Comparison of Cloud Liquid Content Measured by Two Independent Ground-Based Systems

J. B. SNIDER, F. O. GUIRAUD AND D. C. HOGG

Wave Propagation Laboratory, NOAA Environmental Research Laboratories, Boulder, CO 80303

(Manuscript received 9 November 1979, in final form 25 February 1980)

ABSTRACT

We report on observations of liquid water in clouds made by two independent ground-based microwave instruments. One system is a dual-frequency (20.6, 31.65 GHz) microwave radiometer designed to measure emission from the precipitable water vapor and from liquid in the zenith direction; we refer to this as System 1. The other system is a combination receiver-radiometer that utilizes absorption of a 28 GHz signal from the COMSTAR satellite to measure the liquid content of clouds; we refer to this as System 2. Comparative measurements on liquid-bearing clouds in Colorado are given.

1. Introduction

The amount of a substance can be determined by measuring the loss experienced by a wave transmitted through it, provided the absorption coefficient appropriate to the particular wavelength is known. This method is not uncommon at infrared wavelengths where *in situ* determinations of hydrocarbons and other gases in the atmosphere are made. In simplest terms, the amount of the substance Q, i.e., the integrated value along the path of transmission, is given by

$$Q = K(1 - e^{-a}),$$

where a is the absorption and K a constant for a given temperature and pressure.

It is also true that emission by the substance can provide a measure of amount since emission is created by virtue of the absorption by the substance. Thus, radiometric (passive) techniques can also be used to measure amount. In that case, the relationship is the same as above where the absorption is now determined from the radiometric measurement of brightness temperature T_B emitted by the substance:

$$a = \ln\left(\frac{T_m}{T_m - T_B}\right),$$

where T_m is the temperature of the medium.

At microwave frequencies, radiometric techniques are used successfully to measure precipitable water vapor (Guiraud *et al.*, 1979). Two radiometric frequencies are used; one of these is near an absorption line of water vapor, and therefore monitors primarily the water vapor. The second frequency is used to provide corrections to the measurement of precipitable water vapor when liquid-bearing clouds or rain is overhead;[1] this is necessary because liquid water is absorptive, and therefore also emissive at these frequencies. The measurements of precipitable water vapor are verified by continual comparison with radiosonde data at operational National Weather Service locations. However, verification of the amount of liquid overhead in clouds cannot be achieved with a radiosonde because they do not incorporate a liquid sensor. It is for this reason that an independent measuring system, utilizing absorption of a microwave satellite signal, was constructed (Snider *et al.*, 1980).

The following briefly describes the two measuring systems. A little theory and typical comparative measurements in the presence of liquid-bearing clouds are then discussed. It should be emphasized that since ice is essentially transparent at microwave frequencies, clouds formed of ice particles do not affect a signal by absorption nor do they produce any emission or brightness temperature in a radiometer.

2. Description of the methods

Both systems make use of the absorption of microwave energy by liquid water as the basis for measurement of cloud liquid content.

The vapor-liquid instrument (System 1) employs radiometers operating at two frequencies: the first, 20.6 GHz, being near a vapor absorption line experiences strong emission by water vapor; the second, 31.65 GHz, is sensitive to liquid water, more so than at 20.6 GHz. By estimating the absorption at each frequency from the observed emission, the integrated water vapor and liquid through the atmospheric path within the 2° antenna beam of the radiometer can be determined. With this method, an average temperature for the liquid (from *a priori* radiosonde statistics) must be obtained in order to compute the amount of liquid from the emission

---

[1] The radiometers can also be designed to scan with full-sky coverage.

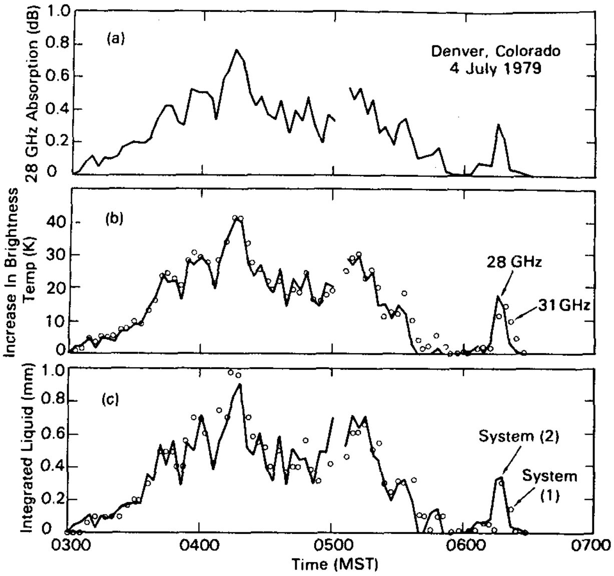

FIG. 1. Cloud absorption event of 4 July 1979. Solid lines are data from System 1; circles are data from System 2.

measurement. The integrated liquid L and vapor V in centimeters, are obtained from

$$L = -0.010 - 0.229a_{20} + 0.563a_{31}, \quad (1)$$

$$V = -0.010 + 26.970a_{20} - 11.770a_{31}, \quad (2)$$

where a_{20} and a_{31} are the absorptions at 20 and 31 GHz (obtained from the radiometric measurements of brightness temperature T_B). The above coefficients, given for Denver, Colorado, will vary somewhat with geographic area; they are calculated from a history of radiosonde data for the region of interest. Both the instrumentation and measurement technique are described in a recent paper by Guiraud *et al.* (1979).

The technique employed in System 2 consists of simultaneous measurement of the absorption by liquid water of a 28 GHz signal transmitted from the COMSTAR-3 geosynchronous satellite (87°W), and the associated increase in microwave brightness temperature emitted by the liquid. Since the magnitude of the absorption depends on the temperature of the liquid, accurate determination of the average temperature of the liquid in the clouds is important. An advantage of System 2 is that is provides an estimate of the liquid temperature simultaneously with the observed absorption of a signal at a microwave frequency. These simultaneous measurements allow more accurate estimation of the temperature of the liquid than is possible with the dual-frequency instrument (System 1). Therefore, data obtained with System 2 can be used to "calibrate" System 1.

By an appropriate combination of the above two quantities, the integrated liquid along the earth-satellite path through the cloud is computed. the integrated liquid content L in mm, is given by (Snider *et al.*, 1980)

$$L = \frac{\gamma_w}{43.164 - 0.287T_c + 0.000482T_c^2}, \quad (3)$$

where γ_w is the measured absorption (dB), by the cloud and T_c the average liquid temperature (K). The average liquid temperature is obtained from the increase in brightness temperature of the cloud T_{bw} and the measured absorption by

$$T_c = \frac{T_{bw}}{1 - \exp[-(\gamma_w/4.343)]}. \quad (4)$$

3. Results

Both instruments have been operated, continuously and unattended, at the National Weather Service radiosonde launch site, Stapleton Airport, Denver, Colorado, for several months. The antennas of both systems are pointed in the direction of the COMSTAR-3 satellite (40.4° elevation, 153.2° azimuth). Therefore, the liquid content measured by the instruments, as clouds drift through the antenna beams, can be directly compared.

As an example, in Fig. 1 we present data from both instruments obtained during a 3.5 h period on 4 July 1979; precipitation was not observed from these clouds. The upper curve (Fig. 1a) shows the absorption of the 28 GHz beacon signal from the satellite as the clouds traverse the antenna beam. The simultaneous increase in brightness temperature in System 2 at 28 GHz (solid line) and in System 1 at 31 GHz (circles) are given in Fig. 1b; the break in the solid curves near 0500 is due to an automatic calibration interval when the systems are briefly disconnected from the microwave antennas. Integrated liquid values computed from System 1 and System 2 data, using (1) and (3), respectively, are plotted in Fig. 1c. For these data, read at 3 min intervals, the rms scatter about a linear regression line with System 2 data as the independent variable (abscissa in the regression analysis) is 0.1 mm; the correlation coefficient of the regression is 0.92.

The result presented in Fig. 1 is typical of most measurements obtained to date. For a number of cloud absorption events occurring on eight days during August 1979, the rms variation about linear regression between the two measurements (709 data points sampled at 1.5 min intervals) is 0.29 mm with a correlation coefficient of 0.93; the data are shown in Fig. 2. Integrated liquid values up to 5.2 mm were observed by System 1; the mean liquid content for all clouds was 0.58 mm. The slope of the regression line is 1.092 for the 709-point sample; 95% confidence limits on the slope are 1.061–1.123. The mean slope for clouds observed during July 1979 (385 data points) was 1.109 with 95% confidence limits of 1.072 and 1.146. Therefore, on the average the dual-frequency derived liquid water content from System 1 appears to be about 11% higher than that obtained with the satellite receiver-radiometer, System 2.

4. Discussion of results

The observed agreement is considered satisfactory in view of the difference in antenna beamwidth employed by the two systems: 2.5° at 20 and 31 GHz (System 1) and 0.6° at 28 GHz (System 2). Because the beamwidths differ, some clouds that completely fill the small beam only partially fill the larger beam. Since the brightness temperature observed by a radiometer is equal to the convolution of the antenna power patterns and the cloud brightness distribution, incomplete beam filling can be expected to result in underestimation of the liquid content. Although some differences may be traced to the beam-filling effect, the overall comparison indicates that, for the clouds observed thus far, cloud liquid densities are fairly uniform over the antenna beamwidths used by these systems.

Another effect that can produce discrepancies is introduced in the measurement of the absorption of the satellite beacon signal. Although the brightness temperature is affected by the antenna power pattern, the absorption measurement is effective only over the Fresnel zone (see, e.g., Frank, 1950) in the transmission path. To indicate the relative size scales, for clouds at a range of 5 km, the half-power beamwidths of the antennas subtend distances of 220 m at 20, and 31 GHz and 50 m at 28 Ghz; the diameter of the first Fresnel zone is ~15 m at 28 GHz. Therefore, variations in liquid density of lateral dimensions of the order 15–50 m can cause inconsistency in absorption and brightness temperatures.

Another reason for possible differences between the two sets of measurements is the use of different sampling methods for the output data in the two systems. The output of the dual-frequency system consists of 2 min averages of 0.1 s samples while the satellite receiver-radiometer's output is not averaged beyond that inherent in a 10 s time constant. As a result, for small or rapidly moving clouds, the different sampling methods may cause somewhat poorer agreement between liquid estimates than when more uniform clouds are in the antenna beams.

It should be noted that the preceding situations are often readily identified in the output data. For example, incomplete beam filling is indicated by somewhat different increases in brightness temperature at 28 and 31 GHz. [As absorptions are nearly identical at these frequencies, the increase in brightness temperature is nearly the same for uniform beam filling (see Fig. 1b).] Therefore, data pairs where incomplete beam filling is indicated can be detected and removed from the measurements. Similarly, small or fast moving clouds may be indicated by a rapid variation of the absorption and brightness temperature; such cases should be carefully examined to prevent reduction of data that have been biased by the sampling method. However, the preliminary results described above are presented without editing.

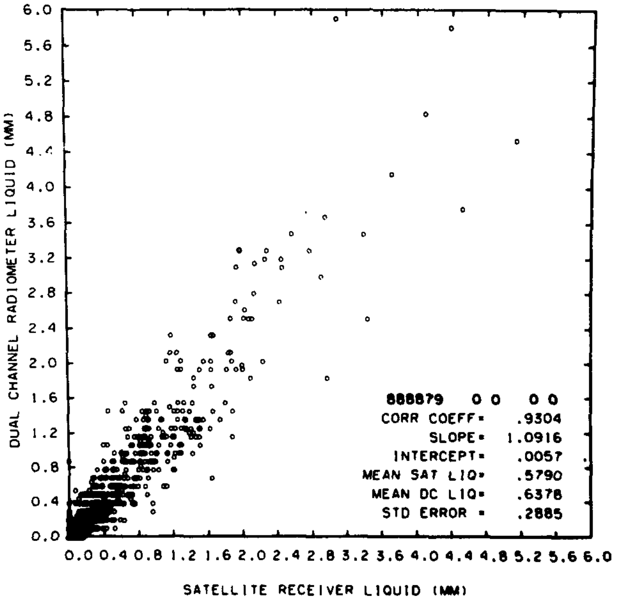

FIG. 2. Comparison of cloud liquid measured by dual-channel radiometer (ordinate) and satellite receiver (abscissa). Measurements were made during August 1979, at the National Weather Service Forecast Office, Denver, Colorado.

In summary, we find that preliminary comparison of integrated cloud liquid measured by independent ground-based microwave instruments and techniques show good agreement with a bias of ~11% (System 1 being high) and an rms error of 0.28 mm. However, further data on a wide variety of cloud types must be acquired before an instrumental bias can be verified. Nevertheless, the consistency in integrated liquid measured by the two techniques appears to confirm satisfactory accuracy for the dual-frequency radiometric technique, System 1. Because of their ability to measure liquid in clouds, both of these systems are of interest in weather-modification experiments. Currently, measurements using System 2 are being compared with liquid water measured by probes on an aircraft flying near the transmission path.

REFERENCES

Frank, N. H., 1950: *Introduction to Electricity and Optics.* McGraw-Hill, 440 pp.

Guiraud, F. O., J. Howard and D. C. Hogg, 1979: A dual-channel microwave radiometer for measurement of precipitable water vapor and liquid. *IEEE Trans. Geosci. Electron.*, **GE-17**, 129–136.

Snider, J. B., H. M. Burdick and D. C. Hogg, 1980: Cloud liquid measurement with a ground-based microwave instrument. *Radio Sci.* **15** (in press).