NOTES AND CORRESPONDENCE

Utilization of the 4 m Microwave Telescope for the Measurement of
Liquid Water Path in Cirrus Clouds

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1. Introduction

Since the microwave telescope, which is usually used for the observations of interstellar molecules such as CO, has large aperture and is equipped with a low-noise detector, it is expected that the telescope has the ability to observe the liquid-phase water in atmospheric clouds very sensitively.

Recently, many investigators have been concerned about the liquid water droplets in cold cirrus clouds (near -40°C) because they are considered to play an important microphysical role in the generation region of the clouds and to cause important changes in the radiative process in the atmosphere. Many observations have been made to confirm the existence of liquid water droplets in cirrus clouds and to observe their microphysical properties (Curran and Wu, 1982; Platt, 1977; Sassen, 1984; Sassen *et al.*, 1985, 1989).

On the other hand, many numerical models have been developed to simulate the microphysical properties in the convective region of the clouds which contain both of liquid water and ice crystals. These models indicate that the dominant process which controls the freezing of the supercooled water droplets is homogeneous nucleation. Sassen and Dodd (1988) evaluated the homogeneous nucleation rate to account for the vertical profiles of the concentrations of the droplets and crystals observed near the cloud base by *in situ* measurements. However, the evaluated value is very large compared with that

predicted by classical theory, but very small compared with that of laboratory measurements. It can be said that this problem is still open.

Furthermore, the models predict some interesting features such as that haze particles can be created as the residue of water droplets by the water vapor competition effects between water droplets and ice crystals, and that the ice crystals are, eventually, generated in a pulse-like fashion in the clouds (Heymsfield and Sabin, 1989; Sassen and Dodd, 1988, 1989; Wesley and Cox, 1988). These features have not yet been observed in actual clouds. To confirm these phenomena and to take more the measurements for the estimation of the appropriate value of the nucleation rate in clouds, further observations of actual clouds are needed in future investigations.

A ground-based microwave radiometer is very useful equipment for the remote sensing of the integrated liquid water content (liquid water path) in clouds. However, as the integrated values in cirrus clouds are mostly very small compared with those of deep convective clouds such as cumulus, the sensitivities of most of the radiometers are not adequate to observe the microstructures in the clouds. Further, the fields of view of the radiometers are more than ten times wider than that of lidar systems, which are effective for observing the cloud structures, but the differences make it difficult to compare the results observed with these two instruments. More-sensitive and narrower-view radiometers are required in order to compare the model pre-

Fig. 1. Transmittance in a microwave region calculated for the standard atmosphere. Small arrows indicate the H_2O and O_2 absorption bands. A large arrow indicates the frequency of 110 GHz used in the observation.

dicted characteristics with those of actual clouds.

The utilizations of microwave telescopes for cloud observations have been suggested by some investigators, but have not been tried in practice. In this paper, we show the result of the measurement of liquid water path in a cirrus cloud using a 4m microwave telescope, and additionally show the result of the measurement by a polarization lidar which was used to observe the cloud structure and to identify the phase of the cloud particles.

2. The microwave telescope and data analysis

a. The microwave telescope

The 4m microwave telescope of the Department of Astrophysics of Nagoya University was operated in the vertical-pointing mode to observe the atmosphere. The frequency used was 110 GHz, which is between the absorption bands of oxygen (see Fig. 1, which is the frequency dependence of the transmittance in a microwave region calculated theoretically for the U.S. standard atmosphere (1976)). The telescope is equipped with a cooled diode mixer and two acousto-optical spectrometers, and the frequency range available is between 80 and 300 GHz with frequency resolutions of 40 kHz or 250 kHz. The receiver noise temperature is 200–250K DSB (at present, that is improved to be 17–25K). The full width between the half maximum of the main beam is $2'.7$ at 110 GHz, and this width is almost the same as that of the lidar. The telescope has one internal absorber controlled at 297K, and which was referred at an interval of 30 sec to correct system gain drift. To calculate the absolute gain, the operation of what is called 'R-sky observation' was employed. In this operation, the parameters which are necessary for the derivation of the optical thickness of the clear sky τ is estimated from the elevation scanning data. This is a familiar technique in

radio astronomy, and a similar operation was used in previous studies (e.g., Hogg *et al.* (1983)). The observed data in the first 1 sec of each 3 sec were recorded with a sampling rate of 10 Hz. As a sample and hold type of recorder was used, we take the running mean of the data. Details of the telescope were described in a previous paper (Kawabata *et al.*, 1985).

The lidar systems of the Water Research Institute of Nagoya University were also used. The systems are located at about 150 m southeast of the 4 m telescope. The laser wavelength and repetition rate are 6943 Å and 0.5 pps, respectively. The instantaneous field of view of the receiver is 1.5 mrad. Returned signals were separated by a half mirror into two polarization components, parallel and perpendicular to the polarization plain of transmitted laser power, and then the two components were detected by two photomultipliers simultaneously.

b. Data analysis

We can obtain the microwave data in terms of a equivalent black body temperature T_{bb} by the calibrated system. In general, two analytical procedures are available to evaluate the liquid water path L from the 1-channel microwave data. One is to separate the contributions of absorbing gases from observed value of T_{bb} based on direct measurements such as soundings. The other is to compare the values of T_{bb} observed under the clear and cloudy conditions, assuming that the difference in T_{bb} is only due to the existence of clouds. In the former method, we do not need the clear sky observation, but vertical profiles of temperature and water vapor mixing ratio should be derived exactly from sounding and so on. On the other hand, in the latter method, we do not need the water vapor data, but it should be assumed that the vertical profiles of temperature and water vapor mixing ratio of the cloudy sky do not differ from those of clear sky. In this study, as we were able to get the microwave data at the rifts in the cloud, we adopt the latter method.

In the analysis, we divide the atmosphere into 3 layers, *i.e.*, cloud layer, layers above and below the cloud. The emissivity of the cloud ϵ_c is expressed by Liu and Takeda (1988) in the form:

$$\epsilon_c = \frac{T_{bb} - T_a}{T_c \cdot \exp(-\tau)}, \quad (1)$$

where T_{bb} and T_a are equivalent black body temperatures observed for cloudy and clear sky, respectively. T_c is the cloud temperature. τ is the optical depth for the clear sky.

On the other hand, ϵ_c is expressed on the basis of Rayleigh scattering approximation by Gunn and East (1954) in the form:

$$\epsilon_c = 1 - \exp(-AL), \quad (2)$$

$$A = \frac{6\pi}{\lambda\rho} I_m(-K), \quad (3)$$

$$K = \frac{n^2 - 1}{n^2 + 2}, \quad (4)$$

$$n = n(T_c, \lambda). \quad (5)$$

where L is the liquid water pass and n is the complex index of refraction. The n is formulated by Ray (1972) as a function of temperature and wavelength. ρ and λ are density of water and wavelength, respectively. $I_m(-K)$ represents taking the imaginary part of $(-K)$.

Combining Eqs. (1) and (2), L can be related to the observed values T_{bb} and T_a .

$$L = -\frac{1}{A} \ln \left\{ 1 - \frac{T_{bb} - T_a}{T_c \cdot \exp(\tau)} \right\}. \quad (6)$$

It is obvious that L is in inverse proportion to A . The calculated values of A are shown as a function of temperature for water and ice in Fig. 2.

In this study, T_c is based on the local sounding data at Hamamatsu (about 100 km northeast of Nagoya) taken about 5 hours before, and τ is derived from R-sky observation taken just before the cloud observation.

The analytical method to evaluate the integrated backscattering coefficient from lidar observation data was described in another paper (Imasu and Iwasaka, 1991).

3. Results

The observation was made in a period from 14:03 to 14:30 JST on 4 November 1988. The synoptic scale analyses for the day showed that most of Japan was covered by a high pressure at 9:00 JST, but after its passage, two weak low pressures appeared and were located about 500 km east and southwest of the observation site at 21:00 JST. The atmospheric stability was stable in the region above the mid-troposphere at the time of 9:00 JST, but it changed to be almost neutral at 21:00 JST. The infrared satellite imagery (GMS-3) showed that the easterly edge of the cloud cluster corresponding to the low pressure was approaching the observation site when measurement was taken. Most parts of the sky, as far as the eye could reach, were covered by many long bands of cirrus clouds, which lay from west-southwest to east-southeast and was moving also to east-southeast. The depth of the cloud observed was not uniform along the direction of the longer axis of the cloud band, but it seemed not to contain the convective cells such as that contained in cirrus uncinus clouds which take hook like shapes. During the observation period, no low level clouds such as cumulus were observed. The cloud types and coverages were reported as Ci 7, Cu 0⁺ at 12:00 JST and Ci

Fig. 2. Calculated values of 'A' for water and ice at a frequency of 110 GHz.

10⁻, Cu 2 at 15:00 JST at the local meteorological observatory of Nagoya.

Liquid water path L measured is shown as a function of local time in Fig. 3. Three dense regions of the cloud were observed in the observation period accompanying the increases of L . The maximum value of L was about 1.9 mg/cm². The variations in L with a time scale of about 10 minute and some smaller ones with about 1 minute are noticeable in the figure. The former scale changes corresponded to the passage of the dense region of the cloud. The variations in L of the latter scale changes were about 0.2 to 0.5 mg/cm².

The lidar observation of the cloud was carried out from 14:11. The time-height cross section of backscattering coefficient (no extinction correction) and depolarization ratio are shown with temperature in Fig. 4a and 4b, respectively. The centers of the field of view of the telescope and lidar are about 150 m apart from each other. However, considering the horizontal scale of the cloud, it can be said that the increases in both the liquid water path and lidar backscattering coefficient appeared from 14:12 corresponded to the same patch of cloud.

The backscattering coefficient display shows some interesting features. The thin layer at 7 km (indicated as layer B in Fig. 4a) is very stable from the beginning of the measurement up to 14:13, but after then it began to descend accompanying the increase of reflectivity. Another region which fell from about 8 km at 14:10 (layer A) penetrated the stable layer B at 7 km, and the returned power was gradually increased below the stable layer. The maximum integrated backscattering coefficient of the cloud was 0.172 strad⁻¹ just before 14:16. This value corresponds to 0.179 of transmittance using a value of 10 for the scattering parameter S (=extinction/backscattering coefficient). The structures

Fig. 3. Liquid water path as a function of local time observed on 4 November 1988. Each point shows a running mean value for a period of 30 sec. An arrow indicates the time period of the lidar observation.

Fig. 4. Time-height cross section of (a) backscattering coefficient (no extinction correction) and (b) depolarization ratio observed by the lidar.

which might correspond to the variation in L with a time scale of 1 minute are not noticeable in the displays.

In the high reflective region (A, B and C) shown in Fig. 4a, the depolarization ratio is relatively low, varying around 10 % and indicating the existence of liquid water (or mixed-phase) particles or horizontally oriented ice plates. Especially at the height of 7 km, they were very close to 0 % from 14:00 to 14:13. The gradual increase in depolarization ratio was observed along the laser path in the densest region C from 14:15 to 14:16.

At the mid-cloud height, the wind speed was about 20 m/s, and the length of the observation period, 10 minutes, corresponded to a horizontal scale of 12 km under the assumption that the cloud was not generated and/or disappeared within the time period.

A microwave radar ($\lambda=0.86$ cm) had been operated through all the observation period. However, no significant echo could be detected from the clouds.

4. Discussion

It is important to discuss whether the increasing feature shown in terms of liquid water path in Fig. 3 was caused only by the increase of actual liquid-phase water or by the changes of other quantities such as ice particle concentration, temperature and water vapor concentration in the cloud.

When we assume that the cloud consisted of only ice crystals, the integrated ice water content corresponding to the maximum value of liquid water 1.9 mg/cm^2 is evaluated to be 33.2 g/cm^2 using the value of A for ice shown in Fig. 2. This value is not reasonable in the atmosphere. On another day, we observed another type of cloud which seemed to consist of large ice particles based on the depolarization data and the microwave radar data. In this case, no significant increase in liquid water path was not observed.

In the analytical procedure described in Section 2b, we assume that clear and cloudy sky have the same vertical profiles of temperature and water vapor concentration. However, these two quantities sometimes differ between in and out of cloud, and affect the value derived as the liquid water path. We estimated the differences in Tbb caused by the changes of temperature and relative humidity at the cloud height using the FASCODE 2 program on the basis of the sounding data. The FASCODE 2 is a line-by-line calculation code developed in the Air Force Geophysics Laboratory of U.S.A., and by which we can calculate the optical depth, transmittance and radiance for many types of atmospheric models based on the molecular absorption data base HITRAN 86 (Clough *et al.*, 1986; Rothman *et al.*, 1987). The results show that under a clear sky con-

dition, the increase in temperature of 5°C and in relative humidity of 10 % causes the increase in Tbb of 0.014 and 0.110°C , respectively, and these values are equivalent to the increases in L of 0.005 and 0.040 mg/cm^2 . We also estimated the changes in L caused by the inaccuracy of the cloud temperature T_c used in the analytical procedure. The results show that an underestimation in T_c of 5°C causes the increase in L of 0.021 mg/cm^2 when the actual value of L is 1 mg/cm^2 .

Consequently, we can conclude that the increasing features shown in Fig. 3 are mainly due to the increase of liquid water droplets in the cloud, and the variations in L of 0.2 to 0.5 mg/cm^2 with a time scale of about 1 minute would be significant. We can also say that the simultaneous measurement of water vapor concentration using the microwave radiometer at some water vapor channels is effective in improving the accuracy of measurement of the liquid water path in clouds.

In general, the minimum detectable value of detector or S/N ratio depends on the hardware of the systems (especially on the noise temperature and effective aperture of the receiver), and in ordinary operation, this quantity directly depends on the integration time of detected signals. Eventually, the minimum detectable value and time resolution of measurement are alternatively determined. Further, the error estimation for the absolute values of liquid water path measured by single or double microwave radiometers is not easy because it strongly depends on the analytical procedure employed and errors in many unknown parameters used in the procedure. Therefore, only very gross estimations of absolute errors in measurements have been discussed for ordinary types of radiometers. For example, the minimum value was estimated to be in the order of 1 mg/cm^2 in terms of liquid water path with an integration time of a few minutes in a study of Liu and Takeda (1988, personal communication), and this value seems not to be an exceptional value compared with other studies (Ulaby *et al.*, 1981).

Considering the above discussions, the minimum detectable value of L for the microwave telescope seems to be of the order of 0.1 mg/cm^2 . It can be said that the telescope is more effective for the detection of liquid water path in clouds at least by one order of magnitude compared with ordinary microwave radiometers (*e.g.* Hogg *et al.*, 1983; Liu and Takeda, 1988). Further, it is expected that we could reduce the noise level, hence S/N ratio, of detected signal by more than one order of magnitude by the use of a Lock-in amplifier (this type of amplifier is useful equipment to detect the objective signal buried in random noises by the integration of signals). Since the model predicted that the value of liquid water in the convective region near the cloud base is about 0.05 mg/cm^2 in terms of liquid water

path (Sassen and Dodd, 1988), these water droplets may be detectable by use of the microwave telescope equipped with this type of amplifier.

It is very interesting to discuss which layer shown in Fig. 4a contained the liquid water measured by the microwave telescope. In general, high reflectivity and low depolarization in lidar backscattered signals is caused by liquid water droplets or horizontally oriented ice plates in clouds (Platt, 1977, 1978; Sassen, 1984). However, these two cases can be distinguished on the basis of a gradual increase in depolarization ratio along the laser path which occurs only in water clouds owing to the multiple scattering effect of the laser pulse (Allen and Platt, 1977; Platt, 1977; Sassen, 1984). The change in depolarization ratio was observed in the densest region C appeared from 14:15 to 14:16. This is not inconsistent with the existence of water droplets in the highly reflective region of the cloud.

The internal structures of the cloud shown in Fig. 4 are somewhat different from those of multi-layered clouds or developing cirrus clouds observed by Platt (1977), Sassen (1984) and Sassen *et al.* (1985, 1989). The crossing feature of two highly reflective layers is especially interesting. Further investigations are needed on this kind of clouds to make clear the generation mechanisms involved.

5. Summary

A liquid water path in a cirrus cloud of about 1 to 2 mg/cm² was obtained from measurements with the 4 m microwave telescope. These values could not be explained only by the existence of ice crystals. Lidar observations suggested that the liquid water existed in the highly reflective regions of the cloud. The variations in L of 0.2 to 0.5 mg/cm² with a time scale of about 1 minute were observed, and considering the sensitivity of the telescope, it can be said that these variations in L corresponded to the changes in the cloud composition. The internal structures of the cloud derived from lidar observation were somewhat different from those of multi-layered or developing cirrus clouds described in previous studies. Further investigations are needed on them.

We estimated the sensitivity of T_{bb} measured by the telescope to the temperature and relative humidity at the cloud height under the clear sky condition by theoretical calculations using the FASCODE 2 program based on the sounding data. The results show that an increase in temperature of 5°C and in relative humidity of 10% causes an increase in T_{bb} of 0.014 and 0.110°C, respectively, and that these values correspond to a liquid water path L of 0.005 mg/cm² and 0.040 mg/cm², respectively. We also estimated the changes in L caused by the inaccuracy of the cloud temperature T_c used in the analytical procedure, and the result shows that an underesti-

mation of 5°C in T_c causes an increase in L of 0.021 mg/cm² when the actual value of L is 1 mg/cm².

The minimum detectable value of L for the microwave telescope may be of the order of 0.1 mg/cm², and an improvement of the sensitivity by more than one order of magnitude would be expected when a Lock-in amplifier is used. Consequently, it can be said that the telescope is more effective for the detection of liquid water path in clouds at least by one order of magnitude compared with ordinary microwave radiometers.

We emphasize that the simultaneous measurement of water vapor concentration using a microwave radiometer at some water vapor channels is very effective in improving the accuracy of measurement of liquid water path in clouds.

We conclude that the comprehensive remote sensing measurements including the microwave telescope would be effective in understanding the behavior of both of ice and liquid water droplets in cirrus clouds.

Acknowledgments

The authors would like to express their hearty thanks to Professor K. Kawabata and Dr. S. Nozawa of Nagoya University for affording them opportunities for observation of cirrus cloud with the telescope. The authors also wish to thank Dr. G. Liu for his good advice on data analysis, and Dr. S.A. Clough, Dr. L.S. Rothman and their co-workers for their providing them with the FASCODE 2 program and HITRAN (86) database.

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4 m マイクロ波望遠鏡を用いた巻雲中の積算雲水量の測定

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