IMPACT OF URBAN AEROSOLS ON CONVECTIVE PRECIPITATIONS

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Abstract

An original spectral-bin cloud scheme is implemented in the Multi-Scale Simulator for the Geoenvironment (MSSG), which is an atmosphere-ocean coupled model designed for seamless weather and climate simulations, in order to investigate the impact of urban aerosols on cloud development and precipitations. The bin scheme is based on an Eulerian-in-radius discretization scheme and therefore able to deal with the size of cloud droplet explicitly, and suitable for investigating the detail impact of aerosols. Urban aerosols typically have giant CCN (cloud condensate nuclei) in addition to ordinary CCN. In this study, we perform convective precipitation simulations with and without considering the effect of the giant CCN (GCCN). In addition, we investigated the effect of turbulent collision growth of cloud droplets, which is another hot issue in cloud physics. Comparison results reveal the coupling effect of GCCN and turbulent droplet collisions on convective precipitations.

Key words: spectral bin cloud physics, urban aerosol, convective clouds

1. INTRODUCTION

Numerous studies have been conducted to understand how urban regions influence cloud system over and downwind of these regions. Many hypotheses have been proposed to explain the effect of urban regions. Examples are (1) larger surface roughness of urban regions leads to stronger surface convergence (e.g., Rozoff et al. 2003), (2) urban regions act as large sources of moisture (e.g., Dixon and Mote 2003), (3) anthropogenic heat fluxes within urban regions and thermal perturbations by urban buildings affect convections and (4) giant cloud condensate nuclei (GCCN) broaden the initial size distribution of cloud droplets and eventually influence the cloud development (e.g., van den Heever and Cotton 2008). Numerical models are useful and promising tool to study the effect of urban regions. However, relatively few numerical studies on the urban aerosol effect, i.e., the effect of GCCN, have been cited in the literature. This is attributed to inadequate representation of cloud microphysical processes, the lack of ability to represent aerosol process, and computer limitations.

We have developed and implemented an original spectral-bin cloud scheme in the Multi-Scale Simulator for the Geoenvironment (MSSG), which is an atmosphere-ocean coupled model designed for seamless climate and weather simulations (Takahashi et al. 2005, Baba et al. 2009). The bin scheme is based on an Eulerian-in-radius discretization scheme and therefore able to deal with the size of cloud droplet explicitly, and suitable for investigating the detail impact of aerosols on cloud development and precipitation processes. Although the bin scheme is costly compared to conventional bulk schemes, three-dimensional mesoscale cloud simulations are feasible on the high-end supercomputers such as the Earth Simulator in Yokohama, Japan. In addition, the MSSG-spectral-bin scheme is capable of dealing with the turbulent collision growth of cloud droplets, which is another hot issue in cloud physics. It is suggested that, in convective clouds, air turbulence generated by updraft enhances the droplet collisions. However, it is not clarified how much it affects the convections and cloud development (e.g. Falkovich et al. 2002, Shaw 2003).

This study, therefore, aims to investigate the urban aerosol effect and turbulent droplet collision effect on cloud development separately and together, and reveal the relative importance of them, using the developed MSSG-spectral-bin scheme.

2. MODEL DESCRIPTION

2.1. Spectral-Bin Scheme in Multi-Scale Simulator for the Geoenvironment (MSSG)

The multi-scale simulation research group in the Earth Simulator Center is developing an atmosphere-ocean coupled seamless meteorological model named “Multi-Scale Simulator for the Geoenvironment (MSSG)” (Takahashi et al. 2005, Baba et al. 2009). In the MSSG, we have two options for cloud microphysics scheme; conventional bulk scheme and spectral-bin scheme. The MSSG-bulk scheme is based on the scheme developed in Reisner et al. (1998) with modifications of Thompson (2004), where water substances are classified into water vapor, cloud, rain, cloud ice, snow and graupel. In contrast, the MSSG-spectral-bin scheme is a hybrid bin scheme, where number distribution functions of liquid water are calculated using several tens of bins (classes) whereas solid (ice-phase) water is calculated in the same manner of the bulk scheme. In addition, the activation process of cloud condensation nuclei (CCN) is calculated. In this study, we concentrate on the warm rain processes (liquid water processes); (i) phase change (condensation/evaporation) process, (ii) collision growth process and (iii) activation process of CCN. Calculation for phase change process is based on the method of Soong (1974). Calculations of the collision growth process and the activation process are described in the subsections of 2.2 and 2.3, respectively. In addition, we discuss the giant CCN (GCCN) in this study, which is described in 2.4.
2.2. Turbulent collision growth of cloud droplets

Change rate of particle number density function, $n_j(r,x,t)$, by the stochastic collision-coalescence process is written as

$$\frac{\partial n_j(r, x, t)}{\partial t} = \frac{1}{2} \int K_{12}(r'' - r') n_j(r') n_j(r'') dr'' - \int K_{12}(r, r') n_j(r) n_j(r') dr' ,$$

where $r'' = (r'' - r')^{1/3}$ and $K_{12}(r, r')$ is the collision kernel describing the rate at which a particle of radius $r_i$ collides with a particle of radius $r_j$. The conventional collision kernel model is the hydrodynamic kernel model, which describes the collision due to the settling velocity difference between two particles with different sizes;

$$K_{12}(r, r') = \pi \omega_r |V_{mr} - V_{sr}| ,$$

where $< >$ denotes an ensemble average, $R_{12}(=r_j + r_i)$ is the collision radius and $V_{mr}$ is the settling velocity of particles with radius $r_i$. Obviously, this hydrodynamic kernel does not describe the collisions due to turbulence. The average collision kernel which involves turbulence enhancement is written in the following form (e.g., Sundaram and Collins 1997, Zhou et al. 2001).

$$K_{12}(r, r') = 2 n_{r1} \pi w_r |V_{sr} - V_{mr}| ,$$

where $w_r$ is the radial relative velocity at contact, which represents “turbulent transport effect” and describes the turbulence-enhanced relative velocities of two colliding particles. The term of $g_{12}(R_{12})$ is called the radial distribution function (RDF) at contact, which represents “accumulation effect” measuring the effect of particle preferential distributions. Although many numerical models for $w_r$ have been proposed, there have been few models for $g_{12}(R_{12})$. In our previous studies, we proposed a new model for $g_{12}(R_{12})$ and completed a turbulent collision kernel model (Onishi 2005, Onishi et al. 2006).

2.3. Activation processes of cloud condensate nuclei (CCN)

In the humid atmosphere, dry aerosols are deliquesced and become wet cloud condensate nuclei (CCN). This is called activation process. In the MSSG-spectral-bin scheme, the number concentration of activated CCN, $N_{gcc}$, is predicted by the Twomey scheme (Twomey 1959) as $N_{gcc} = N_0 \xi$, where $N_0$ is the initial CCN number concentration and $\xi$ is the supersaturation ratio, while the size distribution of them is prescribed. The exponential form is adopted for the prescribed size distribution (Soong 1974);

$$n_0(r) = N_{w0} \left[ \frac{3.7}{\bar{r}} \right] r^2 \exp\left[ -\left( r/r' \right)^3 \right] .$$

In the MESSG-spectral-bin scheme, we have two options; one for maritime CCN and the other for continental CCN. In the former case, the average activated CCN radius, $\bar{r}$, is 11.0 $\mu m$, $N_{0}=5.0 \times 10^7 \rho_{dry}$ m$^{-3}$ and $\xi=0.4$. In the latter case, $\bar{r}=5.0$ $\mu m$, $N_{0}=5.0 \times 10^6 \rho_{dry}$ m$^{-3}$ and $\xi=0.7$. In general, maritime CCN have smaller number of droplets with larger size.

2.4. Activation processes of giant cloud condensate nuclei (GCCN)

Our calculation procedure for GCCN activation follows Mecham and Kogan (2008). According to Ivanova et al. (1977), the activated nuclei become larger than the dry nuclei by a factor of $k$;

$$r = kr_d,$$

and

$$k(r_d)=\omega_r^{0.12} \rho_{dry}^{0.214} ,$$

where $\omega_r$ is vertical velocity, and $r_d$ is GCCN dry radius. For a typical stratocumulus vertical velocity of 0.6 m s$^{-1}$ and GCCN radii from 1 to 10 $\mu m$, the factor $k$ ranges from 6.2 to 3.8. In this study, the factor $k$ is fixed at 5.0 for simplicity. This simplification cannot be well justified, but it still allows us to see the qualitative impact of GCCN.

According to numerous observations, the aerosol size distribution is expressed as a power law of the form

$$n(r)=C r^{-\alpha} ,$$

where $\alpha$ typically varies between 3 and 4. The constant $C$ is expressed as a function of the total concentration of GCCN ($N_{gcc}$) and the shape parameter $\alpha$;

$$C= N_{gcc} \alpha r_0^{\alpha-3} ,$$

where $N_{gcc}$, $r_0$, and $\alpha$ constitute specification of the GCCN properties, and they are set as, e.g., $N_{gcc}=0.2$ cm$^{-3}$, $r_0=1$ $\mu m$, $\alpha=3$.

3. CONVECTIVE CLOUD SIMULATION

3.1. Experiment Setup

In this study, we run shallow cumulus simulations following the protocol for RICO model intercomparison. The ‘RICO’ stands for ‘Rain In Cumulus over the Ocean’, which is a measurement campaign for shallow cumuli
conducted in the vicinity of the Caribbean islands Antigua and Barbuda during Dec 2004 - Jan 2005 (http://www.convection.info/blclouds/). Based on the campaign, the following protocol was proposed to discuss the difference between cloud microphysics schemes of different numerical models (http://www.knmi.nl/samenw/rico/). As shown in Figure 1, domain size is 12.8 x 12.8 x 4.0 km with 128 x 128 x 100 grids, implying \(dx=dy=100\) m and \(dz=40\) m. Periodic conditions are imposed on the lateral boundaries. In order to minimize spurious reflection of upward propagating gravity waves, it is recommended to put sponge layer near the top boundary for damping perturbations. Momentum, sensible and latent heat fluxes are parameterized over the surface roughness of typical sea. Simulation duration is 24 hours, while the last 4 hours are analyzed. Large scale forcings are applied on moisture, heat and velocity in order to achieve a quasi-steady state in the analysis period.

![Figure 1: Computational domain for RICO model intercomparison experiment.](image)

3.2. Case Description

In order to investigate the coupling effect of turbulent collision and GCCN, we run the MSSG with different options under the RICO setup described in the previous subsection. For investigating the effect of turbulent collisions, we performed the MSSG with hydrodynamic collision kernel (no turbulent collisions) or with turbulent collision kernel, and for the impact of GCCN, the MSSG with or without GCCN activation process. Totally, 2 x 2 runs are performed (see Table 1). In all simulations, 33 bins (classes) were used for resolving the size of liquid water and the sponge layer with time constant of 600 s was laid in the top 400 m.

<table>
<thead>
<tr>
<th></th>
<th>collision kernel</th>
<th>GCCN activation</th>
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<tbody>
<tr>
<td>RUN-hyd</td>
<td>hydrodynamic (eq. (2))</td>
<td>no</td>
</tr>
<tr>
<td>RUN-turb</td>
<td>turbulent (eq. (3))</td>
<td>no</td>
</tr>
<tr>
<td>RUN-hyd.GCCN</td>
<td>hydrodynamic</td>
<td>yes</td>
</tr>
<tr>
<td>RUN-turb.GCCN</td>
<td>turbulent</td>
<td>yes</td>
</tr>
</tbody>
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3.3 Preliminary Results

Preliminary results on surface precipitation show that RUN-turb and RUN-turb.GCCN have larger precipitations than RUN-hyd and RUN-hyd.GCCN. This means turbulent collision process has larger impact than the presence of GCCN. However, the results come under the maritime CCN atmosphere. Maritime CCN already has some large aerosols and this might hide the influence of GCCN. As a next step, we performed simulations under continental CCN atmosphere. Then, the results show that the presence of GCCN has similar impact with the turbulent collisions.

4. CONCLUDING REMARKS

We have implemented the GCCN activation process in the MSSG-spectral-bin scheme, which enables us to investigate the urban aerosol effect on cloud development. Using the new MSSG-spectral-bin scheme, we have performed shallow cumulus simulations with and without considering the effect of GCCN. In addition, we have investigated the effect of turbulent collisions of cloud droplets. Comparison results have revealed the relative importance of the GCCN and the turbulent collisions: GCCN has smaller impact than turbulent collisions under maritime CCN atmosphere, while it has similar impact under continental CCN atmosphere.

ACKNOWLEDGEMENT

This research was partially supported by Core Research for Evoloutional Science and Technology (CREST) Program "Advanced Model Development and Simulations for Disaster Countermeasures" of Japan Science and
Technology Agency (JST). The simulations were carried out on the Earth Simulator 2 in Japan Agency for marine-Earth Science and Technology (JAMSTEC).

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