Numerical study of the aerosol effect on water cloud optical properties with non-hydrostatic explicit microphysics cloud model

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Abstract

In the present study, we developed a non-hydrostatic spectral microphysics cloud model and performed numerical experiments with the model to investigate the aerosol effect on a water cloud microphysics. Numerical model used for the experiments is a coupled model of non-hydrostatic dynamical framework and spectral microphysics binned cloud model, both of which were newly constructed in the present study. Numerical experiments were performed with this model to investigate the interaction between aerosol and water cloud. It was found that the simulated correlation pattern between cloud particle effective radius and optical thickness was consistent with those acquired by satellite observation. Cloud effective radius and optical thickness are positively correlated when the cloud is not drizzling, contrary to negative correlation when the cloud is accompanied by drizzle-sized particles. We also investigated the dependence of cloud properties on column aerosol particle number obtained from the simulation. Cloud particle effective radius and optical thickness was simulated to be negatively and positively correlated with column aerosol particle number, respectively, resulting an approximate constancy of Liquid Water Path (LWP) independent of aerosol particle number because LWP is proportional to optical thickness multiplied by effective radius. Column cloud particle number was simulated to increase with column aerosol particle number. These characteristics are qualitatively consistent with those reported from the statistics obtained by satellite observation, although the sensitivity of cloud properties to aerosol amount was somewhat larger in this simple numerical experiment than global statistics from satellite observation.

Keyword: aerosol, cloud microphysics, aerosol indirect effect, cloud-aerosol interaction

1. Introduction

Cloud microphysical structure, which has a fundamental role in determining the optical and hydrologic properties of clouds, is known to be modified by atmospheric aerosols acting as cloud condensation nuclei (CCN). This indirect effect of aerosol is one of key issues important in understanding the global climate change, but the uncertainty in the evaluation of aerosol indirect radiative forcing is still very large (IPCC, 2001). Recent progress in satellite remote sensing provided us with useful data of cloud and aerosol optical properties over global scale. Global analysis with the data revealed that the water cloud optical properties such as effective particle radius and optical thickness are significantly correlated with aerosol particle number (Nakajima et al., 2001). Numerical simulations with General Circulation Model (GCM) have been performed by parameterizing the aerosol effect on cloud property. Recent modeling studies (Lohmann and Lesins, 2002; Suzuki et al., 2004) compared the model-simulated result of aerosol indirect effect with satellite observation at global scale and reported that the global sensitivity of cloud properties to aerosol amount largely depends on the choice of parameterization for cloud microphysics. Such ambiguity in cloud parameterization is a main source of uncertainty in the estimate of aerosol indirect radiative forcing.

It is necessary for reducing the uncertainty to study with numerical cloud model which explicitly calculates the cloud particle growth by treating microphysical processes in proper way rather than bulk parameterizations. In the present study, we developed a non-hydrostatic spectral microphysics cloud model and performed numerical simulations for investigating the cloud particle growth process and the aerosol effect on water cloud optical properties. Model description and experimental design are briefly introduced in section 2, and the results of numerical simulation are given in section 3. The conclusion of this study will be presented in section 4.

2. Model experiment

The model used for numerical experiment was newly developed in the present study. This is a coupled model of non-hydrostatic dynamical framework and spectral bin microphysics cloud scheme. Non-hydrostatic dynamics was chosen for explicitly calculating updraft velocity, which is important in the formation of cloud and rain. Since the aim of this study is an investigation of aerosol effect on cloud microphysics, spectral bin method was used for explicitly calculating a particle growth process. We consider several types of particles, i.e., aerosol, liquid droplet, ice crystals, snowflake, graupel and hail, and explicitly predict the size distribution functions (SDF) of these particles by taking into account the microphysical processes responsible for the change of SDFs. Aerosol and cloud particles are interacting through the nucleation and wash out processes. Nucleation is based on Kohler theory and the wash-out is calculated from collision between aerosol and water droplet. The latent heat release through the change of SDFs due to condensation, evaporation and sublimation causes a feedback on dynamics and SDFs are modified by advection with wind field from dynamical process.

Numerical experiment was performed with this model in two-dimensional computational domain of 20km in horizontal and 4km in vertical. The resolution was horizontally 500m and vertically 200m. We set an initial profile of temperature and humidity which is conditionally unstable in lower layer (0-2km in height) with inversion layer in upper layer (2-4km in height) for forming a low cloud, which is known to be most effectively modified by aerosols. The warm bubble was initially located to trigger a convection. We get a cycle of cloud and drizzle formation in this simple experiment.

3. Result

3.1. Correlation between cloud effective radius and optical thickness

The result of the numerical experiment mentioned in previous section was analyzed from a viewpoint of cloud optical property such as cloud particle effective radius and optical thickness. These two properties have been retrieved from satellite remote sensing and the correlation pattern between them is known to have remarkable characteristics related to cloud lifecycle (Nakajima and Nakajima, 1995). Cloud optical thickness is positively correlated with effective particle radius at no-drizzle stage, illustrating that the cloud water increases with the grow of cloud particles. On the contrary, cloud optical thickness is negatively correlated with effective radius in drizzling stage, implying a decrease of cloud water due to a conversion into drizzle-sized particles with the grow of particles. These two correlations are combined to form a triangular pattern as schematically shown in Fig.1, which illustrates a microphysical lifecycle of cloud.

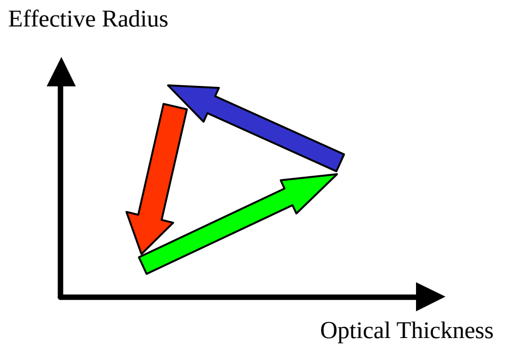

Fig.1. Schematic diagram of effective radius and optical thickness over cloud lifecycle. Green, blue and red arrow corresponds to the cloud regime of before drizzling, drizzling and after drizling, respectively.

We made a similar scatterplot between effective radius and optical thickness also from the result of model calculation as shown in Fig.2. The upper panel of Fig.2 shows a simulated correlation over whole lifecycle of the cloud, which is composed by two branches of positive and negative correlation. Positive and negative correlation branch represents a cloud regime before drizzling and drizzling, respectively. The lower panel of Fig.2 shows a correlation for the case of simulation without collision-coagulation process. It is found that only positive correlation branch appeared when the collision-coagulation process was removed from the simulation because the drizzle particles are not formed.

Sensitivity experiment to change aerosol amount was also performed for investigating the impact of aerosol on the correlation pattern, and the result is shown in Fig.3. The increase in aerosol amount causes more abundant cloud particles, which in turn reduces the supersaturation due to the consumption of water vapor by condensational growth of the particles. The decrease in supersaturation delays the condensational growth of particles and thus the cloud tends to have smaller effective radius and to become optically thicker, resulting a modification of correlation pattern as shown in Fig.3. This result illustrates the effect of aerosols on cloud microphysical lifecycle.

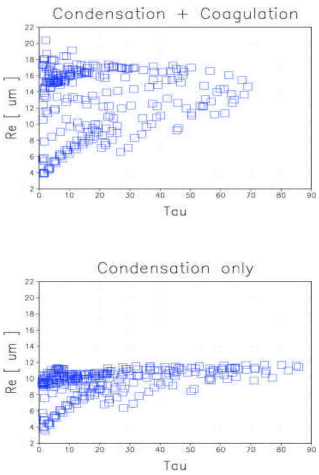

Fig.2. Scatterplot of effective radius and optical thickness obtained from simulation with (upper) and without (lower) collision-coagulation process.

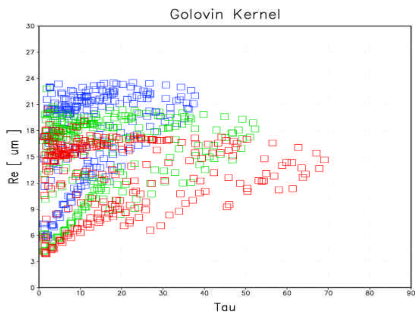

Fig.3. Scatterplot of effective radius and optical thickness obtained from simulation with different aerosol amount (blue: clean, green: modest, red: polluted).

3.2. Sensitivity of cloud properties to aerosol particle number

In previous subsection, the cloud microphysical lifecycle was found to be affected by aerosol amount as revealed by modification of correlation pattern between optical thickness and effective radius. This subsection is contributed to discussion on the sensitivity of cloud properties to aerosol particle number. Fig.4 shows a scatterplot of cloud effective radius r_e, optical thickness t_c, liquid water path *LWP* and column cloud particle number N_c as a function of column aerosol particle number N_a. Cloud effective radius and optical thickness is negatively and positively correlated with N_a, respectively. LWP tends to be independent of N_a for turbid air condition of $N_a > 10^{7.5}$ cm^{-2} because LWP is proportional to optical thickness multiplied by effective radius. Column cloud particle number N_c is increased with increasing N_a. These characteristics are qualitatively consistent with global statistics obtained from satellite observation. Cloud particle number N_c is roughly linear with aerosol particle number N_a following the relationship $N_c \propto N_a^k$. The exponent k represents a sensitivity of cloud property to aerosol amount. The value of exponent k was estimated to be 0.72 in the present simulation. This is close to those from past research Kaufman et al. (1991), which reported k=0.7-0.8 based on observational analysis of biomass burning event. Global statistics obtained from satellite observation (Nakajima et al., 2001) reported somewhat smaller sensitivity as k=0.50 because various types of clouds are included in global analysis and thus the signal of aerosol indirect effect is diluted.

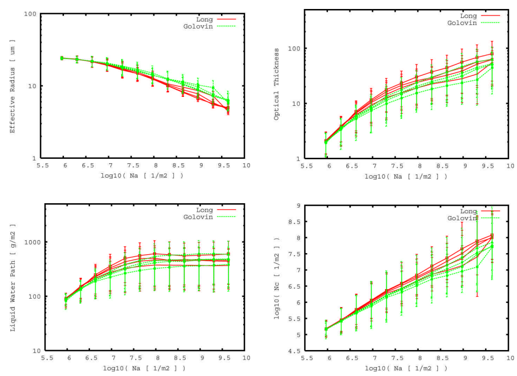

Fig.4. Scatterplot of cloud effective radius, optical thickness, liquid water path and column cloud particle number as a function of column aerosol particle number obtained from the simulation. Different colors (red and green) show the results with different function for collision efficiency between particles. Several lines within a same color show the results under different dynamical stability condition.

4. Conclusion

In the present study, non-hydrostatic spectral microphysics cloud model was developed and the numerical experiment was performed for the formation of water clouds in lower layer of 1-2 km height. Correlation pattern between cloud optical thickness and effective radius was simulated to be similar to those obtained from satellite observation. Cloud optical thickness was found to be positively correlated with effective radius for no-drizzle clouds, contrary to negative correlation for drizzling clouds. The correlation pattern was simulated to be sensitive to aerosol amount. The simulated sensitivity of cloud properties to aerosol particle number was also found to be qualitatively consistent with satellite observation. Quantitative comparison of the sensitivity implied that the global statistics from satellite observation estimated somewhat smaller dependence of cloud on aerosol amount due to the mixture of various cloud types.

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