A parcel model simulation of graupel and snowflake formation in convective snow clouds over the Sea of Japan

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1. Introduction

In winter monsoon seasons, convective snow clouds frequently develop over the Sea of Japan and bring great amount of snowfall along coastal regions. The main types of precipitating particles are graupels and snowflakes; the former causes local severe snowfall and the latter produces a long-term heavy snow. A modeling of the formation of graupels and snowflakes are important for snowfall forecasting as well as an improvement of general circulation models for predicting climate changes.

One typical procedure to simulate various types of snow particles is categorizing ice crystals into several classes such as cloud ice, snow, graupels and hails. A bulk cloud scheme calculates mixing ratio (and sometimes with number concentration) of each class, while spectral bin model predicts number density of particles every size bin. In such categorizing methods, however, particles having intermediate property between the classes are not taken into account, and a crystal in one class "jumps" into another class with its growth.

In order to simulate the formation of various types of precipitating particles, we need a microphysical model capable for calculating "continuous" transition between the classes. The model proposed by Chen and Lamb (1994) is very sophisticated, in which ice-crystal properties are represented in a multi-dimensional bin framework, including components of water mass, solute mass and aspect ratio. In the present study, we added "volume" as a new dimension to Chen and Lamb's model to simulate the formation of graupels and snowflakes more precisely. In this presentation we apply the modified Chen and Lamb's model to convective snow clouds over the Sea of Japan in a parcel model framework to understand the formation of solid precipitation.

2. Numerical simulation

The cloud model used in this study is a modified version of multi-dimensional bin model developed by Chen and Lamb (1994). Because the treatment of liquid water is the same as in the original model, we describe the calculation for ice particles here. We have six prognostic valuables in this model; total number, total heat, total water mass, total solute mass, total volume, and the sum of aspect ratio of particles. The calculation of chemical processes in the original model is not conducted here. Each prognostic valuable have four dimensions; water mass, solute mass, aspect ratio, and volume (Fig.1). The shape of ice crystals is assumed to be spheroid.

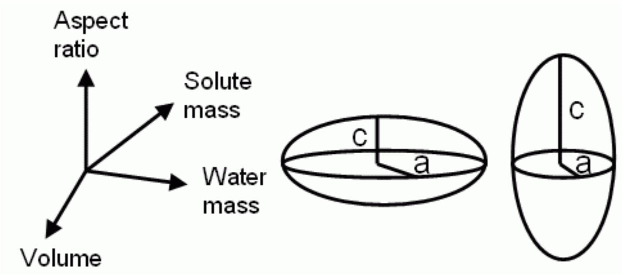

Fig.1. Shape of ice crystals and four components of dimensions.

Microphysical equations used here are essentially the same as in Chen and Lamb (1994), except for a slight modification in the aggregation efficiency. In order to avoid aggregation between graupels, we set aggregation efficiency as:

$$E_{agg} = \begin{cases} 1 - 0.99\,\rho_i / 0.2 & (\rho_i < 0.2\,gcm^{-3}) \\ 0.01 & (\rho_i \geq 0.2\,gcm^{-3}) \end{cases}$$

Here ρ_i is an averaged bulk density of colliding particles.

Numbers of bins for components of water mass, solute mass, aspect ratio and volume are 46, 45, 21 and 94, respectively. Because we pay our attention to the variation of bulk density, we set many bins for the volume. The calculation is conducted in a parcel model framework in which an air parcel rises adiabatically. Fallout of precipitating particles from the air parcel is not considered; thus our simulation is restricted to the development stage of convective snow clouds. We assumed a 1500 m-depth, parabolic updraft with maximum speed of 4 m/s. The beginning point of rising parcel is a cloud base at 900 hPa and -10°C. Calculation cases are listed in Table 1. In case *Control*, we use the "maritime surface" distribution of Whitby (1978) for hygroscopic aerosols. Case *Urban* uses "urban average" aerosol distribution to test the sensitivity to the number of CCN. Homogeneous and immersion freezing of drops is off in case *No freeze* where we discuss the effects of drop freezing on the formation of precipitating particles. Case *Bulk* is the same calculation as *Control* except for using 1-moment bulk cloud scheme of Rutledge and Hobbs (1984). The numerical integrations were carried out until the parcels reach cloud top (20 minutes).

Table 1. Cases for calculation

Case	Physical process	Aerosols
Control	Full	Maritime surface
Urban	Full	Urban average
No freeze	No homogeneous/ immersion freezing	Maritime surface
Bulk	1-moment bulk model	

3. Results of the control case

The temperature of the parcel decreased almost linearly with height and reached -21.7℃ at the cloud top. This temperature is not out of the range of a typical convective snow clouds over the Sea of Japan (～-20℃). The CCN were activated just above the cloud base and formed cloud drops with 110 cm^{-3} in number density. Number of cloud drops slowly decreased with height due to their coalescence, and rapidly decreased at the cloud top by evaporation. Number concentration of ice particles, on the other hand, increased with height, and it reached 45 L^{-1} at the cloud top. This value is almost one order smaller than that of the video-sonde observation by Murakami et al. (1994) (300 L^{-1}). Particles with small aspect ratio (plates) prevailed below 1300 m, while spherical particles with high bulk density (graupels and densely rimed crystals) formed near the cloud top.

Size distributions of ice particles at the cloud top are shown in Fig.2. There are two peaks in the number concentration; one is at 200 μm and the other is 750 μm in the melted diameter. Takahashi (1993) found two separate modes in the graupel size in a convective snow clouds by his aircraft observation. However it is not clear whether the simulated two peaks correspond to his findings. Figure 3 is a visual illustration of the simulated ice particles "sampled" near the cloud top. Almost all particles show spherical shape with bulk density greater than 0.1 gcm^{-3}, which indicate the formation of graupels and densely rimed crystals.

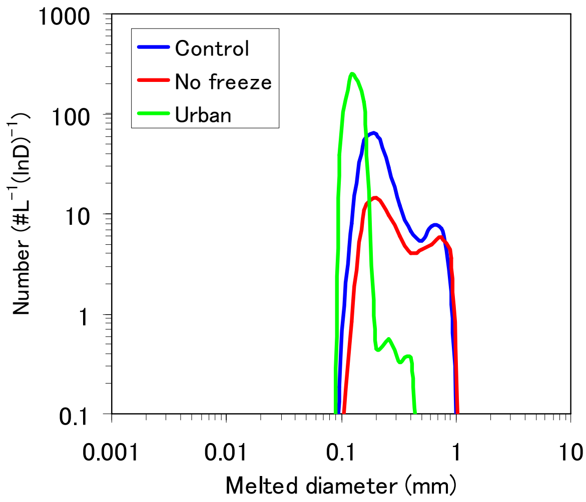

Fig.2. Size distribution of ice particles at the cloud top (20 minutes)

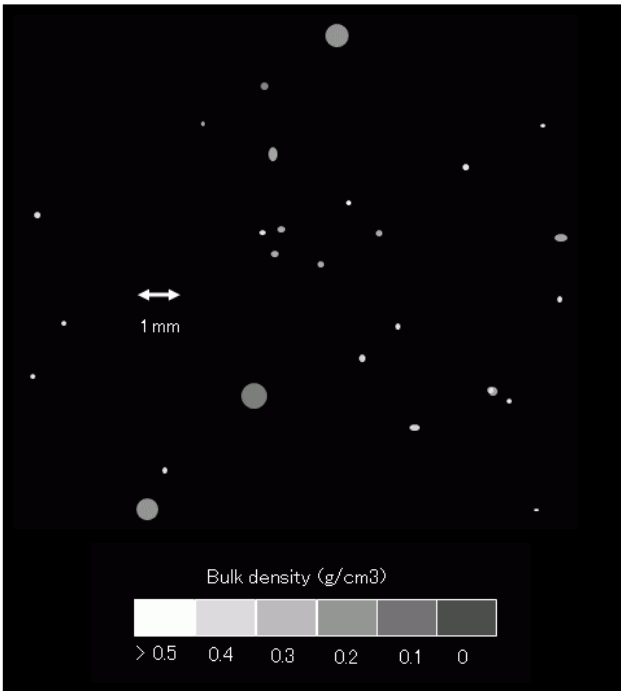

Fig. 3. Illustration of ice particles "sampled" at the cloud top in case *Control*. Oblate and prolate spheroids are drawn as horizontally long and vertically long ellipses, respectively. The gray scale indicates bulk density.

4. Results of sensitivity tests

In case *Urban,* in which urban average distribution of aerosols were given, number concentration of cloud drops exceeded 5000 cm^{-3} and more than 150 L^{-1} of ice crystals were formed. The excess amount of ice particles restricted their growth and the number of particles larger than 200 μm was much smaller than that in *Control* (Fig.2). In case *No freeze*, the number of ice particles with diameter around 200 μm decreased, while that around 750 μm was not so changed. This suggests that plate-like crystals originating from deposition or condensation-freezing nucleation act as embryo of large particles formed near the cloud top. Case *Bulk* successfully simulated the total mixing ratio of ice particles and the lack of small crystals (cloud ice) at the cloud top. However "snow" did not exist in the bulk model, although ice particles with bulk density smaller than 0.2 gcm^{-3} existed in case *Control*.

5. Summary

Using a modified version of the multi-dimensional bin model of Chen and Lamb (1994), we conducted a parcel model simulation of convective snow clouds over the Sea of Japan. The results are summarized as follows:

1) Both deposition/condensation-freezing nucleation and homogeneous/immersion freezing of drops were effective for ice initiation of convective snow clouds over the Sea of Japan. However the simulated ice number concentration was almost one order smaller than that of observations.
2) At the cloud top there were two peaks in number concentration of ice particles. Sensitivity tests suggest that the embryos of the smaller peak consisted of frozen-drops, while those of the larger peaks were plate-like crystals originating from ice nuclei.
3) Excess amount of CCN increased number concentration of ice but restricted their growth.
4) The 1-moment bulk cloud scheme by Rutledge and Hobbs (1984) showed almost consistent results to our model, except for the absence of "snow".

Now the cloud model shown in this study is being installed in the Japan Meteorological Agency Non-Hydrostatic Model (JMA-NHM) under the Japanese Cloud Seeding Experiment for Precipitation Augmentation (JCSEPA). The model is also being used for improvement of the snow forecasting model in the Snow and Ice Research Group, NIED, in the Research Project for Developing a Snow Disaster Forecasting System and Snow Hazard Maps.

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