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MULTI-SENSOR ANALYSIS OF A-TRAIN OBSERVATIONS FOR INVESTIGATING THE WARM CLOUD MICROPHYSICAL PROCESSES

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1. INTRODUCTION

Warm cloud microphysics is an important process that determines how the liquid precipitation takes place and also controls the optical properties of liquid clouds. The launch of CloudSat on April 2006 brought new observations of clouds with Cloud Profiling Radar (CPR) operating at 94 GHz, providing a first global observation of vertical cloud structure (Stephens et al., 2008). The CloudSat also flies as part of the A-Train satellite constellation that includes various active and passive sensors (Stephens et al., 2002). The new A-Train satellite measurement system offers a unique opportunity to simultaneously observe various aspects of cloud-to-precipitation processes.

Also important for studying cloud microphysics is an emergence of a global cloud-resolving model NICAM (Nonhydrostatic ICosahedral Atmospheric Model) developed by Tomita and Satoh (2004) and Satoh et al. (2008). The NICAM model has recently been implemented with an aerosol transport model SPRINTARS (Spectral Radiation-Transport Model for Aerosol Species; Takemura et al., 2000) for simulating the aerosol-cloud interactions with resolutions of several kilometers on the global scale (Suzuki et al., 2008). This NICAM-SPRINTARS model has been demonstrated to reproduce several key characteristics of warm cloud properties and their interactions with aerosols. This includes a detailed spatial pattern of cloud droplet radius over the tropics, global correlation statistics of liquid water path with aerosol index and vertical growth pattern of cloud particles (Suzuki et al., 2008). These comparisons highlight the new capability of studying the cloud microphysics with synergistic use of satellite observations and cloud-resolving models.

In this paper, we report our recent studies that combine different sensors of the A-Train to

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investigate several key aspects of the warm rain formation processes, and demonstrate how the new CloudSat and A-Train observations can be used for obtaining new insights into warm cloud microphysics. We also discuss how these new observational analyses can be employed for evaluating the cloud-resolving models in terms of cloud microphysics parameterizations.

2. CLOUD-TO-RAIN CONVERSION

The cloud-to-rain formation process is characterized by conversion from cloud water to rain water. Stephens and Haynes (2007) examined this conversion process with combined use of CloudSat and MODIS included in the A-Train. They estimated the coalescence rate from the MODIS-derived liquid water path and CloudSat-observed radar reflectivity based on a theoretical consideration of continuous collection model for cloud droplets. They found that the CloudSat-observed radar reflectivity Z_e is inversely proportional to the time scale τ_p of warm rain formation, i.e. $\tau_p \sim Z_e^{-1.0}$, within their theoretical framework which assumed that the collection kernel function is proportional to six power of particle radius as suggested by a classical literature of cloud physics (Long, 1974).

Their finding was further investigated by Suzuki and Stephens (2009a) in the context of a global cloud-resolving model, NICAM, based on cloud physics parameterizations in which the collection kernel depends on particle radius in a manner different from Long (1974). Suzuki and Stephens (2009a) analyzed the cloud physics parameterization of the NICAM model, and found that the rain formation time-scale is closely related with radar reflectivity as $\tau_p \sim Z_e^{-0.51}$. Although this relationship is somewhat different from that suggested by Stephens and Haynes (2007), this finding implies that the radar reflectivity is a gross measure of the time-scale for warm rain formation.

This implication for the time scale from radar reflectivity provides a way of comparing the water conversion process of the model against the CloudSat observations. The comparison indeed shows a systematic difference in radar reflectivity and thus in time scale of warm rain formation (Suzuki and Stephens, 2009a). According to the analysis of cloud physics parameterizations, this difference suggests a systematic bias regarding the cloud-rain water composition in the model that leads to a more rapid conversion from cloud water to rain water compared to reality. This result points to a possible area of model improvement in terms of warm rain formation processes.

3. PARTICLE GROWTH PROCESSES

From the microphysical point of view, the warm rain formation takes place through growth processes of liquid particles. The liquid cloud particles are considered to grow through condensation process for early stage of cloud development and through coagulation in mature stages especially with significant concentrations of drizzle particles.

These particle growth processes are detected by A-Train observations with combined analysis of radar reflectivity and effective particle radius (Suzuki and Stephens, 2008). The radar reflectivity Z_e, which is defined as sixth moment of size distribution function, theoretically relates to effective particle radius

R_e through six-power relationship for a constant number concentration and through cubic relationship under the condition of constant mass concentration. The former condition tends to take place when the condensation particle growth process is dominant because the condensation process conserves the number concentration. The latter relationship tends to occur when the coagulation process controls the particle growth, where total mass concentration tends to be conserved.

Suzuki et al. (2008) showed that these relationships are indeed found in seasonally averaged joint analysis of the CloudSat-observed radar reflectivity Z_e and the columnar effective radius R_e obtained from MODIS optical depth and AMSR-E liquid water path with the method of Masunaga et al. (2002). The sixth power and cubic relationships are found for Z_e smaller and larger than about -10dBZ, respectively. This result suggests that the condensation and coagulation processes indeed occur in real atmosphere on the global and seasonal scales.

The corresponding statistics can also be constructed using the output of numerical cloud models such as Regional Atmospheric Modeling System (RAMS; van den Heever et al., 2009) as well as NICAM for examining how the models represent these microphysical processes. Such comparisons would provide a more direct evaluation of the cloud physics parameterizations than have been attempted.

4. DROP COLLECTION PROCESS

The information of vertical cloud profile provided by CloudSat also offers an insight into how the drop collection process takes place in vertical direction. Drizzling clouds subject to collection processes typically have reflectivity profiles with a minimum value near the cloud top and a maximum value in lower levels. This vertical change in radar reflectivity can be interpreted as induced by the collection of cloud droplets represented by MODIS-derived liquid water path. Suzuki and Stephens (2009b) constructed a theoretical relationship between these observables based on a simple continuous collection model for investigating how the drop collection process occurs in real clouds. This model involves the collection efficiency factor, which is then inferred from these observations by exploiting the differing sensitivities of these sensors to cloud particle sizes. This study shows that the inferred collection efficiency factor ranges from the order of 0.001 to that of 1.0 and tends to increase with particle radius in a manner similar to classical relationships suggested by Long (1974). These results suggest that the inferred collection efficiencies are a gross measure of real collection efficiency and that the drop collection model appears to explain the vertical change in radar reflectivity.

The CloudSat-observed vertical cloud profiles are also combined with MODIS shortwave analysis as demonstrated by Nakajima et al. (2009a,b). They suggested a new type of diagram called CFODD (Contoured Frequency Optical Depth Diagram) that describes vertical structure of warm clouds using layered optical depth as a vertical axis and shows the normalized frequency of radar reflectivity for each layer of optical depth. Unlike the traditional CFAD (Contoured Frequency Altitude Diagram) based on geometric altitudes taken as vertical axis, the

CFODD describes the vertical profile of radar reflectivity in a manner that stretches lower levels with the weigh of optical thickness. The CFODD can therefore focus on change in radar reflectivity within lower cloud layers where the cloud-to-rain formation process mainly occurs. Nakajima et al. (2009a,b) indeed demonstrated that the CFODD conveniently describes how the particle growth processes take place in vertical direction within the cloud layer. They also showed that the growth patterns dictated in CFODDs systematically change with effective radius retrieved from MODIS 2.1μm radiances. Such combined analysis will help understand how the effective radii derived from several wavelengths of MODIS link to the vertical particle growth processes.

5. CONCLUSION

This paper highlighted our recent studies of warm cloud microphysics using the CloudSat and the A-Train multi-sensor satellite observations and their comparisons with numerical cloud models. This includes a use of CloudSat-observed radar reflectivity to infer the time scale of warm rain formation, a diagnosis of cloud particle growth process with a combined analysis of A-Train different sensors and an analysis of radar reflectivity profiles of CloudSat in terms of drop collection processes. The comparisons between A-Train observational analysis and the models provide a new way of evaluating the cloud physics parameterizations in the models.

References

Long, A. B., 1974: Solutions to the droplet collection equation for polynomial kernels. *J. Atmos. Sci.*, **31**, 1040-1052.

Masunaga, H., T. Y. Nakajima, T. Nakajima, M. Kachi, R. Oki, and S. Kuroda, 2002: Physical properties of maritime low clouds as retrieved by combined use of Tropical Rainfall Measuring Mission Microwave Imager and Visible/Infrared Scanner. 1. Algorithm. *J. Geophys. Res.*, **107(D19)**, 10.1029/2001JD000743.

Nakajima, T. Y., K. Suzuki, G. L. Stephens, 2009a: Droplet growth in warm water clouds observed by the A-Train. Part I: Sensitivity analysis of the MODIS-derived cloud droplet sizes, *J. Atmos. Sci.*, submitted.

Nakajima, T. Y., K. Suzuki, G. L. Stephens, 2009b: Droplet growth in warm water clouds observed by the A-Train. Part II: Data analyses and comprehensive discussions, *J. Atmos. Sci.*, submitted.

Rogers, R. R., and M. K. Yau, 1989: A short course in cloud physics. Third edition, Pergamon Press, 293pp.

Satoh, M., et al., 2008: Non-hydrostatic Icosahedral Atmospheric Model (NICAM) for global cloud resolving simulations, *J. Comp. Phys.*, **227**, 3486-3514.

Stephens, G. L., et al., 2002: The CloudSat and the A-Train, *Bull. Am. Meteorol. Soc.*, **83**, 1771-1790.

Stephens, G. L., et al., 2008: The CloudSat mission: performance and early science after the first year of operation. *J. Geophys. Res.*, **113**, D00A18, doi:10.1029/2008JD009982.

Stephens, G. L., and J. M. Haynes, 2007: Near global observations of the warm rain coalescence process, *Geophys. Res. Lett.*, **34**, L20805. doi:10.1029/2007GL030259.

Suzuki, K., T. Nakajima, M. Satoh, H. Tomita, T. Takemura, T. Y. Nakajima, and G. L. Stephens, 2008: Global cloud-system-resolving simulation of aerosol effect on warm clouds, *Geophys. Res. Lett.*, **35**, L19817, doi:10.1029/2008GL035449.

Suzuki, K., and G. L. Stephens, 2008: Global identification of warm cloud microphysics with combined use of A-Train observations. *Geophys. Res. Lett.*, **35**, L08805, doi:10.1029/2008GL033590.

Suzuki, K., and G. L. Stephens, 2009a: Relationship between radar reflectivity and the time scale of warm rain formation in a global cloud-resolving model. *Atmos. Res.*, **92**, 411-419.

Suzuki, K., and G. L. Stephens, 2009b: A possible use of multi-sensor satellite observations for inferring the drop collection efficiency of warm clouds. *SOLA*, **5**, 125-128.

Takemura, T., H. Okamoto, Y. Maruyama, A. Numaguti, A. Higurashi, and T. Nakajima, 2000: Global three dimensional simulation of aerosol optical thickness distribution of various origins. *J. Geophys. Res.*, **105**, 17853-17873.

Tomita, H., and M. Satoh, 2004: A new dynamical framework of nonhydrostatic global model using the icosahedral grid. *Fluid. Dyn. Res.*, **34**, 357-400.

Van den Heever, S. C., G. L. Stephens, and N. B. Wood, 2009: The impacts of enhanced cloud condensation nuclei concentrations on tropical convection characteristics under conditions of radiative convective equilibrium. *J. Atmos. Sci.*, submitted.