

# High-resolution simulations for turbulent clouds developing over the ocean

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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. The spectral-bin scheme is based on an Eulerian-in-radius discretization scheme and, therefore, able to deal with the size of cloud droplet explicitly without drastic parameterizations. In this study, we perform three-dimensional simulations of turbulent clouds with and without considering the effect of turbulent collision growth of cloud droplets under different aerosol circumstances. Preliminary results show that the turbulent collisions have significant impact on cloud development and that the impact is strongly influenced by the aerosol circumstance.

**Key Words:** cloud microphysics, spectral-bin scheme, turbulent particle collision, aerosol

## 1. Introduction

This study focuses on turbulent clouds, in other words, convective clouds or cumuli. Numerous numerical studies have been conducted to investigate physical processes in clouds such as (i) droplet initiation, (ii) condensation / evaporation of droplets, and (iii) collision-coalescence of droplets. Conventional cloud simulations have been using so-called bulk schemes for the cloud microphysical processes (e.g., Thompson *et al.* 2009, Hong and Lim 2006). In the bulk schemes, water droplets are classified into a couple of categories such as cloud water and rain water, and conversions between the categories are calculated based on empirical parameterizations. The parameterizations often limit our investigations

on microphysical processes. Spectral-bin cloud schemes, in contrast, use several tens of bins (classes) to handle the size of water droplets and explicitly calculate the size growth. Spectral-bin schemes are, therefore, suitable for detail investigation of microphysical processes.

We have developed an original spectral-bin cloud scheme named MSSG-Bin scheme and implemented it in the Multi-Scale Simulator for the Geoenvironment (MSSG) (e.g., Takahashi *et al.* 2005), which is an atmosphere-ocean coupled model designed for seamless climate and weather simulations. Although the spectral-bin scheme is much more costly than conventional bulk schemes, intense tuning for high-performance computing and the use of the Earth Simulator make it feasible to perform three-dimensional mesoscale simulations with the MSSG-Bin scheme.

Recent studies suggest that the collision frequency of cloud droplets is remarkably increased by turbulence (e.g., Falkovich *et al.* 2002; Shaw 2003). Most of the studies are based on parcel models and two-dimensional models. It is still open to dispute how significant the turbulence enhancement of droplet collisions is in mesoscale-cloud development. Lynn *et al.* (2005) simulated a squall line developed over Florida using the three-dimensional fifth-generation Penn State-NCAR Mesoscale Model (MM5) with a spectral-bin scheme. They increased the collision frequency by a constant factor to imitate the turbulence enhancement on droplet collisions and reported that the inclusion of the turbulence enhancement improves the evolution of surface precipitation. Their research is the first attempt to investigate the influence of turbulent collisions of cloud droplets in mesoscale clouds over real topography. However, they used a constant factor to imitate the turbulence enhancement. The use of a constant factor as a turbulence enhancement fails to neglect the locality of turbulence. In contrast, Onishi *et al.* (2006a) used a turbulent collision kernel depending on local turbulence statistics, and investigated the turbulence impact in three-dimensional orographic clouds, i.e., forced-convective clouds, using a preliminary version of the MSSG-Bin scheme. Their research successfully revealed significant impacts of turbulent collisions in size evolutions of droplets in the forced-convective clouds. However, it is still unclear whether significant impacts are also seen in free-convective clouds.

The main aim of this study is, therefore, to clarify the turbulence impact on cloud droplet collisions in free-convective clouds using the MSSG-Bin scheme. We also aim to see how the turbulence impact alters under different aerosol circumstances. Firstly, we describe the MSSG-Bin cloud microphysical scheme in section 2. Simulation setup is explained in section 3. Results and discussion are presented in section 4. Conclusions are presented in section 5.

## 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) (e.g., Takahashi *et al.* 2005). The MSSG has a conventional bulk cloud microphysical scheme, which is named MSSG-Bulk scheme, based on Reisner *et al.* (1998) with modifications of Thompson (2004). We are also developing a spectral-bin scheme for very fine resolution simulations. The MSSG spectral-bin (MSSG-Bin) scheme is actually a hybrid scheme; a spectral-bin scheme for liquid water, while a bulk scheme for solid water such as cloud ice, snow and graupel. This study focuses on tropical shallow cumuli, where even cloud-top temperature does not drop below the freezing temperature 273 K. Therefore, the MSSG-Bin scheme works as a pure spectral-bin scheme in this study. The cloud processes considered here are (i) droplet initiation, in other words, activation of cloud condensate nuclei (CCN), (ii) phase change (condensation/evaporation) process and (iii) collision growth process. Calculation methods for collision and activation processes are described in the subsections of 2.2 and 2.3, respectively.

### 2.2 Turbulent collision growth of cloud droplets

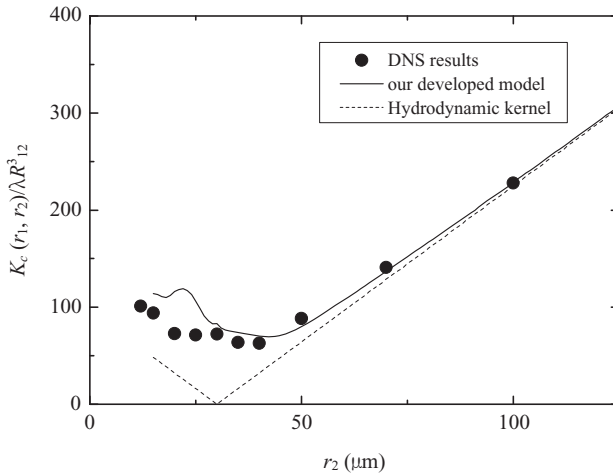
Change rate of particle number density function,  $n_i(r, x_i, t)$ , by the stochastic collision-coalescence process is written as

$$\left( \frac{\partial n_i(r, x_i, t)}{\partial t} \right)_{\text{col}} = \frac{1}{2} \int_0^r K_c(r', r'') n_j(r') n_j(r'') dr' - \int_0^\infty K_c(r, r') n_i(r) n_j(r') dr', \quad (1)$$

where  $r'' = (r^3 - r'^3)^{1/3}$  and  $K_c(r_1, r_2)$  is the collision kernel describing the rate at which a particle with radius  $r_1$  collides with a particle with radius  $r_2$ . Although collisions do not always lead to coalescences because of bouncing and breakups, this study assumes that all the collided pairs coalesce immediately. The conventional collision kernel model is the hydrodynamic kernel model, which describes the collision due to settling velocity differences between two particles with different sizes;

$$\langle K_{c, \text{hydr}, 12} \rangle = \pi R_{12}^2 |V_{\infty, 1} - V_{\infty, 2}|, \quad (2)$$

where  $\langle \rangle$  denotes an ensemble average,  $R_{12} (= r_1 + r_2)$  is the collision radius and  $V_{\infty, i}$  is the settling velocity of particles with radius  $r_i$ . Obviously, this



**Figure 1** Collision kernels normalized by local shear rate,  $\lambda = (\nu/\varepsilon)^{1/2}$ , and collision radius,  $R_{12}(=r_1 + r_2)$ , between the particles with radius  $30 \mu m$  and  $r_2$ .

hydrodynamic kernel does not express the collisions due to turbulence.

The average collision kernel which involves turbulence enhancement is written in the following form (e.g., Saffman and Turner 1956; Falkovich *et al.* 2002; Zhou *et al.* 2001).

$$\langle K_{c,turb,12} \rangle = 2\pi R_{12}^2 \langle |w_r| \rangle g_{12}(R_{12}), \quad (3)$$

where  $w_r$  is called 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 (e.g., Squires and Eaton 1991; Sundaram and Collins 1997; Shaw *et al.* 1998). 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 *et al.* 2006b; Onishi *et al.* 2007; Onishi *et al.* 2009).

Figure 1 shows the prediction results of collision kernel models together with the three-dimensional DNS results in an isotropic flow with Taylor-microscale based Reynolds number,  $Re_\lambda$ , of 44. The vertical axis shows the collision kernel between particles with radius  $r_1$  and  $r_2$ ;  $r_1$  is fixed at  $30 \mu m$  normalized by  $\lambda R_{12}^3$ , where  $\lambda$  is the local shear rate. The horizontal axis shows the  $r_2$ . Significant discrepancy is seen between the predictions of the hydrodynamic model and DNS results at  $r_2 \sim r_1$  ( $=30 \mu m$ ), while good agreement between the predictions of our

developed model and DNS results. This is because collisions between the same size particles are purely induced by turbulence. The turbulence effect is well-predicted by our developed model.

The turbulent collision kernel requires turbulent statistics such as the energy dissipation rate and the turbulent Reynolds number  $Re_\lambda$ , which are usually sub-grid scale values. Those sub-grid scale (SGS) values are estimated from the grid scale (GS) values under the local isotropy assumption (Onishi *et al.* 2006b). When considering the turbulent collisions, we firstly estimate the SGS turbulent statistics in every grid box and prepare the turbulent collision kernel from them, and then calculate the collision growth inside the grid box.

### 2.3 Activation process of cloud condensate nuclei (CCN)

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

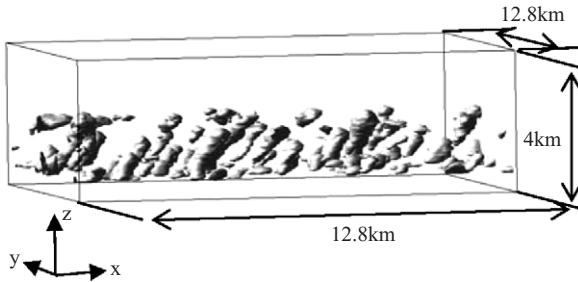
$$n_r(r) = N_{act} (3/r^{-3}) r^2 \exp[-(r/r_m)^3]. \quad (4)$$

The MSSG-Bin scheme provides two options; one for maritime CCN and the other for continental CCN. In the former case, the mean activated CCN radius,  $r_m$ , is  $11.0 \mu\text{m}$ ,  $N_0 = 5.0 \times 10^7 \rho_{\text{dry}} \text{ m}^{-3}$  and  $\xi = 0.4$ . In the latter case,  $r_m = 5.0 \mu\text{m}$ ,  $N_0 = 5.0 \times 10^8 \rho_{\text{dry}} \text{ m}^{-3}$  and  $\xi = 0.7$ . In general, maritime CCN have smaller number of droplets with larger size.

## 3. Convective cloud simulation

### 3.1 Experiment setup

We perform three-dimensional simulations of shallow cumuli following the protocol for RICO model intercomparison. The RICO stands for Rain In Cumulus over the Ocean. It is a field campaign for shallow cumuli in the vicinity of the Caribbean islands Antigua and Barbuda during Dec 2004 - Jan 2005 (<http://www.convection.info/blclouds/>). Based on the observations, the RICO model intercomparison was conducted in order to discuss the difference among cloud schemes of different numerical models (<http://www.knmi.nl/samenw/rico/>). Figure 2 shows the designated domain size, which is  $12.8 \times 12.8 \times 4.0 \text{ km}$  with  $128 \times 128 \times 100$  grids, implying  $dx = dy = 100\text{m}$  and  $dz = 40\text{m}$ . Periodic conditions



**Figure 2** Computational domain for RICO model intercomparison experiment.

**Table 1** Case description.

|            | collision kernel       | CCN type    |
|------------|------------------------|-------------|
| RUN-Hydr/M | hydrodynamic (eq. (2)) | maritime    |
| RUN-Turb/M | turbulent (eq. (3))    | maritime    |
| RUN-Hydr/C | hydrodynamic           | continental |
| RUN-Turb/C | turbulent              | continental |

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 typical surface roughness of ocean. 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.

### 3.2 Case description

In order to investigate the coupling effect of turbulent collision and aerosol type, we run the MSSG with different options under the RICO setup described in the previous subsection. For investigating the impact of turbulent collisions, we performed the MSSG with hydrodynamic collision kernel (no turbulent collisions) or with turbulent collision kernel. In addition, we performed the MSSG with maritime CCN model or with continental CCN model to investigate the influence of aerosol type. Although the use of continental CCN model for the RICO setup, which targets cumuli over the ocean, sounds inconsistent, the inconsistency does not influence the collision process directly. Totally,  $2 \times 2$  runs are performed (see Table 1). In all simulations, 33 bins (classes) were used for resolving the size of liquid water in the MSSG-Bin scheme.

## 4. Results and discussion

### 4.1 Impact of Turbulent Collisions under different aerosol circumstances

Figure 3 shows the column cloud and rain waters in four runs listed in Table 1. Liquid droplets with sizes smaller than  $40\mu\text{m}$  are considered as cloud droplets and larger droplets as rain drops. The column rain water is the mean total mass of rain drops in columns. Runs with turbulent collision kernel show larger column rain water than those with hydrodynamic kernel. This exhibits that the droplets growth is significantly enhanced by turbulent collisions and the conversion from cloud to rain is consequently promoted. In maritime case, the total of cloud and rain water, as well as the rain water, is increased by the turbulent collision. This indicates that the turbulent collisions substantially altered the cloud development. In contrast, the influence of turbulent collisions is less drastic in continental case. Continental aerosols produce larger number of CCN with smaller size compared to maritime case (see subsection 2.3). Condensation is dominant for the growth of smaller droplets. Therefore, collision growth itself is less significant in continental case and, as a result, turbulent collisions play less significant role in continental case than in maritime case.

### 4.2 Photo-Realistic Images of Very High-Resolution Simulation Results

Figure 4 shows a photo-realistic image of shallow cumuli, which were numerically simulated using our MSSG-Bin scheme. The simulation was carried out with spatial resolutions of  $dx=dy=25\text{m}$  (horizontal) and  $dz=20\text{m}$  (vertical) using  $512 \times 512 \times 200$  grid points. A ray-tracing technique is used for the visualization, where the 3D scatterings of light (rays) are physically calculated.

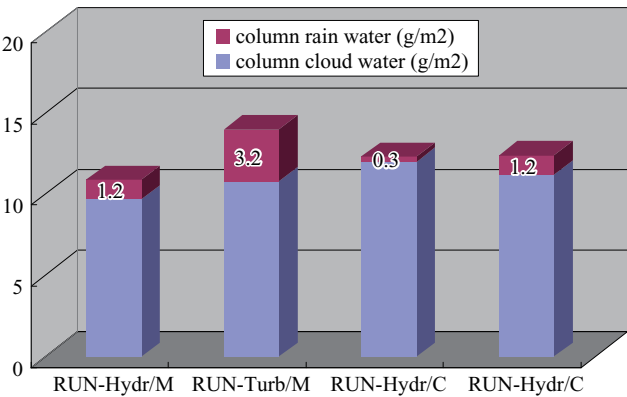


Figure 3 Column cloud and rain waters.



**Figure 4** Photo-realistic image of the result from very high-resolution simulation for cumuli over the ocean. A ray tracing technique is used for the visualization.



**Figure 5** Cumuli over the Kyoto imperial palace. Volume rendering of liquid water content is drawn in the Google Earth.

Taking the droplet size into account, this visualization can express shade and transparency of clouds following optical laws. The brightness of rainbow is also physically calculated: We can see both primary (inner arch) and secondary (outside, larger arch) rainbows. Turbulent clouds have small scale structures due to cloud turbulence. For example, energy scale of turbulent entrainment is several tens of meters. The turbulent entrainment is well-captured by the very fine spatial resolution of 25m and, therefore, small scale structures are reproduced in Figure 4 compared with Figure 2, where 100m spatial resolution was used. The very high-resolution data here is useful for revealing turbulence phenomena in clouds, and it is potentially a reference data for low-resolution simulations which cannot resolve

the turbulent energies.

Figure 5 shows another picture of the cumuli in the aid of Google Earth (<http://earth.google.com/>). The Google Earth is a virtual globe, map and geographic information program and it can superimpose the images obtained from, e.g., satellite imagery and aerial photography. Here we superimpose a volume-rendering image of liquid water over the Kyoto imperial palace. The liquid water data itself is the same with that used for Figure 4. The view with familiar building helps us to grasp the scale of cloud structures. In this sense, the Google Earth has a potential to be a useful research tool.

## 5. Conclusions

We have developed and implemented the original spectral-bin cloud scheme (MSSG-Bin scheme) in the Multi-Scale Simulator for the Geoenvironment (MSSG), which is an atmosphere-ocean coupled model designed for seamless weather and climate simulations. The spectral-bin scheme is based on an Eulerian-in-radius discretization scheme and therefore able to deal with the size of cloud droplet explicitly. In this study, we have performed three-dimensional mesoscale simulations of turbulent clouds with and without considering the turbulent enhancement of droplet collisions in different aerosol circumstances. The results have shown that the in-cloud turbulence significantly enlarges the rate of conversion from cloud droplets to rain drops in free-convective turbulent clouds. They have also shown that the turbulence enhancement is more significant in maritime aerosol circumstance than in continental one.

In this study, we have performed the MSSG-Bin simulation for mesoscale clouds with a very high-resolution up to 25m horizontal resolution. Such high-resolution simulation can resolve the most of the turbulence energy. The high-resolution simulation with the MSSG-Bin scheme, therefore, is a promising tool to investigate the coupling between small-scale turbulence and mesoscale cloud development.

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## References

Falkovich, G., A. Fouxon and M. G. Stepanov (2002), Acceleration of rain initiation by

- cloud turbulence, *Nature*, 419, 151-154.
- Hong, S.-Y., and J.-O. J. Lim (2006), The WRF Single-Moment 6-class microphysics scheme (WSM6), *J. Korean Meteor. Soc.*, 42, 129-151.
- Lynn, B. H., A. P. Khain, J. Dudhia, D. Rosenfeld, A. Pokrovsky and A. Seifert (2005), Spectral (Bin) Microphysics Coupled with a Mesoscale Model (MM5). Part II: Simulation of a CaPE Rain Event with a Squall Line, *Mon. Wea. Rev.*, 133: 59-71.
- Onishi, R. H. Takagi, K. Takahashi and S. Komori (2006a), Turbulence effects on cloud droplet collisions in mesoscale convective clouds, *Turbulence, Heat and Mass Transfer 5* (Eds. K. Hanjalic, Y. Nagano and S. Jakirlic), 709-712.
- Onishi, R., K. Takahashi and S. Komori (2006b), Large-eddy simulation for particle collision growth in turbulent flows (in Japanese), *Trans. JSME B*, 72(722), 2441-2448.
- Onishi, R. and S. Komori (2007), Modeling of the collision kernel of monodisperse particles in turbulent flows (in Japanese), *Trans. JSME B*, 73, 1307-1314.
- Onishi, R., K. Takahashi and S. Komori (2009), Influence of gravity on collisions of monodispersed droplets in homogeneous isotropic turbulence, *Phys. Fluids*, 21, 125108.
- Reisner, R., R. M. Rasmussen and R. T. Brientjes (1998), Explicit forecasting of supercooled liquid water in winter storms using the MM5 mesoscale model. *Q. J. R. Meteorol. Soc.*, 124, 1071-1107.
- RICO model intercomparison (Precipitating shallow cumulus case), <http://www.knmi.nl/samenw/rico/>
- Saffman, P. G. and J.S. Turner (1956), On the collision of drops in turbulent clouds, *J. Fluid Mech.*, 1:16-30.
- Shaw, R. A., W. C. Reade and L.R. Collins (1998), Preferential concentration of cloud droplets by turbulence: effects on the early evolution of cumulus cloud droplet spectra, *J. Atmos. Sci.*, 55:1965-1976.
- Shaw, R. A. (2003), Particle-turbulence interactions in atmospheric clouds, *Annu. Rev. Fluid Mech.*, 35, 183-227.
- Soong, S. -T. (1974), Numerical Simulation of Warm Rain Development in an Axisymmetric Cloud Model, *J. Atmos. Sci.*, 31:1262-1285.
- Squires, K. D. and J.K. Eaton (1991), Preferential concentration of heavy particles in a turbulent channel flow, *Phys. Fluids*, A3:1169-1179.
- Sundaram, S. and L. R. Collins (1997). Collision Statistics in an Isotropic Particle-Laden Turbulent Suspension. Part I. Direct Numerical Simulations, *J. Fluid Mech.*, 335: 75-109.
- Takahashi, K., X. Peng, K. Komine, M. Ohdaira, K. Goto, M. Yamada, H. Fuchigami, T. Sugimura Non-hydrostatic atmospheric GCM development and its computational performance (2005), *Use of High Performance computing in meteorology*, 50-62.
- Thompson, G., R. M. Rasmussen and K. Manning (2004), Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part I: Description and sensitivity analysis, *Mon. Wea. Rev.*, 132, 519-542.
- Thompson, G., P. R. Field, R. M. Rasmussen and W. D. Hall (2009), Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part II: Implementation of a new snow parameterization, *Mon. Wea. Rev.*, 136, 5095-5115.
- Twomey, S. (1959), The nuclei of natural cloud formation: The supersaturation in natural clouds and the variation of cloud droplets concentrations. *Geofis. Pura Appl.*, 43, 243-249.
- Zhou, Y., A. S. Wexler and L. P. Wang (2001). Modelling Turbulent Collision of Bidisperse Inertial Particles, *J. Fluid Mech.*, 433: 77-104.