論文内容の要旨

論文題目 **Development of a two-moment bulk cloud microphysics scheme for a non-hydrostatic atmospheric model and its application to study the cloud optical properties**

(非静力学モデルにおける２モーメント法雲微物理モデルの開発と雲の光学特性に関する研究)

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Past many researchers have made effort to reduce the uncertainties of climate change prediction and reached a recognition that the uncertainties are strongly related with the cloud radiative forcing (CRF). With such a background, Non-hydrostatic ICosahedral Atmospheric Model (NICAM), a global cloud resolving model, has been developed in order to solve the problem of organization of mesoscale convective cloud systems which have never been simulated by conventional general circulation models (GCMs). In contrast to the satisfactory simulations of cloud dynamics, however, several questions regarding suitability of the simulated cloud microphysical conditions have been raised, mainly from the climate community who is facing at the problem of accurate simulation of the radiative characteristics of the cloud system, especially simulation of the cloud radiative forcing, which strongly depends on the cloud microphysical parameterization adopted in numerical models.

In this study we newly developed a two-moment bulk cloud microphysics scheme

(NDW6) based on the formulae of Seifert and Beheng (2006a). This microphysical scheme is expected to be more realistic than the one moment bulk cloud microphysics scheme adopted in the original NICAM. In addition we elaborated the radiative transfer model to be compatible with the size distribution of cloud particles introduced by the two moment cloud microphysics scheme. We also implemented non-spherical scattering optical properties of ice particles proposed by Fu (1996), and Fu et al. (1998). This cloud microphysics scheme thus developed ensures better signal simulation of space-borne optical sensors that provide important information for validating the simulated global cloud microphysical properties.

After development of NDW6, we performed numerical simulations by using NDW6 in three ways. Firstly, we studied how the cloud microphysical parameterizations used in NDW6 to affect the CRF and surface precipitation in a tropical squall line which cannot be studied by conventional GCMs of their coarse spatial resolution. Secondly, we evaluated the accuracy of the simulated prognostic variables and radiation fluxes by using microphysical observation data from a video-sonde and a radiometer-sonde. Finally, we compared statistically the simulated cloud optical properties with data from several space-borne optical sensors taking advantages of the two moment bulk scheme that can simulate the cloud optical thickness and effective particle radius. Through these experiments, we obtained the following insights regarding the several important cloud microphysical processes that affect the cloud formation.

Contribution of large precipitating particles, especially aggregates of ice crystals, cannot be neglected in the computation of CRF, though these are neglected in most of GCMs. Moreover, use of prescribed effective radii in the radiative transfer model caused significant differences up to about 50 % in shortwave (SW) CRF, and about 20 % in longwave (LW) CRF in the tropical squall line case. In particular, the relative differences are remarkable for optically thin clouds.

The sensitivity experiments demonstrated several pathways of feedback mechanisms in the cloud formation process in the tropical squall line case. Rapid condensation by supply of CCN invigorates the cloud convective system due to latent heat release as well as increase of freezing liquid droplets by increase of CCN as also suggested by past researchers. It was also found that application of the saturation adjustment scheme overestimates the condensation growth of hydrometeors. Consequently, secondary cloud growth via ice phase process causes a noticable decrease in the cloud fraction, and also in CRF. Reduction of the cloud fraction of anvil cirrus was then explained by significant scavenging of ice water content (IWC) and liquid water content (LWC) by rain and graupel. The growth rate of liquid droplets and their terminal velocity can control the balance between scavenging rate and the degree of invigoration because the invigoration of convection via ice phase process depends on the total amount of liquid droplets lifted up to the freezing level. This delicate balance between scavenging rate and the intensity of invigoration was also found to be significantly dependent on the treatment of terminal velocity of hydrometeors. We confirmed this point by the fact that an introduction of the diagnosis method of the third moment of the droplet size distribution of rain droplets changed the balance through modification of the terminal velocity of rain. By the combination of several mechanisms as explained above, it was also suggested that the one-moment cloud microphysics scheme adopted in the original NICAM produces too much intensive surface precipitation and hence underestimates the area of anvil cirrus and their CRF.

Introduction of the non-spherical scattering model resulted in a significant improvement of the vertical radiation fluxes profiles compared with an observation by the radiometer sonde. The impact of improvement on outgoing longwave radiation flux at TOA was about 10 Wm^{-2}, and outgoing shortwave radiation flux at TOA was about 20 Wm^{-2} during daytime over the Baiu front. We need a future validation study of the number concentration of ice particles to evaluate the accuracy of the simulated cloud radiative forcing quantitatively.

It was found that radar echo signals around the freezing level were well represented by NDW6. This result suggested that the various growth processes of rain droplets in the convective core, such as warm phase collection, riming between rain and graupel, and graupel formation by freezing were adequately simulated in NDW6. On the other hand, it was found that the simulated vertical profiles of the radar echo signals of deep convective clouds are affected by the shape of ice crystals assumed in the model. In global simulations, the shape of ice crystals must be suitably assumed depending on the geographical location and thermodynamical conditions. Thus, we need to carry out future studies of the global distribution of dominant ice crystal shapes and number concentrations.

As a summary of the present study, the new two-moment bulk cloud microphysics scheme, NDW6, is found to be accurate enough to provide realistic numerical simulations that help understanding the various feedback mechanisms to affect the formation process of cloud systems and their radiative properties.