MEASUREMENT OF MICROPHYSICAL AND RADIATIVE PROPERTIES OF STRATIFORM CLOUDS IN THE JAPANESE CLOUD-CLIMATE STUDY (JACCS) PROGRAM

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1. Introduction

The Japanese Cloud-Climate Study (JACCS) program is one of Japanese research efforts, sponsored by the Science and Technology Agency of the Japanese Government, focusing on the issues related to cloud-radiation interactions (Asano et al., 1994). The JACCS program has been operated from FY1991 through FY1999. Major scientific objectives of the JACCS program are (1) to advance our understanding of the relationships between cloud microphysical and macrophysical structures and the radiative properties of various midlatitude clouds, (2) to develop advanced use of satellite data in the cloud-climate study, and (3) to develop better parameterizations of radiation and cloud processes used in GCMs. About 40 researchers participate in the JACCS program mostly from the Meteorological Research Institute (MRI) and from three other national institutes.

The JACCS/MRI program involves such research activities as field experiments on cloud-radiation interactions, satellite data analyses, and the numerical modeling of radiation and cloud processes. Two types of field experiments have been conducted for various midlatitude clouds around Japan; one involves the ground-based observations (no direct aircraft measurement available) of ice clouds associated with midlatitude fronts in spring through early summer season (Asano et al., 1997). The other field experiment involves aircraft observations for boundary-layer water and mixed-phase clouds over the sea (Asano et al., 1998). Several new instruments and observational techniques have been developed in the first stage (FY1991 - FY1994) of the JACCS period. During the second stage from FY1995 through FY1999, extensive field experiments have been implemented after performance tests of the observational systems.

Here we shall review the JACCS aircraft experiments and present some highlighted results on the microphysical and optical properties of polluted water and mixed-phase boundary-layer stratocumulus clouds, and on the remote sensing of cloud microphysical properties from the airborne spectral solar reflectance measurements for the stratocumulus clouds.

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JACCS/MRI home-page: *http://www.mri-jma.go.jp/Proj/JACCS/jaccs.html*

2. Aircraft Observation System

For simultaneous measurements of clouds and radiation, we have developed an Airborne Cloud- Radiation Observing System (ACROS) by using two aircraft equipped with various instruments. A Cessna 404 Titan aircraft (named C404 hereafter), flying over cloud layers, is used for radiation and remote sensing measurements with a microwave radiometer (MWR), an FT-IR spectroradiometer, and a Multichannel Cloud Pyranometer (MCP) system developed by Asano et al. (1995a). The cloud-physical parameters such as visible optical depth, effective particle radius, liquid-water-content and liquid-water-path can be retrieved from the solar spectral reflectances measured by the MCP system (Asano et al., 1995b).

The second aircraft, Beechcraft B200 Super-King-Air (B200), is used for *in-situ* measurements of cloud microphysical and thermodynamic properties by installing various probes and sensors on the wingtip mounts. A few sets of broadband pyranometers and pyrgeometers are also installed on the top and bottom of the two aircraft fuselages, respectively, for measuring the downward and upward solar and infrared fluxes.

In the January 1999 experiment, we have used the Polar Nephelometer developed by Gayet et al. (1997) for measuring light scattering phase functions by cloud particles (Gayet et al, 2000). Synchronized and collocated flight by the two aircraft is our essential strategy for measuring the radiation budget by clouds and for validation of the remote sensing of cloud parameters (Asano et al., 2000).

Here, we discuss the microphysical and optical properties measured for the following three cases of wintertime boundary-layer clouds over the sea as; (A) water stratocumulus cloud observed on February 2, 1998, (B) super-cooled water stratocumulus cloud polluted by mineral aerosols on January 21, 1999, and (C) inhomogeneous, mixed-phased stratiform clouds observed on January 30, 1999.

3. Observational Results

(A) Liquid water stratocumulus on Feb. 2, 1998

The cloud layer was observed over the south-east part of the East-China Sea centered at (29°N, 129°E) (Asano et al., 2000). The cloud-top height was at about 2km with temperature of 2°C; the observed temperature profile assures that the cloud layer consisted purely of liquid water droplets. **Figure 1** shows the altitude distributions of effective cloud-particle radius R_{eff}, liquid-water-content *LWC*, and cloud-particle and aerosol concentrations measured by the cloud microphysics probes onboard B200. Horizontal scattering of the data points at a few different altitudes indicates horizontal variability of the microphysical properties in the cloud. Compared with *LWC*, the effective radius R_{eff} measured by the Gerber probe (Gerber et al., 1994) was rather uniformly distributed between 6μm and 11μm. On the other hand, *LWC* mainly increased with altitude up to 1gm^{-3}, but there were large horizontal fluctuations due to wide variations of cloud-particle concentrations. The horizontally averaged concentrations increased with altitude from 200cm^{-3} to 300cm^{-3}. The lower atmosphere became turbid with time, with an increase of aerosol concentration measured by PCASP from 400cm^{-3} (S-1 leg) to 700cm^{-3} (S-3 leg) below the cloud layer. These cloud microphysical properties rely on maritime

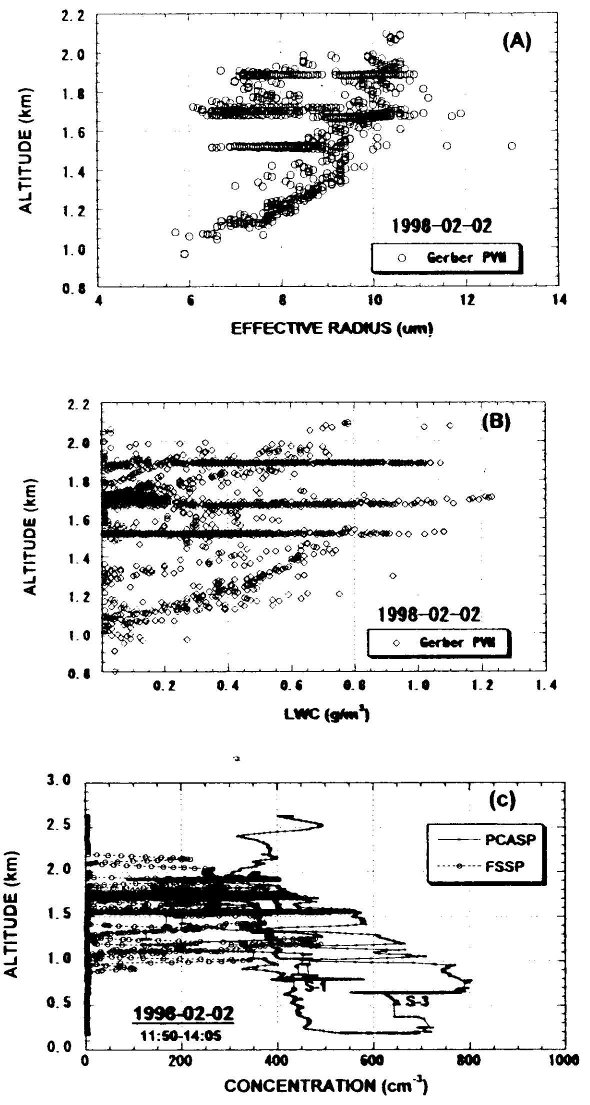


Fig. 1 Vertical distributions of (A) effective particle radius R_{eff} and (B) liquid-water-content *LWC* measured by the Gerber probe, and (C) cloud-particle and aerosol concentrations measured respectively by the FSSP and PCASP on board the B200 aircraft for the stratocumulus cloud observed on Feb. 2, 1998.

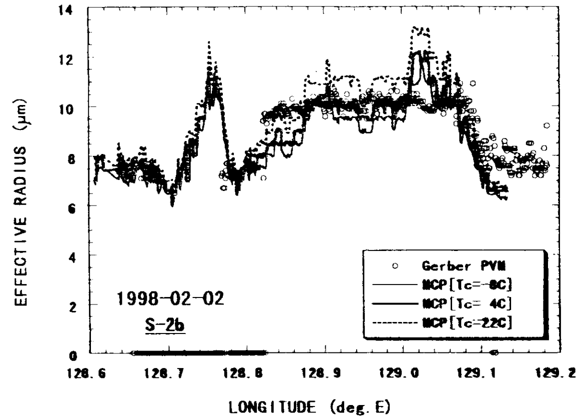


Fig. 2 Comparison of the MCP-retrieved effective radii with those measured by the Gerber probe C404 along a collocated flight leg S-2b for the stratocumulus cloud observed on Feb. 2, 1998. The MCP-retrieval was made for three cloud temperatures by employing the refractive index of water by Kuo et al. (1993).

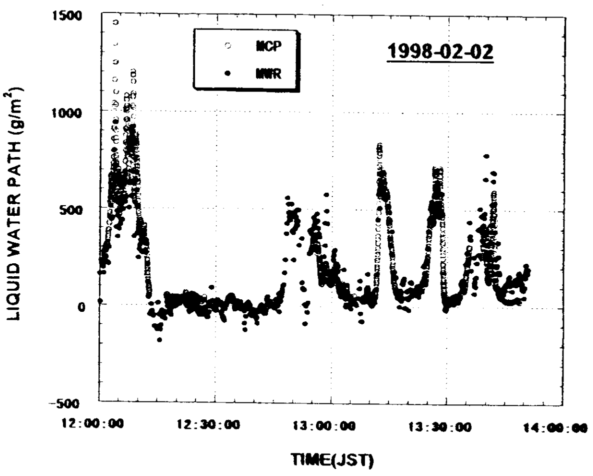


Fig. 3 Comparison in time-series of the MCP-retrieved liquid-eater-path (*LWP*) with those measured by the microwave radiometer (MWR) on board C404 for the stratocumulus cloud observed on Feb. 2, 1998.

airmass that is confirmed by the rather low concentrations of cloud particles and aerosols.

Figure 2 compares the MCP-retrieved effective radius with those measured by the Gerber prove (PVM). The MCP-retrieval was made for different cloud temperatures by employing the temperature dependence of the refractive index of water reported by Kou et al. (1993). The figure indicates that the retrieval of R_{eff}, with a suitable cloud temperature, from the MCP-measured spectral reflectance yields good agreement with the *in-situ* measurement. **Figure 3** shows a comparison in time series of the MCP-retrieved liquid-water-path (*LWP*) with those measured by the microwave radiometer (MWR) on board C404. The MCP-retrieved *LWP* was estimated from the approximate relation as $LWP=2\tau_v R_{eff}/3$, where τ_v and R_{eff} are the visible optical thickness and effective radius, respectively, retrieved from the MCP spectral reflectances. The figure again indicates a good performance of the MCP- retrievals for the water stratocumulus cloud.

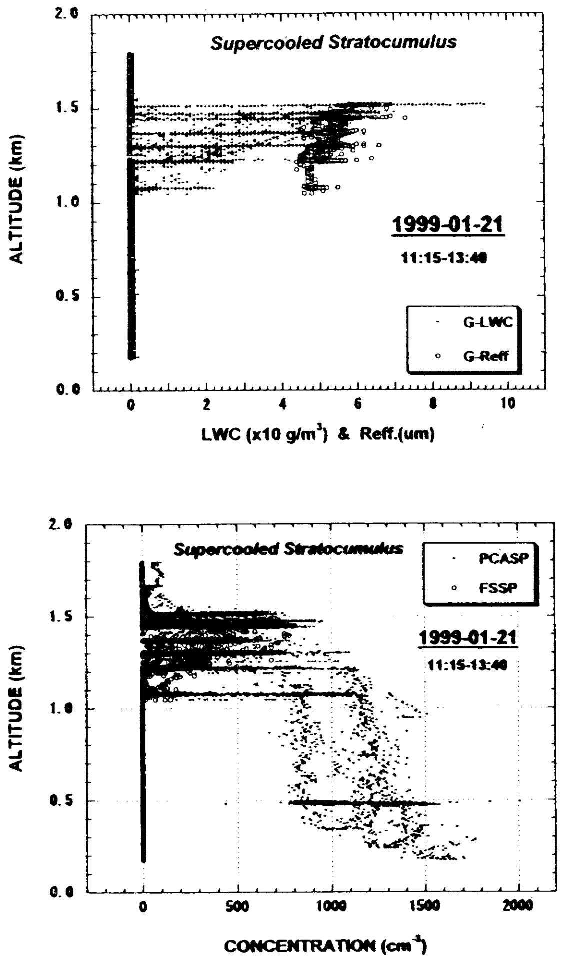
(B) Aerosol-contaminated cloud on Jan. 21, 1999

The stratocumulus cloud was observed over the sea centered at 32.2°N and 129.5°E, west off the Kyûshyû Island (Gayet et al., 2000). On the day there was an outbreak of cold airmass from the eastern Asian continent under a typical winter-type pressure pattern. The cloud layer was about 500m deep, and the cloud-top was at 1.5km height from the sea surface with a temperature of –6°C. **Figure 4** shows the vertical profiles of liquid-water-content and effective radius, and concentrations of cloud particles and aerosols. The cloud was characterized by very high aerosol concentrations in the sub-cloud layer and fairly high cloud droplet concentrations. The feature leads the cloud to be of continental-type and non-precipitating structure. The cloud can be optically regarded as a liquid water cloud because the measured scattering phase functions fit well with those calculated from Mie theory for the simultaneously measured FSSP size distributions (Gayet et al., 2000). We found that the cloud layer with the average thickness of 500m absorbed appreciable (7%) and reasonable (21%) amounts of solar radiation in the visible and near-IR bands, respectively. From the radiative transfer model calculations and the airflow back-trajectory analysis, the measured visible solar absorption might be caused by mineral aerosols transported from the desert area in the northwest part of China.

Figure 5 compares the MCP-retrieved R_{eff} with those measured by FSSP and the MCP-retrieved *LWP* with those measured by MWR, respectively, where the MCP-retrieval was made under the assumption that the cloud was composed of pure liquid-water droplets. The MCP-retrieved R_{eff} were overestimated than the *in-situ* measured values by 2 to 3μm. On the other hand, the MCP-retrieved *LWP* were slightly underestimated due to significant under-estimation of the visible optical thickness. This result suggests that in the visible through near-IR spectral regions the cloud should be actually more absorptive than the assumed pure water cloud is. This suggestion is consistent with the above-mentioned finding that the cloud layer absorbed the visible solar radiation.

(C) Mixed-phased cloud on Jan. 30, 1999

The cloud was observed over the Japan Sea centered at 35.9N and 135.4E, north of the Wakasa bay (Gayet et al., 2000). We often observed the optical phenomena of sub-sun and



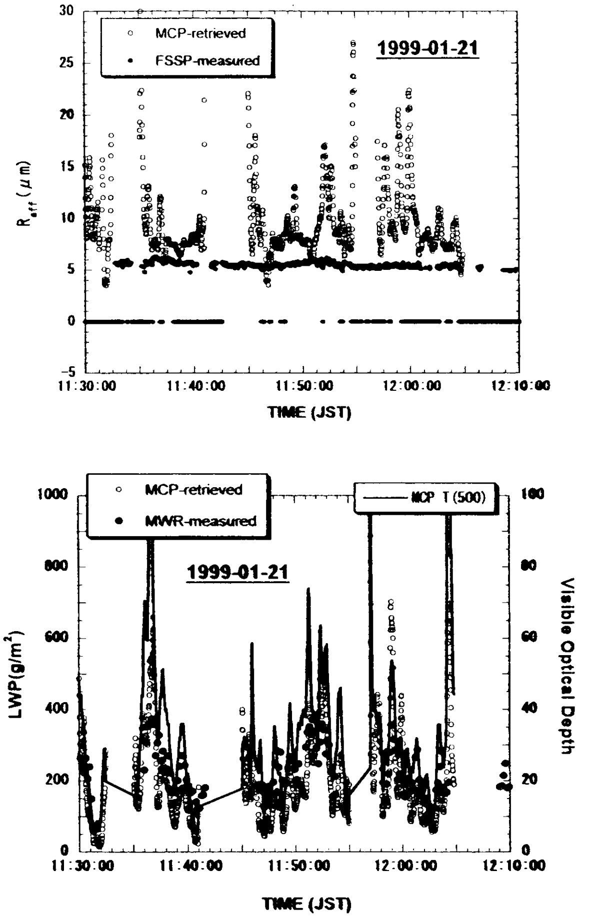


Fig. 4 [TOP] Vertical distributions of the liquid-water-content (*G-LWC*) and effective radius (*G-Reff*) measured by the Gerber probe. [BOTTOM] Vertical distributions of concentrations of cloud particle (*FSSP*) and aerosol (*PCASP*) measured respectively by the FSSP and PCASP on the B200 aircraft for the stratocumulus cloud observed on Jan. 21, 1999

Fig. 5 [TOP] Time series comparison of the MCP-retrieved effective radii R_{eff} with those measured by the FSSP on board B200 for the stratocumulus cloud observed on Jan. 21, 1999. [BOTTOM] Time series comparison of the MCP-retrieved liquid-water-path *LWP* with those measured by the microwave radiometer (MWR) on board C404 for the same case. In the panel, the MCP-retrieved visible optical depth is also depicted with a scale on the right margin.

glory from C404 flying above the clouds, this indicates that the cloud layer contained water droplets as well as ice particles. The cloud-top was at about 2.3km with temperatures around −13°C, and the cloud-base was near 1km with -7°C. We occasionally encountered snowfalls below the cloud layer. On an average over a long flight distance, the visible solar absorption was almost zero and the near-IR absorption was about 24% for the mixed-phase cloud layers with the average thickness of 1.3km.

Figure 6 shows the time-series of B200 flight altitude, liquid-water-content, cloud droplet concentration, effective diameter, 2D-C particle concentration, and extinction coefficient and asymmetry factors (Gayet et al., 2000). The last two optical parameters were inferred from the Polar Nephelometer measurements. **Figure 7** shows the vertical profiles of *LWC* and R_{eff} measured by the Gerber probe and cloud droplets and aerosol concentrations. These figures indicate that the cloud was highly inhomogeneous both horizontally and vertically with different mixing ratios of liquid water droplets and precipitating ice particles. Further, the measured scattering phase function shows that ice particles strongly affect the cloud optical properties by converting large number of liquid-water droplets with high extinction coefficient values into much smaller number of large ice particles with low extinction coefficients (Gayet et al., 2000).

Figure 8 compares the MCP-retrieved R_{eff} with those measured by FSSP and the MCP-retrieved *LWP* with those measured by MWR, respectively, where the MCP-retrieval was again made under the assumption that the cloud was purely composed of liquid-water droplets. The MCP-retrieved R_{eff} is unreasonably larger than the FSSP–measured ones. The MCP-retrieved *LWP* was overestimated than the MWR-measured *LWP* values at the places observed around 11:10 where ice particles were dominant (see Fig. 6). On the other hand, for places around 11:25 and 11:35 where water droplets were dominant, the MCP-retrieved *LWP* and the MWR-measured *LWP* are in fairly good agreement. It should be noted that the microwave radiometer is only effective to liquid-water droplets, but not sensitive to ice particles.

4. Conclusions

We have retrieved the cloud parameters from the spectral reflectance measured by the Multi-channel Cloud Pyranomater (MCP) system on board the C404 aircraft flying over cloud layers for various boundary layer clouds, and compared them with those *in-situ* measured by the cloud probes on board the B200 aircraft through the collocated flights.

For the pure liquid-water clouds, the visible optical depth and effective cloud-particle radius were successfully estimated simultaneously from the MCP reflectances at the visible and near-IR channels. The effective radii retrieved by considering the temperature dependence of water absorption coefficients were in good agreement with the *in-situ* measured values. In addition, the liquid-water-content was reasonably retrieved from the MCP-reflectance at 760nm channel for liquid-water clouds with optical depths less than about 50. Further, the liquid-water-path estimated from the MCP-retrieved optical thickness and effective radius was in good agreement with those measured by the microwave radiometer on the C404 aircraft.

For the water clouds contaminated by absorbing aerosols, the present MCP-retrieval,

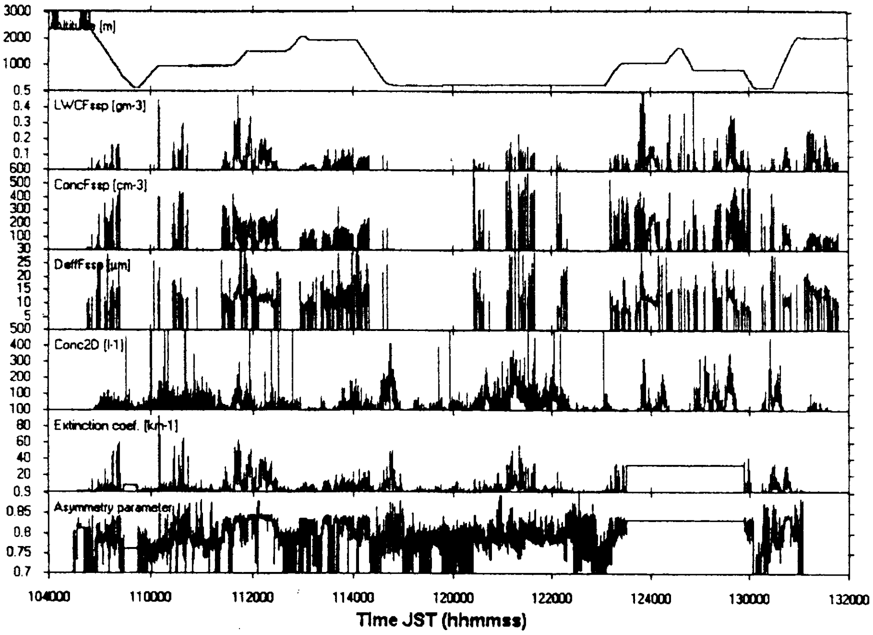
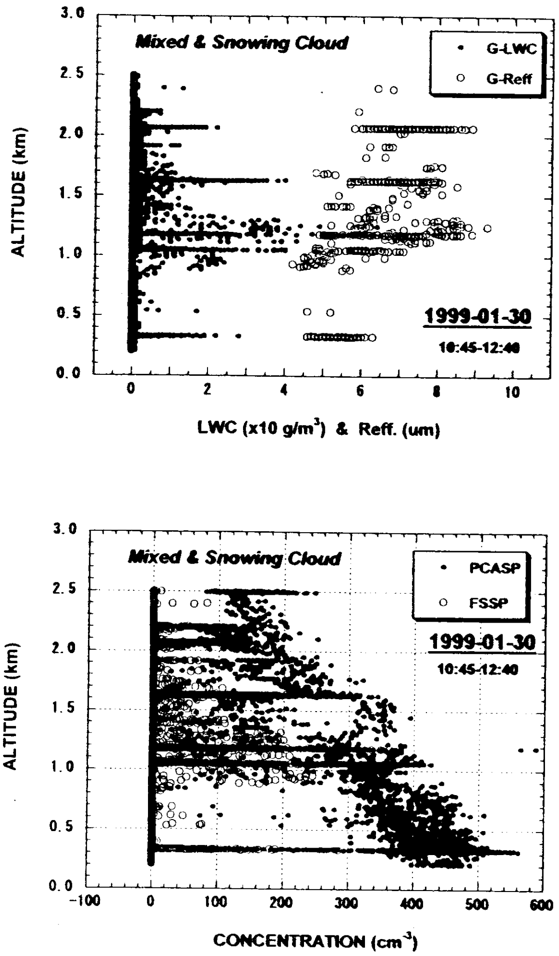


Fig. 6 Time-series of B200 parameters measured during the flight for the mixed-phase stratiform cloud on January 30, 1999. Altitude, LWCFssp; liquid-water-content by FSSP, ConcFssp; cloud droplet concentration by FSSP, DeffFssp; effective diameter by FSSP, Conc2D; ice particle concentration by the 2D-C probe, Extinction coefficient and Asymmetry parameter estimated from the Polar Nephelometer measurement.



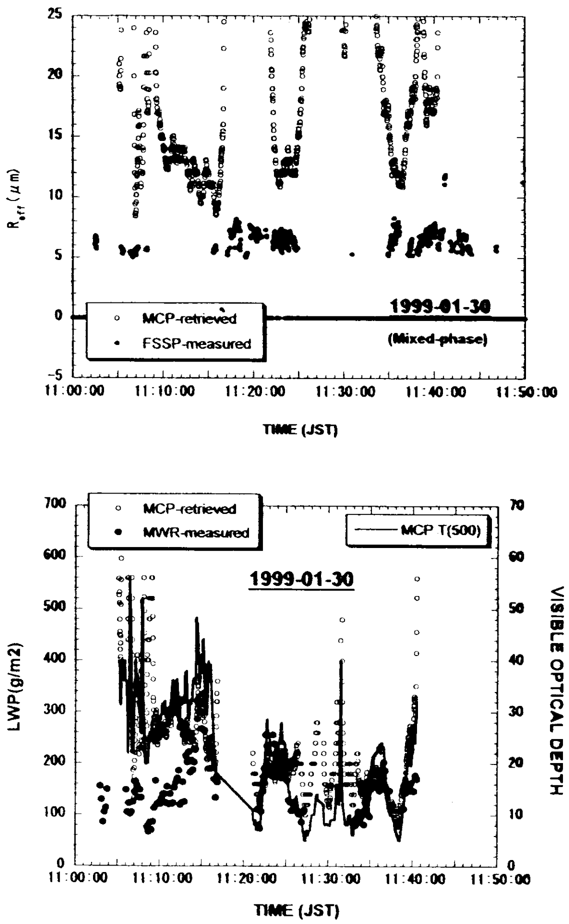


Fig. 7 Same as Fig. 4, but for the mixed-phase stratiform cloud observed on Jan. 30, 1999.

Fig. 8 Same as Fig. 5, but for the mixed-phase stratiform cloud observed on Jan. 30, 1999.

under the assumption of pure liquid-water clouds, has underestimated the visible optical thickness and overestimated the effective radius.

For the mixed-phase clouds, the cloud optical properties were strongly affected by ice particles with smaller concentrations but larger volumes than those of water droplets. The present MCP-retrieval, under the assumption of pure liquid-water clouds, has unreasonably overestimated the effective particle radius.

The above results suggest that new remote sensing techniques should be developed to discriminate and to simultaneously evaluate the effects of cloud-particles and aerosols, and water droplets and ice particles. Further, it is suggested that a new active remote sensing by such as Cloud-Profile-Radar and/or lidar will be highly desired for quantitative evaluation of liquid-water-content and ice-water-content.

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