JP4.3 SIMULATIONS OF THE VISIBLE AND NEAR-INFRARED RADIATIVE PROPERTIES OF MIXED-PHASED STRATOCUMULUS CLOUD OVER THE SEA

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1. INTRODUCTION

Low-level boundary-layer clouds are important components of Earth's climate system due to their effects on the radiation budget. Many studies on the cloud-radiation interaction often assume that low-level clouds are in liquid phase. In reality, however, low-level clouds are often partially glaciated or of mixed-phase. Unfortunately, both microphysical and radiative properties of such mixed-phased clouds are not completely understood, because simultaneous observations were still insufficient.

An intensive aircraft field observation of clouds and radiation was conducted by the Meteorological Research Institute (MRI) within the Japanese Cloud and Climate Study (JACCS) program (Asano et al. 1994). In JACCS program, wintertime boundary-layer clouds over the sea around Japan were observed in January 1999. By using two instrumented aircraft, the microphysical and radiative properties of mixed-phase stratiform cloud have been simultaneously measured. The stratocumulus cloud observed on January 30 was highly heterogeneous vertically and horizontally with different mixing ratios of water droplets and ice particles. In this study, we made simulation calculations of the radiative properties for cloud models based on the measured cloud parameters.

2. OBSERVATIONAL RESULTS

Here, we briefly show the JACCS observational results of mixed-phase cloud over the Japan Sea observed on January 30, 1999. The mixed-phase cloud was observed in an area of 50km x 50km centered at 35.9°N and 135.4°E. More detailed description of the results can be found in Gayet et al. (2002) for cloud microphysics and in Asano et al. (2002) for radiative properties. Further, Asano et al. (2000) gives the detailed information of the radiometers and microphysical probes installed on the two aircraft of Cessna 404 Titan aircraft (abbreviated as C404 hereafter) and Beechcraft B200 Super King Air (abbreviated as B200 hereafter).

Flight paths are based on a 'L-pattern'; one of the 'L'-shape legs was flown along longitude (north-south direction), and the other along latitude (east-west direction). Synchronized and collocated level flight by the two aircraft, flying respectively above and below the cloud layer with almost same distances from the cloud top and bottom, was conducted for measuring the cloud radiation budgets. Before and after radiation budgets menu, in-situ cloud survey by B200 and remote sensing from C404, flying in (B200) and above (C404) the cloud layer were conducted.

On January 30, the cloud-top was observed at about 2.3km from the sea surface with temperature around -15°C, and the cloud-base was nearly at 1km with -7°C. Above the cloud top, the atmosphere was clear and dry. On the other hand, there were occasional snowfalls below the cloud layer. The cloud was in heavily mixed-phased condition and highly inhomogeneous both horizontally and vertically with different mixing ratios of liquid water droplets and ice particles. From the solar fluxes measured on C404 and B200, the radiative properties such as cloud reflectance, transmittance, and absorptance for the cloud-atmosphere column were evaluated by using the same method of Asano et al. (2000). On an average over flight legs, the mixed-phase cloud absorbed almost 0% and 24%, and reflected 75% and 62%, of the incident solar radiation in the visible (VIS; wavelength < 0.7 µm) and near-infrared (NIR; > 0.7µm) bands, respectively (Asano et al., 2002).

3. SIMULATIONS AND SENSITIVITY STUDY

(1) Simulation of the cloud radiative properties

Here we compare the JACCS observational results with theoretically simulated counterparts for modeled cloud layers. The solar radiation budget and the radiative properties have been computed for the assumed cloud-atmosphere column between the altitudes of 3.5km (C404) and 0.3km (B200). The entire solar spectral region between 0.3µm and 3.0µm was divided into 54 bands. Band-by-band radiative transfer calculations were carried out by employing the doubling-adding scheme. Gaseous absorption by water

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vapor, ozone, oxygen and carbon dioxide, as well as molecular scattering were taken into account. The temperature and humidity profiles measured through the aircraft experiment were employed up to 2.5km, and above 2.5km they were adjusted to the radiosonde profile measured at the JMA Yonago observatory (35.26°N, 133.21°E) on that morning. We included an isotropically reflecting sea surface with albedo of 0.06 in the VIS-band and 0.02 in the NIR-band. We have also taken into account aerosols by employing the optical properties for oceanic aerosols at 90% relative humidity but with the concentration profile measured by the PMS Passive Cabity Aerosol Scattering probe. Although the observed cloud layer was heavily inhomogeneous both horizontally and vertically, we assumed a plane-parallel cloud layer with mean values of the measured microphysical properties (Figure 1). In the figure, it is characteristic that a liquid-droplet-prevailing layer was observed in the cloud-top-layer, where ice water content was very small. In the radiative transfer scheme, the cloud layer was divided into 13 sub-layers from 1.0km to 2.3km. We also consider a snowfall region in the sub-cloud layer from 0.3km to 1.0km. The single-scattering properties of liquid water droplets and ice particles (including snowflakes) were calculated by Mie scattering theory assuming a lognormal size distribution and by anomalous diffraction theory with a modified-gamma size distribution (Mitchell et al. 1996), respectively.

Table 1 compares the simulated radiative properties for a pure liquid-water cloud and an ice cloud with the flight-leg-mean observed ones. Here the visible cloud optical thickness was adjusted to fit the simulated VIS-band reflectances to the observed value. In the VIS-band, we found almost no difference, exceeding the measurement accuracy of ±0.02, among the radiative properties, since the VIS reflectance was adjusted, and neither water droplets nor ice particles show appreciable absorption. On the other hand, in the NIR-band, the pure water cloud simulation overestimates the refectance and underestimates the absorptance, and vice versa for the ice cloud simulation. It is suggested that the mixed-phase cloud observed on January 30 had NIR-band reflectance and absorptance close to those of water cloud and ice cloud, respectively.

Table 2 shows the simulated radiative properties calculated with the flight-leg-mean observed microphysics values shown in Fig. 1, and also the visible cloud optical thickness was adjusted to fit the simulated VIS-band reflectances to the observed value. Here PP-model indicates plane-parallel cloud model; and IPA-model indicates cloud model of independent-

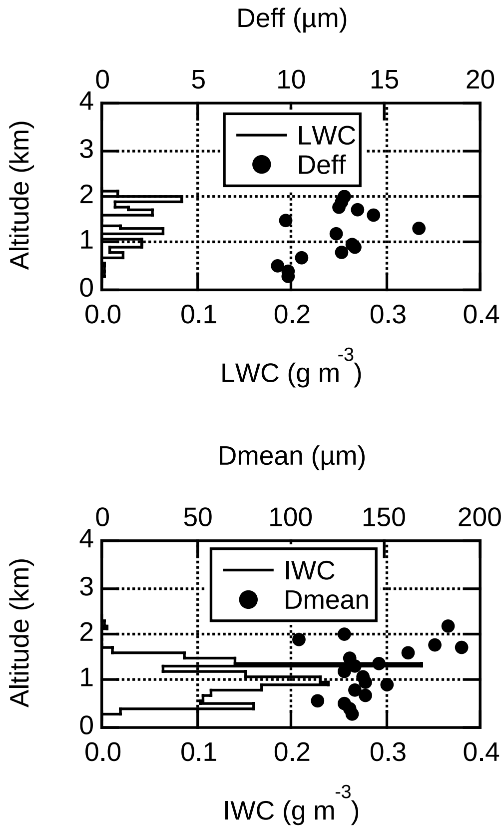

Fig. 1. Vertical profiles of averaged sizes and water contents of water droplets (top) and ice particles (bottom) measured on January 30.

		obs.	Water	Ice
VIS	R	0.754	0.754	0.754
	T	0.253	0.241	0.239
	A	-0.007	0.005	0.007
NIR	R	0.623	0.643	0.584
	T	0.140	0.159	0.172
	A	0.237	0.198	0.244

Table 1. Comparison of the measured and simulated VIS-band and NIR-band reflectance (R), transmittance (T), and absorptance (A), averaged over a long leg distance for the mixed-phase cloud.

pixel-approximation by using the frequency distribution of the cloud top heights along the legs. The cloud-top height distribution was derived from the cloud-top temperature distributions measured by the nadir-looking infrared thermometer onboard the C404 (Gayet et al., 2002). In IPA-model, liquid and ice water content of each cloud sub-layers were modified to agree its mean water content values include clear region with PP-model values (Figure 2). Although the IPA-model simulation gives slightly darker NIR reflectance than the PP-model simulation does, the both simulations agree well with each other. This means that uncertainties caused by cloud horizontal inhomogeneity are almost canceled out by taking an average over some long flight distance (about ~70km in this case). On the other hand, the simulation underestimates the observed absorptance in the NIR-band by amounts slightly exceeding the estimated measurement uncertainties. We considered the effect of net horizontal transport of radiation to be small, since the observed VIS-band absorptance was almost zero. This underestimation might be caused by the approximated calculation of the single scattering properties of ice particles and snowflakes. Also, it might be caused by changes of cloud microphysical properties during the time-intervals for the in-situ cloud survey menu and the radiation budget menu.

(2) Sensitivity study

Next, we have investigated the effect of the liquid-droplet-prevailing layer near the cloud-top on the radiative properties of mixed-phase clouds. Sensitivity study for the radiative properties of mixed-phase cloud with various vertical distribution of water droplet layers was conducted. Here the vertical profiles of ice particles was kept the same as the initial profile shown in Fig. 1 (bottom). With a fixed liquid water path, a single mixed-phase-layer model and a double mixed-phase-layer model are considered (Figure 3). In the double mixed-phase-layer model, one of the mixed-phase layers is fixed at the cloud bottom. The VIS-band radiative properties are not appreciably affected by vertical distribution of ice and water. On the other hand, the NIR-band radiative properties, shown in Figure 4, get closer to those of pure water clouds, as the mixed-phase layer is going up to the cloud-top. This result indicates vertical distribution of liquid-water droplets and ice particles are very important for the NIR-band radiative properties of mixed-phase clouds. In the present case, the maximum LWC layer detected at 2.0km (Fig. 1 top) could produce the relatively high NIR-band reflectance, and ice particles that dominated in the

		PP	IPA
VIS	R	0.754	0.754
	T	0.240	0.240
	A	0.006	0.006
NIR	R	0.622	0.619
	T	0.165	0.166
	A	0.213	0.215

Table 2. Comparison of the VIS-band and NIR-band radiative properties for plane-parallel cloud model (PP) and independent-cloud-approximation cloud model (IPA).

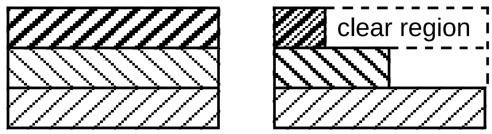

Fig. 2. Schematics of PP-model (left) and IPA-model (right). In IPA-model, liquid and ice water content of each cloud sub-layers were modified to agree its mean water content values include clear region with PP-model values.

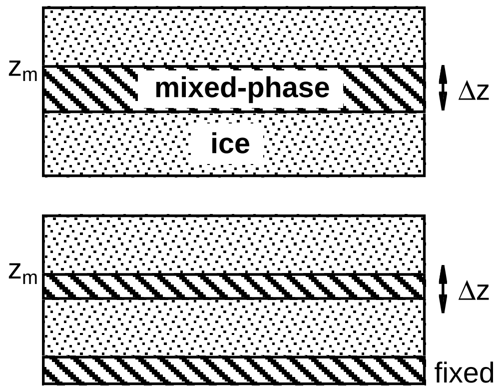

Fig. 3. Schematics of two models of vertical distribution of mixed-phased region. Top: single mixed-phase-layer model. Bottom: double mixed-phase-layer model.

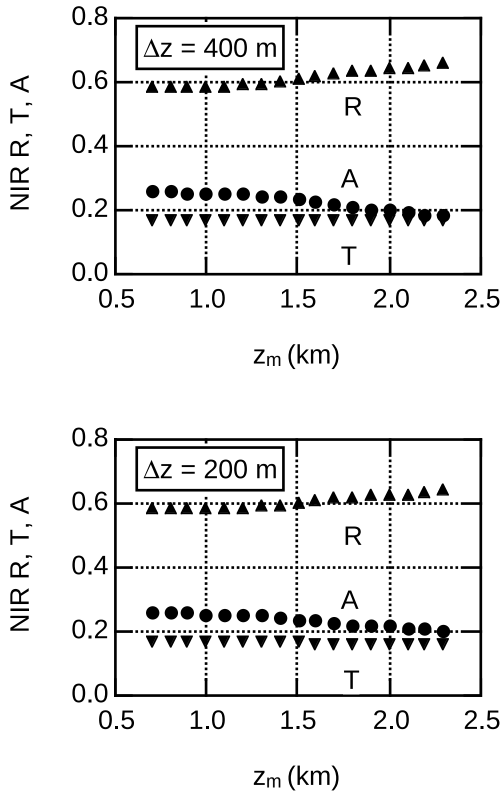

Fig. 4. Sensitivity of the NIR-band radiative properties to height of mixed-phased region. Top: single mixed-phase-layer model. Bottom: double mixed-phase-layer model.

lower part of cloud layer could contribute to the rather large absorptance. Thus, the observed mixed-phase cloud exhibits water-cloud-like reflectance and ice-cloud-like absorptance in the NIR-band.

The present study also suggests that suggested that retrieval of cloud microphysical parameters using reflectance in the VIS and NIR spectral region (Asano et al., 1995), under the assumption of a homogeneous pure liquid-water cloud, might overestimate effective diameter of water droplets. For instance, a homogeneous pure water cloud which has LWP = $300gm^{-2}$ with D_{eff} = 30µm could reproduce similar radiative properties to the observed ones both for the VIS and NIR-band.

4. SUMMARY

The principal findings in this study are as follows:

• In radiative transfer calculations, mixed-phase cloud can be considered as mixtures of independent scatterers of water droplets and ice particles.
• Uncertainties in the cloud radiative properties caused by cloud horizontal inhomogeneity can be reduced by taking an average over some long enough flight distances.
• The NIR-band radiative properties depend both on cloud optical thickness and vertical profiles of microphysical properties.
• The observed radiative properties showed water-cloud-like reflectance and ice-cloud-like absorptance in the NIR-band. This was caused from vertical distributions of water droplets and ice particles. In this case, the maximum LWC layer at 2.0km could produce relatively high reflectance, and ice particles dominated below that layer might produce high absorptance in the NIR-band.

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