9.3 EFFECT OF CLOUD CONDENSATION NUCLEI ON THE PRECIPITATION – NUMERICAL SIMULATION WITH A HYBRID MICROPHYSICAL MODEL –

Naomi Kuba *
Frontier Research System for Global Change (FRSGC), Yokohama, Japan

1. INTRODUCTION

The number concentration of cloud droplets, which influences significantly the radiative properties and precipitation efficiency of clouds, depends on cloud condensation nuclei (CCN) spectrum and the maximum value of supersaturation which the air mass has experienced. This maximum value can not be estimated by values on the grid points with an interval larger than ten meters. In addition, the supersaturation is affected not only by the updraft velocity but also by the number of activated nuclei. Therefore it is desired to calculate the condensation growth of CCN in the Lagrangian framework accurately in order to find out if each nucleus can be activated.

2. CLOUD-MICROPHYSICAL MODEL

To accurately estimate the number concentration of cloud droplets and the effect of CCN on the microstructure of clouds, the hybrid microphysical cloud model was developed. Our microphysical cloud model estimates the maximum values of supersaturation and the number concentration of cloud droplets by using the parcel model with Lagrangian framework. And our model estimates condensation, coalescence, sedimentation and advection of cloud droplets and raindrops by using bin model on the grid points with Eurelian framework. These two schemes are shown in Table 1.

2.1 Lagrangian framework

In our hybrid microphysical cloud model, each grid point has a parcel model to estimate the activation of nuclei. In the case that the relative humidity of the grid point reaches 100% for the first time, or the case that relative humidity of the grid point is larger than 100% and cloud water on the windward side of the point does not exist, air parcel including CCN and vapor starts to rise from the windward side of the point. In each parcel, the condensation growth of CCN is estimated in Lagrangian framework using the microphysical model described in Takeda and Kuba (1982). When droplets condensed on CCN grow enough to be distinguished from embryo, which can not become cloud droplets, the cloud droplets size distribution, the mixing ratio of vapor and potential temperature in the parcel are given to the grid points.

2.2 Eulerian framework

The cloud droplet size distribution on the grid point is formulated using bins of fixed radii, and their growth by condensation and coalescence is calculated in the Eulerian framework with special attention to prevent numerical diffusion of cloud droplet size distribution. Condensational growth is estimated by using modified Bott's (1989) method, and coalescence is estimated by using Bott's (1998) method. Sedimentation and advection of droplets are estimated in the Eulerian framework among grid points.

3. CLOUD-DYNAMICAL MODEL

To compare the development of rain in a shallow cloud using this hybrid microphysical cloud model with that using another model or that given by observation, our model is installed in the dynamical cloud model provided by Szumowski et al. (1998). This dynamical cloud model was designed to test the warm rain microphysical model in the Case1 of the fifth WMO Cloud Modeling Workshop (2000, Aug, 7-11, Colorado). The dynamical cloud model prescribes an evolving flow (0 - 50 min) and performs 2D advection of the temperature and water variables (domain: 9 km x 3 km, dx and dz: 50 m, dt: 3 s). Figure 1 shows the wind field at 25 min, which corresponds to the peak stage of the updraft.

4. RESULTS

To study the effect of CCN on the precipitation efficiency of clouds, the seven size distributions of CCN are prepared as shown in Table 2 and Fig. 2. A1 is based on the observation of the supersaturation spectrum of CCN shown in Szumowski et al. (1998), and is transformed to the size distribution with assumption that the constituent of CCN is NaCl.

Figure 3 shows the simulated accumulated rainfall at the surface for the cases of A1, B1 and C1. Only Aitken particle CCN $(r < 0.1\ \mu m)$ number concentrations are different among these three cases (the ratio is 1 : 5 : 10). In case A1 (Fig. 3a), precipitation starts at 31 min at the place about 1 km from the center

* *Correspoding author address:* Naomi Kuba, Frontier Research System for Global Change (FRSGC), 3173-25 Showa-machi Kanazawa-ku Yokohama, 236-0001, Japan; e-mail: kuba@jamstec.go.jp

of the domain. At this time, the updraft at the center is so strong, that raindrops can not fall against the updraft. But raindrops start to fall when the updraft becomes weaker at the center. The accumulated rainfall for 50 minutes exceeds 6 mm at the center of the domain. In case B1 (Fig. 3b), precipitation starts at 36 min at the place about 2.5 km from the center of the domain. The accumulated rainfall for 50 minutes dose not exceed 2 mm. In case C1 (Fig. 3c), precipitation starts at 43 min at the place about 4 km from the center of the domain. The maximum accumulated rainfall for 50 minutes is smaller than 1 mm.

It is found that the increase in the number concentration of Aitken particle CCN reduces the amount of rainfall, delays the rain initiation and modify the place of precipitation. It means that the increase in the number concentration of Aitken particle CCN reduces significantly not only the efficiency of generation of rainwater but also falling velocity of raindrops.

Figure 4 shows the size distribution of droplets at the three altitudes of the center of domain for cases A1 and C1. At the time of 20 min, the cloud droplet size distribution in case A1, which has lower number concentration and larger mean radius, grows by coalescence with altitude more significantly than in case C1. At the altitude of 2.225 km at 40 min, more raindrops are produced in case A1 than in case C1. At the altitude of 0.825 km at 40 min, more and larger raindrops exist in case A1 than in case C1, which are produced by coalescence during falling. In case C1, the growth of raindrops takes longer time than in case A1, so that raindrops move to the edges of the domain along the flow. The shapes of size distributions in Fig. 4 are somewhat bumpy, so that the number of bins for size distribution and grid size in domain should be tuned and the scheme of activation of droplets should be examined in this model.

The comparison among the results of cases A1, A2 and A3, or cases C1, C2 and C3, demonstrates the role of large $(0.1 \le r < 1\ \mu m)$ or giant $(r \ge 1\ \mu m)$ CCN for the precipitation. However, there is very little difference among the results of cases A1, A2 and A3, or cases C1, C2 and C3 (not shown here). Therefore, it is found that in the case of a shallow cumulus cloud with the maximum updraft velocity of about 10 m s^{-1}, only Aitken particle CCN determines the properties of precipitation,

Kessler's parameterization is also applied to this simulation for comparison. In this parameterization, the production rate of rainwater R is expressed as follows;

$$R = A(Q_c - Q_{c0}) + BQ_cQ_r^{0.875}$$

Q_c and Q_r are the mixing ratio of cloud water and rainwater, respectively. The three coefficients (A, Q_{c0}, B) are tuned to harmonize the results from Kessler's parameterization with the results from our hybrid microphysical cloud model. Figure 5 shows the accumulated rainfall for 50 minutes. Three coefficients are shown in Table 3. The coefficients in case K1 are commomly used in many studies. However, the accumulated rainfall in case K1 is much larger than that in Fig. 3. The accumulated rainfall in case K4 with very small A is similar to that in case A1 in Fig. 3. The time evolution of accumulated rainfall in case K4 is shown in Fig. 6. It shows that the precipitation area in case K4 is smaller than that in case A1 (Fig. 3a). It means that drops fall in a wide area according to their terminal velocity in case A1 but they fall at the large mean terminal velocity in a small area in case K4. It can be said that these coefficients can tune the amount of rainfall, but can not express the variety of the fall velocity of raindrops sufficiently. In addition, no combination of the three coefficients can produce the rainfall pattern like Figs. 3b and 3c.

5. CONCLUSIONS

The numerical experiments using our hybrid microphysical cloud model, reveal that the number concentration of Aitken particle CCN is the important factor to decide the precipitation efficiency of clouds. The increase in the number concentration of Aitken particle CCN reduces the amount of rainfall, delays the rain initiation and modify the place of precipitation.

It is found that in the case of a shallow cumulus cloud with the maximum updraft velocity of about 10 m s^{-1}, large and giant particle CCN do not play an important role in the precipitation, only Aitken particle CCN determines the properties of precipitation.

Modification of three coefficients in Kessler's parameterization can not produce the equivalent results with that from our hybrid microphysical cloud model. The difference in CCN size distribution makes the larger difference in the terminal velocity of raindrops than that assumed in Kessler's parameterization. To express this difference, raindrops $(r \ge 40\ \mu m)$ should be partitioned into several bins even in the bulk model.

6. REFERECES

Bott, A., 1989: A positive definite advection scheme obtained by nonlinear renormalization of the advective fluxes. *Mon. Wea. Rev.,* **117**, 1006-1015.

Bott, A., 1998: A flux method for the numerical solution of the stochastic collection equation. *J.Atmos.Sci.,* **55**, 2284-2293.

Szumowski, M. J., W. W. Grabowski and H. T. Ochs III, 1998: Simple two-dimensional kinematic framework designed to test warm rain micro-physical models. *Atmos. Res.,* **45**, 299-326.

Takeda, T. and N. Kuba, 1982: Numerical Study of the effect of CCN on the size distribution of cloud droplets. Part I. Cloud droplets in the stage of condensation growth. *J.Meteor.Soc.Japan,* **60**, 4, 978-993.

Table 1. Two schemes of microphysical cloud model.

	In the parcel	On the grid
Framework	Lagrangian	Eulerian
Fixed values	n_j Number concentration of CCN included in each class. ($j = 1,2 \cdots,200$)	$r_i = r_1 \cdot 2^{\frac{i-1}{3k}}$ Representative radius of droplets included in each bin. ($i = 1,2 \cdots,150$)
Variable values	$r_j(t)$ Radius of droplets forming on CCN included in each class.	$n_i(t)$ Number concentration of droplets included in each bin.
Activation	Takeda and Kuba (1982)	not considered
Condensation	Takeda and Kuba (1982)	modified Bott's(1989) method
Coalescence	not considered	Bott's (1998) method
Δt	0.05 s	0.5 s

Table 2. Ratio of number concentration of CCN to A1

Case	Aitken (r < 0.1 μm) 0.044 % < Sc	large (0.1 < r < 1 μm) 0.0014 <Sc < 0.044 %	giant (1 μm < r) Sc < 0.0014 %
A1	1	1	1
A2	1	10	1
A3	1	1	1000
B1	5	1	1
C1	10	1	1
C2	10	10	1
C3	10	1	1000

Table 3. Coefficients of Kessler's parameterization

Case	A	Q_{c0} [gg^{-1}]	B
K1	1.00×10^{-3}	0.5×10^{-3}	2.2
K2	1.00×10^{-3}	2.0×10^{-3}	2.2
K3	0.25×10^{-3}	2.0×10^{-3}	2.2
K4	0.01×10^{-3}	2.0×10^{-3}	2.2

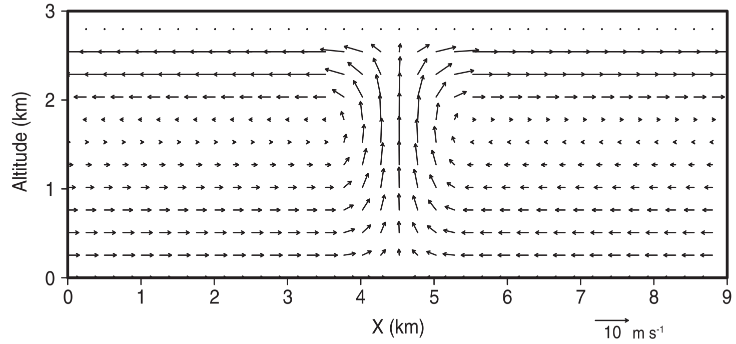

Figure 1 Wind field at 25 min, which corresponds to the peak stage of the updraft.

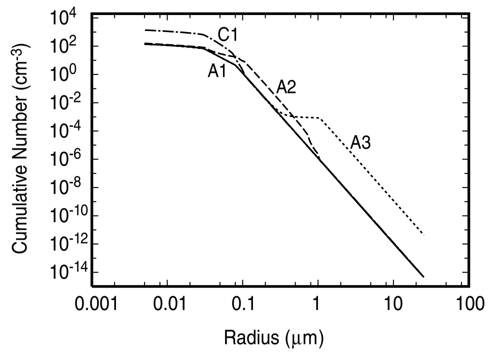

Figure 2 Size distributions of CCN in cases A1, A2, A3 and C1.

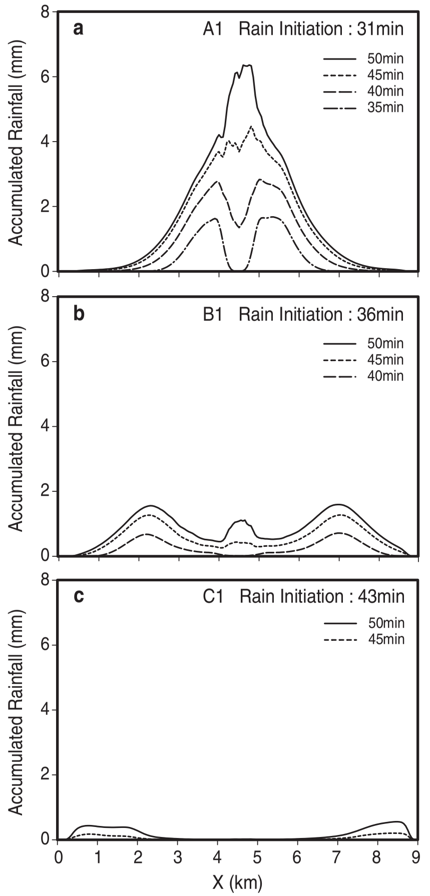

Figure 3 Time evolutions of simulated integrated rainfall at surface. a: case A1, b: case B1, c: case C1.

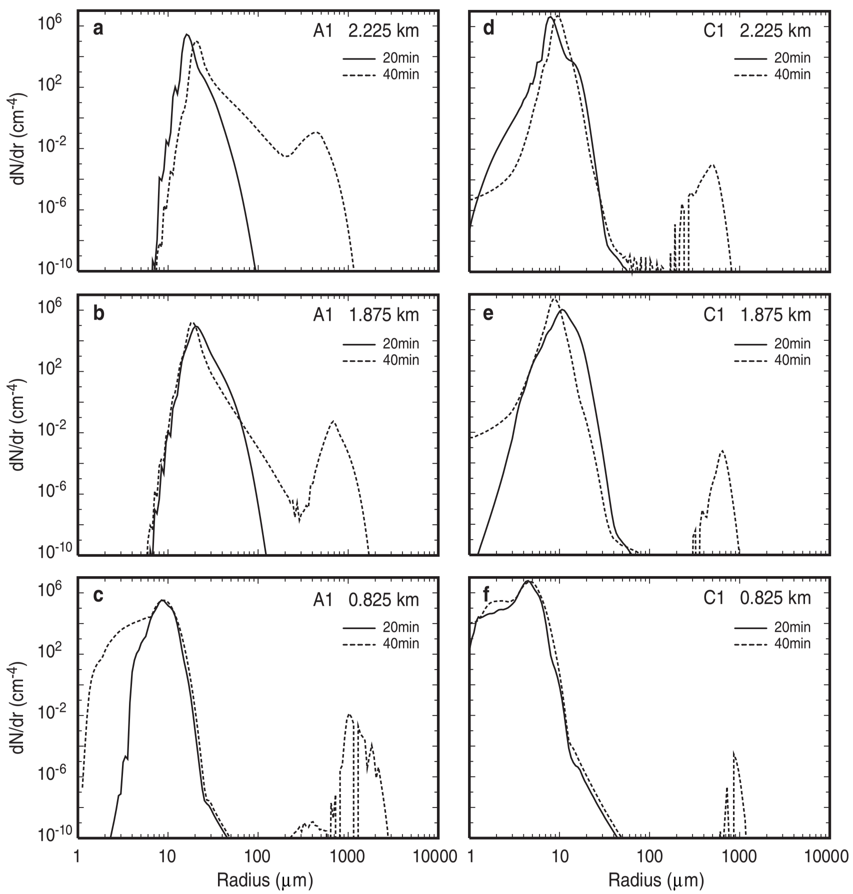

Figure 4 Simulated size distributions of droplets in case A1 at the altitudes of 2.225 km (a), 1.875 km (b), 0.825 km (c) and in case C1 at the altitudes of 2.225 km (d), 1.875 km (e), 0.825 km (f).

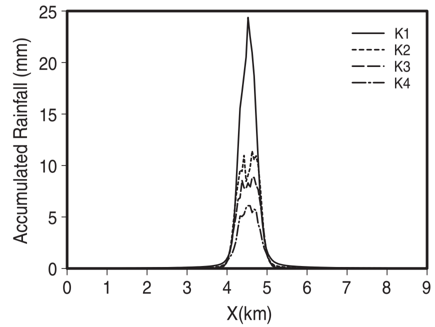

Figure 5 Simulated integrated rainfall for 50 minutes at surface in cases K1, K2, K3 and K4.

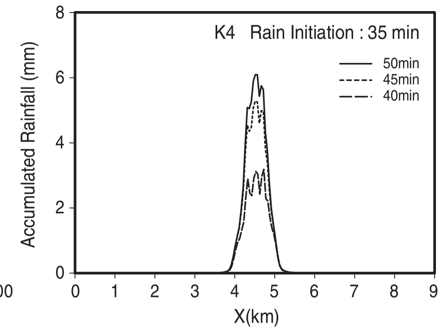

Figure 6 Same as Fig. 3 but in case K4.