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Analysis of integrated cloud liquid and precipitable water vapor retrievals from microwave radiometers during the Surface Heat Budget of the Arctic Ocean project

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Abstract. We investigated a variety of factors that influence the determination of precipitable water vapor (V) and integrated cloud liquid (L) by dual-channel microwave radiometers (MWRs). These factors include radiometric calibration; dry, water vapor, and liquid absorption coefficients; and physical versus statistical retrieval methods. We then applied the analysis to the MWR that was operated by the Atmospheric Radiation Measurement Program (ARM) during the Surface Heat Budget of the Arctic Ocean project. In the work reported here, MWR data taken from April 1 to July 31, 1998, were analyzed. Data acquired in situ did not always agree with the original MWR liquid retrievals, with MWR estimates at times being too large by perhaps a factor of 2. These differences led us to examine in detail several of the assumptions that go into V and L retrievals. The radiometer was carefully examined and found to be well calibrated with a 0.3 K RMS error. The predicted accuracy in the L retrievals, for this 0.3 K RMS radiometric error and a statistical retrieval, was 25 g m^{-2} RMS. This accuracy improves to 10%, if we use the improved knowledge of cloud temperature, as can be obtained using radiosondes and cloud radar/lidar measurements. We also studied the degree to which different clear air and cloud liquid models have an effect on V and L retrievals. The most significant changes from the original ARM retrievals were due to the dry opacity and the cloud liquid dielectric model. Although nothing was found in the original ARM data that was grossly incorrect, application of these models reduced the original ARM retrievals by roughly 20 to 30%. The change of clear-air absorption model from the original to a more recent one has little impact on V retrievals except when V is $<$0.5 cm.

1. Introduction

Dual-frequency, ground-based, microwave radiometers (MWRs) have been used for more than 20 years to derive columnar amounts of both water vapor and cloud liquid [*Hogg et al.*, 1983], and a large number of studies have been made comparing retrievals of precipitable water vapor (V) by MWRs versus radiosondes [*Elgered et al.*, 1982; *Westwater*, 1993] and versus Raman lidar [*England et al.*, 1992; *Han et al.*, 1994]. Comparisons of MWR cloud liquid retrievals are much more limited, primarily because cloud liquid is not a quantity routinely measured by radiosondes. However, MWR retrievals of cloud liquid for warm stratocumulus clouds have compared well with both in situ aircraft and adiabatic estimates [*Albrecht et al.*, 1990; *Fairall et al.*, 1990]. Although MWRs have been used extensively for research on supercooled liquid clouds in winter storms [*Snider and Rottner*, 1982; *Rassmussen et al.*, 1992], comparisons with in situ measurements are scarce. However, the recent arctic experiment Surface Heat Budget of the Arctic Ocean (SHEBA) allowed several comparisons with aircraft in situ data [*Curry et al.*, 2000]. Data acquired in situ did not always agree with the original MWR liquid retrievals, with MWR estimates at times being too large by perhaps a factor of 2. These differences led us to examine in detail several of the assumptions that go into V and integrated cloud liquid (L) retrievals. As a preliminary to our analysis, we first outline the steps taken in moisture retrieval. We then examine several contemporary absorption algorithms for both clear and cloudy skies, and then evaluate differences in moisture retrieval using these algorithms. Finally, we apply these algorithms to the SHEBA MWR data and compare both the original and revised retrievals with each other and with aircraft in situ measurements.

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2. Retrieval Methods

The MWR that was operated during SHEBA was one of the operational units from the Atmospheric Radiation Measure-

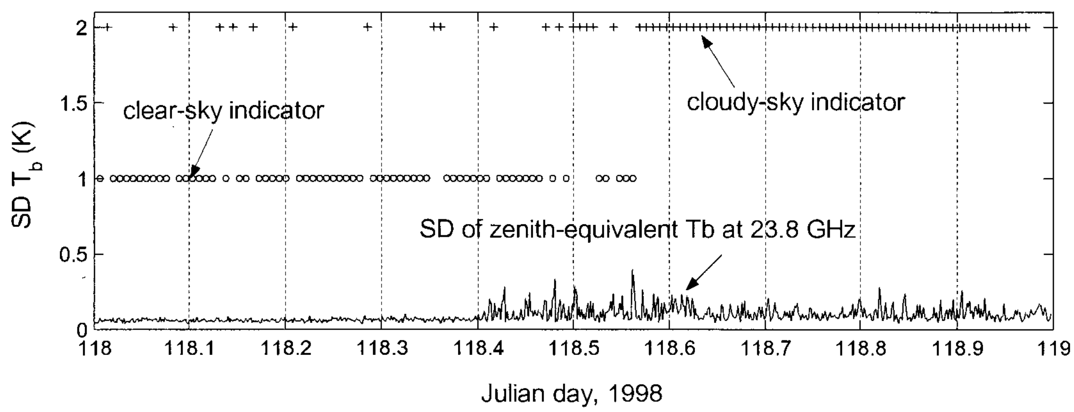

Figure 1. Standard deviation (SD) of equivalent zenith T_b at 23.8 GHz for the MWR as a function of Julian Day 1998 during the SHEBA experiment. Cloudy-sky indicators derived from a combination of lidar and cloud-radar data.

ment (ARM) program [*Stokes and Schwartz*, 1994], and a complete description of this instrument is given by *Liljegren and Lesht* [1996]. The MWR measures brightness temperature T_b at two frequencies: 23.8 and 31.4 GHz. Because of the relative sensitivities of the channels to vapor and liquid, the first and second channels may be called "vapor" and "liquid" channels, respectively. Because T_b is not a linear function of V and L over the range of atmospheric variation of these quantities, it is customary to convert the data into a quantity that is linear; i.e., the opacity τ [*Westwater*, 1993]. We derive opacity τ from the two T_b using the mean radiating temperature T_{mr} and cosmic background temperature T_c:

$$\tau = \ln\left(\frac{T_{mr} - T_c}{T_{mr} - T_b}\right). \tag{1}$$

In (1), T_b is a measured quantity, and T_c (= 2.75 K) is accurately known [*Janssen*, 1993], but T_{mr} is estimated from radiosondes, from surface temperature measurements, or simply from climatology. We then express τ in terms of mass absorption coefficients of water vapor κ_V, cloud liquid water κ_L, and dry opacity τ_d:

$$\tau = \tau_d + \kappa_V V + \kappa_L L. \tag{2}$$

In reality, the mass absorption coefficients κ_V or κ_L depend on the vertical profiles of temperature T, pressure P, and water vapor density ρ_V or cloud liquid density ρ_L. Next, we derive τ from measurements T_b at two frequencies v_1, v_2 and solve for V and L:

$$\begin{pmatrix} V \\ L \end{pmatrix} = \begin{pmatrix} \kappa_{V1} & \kappa_{L1} \\ \kappa_{V2} & \kappa_{L2} \end{pmatrix}^{-1} \begin{pmatrix} \tau_1 - \tau_{1d} \\ \tau_2 - \tau_{2d} \end{pmatrix}. \tag{3}$$

The resulting equations are of the form

$$\hat{V} = c_0 + c_1\tau_1 + c_2\tau_2, \tag{4}$$

$$\hat{L} = b_0 + b_1\tau_1 + b_2\tau_2. \tag{5}$$

We note that (4) and (5), as well as T_{mr}, contain terms that depend on the vertical profiles of T, P, ρ_V, and ρ_L. This information is usually not available on the timescale of the MWR observations, and in the case of ρ_L it is not available at all. We usually estimate these background profiles and couple them with the microwave radiative transfer equation (RTE) [*Janssen*, 1993] to provide estimates of V and L. In addition, minimum variance estimation techniques [*Westwater*, 1993] over an a priori ensemble of profiles lead to equations of the same form as above. The original ARM MWR retrieval algorithms used linear statistical estimation that was based on the oxygen and water vapor absorption coefficient algorithms of *Liebe and Layton* [1987] and the liquid water dielectric constants given by *Grant et al.* [1957].

A single-frequency technique to derive L is possible if a radiosonde profile is available to evaluate τ_d and κ_V:

$$\hat{L} = (\tau - \tau_d - \kappa_V V)/\kappa_L. \tag{6}$$

A variation of this technique (not used here) is to use the radiosonde-measured profiles of T, P, and ρ_V in the RTE model, and then to adjust L until measurements and calculations agree.

3. Issues in the Retrieval of V and L

3.1. Calibration of the Microwave Radiometer

The calibration of the MWR was accomplished through a set of scanning observations that also use measurements of an internal blackbody target and a noise diode, in the so-called "tip cal method" [*Hogg et al.*, 1983; *Han and Westwater*, 2000; *Liljegren*, 2000]. During SHEBA the ARM MWR performed a series of symmetrical scans from zenith to an airmass of 1.5 (elevation angle of 41.8°) that provided the basis of calibration. The quality of the tip cal can be judged in a variety of ways. We used a method that relies on the standard deviation (SD) of equivalent zenith brightness temperatures SD T_b as a measure of calibration quality [*Han and Westwater*, 2000] and find that at least during clear days when the tip cal could be performed, the absolute accuracy of the radiometer was excellent: of the order of 0.3 K RMS. However, as evidenced by negative cloud liquid retrievals on a few occasions, the MWR may have had small calibration drifts. In Figure 1 we present a time series of SD T_b during both clear and cloudy conditions. We note that during clear conditions, as identified by a lidar/cloud radar, SD T_b is generally <0.1 K RMS, but that during the presence of clouds, which tend to be poorly stratified, there is substantially more variation. To be conservative, we use 0.3 K RMS as an estimated noise level in retrieval analysis.

3.2. Dry Opacity

As is evident from (2) for total opacity, from which V and L are derived, the dry opacity τ_d is required. Although this quantity depends on atmospheric conditions, primarily surface pressure and temperature, the largest part of its uncertainty comes from the molecular absorption model used for its evaluation. In this work, we compare three contemporary absorption models [*Liebe and Layton*, 1987; see also *Liebe*, 1989; *Liebe et al.*, 1993; *Rosenkranz*, 1998]. For convenience, we will refer to these models as Liebe87, and Liebe93, and Rosenkranz98. Table 1 shows the average and standard deviation of $\boldsymbol{\tau}_\mathbf{d}$ calculated from an a priori database of Arctic soundings. Here, and in other portions of the text, we use a bold face quantity to represent a vector. This database was constructed from 7 years of radiosonde soundings (1990 to 1996) at Barrow, Alaska. We note first that the differences in the averages between the models are much greater than the climatological variations for a given model. We also note that the differential contributions to the brightness temperatures from the dry component of the three models can be as large as 0.5 K. A difference of this magnitude could certainly be a factor in retrievals of V and L, especially during dry Arctic conditions. Using the Rosenkranz98 model would reduce the amount of inferred liquid or vapor relative to the original ARM data, which used Liebe87.

3.3. Water Vapor Absorption Coefficients

In both dual-frequency (equation (3)) and single-frequency (equation (6)) retrievals, the mass absorption coefficients κ_V enter directly. From our a priori database of Arctic soundings, we computed averages and standard deviations of κ_V and show the results in Table 1. We note that Rosenkranz98 and Liebe87 give comparable results for κ_V, and that Liebe93 is 5 to 10% larger. Thus only the use of Liebe93 would result in differences in either V or L from the original ARM retrievals.

3.4. Cloud Liquid Water Absorption Coefficients

Again, from the basic opacity and moisture retrieval equations, we find that κ_L plays an important role. In addition to uncertainties in determining κ_L from different models, an additional uncertainty arises if the effective temperature of a cloud is unknown. The strong temperature dependence of the dielectric constant of liquid water has been known for more than 40 years [*Grant et al.*, 1957]. Here we evaluate the uncertainties in both V and L retrievals using the dielectric constant equations from three sources [*Grant et al.*, 1957; *Rosenberg*, 1972; and *Liebe et al.*, 1991]. We also assumed Rayleigh absorption, for which the liquid absorption depends only on the total liquid amount and does not depend on the drop size distribution. When the dielectric models are coupled with the Rayleigh absorption equations, we refer to the resulting κ_L models as Grant57, Rosenberg72, and Liebe91. The strong temperature dependence of κ_L is present in all three models, but to differing degrees. The original ARM retrievals were generated using Grant57, and this model had been used by the Environmental Technology Laboratory (ETL) for several years. The model has given good agreement with adiabatic assumptions during conditions of warm stratus clouds [*Albrecht et al.*, 1990]. However, the laboratory data from which this model was developed were taken at temperatures above 0°C. The Rosenberg72 model had been used for several years by Soviet investigators [*Stepanenko et al.*, 1987], and some laboratory data taken at about −8°C were used in the development of this model. Finally, *Liebe et al.* [1991] developed the third model, based on a variety of laboratory data, some of which were taken at temperatures as low as −4°C. Figure 2 shows our calculations of κ_L at 23.8 and 31.4 GHz for each model as a function of cloud temperature. Note the significant departures between the models at temperatures below −10°C.

Table 1. Computed Statistical Variations for Three Absorption Models of Quantities Entering into V and L Retrieval Equations[a]

	23.8 GHz	31.4 GHz
$\langle\boldsymbol{\tau}_\mathbf{d}\rangle$ ± SD, Np Rosenkranz98	0.0172 ± 0.0006	0.0283 ± 0.0011
$\langle\boldsymbol{\tau}_\mathbf{d}\rangle$ ± SD, Np Liebe87	0.0155 ± 0.0006	0.0261 ± 0.0010
$\langle\boldsymbol{\tau}_\mathbf{d}\rangle$ ± SD, Np Liebe93	0.0174 ± 0.0006	0.0285 ± 0.0011
$\langle\mathbf{T_b}\rangle$ ± SD, K Rosenkranz98	7.24 ± 0.16	10.02 ± 0.29
$\langle\mathbf{T_b}\rangle$ ± SD, K Liebe87	6.80 ± 0.16	9.45 ± 0.26
$\langle\mathbf{T_b}\rangle$ ± SD, K Liebe93	7.29 ± 0.16	10.07 ± 0.29
$\langle\boldsymbol{\kappa}_\mathbf{V}\rangle$ ± SD, Np cm^{-1} Rosenkranz98	0.0523 ± 0.0005	0.0178 ± 0.0006
$\langle\boldsymbol{\kappa}_\mathbf{V}\rangle$ ± SD, Np cm^{-1} Liebe87	0.0532 ± 0.0005	0.0179 ± 0.0007
$\langle\boldsymbol{\kappa}_\mathbf{V}\rangle$ ± SD, Np cm^{-1} Liebe93	0.0562 ± 0.0005	0.0211 ± 0.0008
$\langle\mathbf{T_{mr}}\rangle$ ± SD, K Rosenkranz98	266.4 ± 6.2	263.1 ± 6.2
$\langle\mathbf{T_C}\rangle$ ± SD, K	271.7 ± 5.8	271.7 ± 5.8
$\langle\boldsymbol{\kappa}_\mathbf{L}\rangle$ ± SD, Np cm^{-1} Liebe91	1.27 ± .21	2.09 ± .30

[a]Data from Arctic radiosonde soundings at Barrow, Alaska, from 1990–1996, May–July. $\mathbf{T_b}$ is calculated for $V = 0.0$ cm and $L = 0.0$ cm. Sample sizes are 1234 for clear air and 575 for cloudy conditions.

3.5. Model Differences in Physical Retrieval Methods

A variety of retrieval methods can be applied to determine V and L from MWR measurements, and the availability of additional information dictates which method is desirable. If, for example, knowledge of the temperature profile, cloud base height, and cloud thickness is available, a physical method that explicitly calculates κ_L is appropriate. If an MWR is operating without the availability of ancillary data, statistical inversion methods can be used. However, since this inversion problem is well posed (two parameters V and L are determined from two measurements of opacity), the retrievals are not greatly sensitive to reasonable applications of either method. However, each method requires an absorption model. To give insight into the differences between the models in inferring V and L, we studied the temperature dependence of the retrieval coefficients resulting from the method of equation (3). The retrieval coefficients for V (equation (4)) and for L (equation (5)) are shown in Figures 3 and 4, respectively. We ran a special case of $V = 1.33$ cm and $L = 106.2$ g m^{-2}, and the percentage change in the V and L retrievals, relative to the original ARM retrievals, Grant57 for the liquid model and Liebe87 for the oxygen and vapor model, is shown in Figure 5 as a function of cloud temperature. Figure 5 shows that the liquid absorption model changes result in only a small percentage change in V, but that as much as a 25% lowering of L

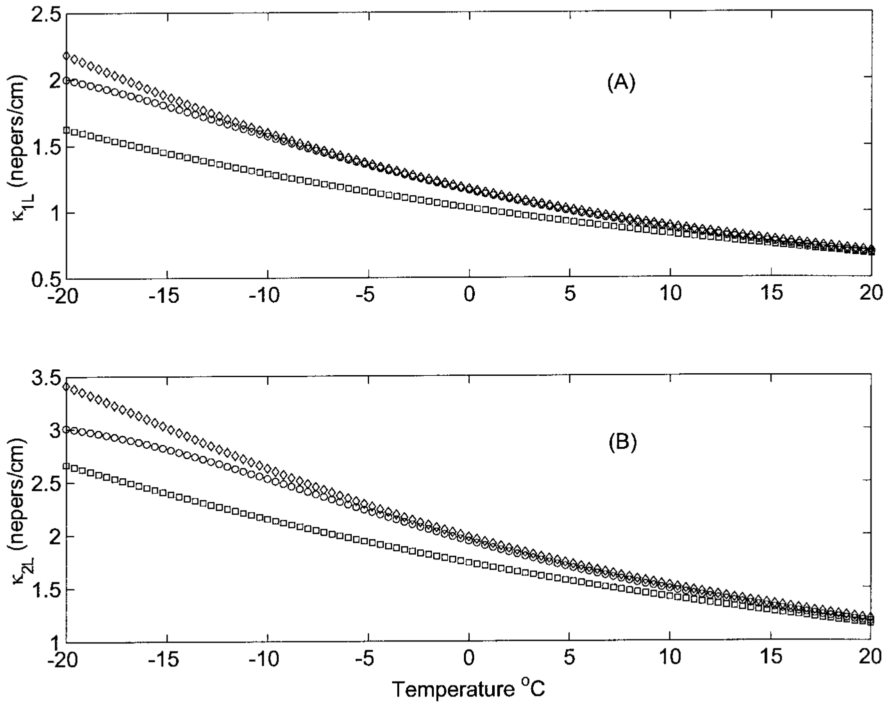

Figure 2. Mass absorption coefficient of liquid water for the models of *Rosenberg* [1972], diamonds; *Liebe et al.* [1991], circles; and *Grant et al.* [1957], squares. (a) 23.8 GHz. (b) 31.4 GHz.

could occur. These theoretical results are consistent with reanalysis of the original data, as we will show.

3.6. Physical Versus Statistical Retrieval Methods

The original ARM retrievals were performed using linear statistical retrievals in which the coefficients of (4) and (5) were evaluated over an a priori database of Arctic radiosonde profiles. For this determination the Liebe87 algorithm was used for water vapor and oxygen absorption, while the Grant57 model was used for the liquid absorption. Changing the absorption model will result in changing the coefficients in (4) and (5). However, for a given absorption model, there still could be substantial differences in the coefficients in (4) and (5) between statistical and physical algorithms for different cloud temperatures. Although statistical retrieval coefficients are constructed to provide minimum variance estimators of V and L over the training set of a priori profiles, the principal difference between the physical and statistical retrieval method is the treatment of variability in cloud temperature. Our statistical inversion method, when applied to the original SHEBA data set, had a fixed set of coefficients for each month of interest. The method also provides an estimate of the accuracy of V and L retrievals. The physical methods that we apply determine κ_V and κ_L from (1) profiles of T, P, and ρ_V interpolated in time from radiosonde soundings launched from the SHEBA site, (2) cloud base height as determined from lidar and cloud radar measurements, and (3) cloud thickness from the adiabatic assumption. The determination of effective cloud temperature T_C is required to determine κ_L and T_{mr} and the principal advantage of the physical method is the use of the additional meteorological information. To illustrate the climatological variations in the quantities directly entering into the retrieval equation (3), we show in Table 1 the means and standard deviations of various radiative quantities. We note that the largest uncertainties in absorption coefficients are in κ_L and this is caused primarily by variations in T_C. We illustrate the differences and similarities in the two methods by comparing retrieval coefficients and by estimating the accuracy of each. For this analysis we chose the Rosenkranz98 and the Liebe91 models to illustrate these effects. Since the largest contribution to the liquid and vapor errors is the uncertainty in T_C and T_{mr} [*Westwater*, 1978], we evaluate this error here. Because of the low amounts of V and L in the arctic, we can neglect errors in $\mathbf{T_b}$ relative to those in $\boldsymbol{\kappa}_\mathbf{L}$ and $\mathbf{T_{mr}}$, and differentiate (1), (4), and (5) to yield

$$\delta\hat{V} = \left(\frac{\partial c_0}{\partial T_C} + \frac{\partial c_1}{\partial T_C}\tau_1 + \frac{\partial c_2}{\partial T_C}\tau_2\right)\delta T_C + \left(c_1\frac{\partial \tau_1}{\partial T_{mr}} + c_2\frac{\partial \tau_2}{\partial T_{mr}}\right)\delta T_{mr}, \tag{7}$$

$$\delta\hat{L} = \left(\frac{\partial b_0}{\partial T_C} + \frac{\partial b_1}{\partial T_C}\tau_1 + \frac{\partial b_2}{\partial T_C}\tau_2\right)\delta T_C + \left(b_1\frac{\partial \tau_1}{\partial T_{mr}} + b_2\frac{\partial \tau_2}{\partial T_{mr}}\right)\delta T_{mr}. \tag{8}$$

We analyzed RMS errors in the retrieval of V and L that were due to a range in uncertainties in T_C and T_{mr} (see Table 1) and show the results in Table 2. The mean conditions of $T_C = -1.2°\mathrm{C}$, $V = 1.34$ cm, and $L = 106.2\ \mathrm{g\ m^{-2}}$ are assumed. For comparison, the predicted RMS errors for using linear statistical inversion are shown in the last column of Table 2. As is seen, the predicted errors using a physical and a statistical method, with the same uncertainties in T_C and T_{mr} are remarkably close. As an example, from Table 2, we can estimate the accuracy in the physical retrieval of L with a RMS temperature uncertainty of 2.5 K ($\delta L = 10\ \mathrm{g\ m^{-2}}$) versus a pure statistical retrieval (temperature uncertainty ~6.5 K) of $\delta L = 25\ \mathrm{g\ m^{-2}}$.

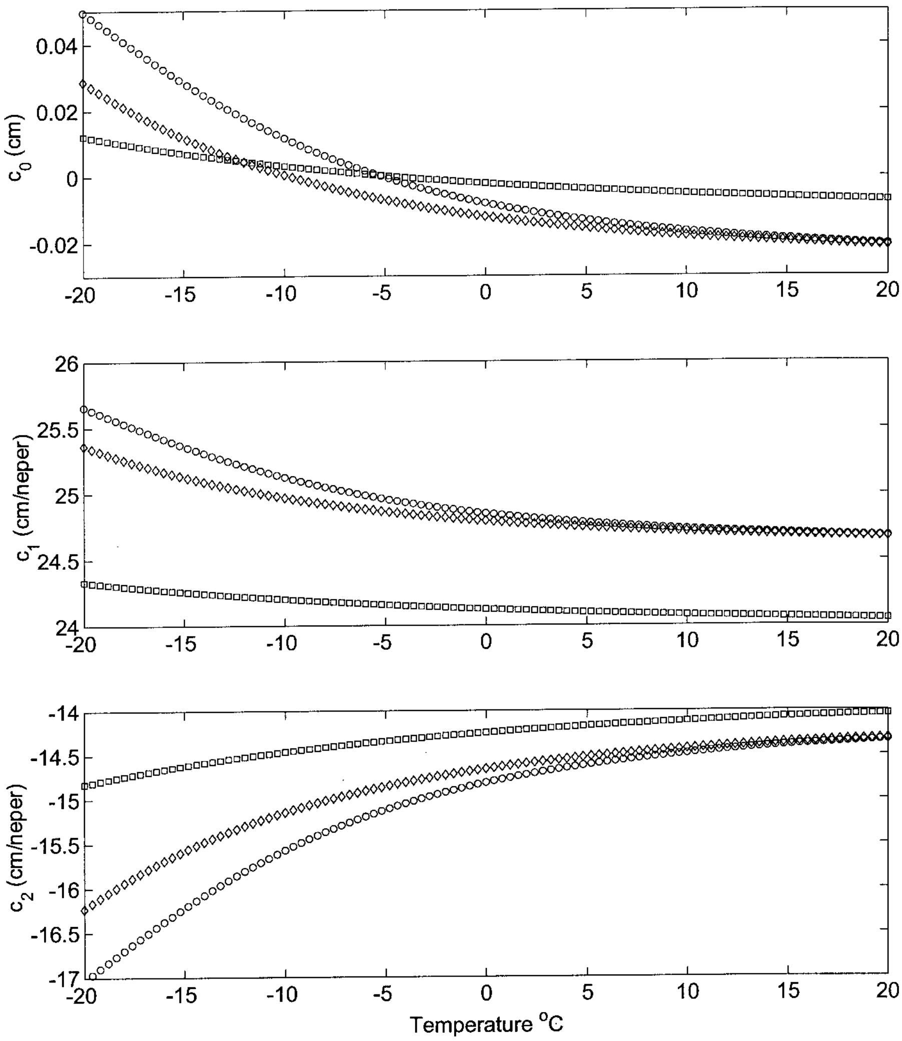

Figure 3. Retrieval coefficients for V (cm) for the three liquid absorption models discussed in the text. The labels for the cloud liquid models are the same as in Figure 2.

3.7. Methods Used in SHEBA MWR Data Analysis

As discussed in section 2, before retrieving V and L we need to estimate several parameters that enter into (3) such as T_{mr}, τ_d, κ_V, and κ_L. For physical retrievals, these parameters are usually obtained by using the estimates of profiles of T, P, ρ_V, and ρ_L and the RTE. The cloud liquid water profiles are mainly used for the computation of κ_L, which is an average of the temperature-dependent cloud liquid absorption coefficient over the cloud layer, weighted by the liquid water content profile. For SHEBA, we obtained the T, P, and ρ_V profiles by interpolating consecutive radiosonde profiles (colocated with the MWR) into the radiometer time grids. During the experiment, radiosondes were launched two to four times a day. The lidar and cloud-radar that were collocated with the radiometer provided cloud boundary measurements. The mean cloud liquid absorption coefficients κ_L, along with other parameters, were estimated iteratively when retrieving V and L. We initially assumed a small amount of L distributed through the cloud and tried both a constant liquid water content profile and an adiabatic profile as distribution functions. We found that the retrieval results were not sensitive to the distribution profiles for the cloud thickness encountered during SHEBA; these thicknesses for liquid clouds were generally <1 km. Because of the cold temperatures many of the clouds were mixed phase containing ice and supercooled liquid water. The microwave radiometer responds strongly only to the liquid. The initial liquid water and the interpolated radiosonde profiles were input into the RTE model and κ_L, and the other parameters are computed and used to retrieve V and an updated L. Then the retrieved L was used again to derive an updated κ_L with other parameters. The iteration was stopped when the difference between two consecutive L retrievals was less than a few tenths of a percent.

For linear statistical retrievals, the parameters in (3) were not directly estimated. Instead, retrieval coefficients (three for V and three for L) were derived through a linear regression. In the regression the dependent variables V and L were obtained from a historical set of radiosondes (for temperature and water vapor profiles) plus a cloud model to determine cloud liquid profiles. Simulated $\mathbf{T_b}$ and $\mathbf{T_{mr}}$ were calculated from the modeled profiles using a RTE model. Gaussian noise with zero mean and 0.3 K standard deviation was added to the simulated brightness temperatures, which were then converted to τ using (1). Our 7-year radiosonde data set collected at Barrow, Alaska, was used to derive the retrieval coefficients.

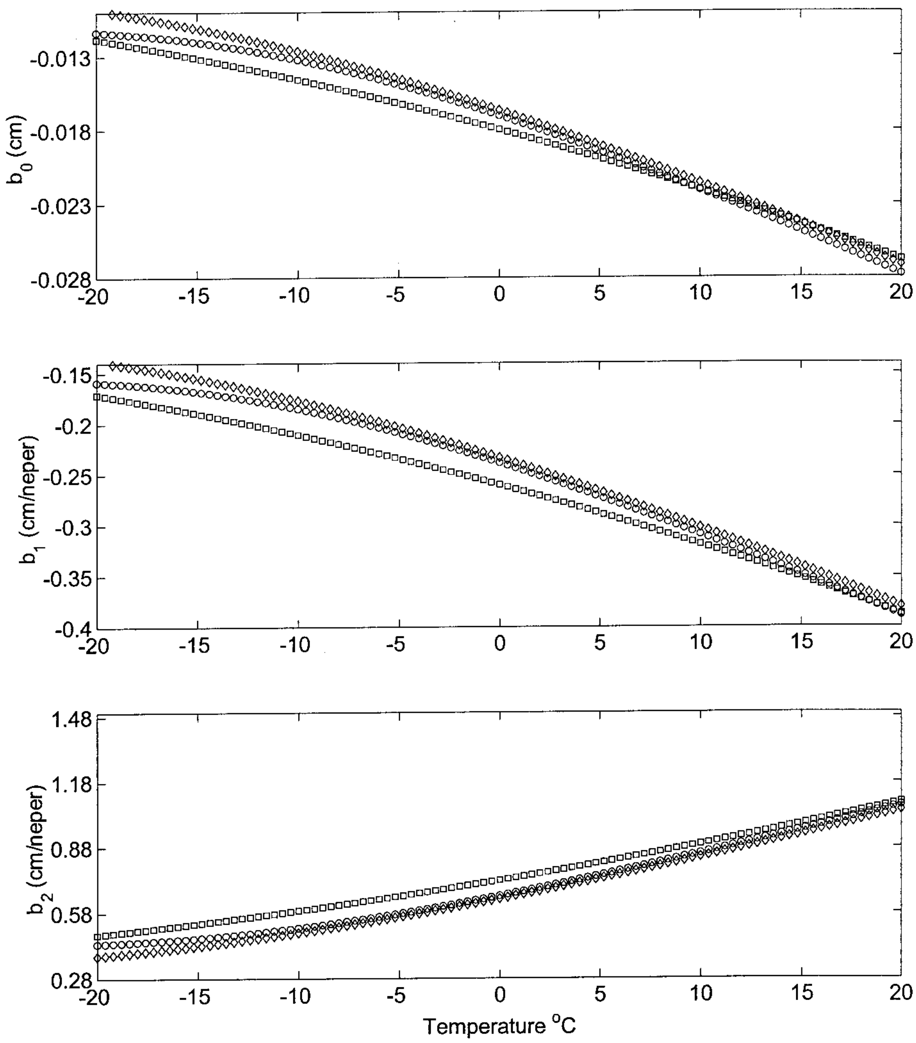

Figure 4. Retrieval coefficients for L (g m^{-2}) for the three liquid absorption models discussed in the text. The labels for the cloud liquid models are the same as in Figure 2.

4. Experimental Results

In the following we present our results. All comparisons, either between retrieval methods or between retrievals and in situ measurements, were conducted at the times when in situ measurements were available. The term "ETL retrievals," either single-channel or dual-channel ones, refers to physical retrievals when the Rosenkranz98 clear-air absorption model and the Liebe91 cloud liquid absorption model were used. The term "original" refers to the original SHEBA archived retrievals that were derived using the statistical method with Liebe87 clear-air absorption models and the Grant57 cloud liquid model. In situ measurements of cloud liquid density were taken by the King hot-wire probe [*King et al.*, 1978] and the Gerber PVM-100A probe [*Gerber et al.*, 1994] mounted in the National Center for Atmospheric Research C-130 research aircraft that flew over the SHEBA site during May 8–May 27, and July 8–July 30, 1998 [*Curry et al.*, 2000]. In the following, we will simply refer to data taken by the *King et al.* [1978] instrument as King data and data taken by the *Gerber et al.* [1994] instrument as Gerber data. With the careful preflight calibration of both of these probes that was done during SHEBA, an accuracy of 10% in ρ_L is achievable [*Gerber*, 1999; H. Gerber, private communication, 2001]. However, the spatial variability in ρ_L is usually more important than sensor accuracy in making comparisons with microwave radiometric retrievals of L.

4.1. ETL Single-Channel Versus ETL Dual-Channel Liquid Retrievals

The single-channel retrievals were derived from the 31.4 GHz channel using (6). In contrast to the dual-channel retrievals, the single-channel retrievals require an additional variable for the input data set: V must be known to account for vapor absorption from the single-channel measurements. The advantage of the single-channel retrieval algorithm is that the calibration of the 23.8 GHz channel plays no role in the retrievals. The disadvantage is that an accurate estimate of V with a fine temporal resolution was difficult to achieve during SHEBA because the interpolated radiosondes were used to estimate V. Figure 6 shows a comparison of the ETL single-channel and dual-channel retrievals for the April–July time period. The mean difference is small, 3 g m^{-2}, but the RMS difference is significant, 11 g m^{-2}. However, point-by-point comparisons reveal that part of the RMS difference between the two re-

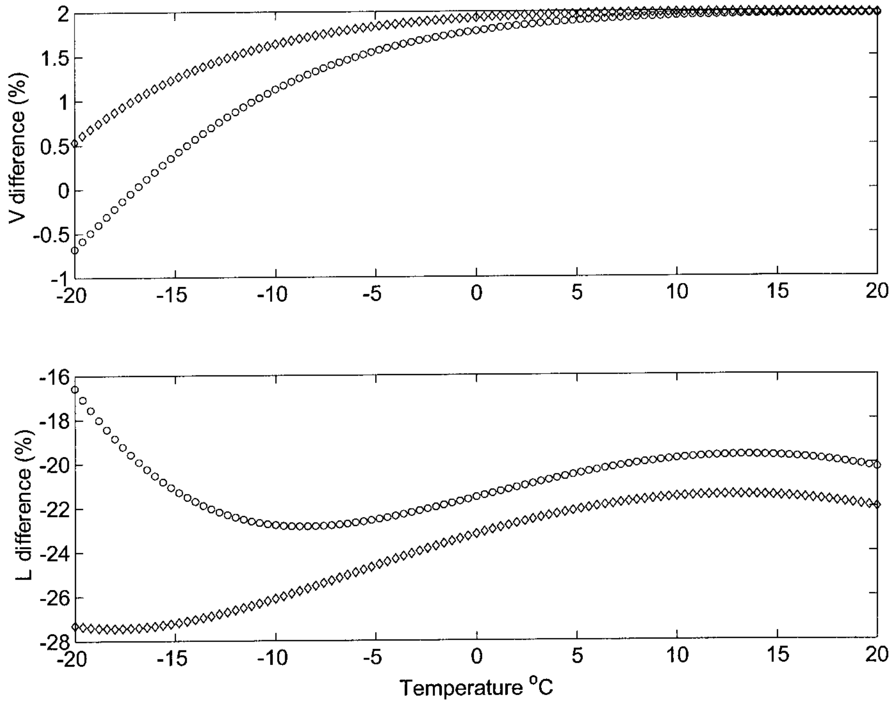

Figure 5. Percentage differences in V and L retrievals relative to the original retrievals using *Grant et al.* [1957]. Circles, Liebe91 minus Grant57; diamonds, Rosenberg72 minus Grant57. The retrieved profile has V = 1.344 cm, and L = 106.2 g m^{-2}.

trieval methods is due to the uncertainties of the V estimates in the single-channel retrieval process. For example, on the Julian day 202 and at the time of 2050 UTC, the L given by the dual-channel technique is 36 g m^{-2}, while that from the single-channel technique is 4 g m^{-2}. Examining the MWR-derived V time series around that time (solid line in Figure 7) shows that there were significant V variations between the two surrounding radiosonde launch times (circles) in Figure 7. Interpolating the sounding data overestimated V by ~16% at 2050 UTC, which, according to (6), resulted in an underestimation of L for the single-channel method. Thus it is clear that variability in V is a limiting factor in single-channel retrievals of L.

4.2. Original Versus ETL Dual-Channel Liquid Retrievals

Comparisons of the original and ETL dual-channel technique (Figure 8) show that the original retrievals of L are higher by 13 g m^{-2} and the RMS difference is 20 g m^{-2}. If we limit the data range to $L < 100$ g m^{-2}, the mean difference is again 13 g m^{-2} and the RMS difference is reduced slightly to 16 g m^{-2}. Assuming a nominal average value of 50 g m^{-2}, this RMS value is 32%. As discussed in previous sections, these differences are due to the differences between the dry absorption and cloud liquid absorption models used in the original and ETL retrieval methods as well as to the difference between the physical and statistical retrieval methods.

Table 2. Computed RMS Accuracy in Physical Retrievals of V and L due to RMS Uncertainties in T_{mr} and T_c

RMS Uncertainties, K			
T_{mr}	T_c	RMS V, cm	RMS L, g m^{-2}
1.0	1.0	0.0016	4.0
2.0	2.0	0.0031	7.9
3.0	3.0	0.0047	11.9
4.0	4.0	0.0062	15.9
5.0	5.0	0.0078	19.8
6.0	6.0	0.0094	23.8
6.2	5.8	0.0100	23.8
6.2[a]	5.8[a]	0.011	25.0

[a]Statistical retrieval accuracy.

4.3. Original Liquid Retrievals Versus in Situ Aircraft Data

We computed the mean and RMS differences between original L retrievals and the aircraft in situ data from the King and Gerber liquid probes. The original retrievals are higher than either the King or Gerber measurements by an average of 69 and 73 g m^{-2}, respectively, and with corresponding RMS differences of 138 and 166 g m^{-2}, respectively. However, the large differences are dominated by points with large L values. If we limit the data range to $L < 100$ g m^{-2}, as shown in Figure 9, the mean and RMS differences between the original retrievals and the King data are 26 and 32 g m^{-2}, respectively, and those between the original retrievals and Gerber data are 16 and 40 g m^{-2}, respectively. Again, assuming an average L of 50 g m^{-2}, these values, expressed as percentage differences, are equal to 52%, 64%, 32%, and 80%, respectively. As discussed in section 3.6, the estimated accuracy of the original L retrievals is 25 g m^{-2}.

4.4. ETL Dual-Channel Liquid Retrievals Versus in Situ Aircraft Data

As shown in Figure 10, for $L < 100$ g m^{-2}, the mean and RMS differences between the ETL dual-channel retrievals and the King data are 14 and 20 g m^{-2} (28% and 40%), respec-

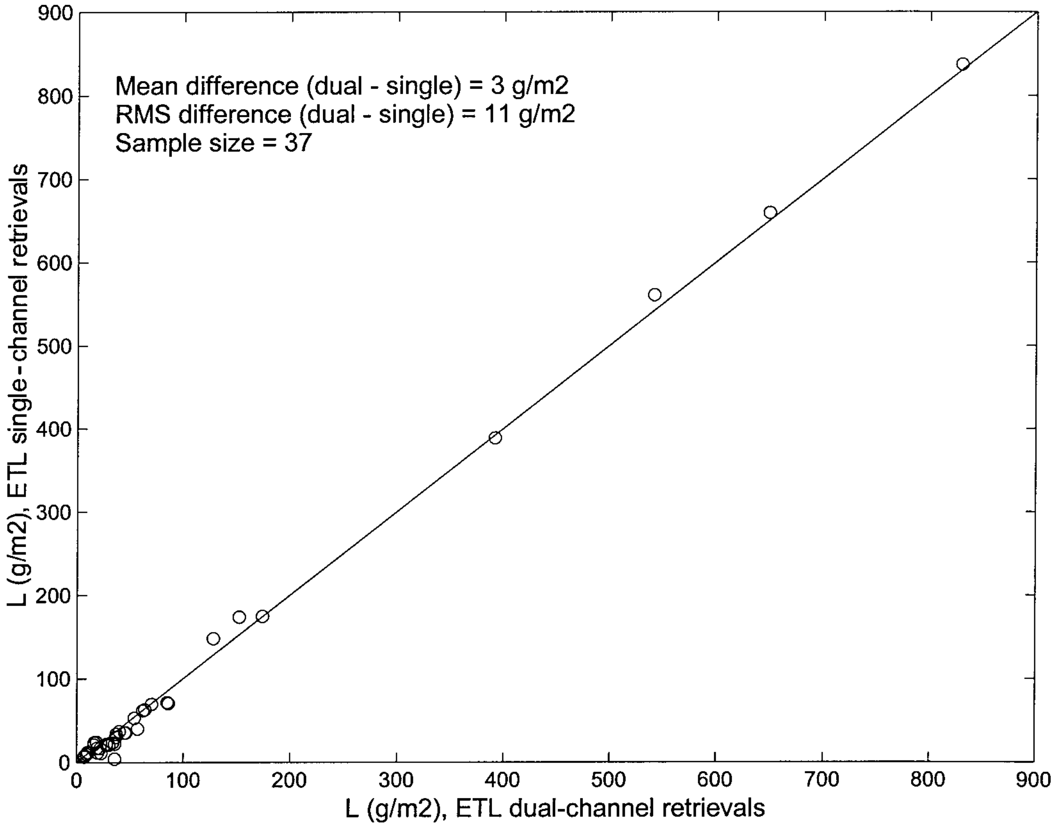

Figure 6. Scatterplot of dual-channel MWR L retrievals versus single-channel 31.4 GHz L retrievals. For the single-channel retrievals, V was determined by interpolation from consecutive radiosondes.

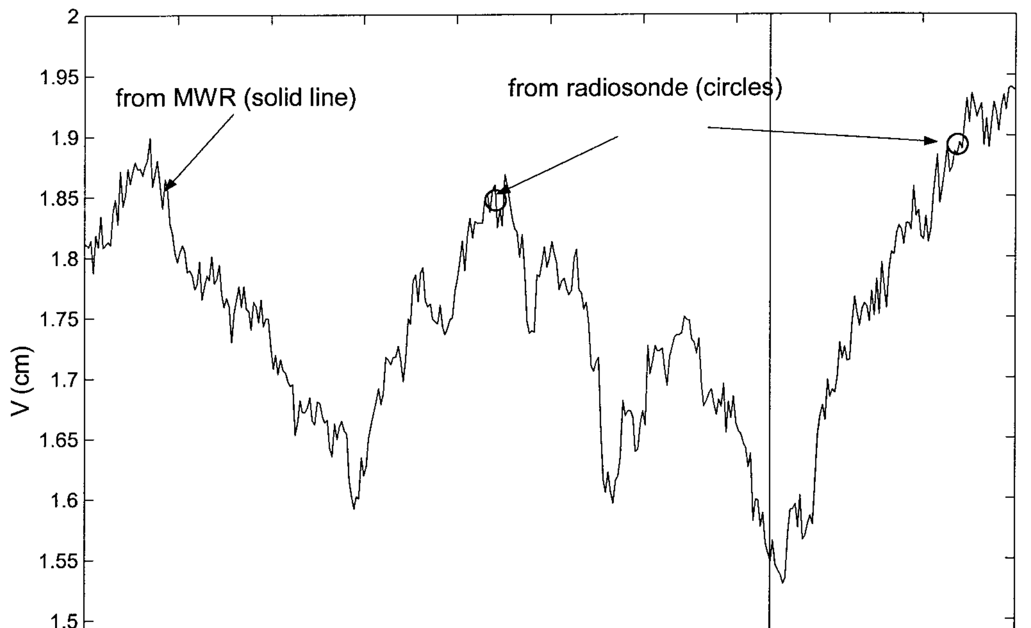

Figure 7. Time series of V derived from the MWR and from radiosondes.

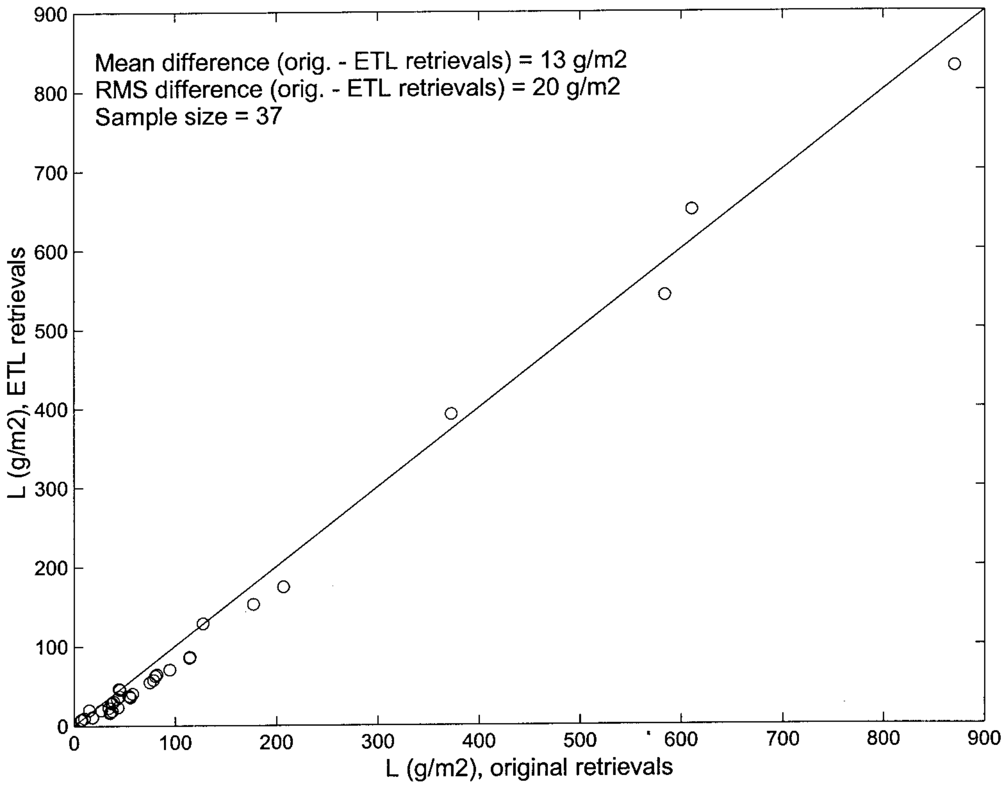

Figure 8. Scatterplot of ETL dual-channel L retrievals versus the original ARM retrievals. The clear-air absorption models of *Rosenkranz* [1998] and the liquid absorption of *Liebe et al.* [1991] were used in the ETL retrievals, while the clear-air absorption models of *Liebe and Layton* [1987] and the liquid absorption of *Grant et al.* [1957] were used in the ARM retrievals.

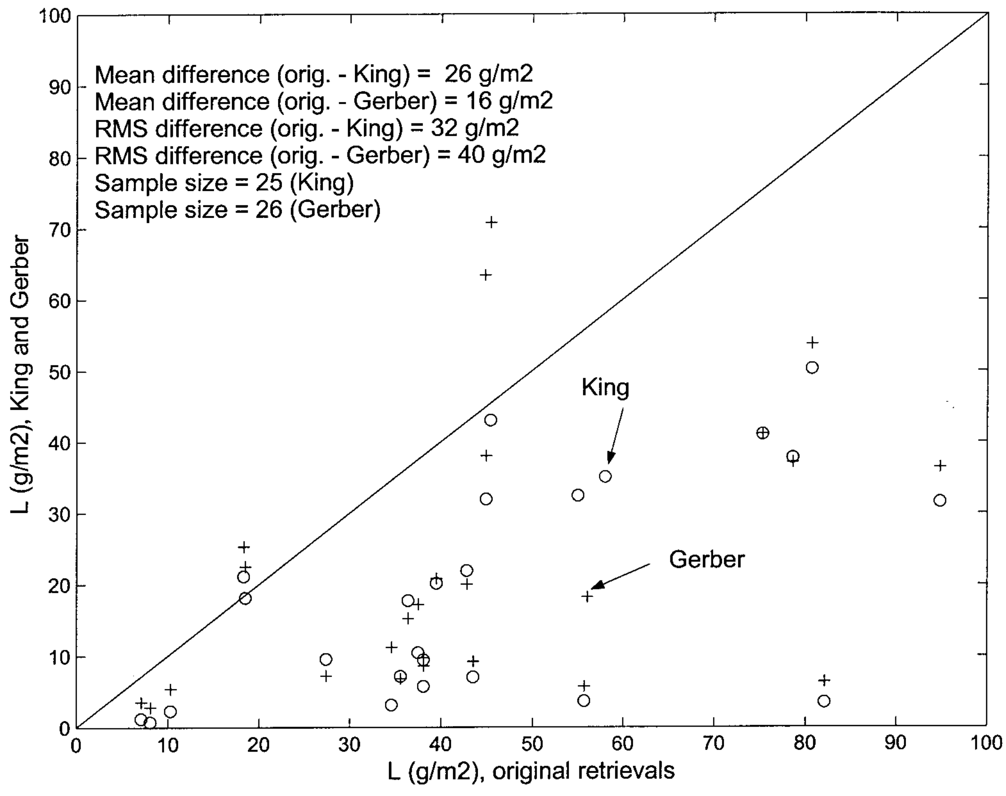

Figure 9. Scatterplot of original L retrievals versus in situ data taken on the NCAR C-130Q aircraft. The liquid density measurements were made by the King hot-wire probe and the Gerber PVM-100A [*Curry et al.*, 2000]. Data measured by the King probe are labeled with open circles, and those from the Gerber probe are labeled with crosses. The estimated RMS accuracy of the original retrievals is 25 g m^{-2}, while the estimated accuracy of the in situ measurements is 10%.

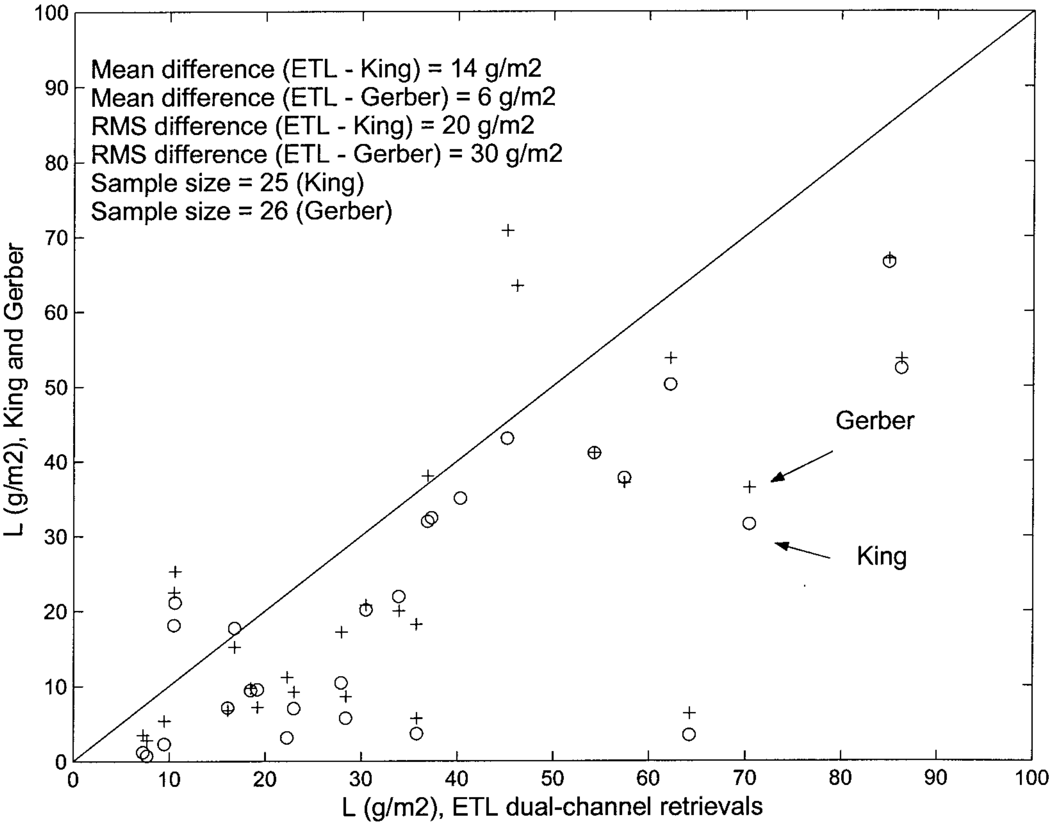

Figure 10. Scatterplot of ETL L retrievals versus in situ aircraft data (see Figure 9 caption). The clear-air absorption models of *Rosenkranz* [1998] and the liquid absorption of *Liebe et al.* [1991] were used in the ETL retrievals. Data measured by the King probe are labeled with open circles, and those from the Gerber probe are labeled with crosses. The estimated RMS accuracy of the ETL physical retrievals is 10 g m^{-2}, while the estimated accuracy of the in situ measurements is 10%.

tively, and those between the ETL retrievals and Gerber data are 6 and 30 g m^{-2} (12% and 60%), respectively. If all the data points are included, the mean and RMS differences between the ETL retrievals and the King data are 54 and 126 g m^{-2}, respectively, and those between the ETL retrievals and the Gerber data are 61 and 161 g m^{-2}, respectively. Comparing these results to those in section 4.3, we see that the ETL retrievals reduced the differences between the original retrievals and in situ measurements by ~10 g m^{-2} (20%). The reduction is due primarily to the differences in dry absorption and cloud liquid models used in the original and ETL retrieval algorithms and the difference of the two retrieval algorithms. As discussed in section 3.6, the estimated accuracy of the ETL physical retrievals of L, with T_C uncertainty of 2.5 K, is 10 g m^{-2}.

4.5. Retrievals of Cloud Liquid Water During Clear-Sky Conditions

Because of various error sources in the retrieval process, the linear L retrievals during clear-sky conditions are usually not exactly zero. One such error source may be the uncertainty in the clear-sky absorption modeling. However, as follows directly from (2) and (3), if there are no errors in τ, τ_d, or κ_V, L must be zero for a two-channel clear-sky retrieval even when imperfect cloud liquid absorption coefficients κ_L are used. Thus, even with imperfect measurements and estimated parameters, the comparisons of L retrievals under clear-sky conditions may guide us to select the clear-sky absorption models used in the retrieval processes. In Table 3 we listed the mean and RMS differences between the MWR L retrievals and the value of $L = 0$ under clear-sky conditions for the period from April 1–July 31 during SHEBA. The cloud liquid absorption model for these physical retrievals was Liebe91 and the lidar/cloud-radar data were used to obtain times of clear-sky conditions. Table 3 shows that the use of the Rosenkranz98 clear-sky absorption model yields the smallest values of clear-sky liquid retrievals. A similar result was obtained from a similar experiment conducted in March 1999 at Barrow, Alaska [*Westwater et al.*, 2000]. These results suggest confidence in using the Rosenkranz98 clear-sky model.

4.6. Original Versus ETL Vapor Retrievals

We found no significant changes in V retrievals when the original retrieval algorithm (statistical, Liebe87, Grant57) was replaced by the ETL retrieval algorithm (physical, Rosenkranz98, Liebe91). However, for small amounts of V (<0.5

Table 3. Mean and RMS Differences Between Clear-Sky L Retrievals and Zero for SHEBA, April 1 to July 31, 1998[a]

	Rosenkranz98	Liebe87	Liebe93
Mean	3.0	14.0	−6.6
RMS	9.0	16.0	10.0

[a]Sample size is 13,128.

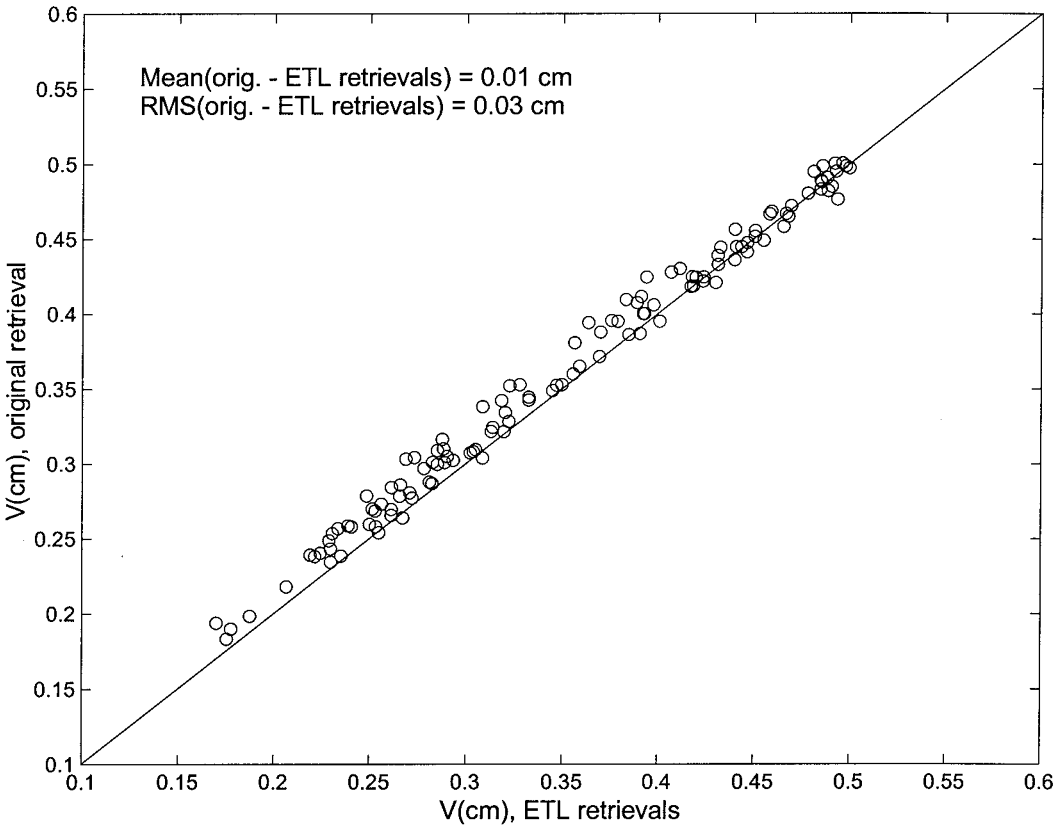

Figure 11. Scatterplot of original versus ETL V retrievals. The clear-air absorption models of *Rosenkranz* [1998] and the liquid absorption model of *Liebe et al.* [1991] were used in the ETL retrievals, while the clear-air absorption models of *Liebe and Layton* [1987] and the liquid absorption of *Grant et al.* [1957] were used in the ARM retrievals.

cm), as shown in Figure 11, The difference in the dry absorption models used in the retrieval algorithms may result in V differences of over 10%. The ETL retrievals are, in general, lower than the original retrievals by an absolute amount of 0.01 cm.

5. Conclusions

We investigated a variety of factors that enter into the determination of precipitable water vapor and integrated cloud liquid by the ARM dual-channel microwave radiometer that was operated during SHEBA. We first carefully examined the radiometer calibration and concluded it was well calibrated with a 0.3 K RMS error. Our main finding is the degree to which both clear-air and cloud liquid models have an effect on the retrievals, especially on L retrievals. The most significant changes we saw were due to the dry opacity and the cloud liquid absorption coefficient. The dry opacity is best modeled by the Rosenkranz98 since the use of this model resulted in the smallest L retrievals during clear-sky conditions. The cloud liquid absorption is best modeled either by Liebe91 or Rosenberg72 since these two models used experimental data at temperatures below 0°C, while Grant57 used data above 0°C. Although we found nothing in the original ARM data that was grossly incorrect, application of these more recent models reduced the original ARM retrievals of L by roughly 20 to 30%. For the MWR parameters of the SHEBA experiment we determined that an accuracy of 2.5 K in cloud temperature would result in a 10 g m^{-2} accuracy in L. The statistical method, used as a default when only a priori data are available, yields an accuracy of ~25 g m^{-2}. Thus the use of cloud temperature information, derived from both in situ and remote sensors, is important.

We also investigated the use of a single-channel retrieval of L when radiosonde data, interpolated in time, were used to provide measurements of ρ_V, P, and T. In this case, the temporal variability of ρ_V (or V) was a limiting factor in retrieval accuracy. In general, the accuracy of the physical retrieval technique depends on the accuracy of background profiles of T, P, and ρ_V, as well as the availability of cloud radar/lidar data.

The change of clear-air absorption models from Liebe87 to Rosenkranz98 has little impact on V retrievals except when V is low. For $V < 0.5$ cm, the V retrievals using Rosenkranz98 may be more than 10% lower than those retrieved using Liebe91.

Uncertainties in the retrieved liquid water path (LWP) have a significant impact on cloud microphysical retrievals that combine radar and MWR measurements to determine profiles of liquid water content and cloud droplet effective radius [e.g., *Frisch et al.*, 1998]. For microphysical retrievals of single phase liquid clouds, a 20% error in LWP would lead to errors of 20% and ~8% in ρ_L and in effective radius, respectively.

In addition to the algorithm and calibration contributions to radiometer-aircraft differences, spatial variability, even in pure phase stratus clouds, is important. As an example, we looked at an (almost) pure liquid cloud on May 18, 1998, during which there was only a very small variability in radar reflectivity, from a very stable stratus cloud of ~500 m thickness. However, even for this case, the 5-min variability in radiometrically measured L was ~25 to 30 g m^{-2}, and, for the day, a range of 80 g m^{-2} was observed. The 5-min differences are at least as large as the differences between the MWR and the aircraft measurements of L. Thus, although aircraft measurements of cloud liquid profiles are currently the only practical way of verifying L retrievals, the limitations of this validation method are evident.

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