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Toward Direct Uses of Satellite Cloudy Radiances in NWP Models. Part II: Radiance Simulations at Microwave Frequencies

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1. INTRODUCTION

Clouds play an important role in regulating global hydrological and energy cycles. However, satellite cloudy radiances are rarely used in the data assimilation system because of uncertainty in cloud properties predicted by numerical weather prediction models. This study will investigate this uncertainty by simulating satellite radiances using a cloud resolving model and comparing model results with the measurements from the satellite microwave sensors. The relationship between surface rainfall and cloud microphysics and the impacts of hydrometeor convergence on quantitative precipitation estimate and forecast and satellite retrievals of surface rain rate will be discussed.

2. SENSIVITY OF CLOUD HYDROMETEOR AND ASSOCIATED RADIANCES TO CLOUD MICROPHYSICS

The 2-D cloud resolving model includes prognostic equations for cloud hydrometeors, cloud microphysics and radiation parameterization schemes (Li et al. 1999, 2002b). The model has been demonstrated to simulate tropical thermodynamic states and surface fluxes and rain rates well during the Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiments (TOGA-COARE).

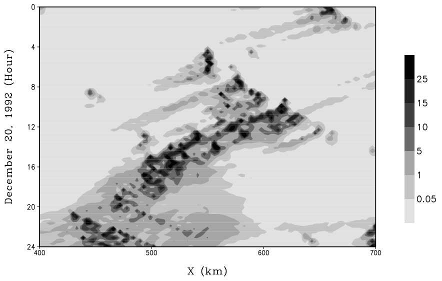

Fig. 1 Time evolution and zonal distribution of surface rain rate (mmh^{-1}) on December 20, 1992 as simulated by cloud resolving model.

Figure 1 shows the time evolution and horizontal distribution of surface rain rate on 20 December 1992. The rainbands propagate westward before hour 20 and they then start to propagate eastward. The change of moving direction of the rainbands results from intensification of lower-tropospheric westerly winds and weakening of mid-tropospheric easterly winds (Li et al. 1999).

A microwave radiative transfer model that includes scattering and polarization developed by Liu and Weng (2002) is applied to compute the radiances at AMSU frequencies and bandwidths based on thermodynamic profiles and cloud information derived from the cloud simulations. Figure 2 shows the pairs of brightness temperatures in simulations and observations. The simulations and observations display the similar slopes of the each pair of brightness temperatures, indicating the capability of simulating cloud structures by the cloud resolving model. However, the amplitude variations show the differences between simulations and observations.

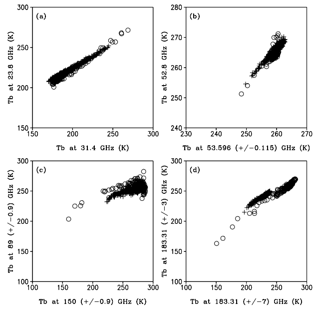

Fig. 2(a) Brightness temperature Tb at AMSU-A Channel 1 (23.8 GHz) versus Channel 2 (31.4 GHz), (b) Tb at AMSU-A Channel 4 (52.8 GHz) versus Channel 5 [53.596 (+/-0.115) GHz), (c) Tb at AMSU-B Channel 16 [89 (+/-0.9) GHz] versus Channel 17 [150 (+/-0.9) GHz], and (d) Tb at AMSU-B Channel 19 [183.31 (+/-3) GHz] versus Channel 20 [183.31 (+/-7) GHz]. The dots represent the observations over (10^oS-10^oN, 140^oE-180^o) from NOAA-15 and 16 satellites in selected days of year 2001, whereas the crosses denote the simulations from microwave radiative transfer model developed by Weng and Liu (2002). The simulations use cloud information from the 2-D cloud radiative simulation from 2200 LT 19 December-1000 LT 21 December 1992. The simulation data are averaged in 32 grid points (48 km-mean), which is similar to the horizontal resolution of AMSU observation at nadir. All data are obtained in cloudy condition in which vertically integrated cloud water is larger than 0.1 mm.

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Figure 3a shows 36-h and domain mean cloud microphysics budget simulated with the accretion of snow by graupel (P_{GACS}) included, whose data are used to simulate radiances in Fig. 2. The vapor condensation rate (P_{CND}: 0.83 mmh^{-1}) is a major source for development of clouds and precipitation. Most of the conversion of cloud water to precipitation occurs primarily through two mechanisms, depending on the temperature when they occurs: through riming of cloud water onto precipitation ice (snow and graupel) ($P_{SACW} + P_{GACW}$: 0.26 mmh^{-1}) at colder than 0^oC and collection of cloud water by rain at warmer temperatures (P_{RACW}: 0.55 mmh^{-1}). The melting of graupel (P_{GMLT}: 0.4 mmh^{-1}) and vapor deposition (P_{DEP}: 0.14 mmh^{-1}) become important in producing rain and ice clouds, respectively (see discussions in Li et al. 2002b).

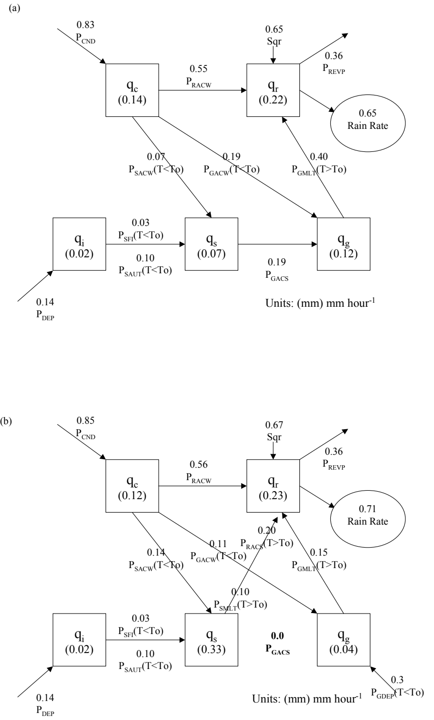

Fig. 3 36-h and domain mean cloud microphysics budgets simulated (a) with P_{GACS} and (b) without P_{GACS} .

The mean cloud microphysics budget (Fig. 3a) reveals that the accretion of snow by graupel (P_{GACS}: 0.19 mmh^{-1}) is as important as the riming of cloud water by graupel (P_{GACW}: 0.19 mmh^{-1}). The P_{GACS} is a strong function of the assumed accretion efficiency of snow by graupel, which is not well known. Thus, this term is set to be zero or very small (e.g., Zeigler 1985; Ferrier et al. 1995), because it is hard to argue that a snowflake colliding with a graupel particle will stick to the graupel. Therefore, an additional experiments with P_{GACS} excluded is carried out (Fig. 3b). The vapor condensation and deposition rates (P_{CND} and P_{DEP}) in the two experiments are similar. The liquid water paths (LWP=qc+qr) in the two experiments are about the same, whereas the ice water path (LWP=qi+qs+qg) in the experiment without $_{PGACS}$ (0.39 mm) is much larger than that in the experiment with P_{GACS} (0.21 mm). Compared to the experiment with P_{GACS}, the mixing ratio of graupel decreases significantly, whereas the mixing ratio of snow increases significantly and becomes the major component of ice clouds. The accretion of snow by rain (P_{RACS}: 0.2 mmh^{-1}) and the melting of snow (P_{SMLT}: 0.1 mmh^{-1}) replacing the melting of graupel become the major sources in the rain budget.

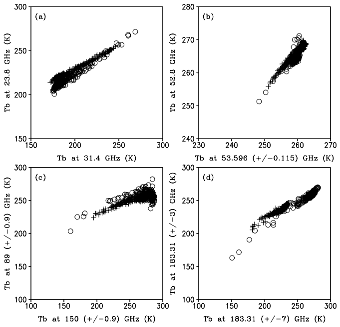

Fig. 4 As in Fig. 2 except for the experiment without P_{GACS}.

Figure 4 shows the pairs of brightness temperatures in observations and simulations without P_{GACS}. The variations of radiances in the experiment without P_{GACS} are closer to the observations than those in the experiment with P_{GACS} (Fig. 2). The signals are much significant in AMSU channels 16 and 17 because of significant variations of ice clouds. The comparison between simulations and observations suggests that the P_{GACS} suppress the development of precipitation ice unrealistically.

3. RELATION BETWEEN SURFACE RAIN RATE AND CLOUD MICROPHYSICS

Cloud microphysics parameterization is one of most important parts in numerical modeling. Li et al. (2002c) showed that the local changes of mass-weighted mean temperature and column-integrated moisture are mainly determined by the residuals between vertical thermal advection and latent heat of condensation and between vertical moisture advection and precipitation respectively. Their error analysis further indicates that the error of the local thermal and moisture changes could be 5-10 times larger than the errors introduced by the cloud microphysics parameterization. Thus, accuracy of cloud microphysics parameterization is fundamentally important in predicting climate changes.

The rates of cloud microphysical processes cannot be directly measured due to technical difficulty. Thus, the relationship between cloud microphysics and some parameters that can be measured in observations such as precipitation should be established. In tropical convective area, heavy rainfall occurs, mainly contributed by raindrop (qr). Thus, the collection of cloud water by rain (P_{RACW}) is the dominant microphysical process responsible for tropical convective rainfall. In tropical stratiform area, ice clouds should be dominant, and the stratiform rain rate should be mainly determined by the conversion from ice clouds to water clouds. These relations can be proved by Figure 5 that shows the good linear relations between surface rain rate and the collection rate of cloud water by rain (P_{RACW}) in convective area and between surface rain rate and the melting rate of graupel (P_{GMLT}) in stratiform area in the experiment with P_{GACS}, indicating that the two dominant cloud microphysical processes can be estimated when reliable precipitation type/rate are available from satellite retrievals.

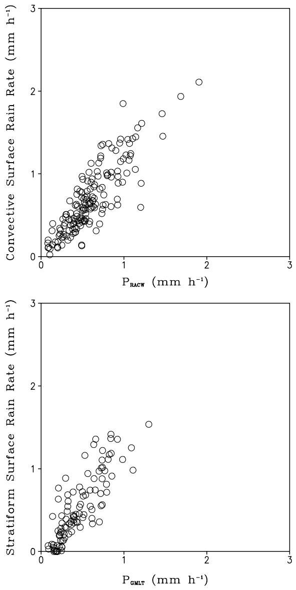

Fig. 5 convective surface rain rate versus the collection rate of cloud water by rain in upper panel and stratiform surface rain rate versus the melting rate of graupel. Unit is mm h^{-1}.

Note that a mean is taken over the area that contains an individual cloud in the calculations in Fig. 5. When the cloud calculations are carried out within the clouds, cloud hydrometeor advection needs to be counted. Sui and Li (2002) calculated cloud microphysics precipitation efficiency (CMPE) as the ratio of surface rain rate to the sum of vapor condensation and deposition rates (Li et al. 2002a) and found that CMPE could be larger than 100% as a result of hydrometeor convergence from the neighboring atmospheric columns. This suggests that a part of surface rain rate could come from the hydrometeor advection from the surroundings. Thus, the surface rain rate can be overestimated or underestimated if the hydrometeor convergence is neglected.

Figure 6 shows difference between surface rain rate (SRR) and raindrop source (Sqr) versus surface rain rate. The difference is mainly due to hydrometeor advection. The hydrometeor convergence has the same order of magnitude as surface rain rate in light rainfall area (SRR<5 mm h^{-1} for 96 and 48 km mean data, and SRR<10 mm h^{-1} for 24 km mean data), indicating the important impacts of hydrometeor convergence on quantitative precipitation estimate and forecast in stratiform rainfall region. There is no clear relation between hydrometeor convergence and the strength of rainfall, which increases technical difficulty for the physically based retrievals of satellite measurements if retrievals are carried out within the clouds.

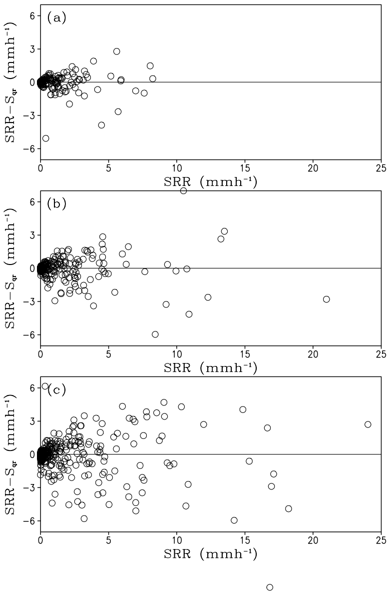

Fig. 6 Difference between surface rain rate (SRR) minus raindrop source (Sqr) versus SRR calculated from (a) 96 km, (b) 48 km and (c) 24 km mean simulation data. Unit is mmh^{-1}.

4. Summary

This paper investigates the sensitivity of cloud hydrometeor and associated microwave radiances to cloud microphysics based on the microwave radiative transfer simulations with the cloud resolving model outputs simulated during TOGA COARE. The sensitivity of cloud microphyscis is selective in different microwave channels due to differences in optical properties. The comparison between simulated and observed radiances suggests that the satellite-measured radiances can be used as the reference for improvement of cloud microphysics parameterization schemes.

The analysis of cloud simulation data shows the dominant cloud microphysical processes associated with convective and stratiform precipitating clouds in which the collection of cloud water by rain and melting of graupel are responsible for convective and stratiform rainfall respectively if each individual cloud is considered.

When the cloud microphysics budgets are calculated within clouds, cloud hydrometeor convergence needs to be considered, in particular, in tropical stratiform rainfall region. However, there is no clear relation between the strength of hydrometeor convergence and strength of cloud systems. Since hydrometeor convergence is related to surrounding parameters such as the wind speed, direction and the gradient of hydrometeors, the hydrometeor convergence increases difficulty of physically based retrievals of surface rain rate using satellite measurements.

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