—研究論文—
Scientific Papers

Estimation of Vertically Integrated Liquid Water Contents in the Atmosphere

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鉛直積分雲水量の見積もり

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要旨: 南極域における気候変動に関する総合研究計画が1987年から開始された．この計画の主テーマの一つが雲と降水の観測である．雲と降水を考える上で，大気中の液体の水の量(雲水量)，固体の水の量(氷水量)は重要な量であるが，測定が難しく観測例が少ない．今回の観測期間中の氷水量については，気象レーダー観測から求めることができた．一方雲水量は，マイクロ波放射計の観測から求めた．しかし放射計の性能の問題，低温での使用上の問題等のため絶対値を正確に求めるためにはデータの質を吟味しながら，十分な処理をしなければならない．今回冬7月と春10月のケースについて，2波長の放射計から得られた値を比較することによって，かなり信頼度の高い結果が得られたので，その方法を紹介する．この結果から見て南極のような低温域では，1波長の放射計からでもかなり信頼度の高い雲水量の値を求めることができると考えられる．

Abstract: A 5-year project of "Antarctic Climate Research (ACR)" started in 1987. One of the main projects of the ACR is an observation of clouds and precipitation. Liquid water content and ice water content are important parameters for considering the characteristics of clouds and precipitation. Ice water content in the atmosphere has been calculated from the data of the vertical pointing radar observation. On the other hand, vertically integrated liquid water content can be estimated by the data of microwave radiometers. It is very difficult to estimate reliable values of vertically integrated liquid water content because of the ability of microwave radiometer in the cold regions, some noises on data recording and difficulty of data calibration. As to some case studies at Syowa Station in Antarctica most reliable values of vertically integrated liquid water contents could be estimated. Moreover, there is a possibility of estimation of vertically integrated liquid water contents in cold areas from careful analysis of data of a microwave radiometer.

1. Introduction

Observations of integrated liquid water content and integrated water vapor amount in the atmosphere were done by some ground-based microwave radiometers, and many researchers (WEI *et al.*, 1989; ASKNE and WESTWATER, 1986; HOGG *et al.*, 1983; SKOOG *et al.*, 1982; SNIDER *et al.*, 1980) have described the methods of calculation

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of vertically integrated liquid water content and precipitable water. LIU and TAKEDA (1988) calculated the vertically integrated liquid water content in middle-level stratiform clouds using the data of a 37-GHz microwave radiometer. The direct measurement of liquid water content of cloud for the purpose of comparison with the data of microwave radiometer was not done yet and the absolute values of vertically integrated liquid water content by microwave radiometer are still uncertain. Moreover, in the Antarctic region observation of liquid water content of cloud in the atmosphere was not operated, although routine meteorological observations of precipitable water using radiosonde have continued at some antarctic stations. However, liquid water content and ice water content are also important parameters for considering the characteristics of clouds and precipitation in cold areas, not only warm areas in low and middle latitudes.

A microwave radiometer receives the power emitted by atmosphere and some matters, and cosmic radiation. When the radiometer was directed to the area near the zenith angle, we should consider only atmospheric and cosmic radiations. The atmospheric microwave radiation is due to oxygen, water vapor and cloud liquid particles. Microwave brightness temperature at the ground is calculated using one-dimensional equation of radiative transfer, if the profiles of air temperature (MEEKS and LILLEY, 1963), humidity (BARRETT and CHUNG, 1962) and liquid water content of cloud are observed. If we could surmise the cloud height in the atmosphere, we can calculate the liquid water content of cloud using brightness temperature obtained from the microwave radiometer, and profiles of air temperature and humidity obtained from the radiosonde observation.

The ability of microwave radiometer and the process of calibration are important for obtaining the reliable values of liquid water content of cloud. This paper describes the means to get the reliable values of liquid water content of cloud and reports some problems concerning the microwave radiometer.

2. Instruments

Two microwave radiometers were used for estimation of vertically integrated liquid water contents. Characteristics of the two microwave radiometers are listed in Table 1. The design of the radiometers is the normal Dicke design. The calibration source we refer to as the reference load is a temperature controlled, waveguide termination; the temperature is controlled at 60°C, higher than the expected ambient. The second

Table 1. Characteristics of two microwave radiometers.

		1	2
Receiver	Frequency	37.0 GHz	19.35 GHz
	Polarization	Lineary pol.	Lineary pol.
	Bandwidth	100 MHz	100 MHz
	Sensitivity	0.2 K	0.5 K
	(integrated time)	(1 s)	(1 s)
	AGC	Yes	Yes
Antenna	Diameter	20 cm	50 cm with radome
	Gain	25 db	33 db

source, "cold load", is also a waveguide termination at the temperature of liquid air. The cold load is connected to a switch connecting in sequence the antenna in case of necessity. Calibrations using the cold load were done twice in 1988. The antenna losses were estimated from the calibration using the cold load.

We define *Ti* as the antenna temperature of a lossy antenna. The output voltage of microwave radiometer *V* is in proportion to the *Ti*. The antenna temperature of a lossy antenna *Ti*(K) is related to the microwave brightness temperature *Tb*(K), the antenna loss L_a and the antenna physical temperature T_a(K). The equation is

$$Ti = a \cdot V + b = Tb \cdot L_a + T_a \cdot (1 - L_a), \qquad (1)$$

where the values of a and b are related to the characteristics of the radiometers. The value of a is due to the ambient temperature. Since the direct measurement of the antenna loss was difficult, it was obtained using the data of brightness temperature calculated from radiosonde observations in the non-cloud atmosphere and the data of output voltage from the microwave radiometer at those times.

Antennas and predetection sections of the two microwave radiometers were set on the roof of the Atmosphere Laboratory, and the other instruments, *e.g.* amplifiers, indicators, recorder, etc., were set in the Atmosphere Laboratory (WADA, 1990) at Syowa Station.

3. The Means to Get the Vertically Integrated Liquid Water Content

3.1. *Model computations*

The basic equation is the radiative transfer equation for non-scattering atmosphere. Computations were made using a ten-layer model with the base pressure corresponding to the surface (KREISS, 1968). The top of the model atmosphere was set at 100 mb. The brightness temperature *Tb* at the surface can be written as

$$\begin{aligned} Tb = {} & (1-t_1) \cdot T_1 + (1-t_2) \cdot T_2 \cdot t_1 \\ & + (1-t_3) \cdot T_3 \cdot t_1 \cdot t_2 + \cdots + (1-t_{10}) \cdot T_{10} \cdot t_1 \cdots t_9, \end{aligned} \qquad (2)$$

where T_i ($i = 1$ to 10) is mean temperature of i-layer, t_i ($i = 1$ to 10) is mean transmissivity of i-layer and can be written as

$$t_i = \exp\left(-\int_z^{z+\Delta z} a(z)\mathrm{d}z\right),$$

where $a(z)$ is absorption coefficient at height z and Δz is a thickness of i-layer. The absorption coefficient at height z is written by

$$a(z) = a(\mathrm{O_2}) + a\,(\text{water vapor}) + a\,(\text{cloud liquid}),$$

where $a(\mathrm{O_2})$ is absorption coefficient due to oxygen (MEEKS and LILLEY, 1963), a (water vapor) is due to water vapor (BARRETT and CHUNG, 1962) and a (cloud liquid) is due to cloud liquid (GUNN and EAST, 1954). The heights of the layer boundary are 100, 200, 300, 400, 500, 600, 700, 800, 850, 900 mb and the surface. A profile of air temperature, relating to $a(\mathrm{O_2})$, and humidity, relating to a (water vapor), was derived from radiosonde observations. The profile of liquid water content, however, was not obtained from radiosonde observation. An absorption coefficient for cloud liquid water, relating to *a* (cloud liquid), was derived from assumption that cloud was in the layer between 800 and 900 mb having homogeneous liquid water content of 1 g/m^3. Comparing the brightness temperature measured by the microwave radiometer with the brightness temperatures in the non-cloudy condition and the above-mentioned cloudy condition, the vertically integrated liquid water content was determined.

It is generally known that the values of both vertically integrated liquid water content and precipitable water in the atmosphere can be obtained using dual frequency microwave radiometers (HOGG *et al.*, 1983). We had intended to estimate vertically integrated liquid water contents and precipitable water using two microwave radiations of different wavelength. However, it is very difficult to detect the variation of precipitable water in the cold areas because of the small precipitable water in low temperature conditions as in the polar region. About 15 K in summer and 12 K in winter at Syowa Station were calculated from the model computation of the brightness temperature only for oxygen and water vapor. The difference of brightness temperatures between summer and winter is about only 3 K at the largest estimate for the variation of precipitable water throughout the year. Therefore, we were unable to observe the variation of precipitable water at Syowa Station, although two microwave radiometers were set there. Using the data of radiosonde observation we tried to measure the vertically integrated liquid water content from two microwave radiometers as the data have uncertainty due to poor conditions of instrument or effects of other noise sources.

3.2. Procedure to estimate reliable values

3.2.1. Antenna loss

The calibrations for getting the values of *a* and *b* were done twice, on March 13 and December 19, 1988. First of all, the values of *a* and *b* are determined from the calibration of March. Next, the brightness temperatures are calculated from eq. (2) using the radiosonde observations of March in the cases of non-cloudy condition. The antenna losses are determined from eq. (1) in each case of non-cloudy condition using the above-mentioned values of *a*, *b*, the brightness temperature, and the antenna physical temperature T_a, which was measured by a thermometer on the surface of the antenna. The average of the obtained antenna losses is determined as the most reliable antenna loss. The antenna loss for 19.35-GHz radiometer is 0.7528 and for 37-GHz radiometer is 0.7447.

3.3.2. The values of *a* and *b*

The values of *a* and *b* must be determined. The value of *b* is supposed to be constant throughout the year because the value of *b* expresses the temperature of reference load and is related to 0 level of amplifier. Then we take 333.2 K (60°C) for the value of *b*. The relationship between the value of *a* and the temperature for 37-GHz radiometer was determined from the measurement in the temperature-controlled room in Japan before carrying the radiometers to Syowa Station. Four solid circles show the measured data and a line means the interpolated curve using the data in Fig. 1. When a gain of amplifier of the radiometer is adjusted, the value of *a* is changed according to the adjustment.

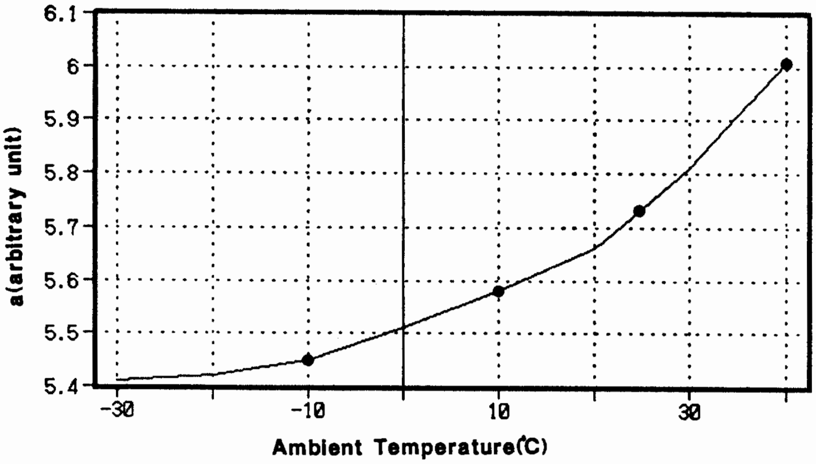

Fig. 1. Relationship between value of a and ambient temperature for 37-GHz microwave radiometer.

Since the relationship between the value of a and the temperature had not been obtained for 19.35-GHz radiometer, the value of a in each month was determined by the following procedure. First, the brightness temperatures are calculated from eq. (2) using the radiosonde observations of each month in the cases of non-cloudy condition. The value of b is also supposed to be constant, 333.2 K. The value of a in each month is calculated from eq. (1) in each case of non-cloudy condition using the above-mentioned antenna loss, the brightness temperature, the value of b and the antenna physical temperature T_a. The average of these obtained values of a in each month is regarded as the value of a of the month.

3.2.3. Vertically integrated liquid water content.

The brightness temperature at every minute is calculated using eq. (1) from the output voltage of microwave radiometers at every minute, with the antenna loss described above, the values of a and b, and the antenna physical temperature T_a. The output voltage of the microwave radiometer depends on some noises from inner and outer origins. In order to remove the long and short-term noises, it is necessary to analyze carefully individual case studies. The brightness temperature (Tb_s) in a non-cloudy atmosphere condition is calculated for individual case from model computation using the data of radiosonde observation. Tb_s generally shows a nearly constant value for a time of one hour or so in the non-cloudy atmosphere condition. Then the brightness temperature (Tb_r) obtained from the microwave radiometer in the case of non-cloudy atmosphere condition is regarded as equal to Tb_s. However, Tb_r is not eqaul to Tb_s because of the noises or some errors of calibration. The difference between Tb_s and Tb_r is DTb, a bias of brightness temperature, namely

$$DTb = Tb_s - Tb_r. \qquad (3)$$

The most reliable brightness temperature (Tb) is expressed by eq. (4) using the brightness temperature obtained from microwave radiometer (Tb_a) at every minute, as

$$Tb = Tb_a + DTb. \qquad (4)$$

From the profiles of the air temperature and the humidity obtained from radiosonde observation, absorption coefficients for oxygen and water vapor are derived. On the other hand, many absorption coefficients for cloud liquid water are calculated from assumed conditions with many cases of cloud liquid water content. The brightness temperatures of the respective conditions are calculated and a value which equals the brightness temperature obtained from the microwave radiometer is selected. From the condition of liquid water content which derived the value vertically integrated liquid water content at that time is determined. Radiosonde observations were made twice a day. Since the difference in the estimates of vertically integrated liquid water content between radiosonde data before and after the observation of microwave radiometer is small because of low temperature and low water vapor in the polar region, the averaged data of radiosonde observations were used.

4. Case Studies

4.1. A case study from 24 July to 28 July 1988

In the case, the cloud amounts were almost 10/10 after 2100 LT 24 July, except for the period from 1800 to 2100 LT 25 July. Snowfalls were often observed in this case. A chart record of a part of the case is shown in Fig. 2. The data of two microwave radiometers, dew point temperature and antenna surface temperature from 1300 LT 24 July to 0800 LT 25 July are shown in this figure. After 1700 LT 24 July the data of both 37-GHz and 19.35-GHz microwave radiometers gradually increased, after that they took the maximum at nearly 2145 LT, fluctuated for a while and gradually decreased. It was considered therefore that these variations correspond with a variation of liquid water content of cloud in the atmosphere. A fairly systematical oscillation is often shown in the data of 19.35-GHz microwave radiometer after 0200 LT 25 July.

Since the data of 37-GHz microwave radiometer around 1500 LT 24 July took

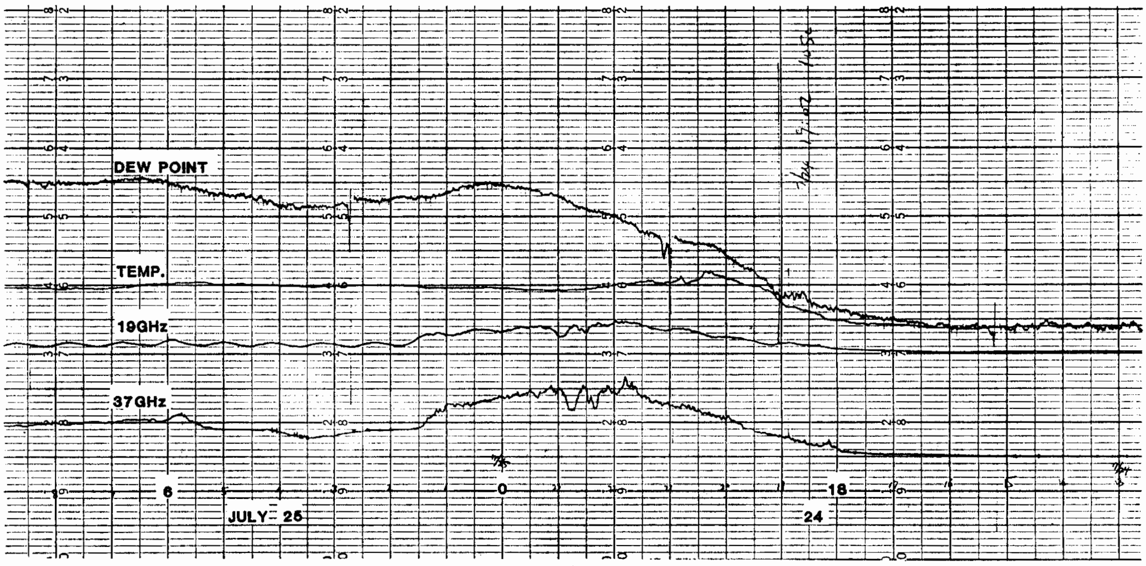

Fig. 2. A chart record of the data by two microwave radiometers, dew point temperature and antenna surface temperature.

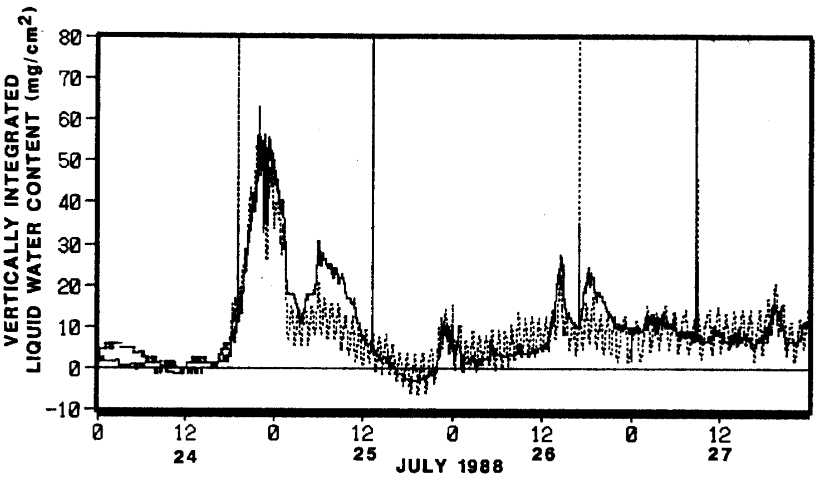

Fig. 3. The variation of vertically integrated liquid water content obtained from 19.35-GHz (dotted line) and 37-GHz (solid line) microwave radiometers in the July case.

approximately minimum during the period from 1300 LT 24 July to 1500 LT 27 July, from calculating the data of both the brightness temperatures by the microwave radiometer (Tb_r) and model computation (Tb_s) using radiosonde data at 1500 LT 24 July, namely, the data of non-cloudy condition, *DTb* of this case can be determined using eq. (3). From the brightness temperature at every minute (Tb_a) of the period, the most reliable brightness temperatures (Tb_{37}: *Tb* of 37-GHz radiometer) can be calculated using eq. (4). The most reliable brightness temperatures of 19.35-GHz (Tb_{19}: *Tb* of 19.35-GHz radiometer) are also calculated using the same procedure. The vertically integrated liquid water contents of both frequencies are calculated from the model computation which considers liquid water content of cloud using Tb_{37} and Tb_{19}. Figure 3 shows the variation of vertically integrated liquid water content during the period from 1500 LT 24 July to 1500 LT 27 July.

Both records in Fig. 3 show fairly good coincidence, though several values are below zero and the records by 19.35-GHz microwave radiometer often show a systematical oscillation.

4.2. *A case study from 23 October to 25 October 1988*

Vertically integrated liquid water contents obtained by 37-GHz and 19.35-GHz microwave radiometers are shown in Fig. 4 from 23 to 25 October. It was sometimes overcast and stratocumulus clouds were reported from 1500 LT 23 to 0300 LT 25 October according to the routine meteorological observation (JAPAN METEOROLOGICAL AGENCY, 1990). However, no snowfall was reported in this case. There was no cloud at 0300 LT 23 October. Therefore, using the data obtained from each microwave radiometer around 0300 LT 23 October and the data obtained from radiosonde observation at 0300 LT. *DTb* of this case can be determined. Vertically integrated liquid water contens are calculated by the same procedure as the case of July described above.

A fairly systematical oscillation is also seen in the records by 19.35-GHz microwave radiometer. Besides, the value increased after 0700 LT, took a peak around

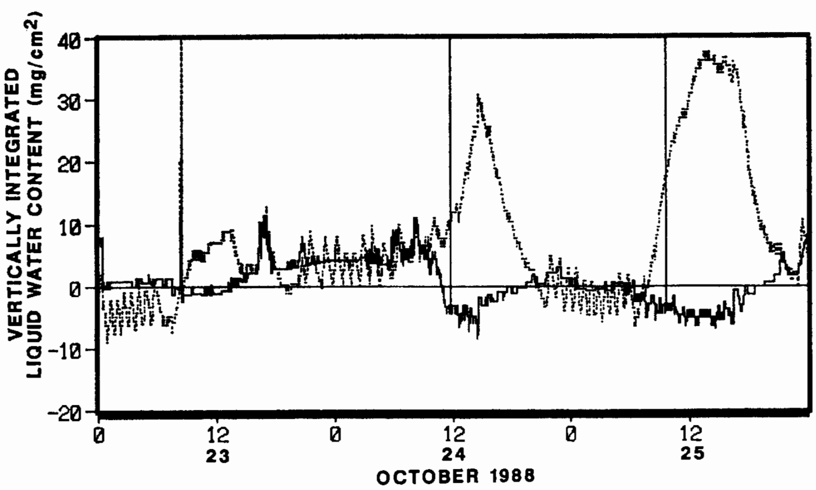

Fig. 4. The variation of vertically integrated liquid water content obtained from 19.35-GHz (dotted line) and 37-GHz (solid line) microwave radiometers in the October case.

1400 LT and decreased to set back around 2000 LT on both of 24 and 25 October. The values in the periods differed largely between 19.35-GHz and 37-GHz microwave radiometers.

5. Discussion

Although the values of vertically integrated liquid water contents obtained by both 19.35-GHz and 37-GHz microwave radiometers showed the fairly good coincidence in the case of July, the daytime (from 0700 LT to 2000 LT) values in the case of October showed a discrepancy between values by 19.35-GHz and by 37-GHz microwave radiometers.

The antennas were exposed to the solar radiation for a longer time in October than in July. A rise of temperature at the surface of 19.35-GHz antenna caused by solar radiation is larger than that of 37-GHz because the 19.35-GHz antenna was covered with radome. Moreover, the antenna physical temperature T_a in eq. (1) was not measured on the surface of 19.35-GHz antenna, but on the surface of 37-GHz antenna. For the 19.35-GHz antenna, the stronger solar radiation, the larger the difference between the real antenna physical temperature T_p and the measured temperature on the surface of 37-GHz antenna T_s, which equals T_a for calculation of 37-GHz brightness temperature, is. Therefore, it is necessary to use T_p instead of T_a in eq. (1) for the calculation of 19.35-GHz brightness temperature, but T_p was not observed. T_p is probably connected with T_s and solar radiation r. Using a factor k, therefore, we express the relationship as;

$$T_p = k \cdot r + T_s. \qquad (5)$$

The relationship between global solar radiation r and $T_p - T_s$ on 22 October when it was almost fine all day is shown in Fig. 5, where T_s is measured by a thermometer on the surface of 37-GHz antenna and T_p is calculated using eq. (1)—T_p means T_a in this

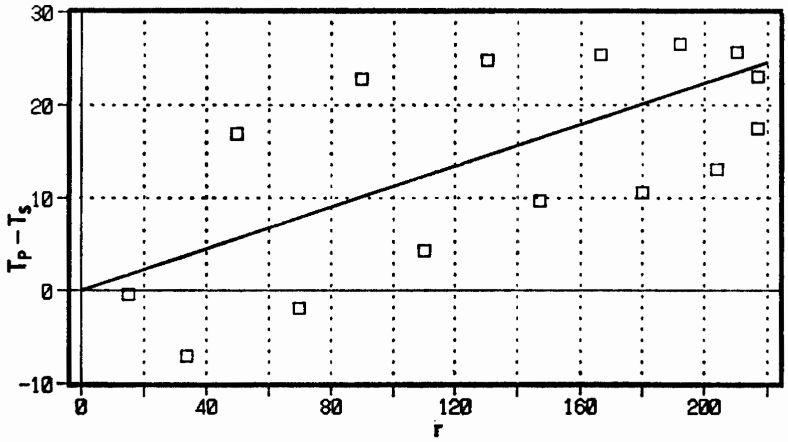

Fig. 5. *Relationship between global solar radiation r and T_p-T_s on 22 October.*

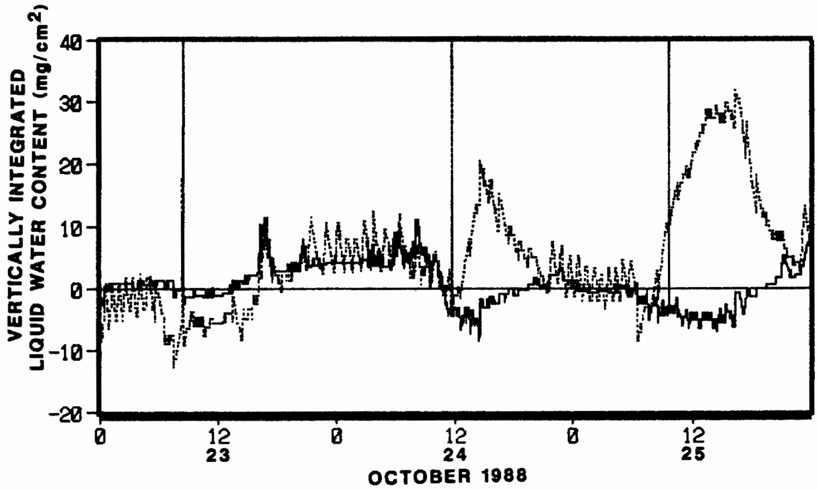

Fig. 6. *The variation of vertically integrated liquid water content recalculated using the above relation (solid line in Fig. 5) and eq. (5).*

case —as *Tb* did not change much in a day. It is difficult to decide the value of *k* in eq. (5), as the data seem to have hysteresis. However, from the relationship (solid line) between values of *r* and T_p-T_s in Fig. 5, we decide the value of *k*. Using the value of *k*, vertically integrated liquid water contents by 19.35-GHz microwave radiometer are recalculated and the result is shown in Fig. 6. Although the effect of solar radiation could be reduced, the result was still imperfect because a precise relationship between *r* and T_p-T_s is not known. During the period of weak solar radiation, however, the values of vertically integrated liquid water contents by both 37-GHz and 19.35-GHz microwave radiometers show good coincidence.

It was recognized that there are often systematical oscillations in the data by 19.35-GHz microwave radiometer. The mean values of the systematical oscillation are nearly the same as the data by 37-GHz microwave radiometer. It was inferred that the systematical oscillation was caused probably by the on-off of heater for preventing coldness in the instrument because it was found only in the chart records when the air temperature was nearly between —5°C and —10°C.

6. Conclusion

It is generally known that the values of both vertically integrated liquid water content and precipitable water in the atmosphere can be obtained using dual frequency microwave radiometer (HOGG *et al.*, 1983). However, it is very difficult to detect the variation of precipitable water in cold areas because of the small precipitable water in such low temperature conditions as the polar region. Using the data of radiosonde observation we tried to measure the vertically integrated liquid water content from two microwave radiometers as the data have uncertainty due to poor conditions of instrument or effects of other noise sources.

From the analysis of two case studies mentioned above, the values of vertically integrated liquid water contents by both 37-GHz and 19.35-GHz microwave radiometers showed good coincidence during the period of weak solar radiation. The both values can be said to be approximately the same in the non-solar radiation. However, the 19.35-GHz microwave radiometer has some problems. Solar radiation has some influence on the antenna physical temperatures since the antenna was covered with radome, and the data by 19.35-GHz microwave radiometer have often systematical oscillation because of the on-off of heater with temperature change.

We have reached the following conclusion. We considered that the values of vertically integrated liquid water contents obtained from 37-GHz microwave radiometer are reliable for the periods when the values by 19.35-GHz and 37-GHz microwave radiometers are approximately the same—if the data of 19.35-GHz radiometer show systematical oscillation, the mean values are selected—because of good coincidence of values obtained from different wavelength radiometers. Moreover, the values by 37-GHz microwave radiometer are also fairly reliable under strong solar radiation even if the values by 19.35-GHz and 37-GHz microwave radiometers are different because of uncertainty of antenna physical temperature of the 19.35-GHz radiometer.

Considering from the conclusion above, vertically integrated liquid water contents in the atmosphere in cold areas may be estimated using only a microwave radiometer like 37-GHz radiometer, if we will examine not only data of microwave radiometer but also routine meteorological data and will watch the condition of microwave radiometer carefully.

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