Rainfall Intensity Estimation by Ground-Based Dual-Frequency Microwave Radiometers

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ABSTRACT

Many investigators have used satellite data to derive rainfall intensity and to compare them with rain gauge data. However, there has always been a problem: what is the optimal time period for the two different types of data? A set of well-controlled data collected by ground-based dual-frequency microwave radiometers at the National Central University (24.9°N, 121.1°E) in Taiwan between January of 1996 and December of 1997 was used to find the answer. The results show that a 1-h interval would be the optimal time period and that hourly data will provide a better accuracy than other options (5, 10, or 30 min or 2 h). Two algorithms, the differential and the brightness temperature, were established to estimate rainfall intensity using ground-based dual-frequency microwave brightness temperature and rain gauge data. The results show that the root-mean-square error and the correlation coefficient are 0.63 mm h^{-1} and 0.88, respectively, for the differential method, and 0.91 mm h^{-1} and 0.71 for the brightness temperature method. The analysis also shows that because the atmospheric background and environmental influence in the continuous observations are identical, the changes in brightness temperature are only caused from the changes in liquid water content in the air. That probably made the differential method a better choice for rainfall intensity estimation than the brightness temperature method. Moreover, ground-based radiometers measure downwelling radiation from bottom up, and little ice-particle scattering or horizontal inhomogeneity is involved. The results can be compared with retrievals from satellite microwave radiometers for a better understanding of the physics of microwave emission and scattering due to raindrops or ice particles.

1. Introduction

Rainfall information is important not only for human activities but also in the study of global energy transformation, atmospheric circulation, and climate analysis. Many investigators have focused upon getting better rainfall intensity information. Generally speaking, the weather stations that provide rainfall information are still insufficient, both spatially and temporally. It is therefore difficult to get enough data for the relevant research. Fortunately, meteorological satellites can provide extensive satellite remote sensing data that can be used to estimate the rainfall intensity.

Earlier research on rainfall intensity estimation used satellite infrared or visible data. However, significant errors existed because these channels could not penetrate cloud layers. The rainfall intensity was frequently overestimated when high cirrus clouds or anvil clouds appeared in the field of view. Contrary to such infrared and visible data, microwave channel data are less influenced by cloud layers and therefore more suitable for rainfall intensity estimation (Liu and Curry 1992; Negri et al. 1994; Barrett and Bellerby 1992; Ferraro et al. 1992; Grody 1991; Spencer et al. 1989). In fact, the importance of microwave remote sensing to better rainfall estimation has been demonstrated by some new experiments, such as the Tropical Rainfall Measuring Mission and the Earth Observing System.

Two theories, the emission and the scattering, are frequently adopted to estimate rainfall intensity with microwave data (Janowiak et al. 1995). The former uses the observed emission radiation of atmospheric liquid particles to estimate the rainfall intensity. The observed radiation is sensitive to the surface emissivity, so it is only applied in ocean areas owing to the sea surface

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emissivity being low and homogenous, and it is believed that this theory is more appropriate for rainfall estimation in areas beneath stratified clouds or shallow convective clouds. The latter method may be employed to estimate rainfall intensity by measuring the extinction of microwave radiation caused by particles of liquid water or ice. However, it is only suitably applied to deep convective systems.

Therefore, the accurate retrieval of rainfall intensity from satellite data must involve the scattering and emission signals, respectively, which makes the retrieval process complex. Moreover, much research has used ground-based rain gauge data to evaluate the accuracy of the rainfall intensity estimation of satellite data. There has always been the problem that the sensors mounted on satellites measure a whole vertical column, but that raindrops or ice particles aloft do not fall to the ground instantly. It is thus only meaningful to compare the rain gauge–measured rainfall intensity with those retrieved from satellite data for a certain time period. However, what is the optimal time period? It is difficult to answer this question for satellite data because of the poor time resolution. On the other hand, the well-controlled data collected by ground-based microwave radiometers could be useful in answering this question because of continuous measurements. Moreover, ground-based microwave radiometers measure the downwelling radiation so only a little inhomogeneity is involved, and the signals come only from the emission of atmospheric liquid particles so the signal of ice scattering is not involved. All the above advantages make the retrievals simpler and more suitable in comparison with satellite retrievals, leading to a better understanding of the physics of microwave emission and scattering due to raindrops or ice particles.

The relative research using ground-based microwave radiometer data began in the 1970s (Ulaby et al. 1986). Guiraud et al. (1979) used a dual-channel microwave radiometer to measure the precipitable water vapor. They indicated that ground-based microwave radiometer data can be used to monitor precipitable water vapor better than conventional radiosonde data can. Westwater (1978) also investigated the accuracy of the estimation of water vapor and cloud liquid water using ground-based microwave radiometer data. Gao et al. (1992) compared different techniques for precipitable water vapor estimation using downlooking, near-infrared, and infrared imaging systems and uplooking microwave radiometers. Their estimates agreed within 0.1 cm of precipitable water vapor. Snider et al. (1995) used ground-based microwave radiometer data for climate research. Some investigators have estimated the vertical water vapor structure by combining different data sources (Han and Westwater 1995; Stankov et al. 1995; Feltz et al. 1996; Spankuch et al. 1996). As compared with the research about precipitable water vapor and liquid water, papers about rainfall intensity estimation using ground-based microwave radiometer data have been fewer. It has motivated us to develop an algorithm for rainfall intensity estimation. The purpose of this study is to find the optimal time period for comparing rain gauge data and radiometry data and to establish an algorithm for rainfall intensity estimation.

TABLE 1. Instrument specifications.

Frequency (GHz)	19.25 22.235
Bandwidth (double size)	1 GHz
Beamwidth (°)	25
Absolute accuracy	0.5–1
Sample time (s)	0.01, 0.05, 0.1, 5, 10
Antenna dimensions (in.)	16 × 9 × 4.5
Antenna weight (lb)	15
Instument controller dimension (in.)	15 × 17 × 7
Instrument controller weight (lb)	25

A short description of the collection and processing of ground-based dual-frequency microwave radiometer and rain gauge data is given in section 2. Section 3 illustrates the methodology used in this paper for rainfall intensity estimation. A discussion and analysis of the results are shown in section 4, and a preliminary summary is shown in section 5.

2. Data

A set of ground-based dual-frequency microwave radiometers was used in this study. They were manufactured by Scientific Technology, Incorporated. This set has been in operation continuously for four years (from January of 1996 to the present) at the National Central University (hereinafter NCU; at 24.9°N, 121.1°E) except for the period of field experiments. The basic characteristics are shown in Table 1. They are operated at 19.25 and 22.235 GHz (hereinafter 19 and 22 GHz), also often used by satellite-borne sensors in rainfall estimation (e.g., Wilheit et al. 1991). The sampling time of these radiometers is changeable (0.01, 0.05, 0.1, 5, 10 s) but has been fixed at 5 s during their operation. The antennas were set at a 45° zenith angle, and a big fan had been set behind the antennas to keep raindrops from falling on the antennas themselves (Fig. 1). To avoid stray radiation from the ground or nearby objects, all unnecessary objects were removed. Also, regular calibration (every six months) of the instruments has been done to correlate the radiometer readings to the absolute antenna temperature and to ensure the data quality. Because a linear relationship exists between the output voltage and the reading temperature, once this relationship is derived, the calibration can be done. In this paper, the controlled room temperature of a black body is set as the warm reference point, and the measured temperature under the situation that the antenna was input and holding radar absorber dipped in liquid nitrogen is set as the cold reference point. The calibration of the instruments can be finished with the aforementioned referenced temperature points and the corresponding voltages.

A tipping bucket rain gauge was used. The rain gauge

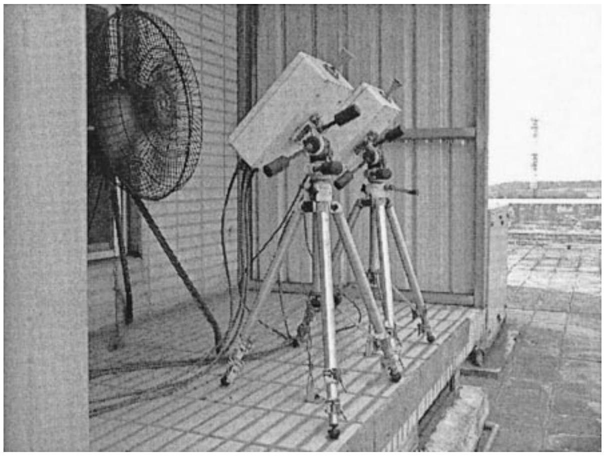

FIG. 1. Surface view of a dual-channel microwave radiometer set.

unit is in millimeters. If the rainfall amounts are larger than 0.3 mm, the bucket will empty and a computer will record the accumulated rainfall instantly. The bucket will also automatically empty once per minute. It is about 300 m between the radiometer and rain gauge locations.

For the purposes of determining the optimal time period for comparisons between rain gauge and rainfall estimations derived from radiometer data, the mean brightness temperature (K) and the rainfall intensity (mm t^{-1}) for 5 time intervals t (5, 10, and 30 min and 1 and 2 h) were calculated and analyzed. The effective samples from January of 1996 to December of 1997 are shown in Table 2.

TABLE 2. The number of effective samples between Jan 1996 and Dec 1997.

Time interval	5 min	10 min	30 min	1 h	2 h
No.	115 586	57 890	18 981	8895	4446

3. Methodology

Much previous research has shown that a good relationship between the microwave brightness temperature and the rainfall intensity exists under certain conditions. Therefore, we try to find this relationship and use it to establish a rainfall intensity estimation model using ground-based dual-frequency microwave brightness temperature data.

For this study, two different estimation methods actually were tested. The first one was the differential method. This method determines the relationship between temporal changes in rainfall intensity and brightness temperature. Because the microwave brightness temperature is influenced by the precipitation, it is reasonable to estimate the rainfall intensity using temporal changes in the brightness temperature. The advantages to this approach are that any unwanted stray radiation from the ground or nearby objects can be eliminated, and the problem of beamfilling of the wide lobe angle (25°) can be reduced. In addition, because the minimal measurement resolution of the rain gauge is 0.3 mm, any rainfall intensity smaller than 0.3 mm t^{-1} is discarded to assure the quality of the data. The differential method can be written as follows:

$$R_i = R_{i-1} + \Delta R_i$$
$$\Delta R_i = a + b\Delta \mathrm{Tb}_{19i} + c\Delta \mathrm{Tb}_{22i}, \qquad (1)$$

where R is the rainfall intensity; Tb is the brightness temperature; Δ is the temporal change in the rainfall intensity or the brightness temperature; i is the time index; 19 and 22 are the values observed at 19 and 22 GHz, respectively; and a, b, and c are the curve-fitting coefficients. Temporal changes in the rainfall intensity can be derived easily by substituting temporal changes in the brightness temperature at 19 and 22 GHz into Eq. (1). The rainfall intensity then can be estimated by adding any temporal changes in rainfall intensity into the rainfall intensity for the previous time step.

The second method is the brightness temperature method. It can find the relationship between the brightness temperature and the instantaneous rainfall intensity as follows:

$$R = a + b \ln(280 - \mathrm{Tb}_{19}) + c \ln(280 - \mathrm{Tb}_{22}). \qquad (2)$$

The rainfall intensity can be derived by substituting the observed brightness temperature at 19 and 22 GHz into Eq. (2).

4. Results and analysis

In the differential method, one-half of the precipitation data were picked up randomly as training data to determine the relationship of hourly changes in the rainfall intensity and in the brightness temperature at 19 and 22 GHz from January of 1996 to December of 1997 at NCU (Figs. 2a,b). The relationships between temporal changes of different time periods for dual channel in the rainfall intensity and in the brightness temperature were examined and are shown in Fig. 3. The variance (R^2) of hourly change is larger than those for the other time periods. Therefore, a 1-h time period serves to be the optimal time period. In addition, the dual-channel mode was tested through training data for a 1-h time period, and it showed that a better correlation could be reached than for the single-channel mode (Table 3).

For the brightness temperature method, one-half of the precipitation data were picked up randomly as training data to determine the relationship between rainfall intensity and brightness temperature of a 1-h period at 19 and 22 GHz from January of 1996 to December of 1997 at NCU (Figs. 4a,b). The relationships of different time periods for dual channel were examined and are shown in Fig. 5. The R^2 of a 1-h period is also larger than the others. The dual-channel mode was also tested

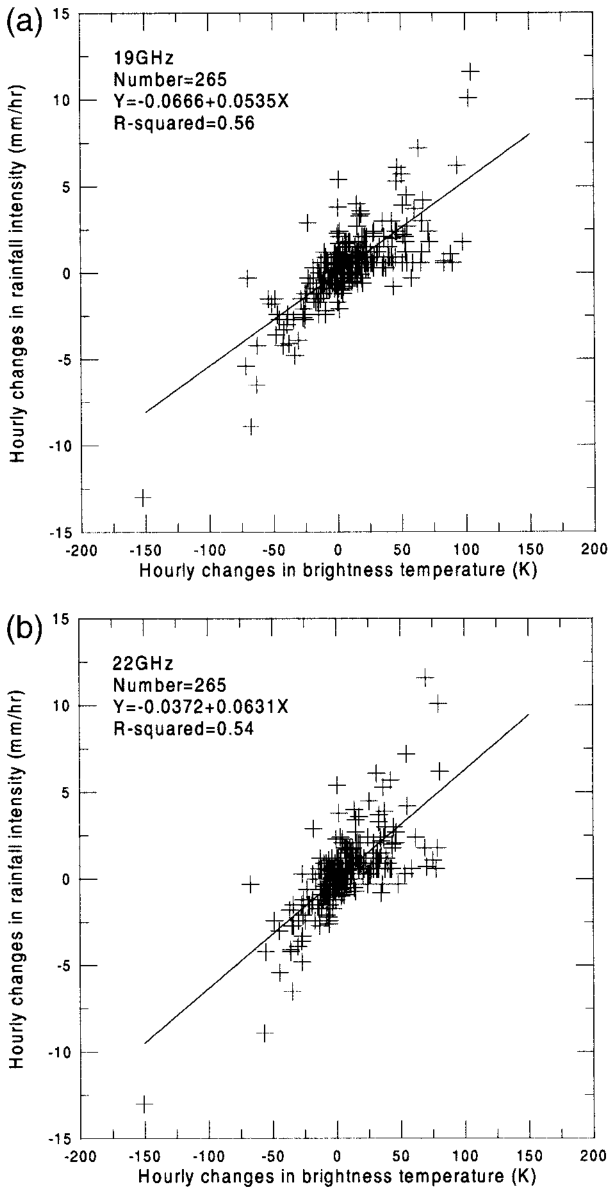

FIG. 2. (a) The relationship between hourly changes in the rainfall intensity and in the brightness temperature at 19 GHz from Jan 1996 to Dec 1997 at NCU. (b) Same as (a) but for 22 GHz.

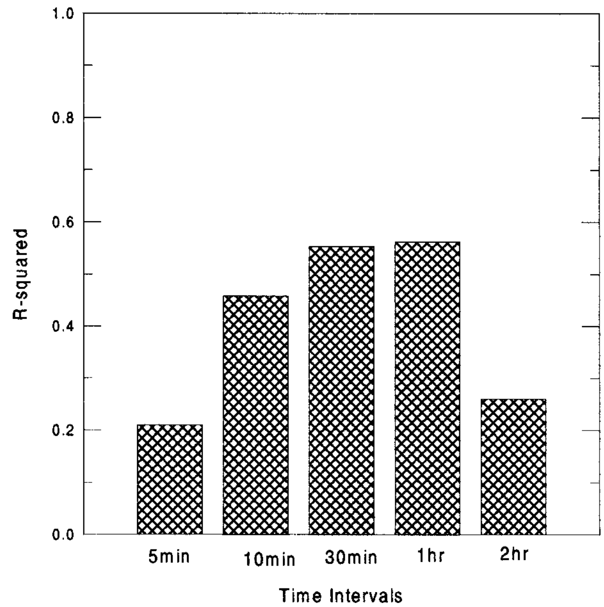

FIG. 3. Variance for different time periods between temporal changes in the rainfall intensity and in the brightness temperature.

through training data, and it showed that a better correlation could be reached than with the single-channel mode (Table 4). Therefore, the optimal time period for the brightness temperature method will also be a 1-h period.

In fact, it is important for our estimation to determine from the brightness temperature observation whether it is raining. All nonprecipitation observations from January of 1996 to December of 1997 were used to establish the appropriate no-rainfall indicator. Histograms for the brightness temperature of nonrainfall observations at 19 and 22 GHz are shown in Figs. 6a and 6b, respectively. The maximum brightness temperature frequency appeared at about 72.58 and 119.26 K, with standard deviations at 14.09 and 26.25 K for 19 and 22 GHz, respectively. Thus, for rainfall observations, the observed brightness temperature for 19 and 22 GHz must be larger than 72.58 and 119.26 K, respectively.

To test the methods above, the remaining one-half of data observed between January of 1996 and December of 1997 were used as testing data. The correlation coefficient and the root-mean-square error (rmse) for the observed and estimated rainfall intensity are determined to be 0.88 and 0.63 mm h^{-1}, respectively, by using the differential method (Fig. 7). Although the number of larger rainfall samples (>10 mm h^{-1}) is insufficient, there is still a good consistency between the estimated rainfall intensity and the observed rainfall intensity. Figure 8 shows the correlation coefficient and rmse for both the observed and the estimated rainfall intensity using the brightness temperature method. They are 0.71 and 0.91 mm h^{-1}, respectively.

Except for the regions near the equator or the North and South Poles, the atmospheric backgrounds of most areas vary seasonally because of different weather systems. For instance, the northerly polar dry and cold high is the dominating weather system in the winter near Taiwan but switches to the southerly tropical wet and

TABLE 3. The curve-fitting results of hourly changes in the brightness temperature and in the rainfall intensity from Jan 1996 to Dec 1997: $\Delta R_i = a + b\Delta Tb_{19i} + c\Delta Tb_{22i}$.

Coefficient	a	b	c	R^2
19 GHz	−0.1124	0.0515		0.5265
22 GHz	−0.0879		0.0581	0.4819
Dual-channel	−0.1115	0.0556	−0.0049	0.5267

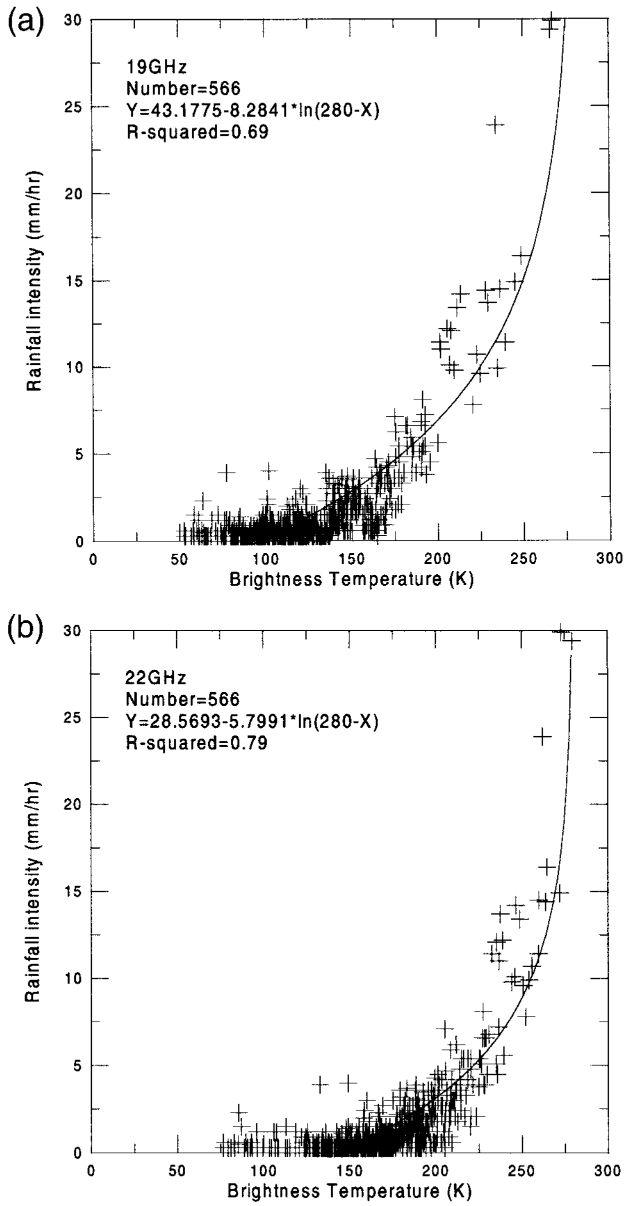

FIG. 4. (a) The relationship between the hourly rainfall intensity and brightness temperature at 19 GHz from Jan 1996 to Dec 1997 at NCU. (b) Same as (a) but for 22 GHz.

warm high in the summer. Consequently, the average nonprecipitation brightness temperature in the summer is higher than that in winter, causing some samples of the radiometers measured in the warm and wet (cold and dry) season possibly to be viewed incorrectly as precipitation (nonprecipitation) because of their larger (smaller) brightness temperature. Theoretically, this kind of mistake will not appear when applying the differential method, because the estimation is dependent on the relationship between the temporal changes in rainfall intensity and in brightness temperature. That reason probably is why the differential method results

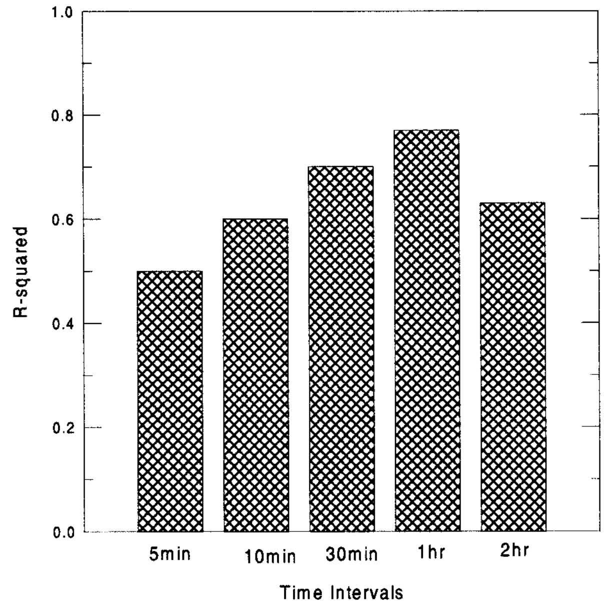

FIG. 5. Variance for different time periods between the rainfall intensity and the brightness temperature.

are better than the brightness temperature ones when rainfall intensity was smaller than 3 mm h^{-1} (Figs. 7 and 8). Besides, the environmental influence is identical in continuous observations, causing changes in brightness temperature to come only from the changes in liquid water content in the air. In contrast, the observed brightness temperature includes information from both environment and liquid water content. This may also explain why the differential method has better results.

Moreover, for showers that sometimes bring heavy rainfall but suddenly stop (or reduce to a slight rainfall), the radiometers may have detected a lower brightness temperature, but the rain gauge may have read a larger rainfall intensity instead. This possibility may lead to incorrect rainfall intensity estimation from the relationship between brightness temperature and rainfall intensity, but the differential method alleviates the problems by mathematical reasons [see Eq. (1)]. That may explain why some special points (A, B, C and A′, B′, C′) in Figs. 7 and 8 also show that the differential method results are better than the brightness temperature ones. In fact, the estimated rainfall intensity at these points from the brightness temperature method was significantly underestimated, because the brightness temperature made a sharp decrease leading to lower rainfall

TABLE 4. The curve-fitting results of hourly brightness temperature and rainfall intensity from Jan 1996 to Dec 1997: $R = a + b \ln(280 - Tb_{19}) + c \ln(280 - Tb_{22})$.

Coefficient	a	b	c	R^2
19 GHz	43.5867	−8.3746		0.7471
22 GHz	30.5934		−6.2446	0.7136
Dual-channel	41.0866	−6.4747	−1.5137	0.7500

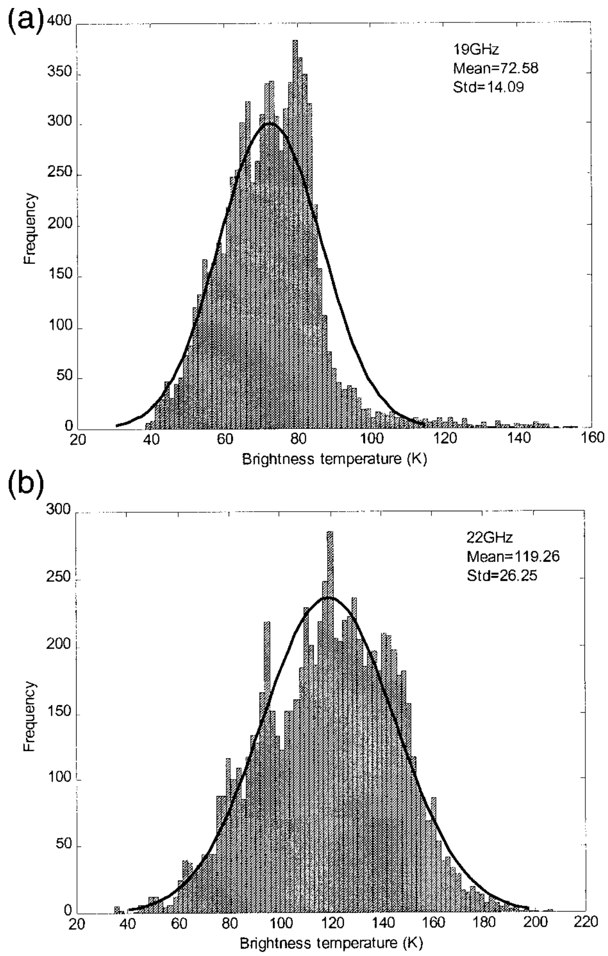

FIG. 6. (a) Histogram for the brightness temperature of nonrainfall observations at 19 GHz from Jan 1996 to Dec 1997. (b) Same as (a) but for 22 GHz.

estimation. When applying the differential method, the derived rainfall was larger because the rainfall intensity was calculated by adding temporal changes into the rainfall intensity for the previous step. The falling brightness temperature made a sharp decrease in the rainfall intensity estimation when applying the brightness temperature method. This result indicates that just after heavy rainfall the differential method may provide a better choice for estimating the rainfall intensity than the brightness temperature method does.

5. Summary

A set of well-controlled data collected by the ground-based dual-frequency microwave radiometers at the National Central University of Taiwan (24.9°N, 121.1°E) from January of 1996 to December of 1997 was used to find the optimal time period for the comparisons between rain gauge rainfall intensity and those retrieved from radiometer data. The results show that a 1-h period will provide a better accuracy than the other options,

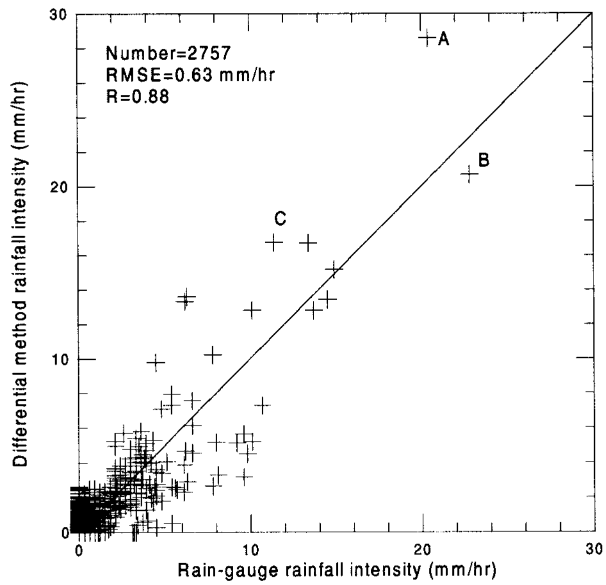

FIG. 7. The relationship of the observed rainfall intensity and the estimated rainfall intensity using the differential method, from Jan 1996 to Dec 1997.

and the appropriate choice in optimal time period is very important in reducing rmse.

Two algorithms, the differential and the brightness temperature, were established for the rainfall intensity estimation by using ground-based dual-frequency microwave brightness temperature and rain gauge data. The results show that rmse and the correlation coefficient are 0.63 mm h^{-1} and 0.88, respectively, for the differential method and 0.91 mm h^{-1} and 0.71 for the

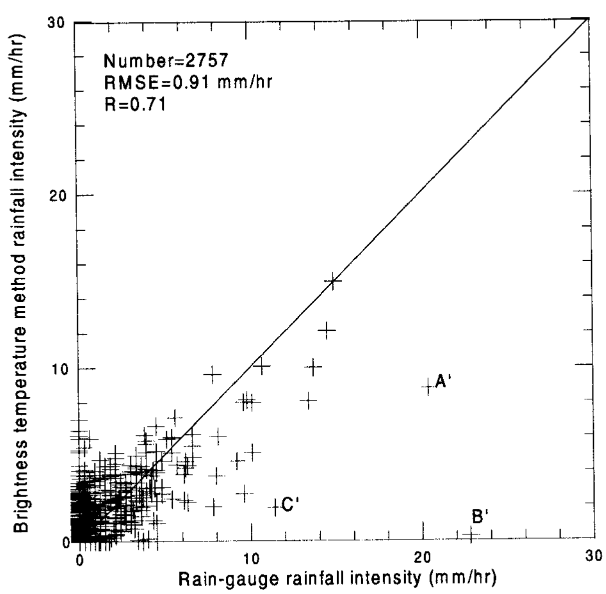

FIG. 8. The relationship of the observed rainfall intensity and the estimated rainfall intensity using the brightness temperature method, from Jan 1996 to Dec 1997.

brightness temperature method. Because the atmospheric background and environmental influence in the continuous observations are identical, the changes in brightness temperature are caused only by the changes in liquid water content in the air. The rainfall intensity of the differential method was calculated by adding temporal changes in rainfall intensity into the rainfall intensity for the previous time step. That probably made the differential method results better, so the differential method should be a better choice for estimating rainfall intensity than the brightness temperature method is.

The application of satellite-borne microwave sensors has dominated visible and infrared sensors, because of its superior capacity to penetrate cloud layers. It is an obvious fact that the microwave band will become a mainstream tool in rainfall monitoring. Hence, more investigations and comparisons under different weather systems (e.g., stratiform and convective clouds) are necessary. The estimated rainfall information by ground-based radiometers can be compared with retrievals from satellite microwave radiometers for a better understanding of the physics of microwave emission and scattering due to raindrops or ice particles. Related research will be done in the future.

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