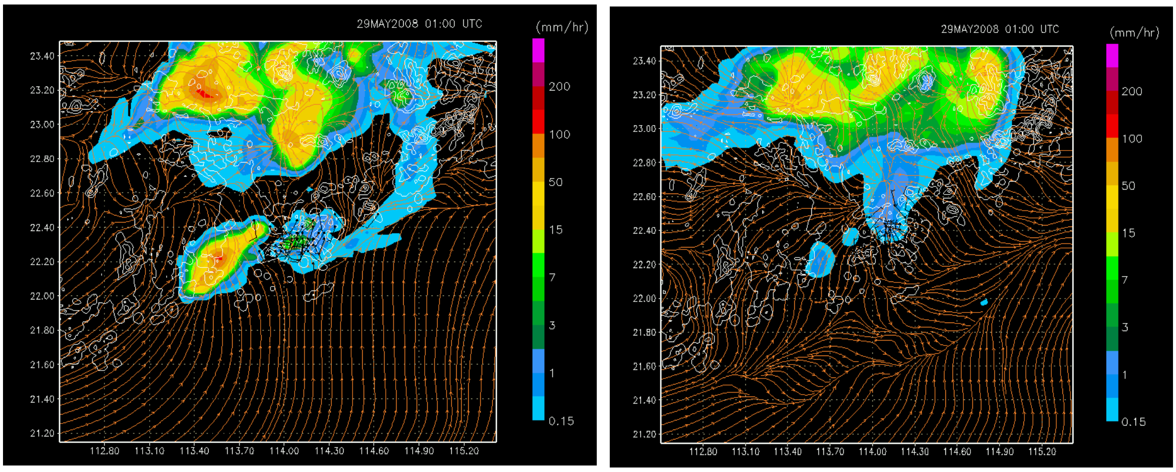
(f) modified KF scheme

Figure 1 Radar observation and the simulation results at 10 UTC, 19 April 2008.



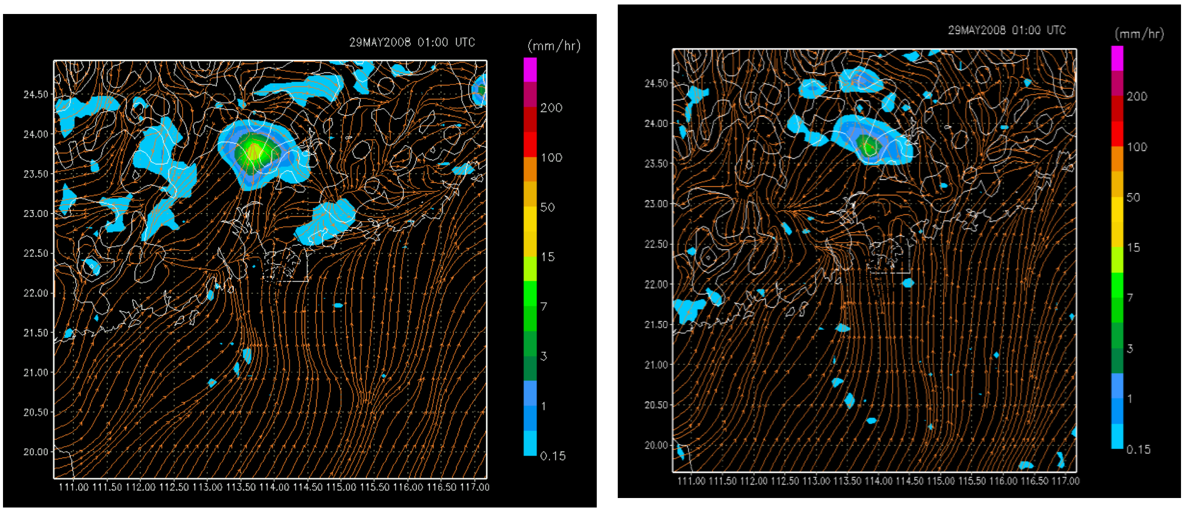
(a) radar picture

(b) cumulus parameterization switched off, and with cloud-top turbulent mixing



(c) cumulus parameterization switched off, and with cloud-top mixing switched off as well;

(d) Kuo scheme



(e) KF scheme

(f) modified KF scheme

Figure 1 Radar observation and the simulation results at 01 UTC, 29 May 2008.