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Comparison of cloud liquid water paths derived from in situ and microwave radiometer data taken during the SHEBA/FIREACE

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Abstract. Mean cloud liquid water path *LWP* derived from microwave measurements using the standard ARM retrieval technique is nearly twice as large as coincident in situ aircraft data taken over the SHEBA ice camp in the Arctic during FIRE ACE. Using an algorithm adopted from satellite remote sensing that more completely accounts for the temperature dependence of water absorption and atmospheric gas absorption results in a 25 to 45 % reduction in *LWP* values relative to the standard ARM estimates. If possible precipitation cases are excluded, the mean results from the new technique differ by only 3% from the in situ data. Greater differences for heavier clouds may result from in situ probe uncertainties. This algorithm should provide accurate *LWP* retrievals for a variety of cloud conditions from the tropics to the highly supercooled Arctic clouds.

1. Introduction

Quantitative knowledge of Arctic cloud microphysics is extremely limited although necessary to advance the understanding and modeling of cloud processes and their interaction with the Arctic surface and atmosphere. As part of a comprehensive observational program to increase the knowledge of Arctic climate and energetics, the Atmospheric Radiation Measurement (ARM) Program deployed uplooking microwave radiometers (MWR) at the Surface Heat Budget of the Arctic Ocean (SHEBA) floating ice camp from October 1997 to October 1998 and for an extended period at the its North Slope of Alaska (NSA) site in Barrow, Alaska. Microwave (MW) remote sensing is generally a reliable means for monitoring *LWP* and column water vapor *CWV* from the surface and from satellites over ocean. Because of extreme conditions in the Arctic, it is not certain that algorithms developed in temperate regions will provide accurate values of *LWP* in polar regions. Aircraft measurements taken during the First ISCCP Regional Experiment Arctic Cloud Experiment (FIRE ACE; *Curry et al.*, [2000]) over the SHEBA camp during spring 1998 provide the opportunity to confidently examine the retrieval of *LWP* from Arctic MWR data.

The amount of MW energy received by the radiometer depends on *LWP* as well as many other geophysical parameters, such as column water vapor *CWV*, cloud water temperature *Tc*, microwave frequency, uplooking elevation angle, oxygen, cloud particle shape, phase and size if it is precipitating, and cosmic background radiation. Any uncertainties in or improper treatment of these parameters, especially *CWV* and *Tc*, in the retrieval algorithm could result in large errors in the standard ARM *LWP* products. For cold and dry weather cases, the contribution of gas continuum absorption to the atmospheric total (gases plus clouds) MW absorption and emission is proportionally greater than that in humid conditions because cloud water amounts are usually small. Different MW gas absorption models can yield significant differences in the gas continuum absorption [*Rosenkranz*, 1998]. The gas continuum absorption, mainly from water vapor, is extremely important for the ARM *LWP* retrievals since the MWR measures microwave radiation near the center of water vapor line (23.8 GHz) and in the atmospheric window (31.4 GHz). Furthermore, microwave absorption coefficients for supercooled water, which were frequently found during FIRE ACE, are much larger than those for warm ($Tc > 0°C$) water [*Lin et al.*, 1998]. *Lin et al.* [1998] showed that the uncertainties in water vapor absorption and cloud water temperature are two major error sources for satellite MW *LWP* measurements over oceans. Thus, the selection of the water and gas absorption models and determination of *Tc* are critical for physically-based *LWP* retrievals in polar regions. This paper examines the uncertainties in *LWP* derived from SHEBA/ARM ground-based data using simultaneous in situ aircraft measurements taken during FIRE ACE.

2. Data Sets

All data used in this study were taken during the FIRE ACE period spanning May through July 1998. Air temperature (*Ta*) and pressure were measured at 2 m on two SHEBA towers and reported hourly as the average of the two tower observations. The hourly data were interpolated to match the MWR measurement times. Cloud heights were computed as the 15-minute means deduced from cloud lidar measurements. Cloud water temperature was inferred from IRT data (discussed later). The IRT measures equivalent blackbody temperature in the atmospheric window between 9.6 and 11.5 μm. The ARM MWR measured downwelling radiances at frequencies of 23.8 and 31.4 GHz every 20 seconds. The bandwidths for both channels are 0.4 GHz. The beamwidths at the two frequencies are 5.9° and 4.5°, respectively. The ARM MWR had automatic self-calibration capability and was accurate to within 0.3K in measured brightness temperature (*Tb*).

The standard technique to retrieve SHEBA/ARM *CWV* and *LWP* data from the MWR *Tb* values is based on a simplified (or equivalent 1-layer atmosphere) MW radiative transfer model (MWRTM) and the *Tc* estimates of the uplooking infrared thermometer (IRT) [*Liljegren*, 1998]. The model was originally developed for data taken over the ARM Southern Great Plains (SGP) site. The retrieval coefficients in the model were obtained empirically from forward MW simulations using sounding data.

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During the forward simulations, the refractive index of *Grant et al.* [1957] and the model of *Liebe and Layton* [1987] (or MPM87) were used to calculate the water and gas absorption coefficients, respectively.

The aircraft cloud water amounts used here were from the Gerber PVM-100A and King Hot Wire Probe, hereafter called the PVM and King instrument, respectively. The agreement between the two aircraft measurements after bias correction (by multiplying the King values by 1.22) are excellent with correlation coefficients r ~ 0.99 and with almost the same means and standard deviations. Because of this good agreement, only the PVM data are considered. A limitation for both probes is their inability to accurately measure water amounts for large cloud particles [*Gerber et al.*, 1994; *Strapp et al.*, 2000; *Wendisch et al.*, 2000]. The sensitivity of the PVM, for example, is ~100% for a 25-µm median volume droplet diameter and decreases to less than 40% for a 45-µm droplet. The liquid water contents from the aircraft slant vertical profiles were integrated over the depth of the cloud to obtain *LWP* values. The *LWP* uncertainties for these instruments, typically about 0.005 - 0.01 mm or 15 – 30 % and ~5 – 10% for thin and average polar water clouds, respectively, are less than those from the MWR. Aircraft generally need short periods of time to measure column cloud water amounts, while ground MWR measurements only represent the *LWP* at a point above the instrument. To compare the retrievals with aircraft measurements of cloud microphysics, the MWR results were averaged for intervals of ±5 minutes centered on each aircraft slant vertical profile centered over the surface measurement site. Of the 38 collocated cases obtained during FIRE ACE, four had extremely large MWR *LWP* values (> 0.5 mm). The SHEBA surface daily records indicate that there was probably some precipitation for these cases.

3. Current retrieval algorithm

For the current retrieval algorithm, the inputs are MWR *Tb* values at both 23.8 and 31.4 GHz, the IRT-measured radiance, lidar cloud height, and SHEBA tower air temperature and pressure measurements. Vertical distributions of temperature and vapor abundance were constructed based on climatological profiles interpolated to conform to the SHEBA ground meteorological observations and assumed *CWV* values, respectively. Clouds with assumed water amounts were inserted into the atmospheric profiles using the lidar cloud heights. Water clouds are assumed to be single-layered and below an altitude of 5 km (or *Tc* >–32 °C). If multilayered clouds were found by cloud lidar, the averaged cloud heights were used. Since temperature inversions are frequently found in polar regions, the layers where clouds are inserted were assigned an air temperature to be consistent with *Tc* obtained during *LWP* retrieval.

The current retrieval algorithm was adopted from the satellite MW remote sensing method developed by *Lin et al.* [1998]. For the ARM uplooking radiometer, only downwelling *Tb* simulations of the MWRTM of *Lin et al.* were used. The several models available to account for gas absorption differ mainly in their treatment of water vapor continuum absorption. The *Liebe* [1989] model (i.e., MPM89) was used here. It yields results that differ negligibly from those of the *Rosenkranz* [1998] model in polar environments. Liquid water absorption coefficients were calculated from the empirical water refractive index formulae of *Ray* [1972], which agree well (relative differences < 5%) with those from *Liebe et al.* [1991] for *Tc* > –15°C. For colder clouds, the uncertainties in the absorption coefficients could be larger by more than 15% [*Lin et al.* 1998] because of a lack of direct measurements of the refractive index.

Cloud water temperature was estimated during the *LWP* retrieval based on the following equation:

$$R_{cld} - R_{clr} \approx (1-exp(-\tau))B(Tc) \qquad (1)$$

where R_{cld} and R_{clr} are cloudy and clear-sky IRT radiances, respectively, τ is the cloud infrared (IR) optical depth, and *B* is the Planck function. Because cloud emission at IR wavelengths is strong, the vertically weighted cloud IR emission temperature is close to the cloud base temperature. At the MWR wavelengths, colder water clouds emit more than warm clouds, so the vertically weighted cloud microwave emission temperature is between the cloud top and center if the cloud water is vertically uniformly distributed. Since R_{clr} cannot be observed in overcast conditions, a lookup table was produced. At IR wavelengths, τ is roughly half of the visible optical depth (or $\tau \approx 75LWP$, where *LWP* is in mm). The *Tc* estimates from (1) could be too small, especially for low-altitude clouds. Underestimation of *Tc* would cancel part of the bias introduced by using the IR *Tc* to represent cloud MW emission temperature noted above.

The *LWP* retrieval scheme iterates between retrieving *LWP* and *CWV* using MWR *Tb* measurements and estimating *Tc* from IRT observations using the following four steps:

1) The ARM standard *LWP* and *CWV* estimates are used with SHEBA measurements of cloud height and *Ta*, as initial inputs for the MWRTM of *Lin et al.* [1998] to construct atmospheric profiles and to estimate *Tc* according to (1).

2) The MWRTM simulates MWR *Tb* values using *LWP*, *CWV*, and *Tc* estimates from step 1. The simulated data are compared with *Tb* observations to adjust *LWP* and *CWV* until the *Tb* differences between the model output and measurements are less than 0.03 K for both MWR channels.

3) *Tc* values are recalculated using the *LWP* results from step 2.

4) Steps 2 and 3 are iterated until the change in *LWP* between consecutive iterations is less than 0.001 mm.

The MWR instrument noise could produce *LWP* errors of ~0.01 mm or ~30% for the thin polar clouds (*LWP* ≈ 0.033 mm) for the current retrieval scheme. For average clouds (*LWP* ≈ 0.1 mm), the relative errors drop significantly to about 10%. If

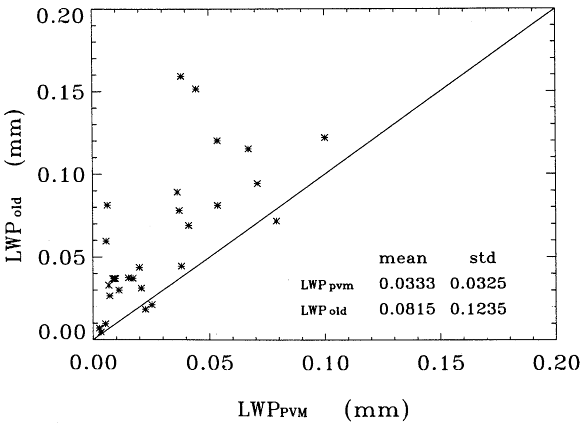

Figure 1. Comparison of *LWP* from aircraft in situ (PVM) and from surface MWR data using standard ARM technique (OLD) during FIRE ACE for non-precipitating clouds.

uncertainties in water and vapor MW absorption coefficients, *Tc*, and atmospheric profiles are considered, the errors can be larger (0.015 mm).

The main differences between the current algorithm and ARM standard approach [*Liljegren*, 1998] are: 1) the ARM approach uses a simplified MWRTM with retrieval coefficients from empirical calculations, while the current MWRTM calculates detailed atmospheric absorption and emission; 2) The refractive index models used to calculate liquid water absorption coefficients are different. The model of *Grant et al.* [1957] used in building up the ARM algorithm generally is not valid for supercooled water since it was obtained from measurements above 0°C, while the *Ray* [1972] formulae used here, at least, can account for water temperature > –15°C; 3) The current algorithm uses an improved model (MPM89) to account for the air temperature, pressure and humidity dependencies of water vapor absorption coefficients compared to that (MPM87) for the ARM standard algorithm.

4. Results

Figure 1 compares the MWR *LWP* retrievals of the ARM technique and simultaneous *LWP* measurements from the PVM on the NCAR C-130 for the cases with *LWP* < 0.2 mm. Extremely large *LWP* cases were excluded to avoid precipitation and extremely large droplets that may not be measured properly with the in situ probes. The two datasets are well correlated, but the standard ARM values exceed their PVM counterparts by a factor of two. The scatter in Figure 1 likely results from uncertainties in the *LWP* retrievals and the spatial and temporal mismatches between the aircraft and ground-based measurements. A comparison of the PVM and hot wire measurements agreed closely suggesting that the MWR retrievals in Figure 1 are too high.

LWP and *CWV* were also retrieved using the current algorithm. Since the MWR 23.8-GHz channel is located near the center of a vapor absorption line, the current *CWV* estimates are very close to old *CWV* retrievals. However, the current *LWP* values are substantially lower, especially for thin to moderately thick (*LWP* < 0.2 mm) clouds. Figure 2 compares the retrievals from both methods for the 38 cases. The mean *LWP* from the current and standard methods are ~0.10 and 0.14 mm, respectively. These values are relatively small because most non-precipitating polar clouds are thin. The standard deviations are about twice as large as their means. If the possibly precipitating cases are excluded (Figure 3), the new means (~0.0312 mm) are about 47% lower than the standard ARM results (~0.0588 mm). The standard deviations are also reduced significantly to a level smaller than their averages. It was found that the *LWP* estimates could be significantly high and close to the ARM values if *Tc* is much warmer than the IRT estimates, or if the MPM93 gas absorption model [*Liebe et al.*, 1993] were used. Within the typical temperature range for water clouds (–15 to +20 °C), the absorption coefficients at the MWR frequencies change by a factor of about 2.5. Stronger continuum vapor absorption in MPM93 compared with that in MPM89 would slightly reduce *CWV* and generate disproportionately larger *LWP* values, especially for thin polar clouds, because *CWV* is about 100 – 300 times larger than that of *LWP*. Thus, accurate column vapor amounts and water and vapor microwave absorption coefficients are critical for *LWP* retrievals, as discussed by *Lin et al.* [1998]. When cloud water amounts are very large, small errors in vapor absorption may not produce big errors in the *LWP* as indicated in Figure 2 because liquid water is a much stronger absorber than the vapor.

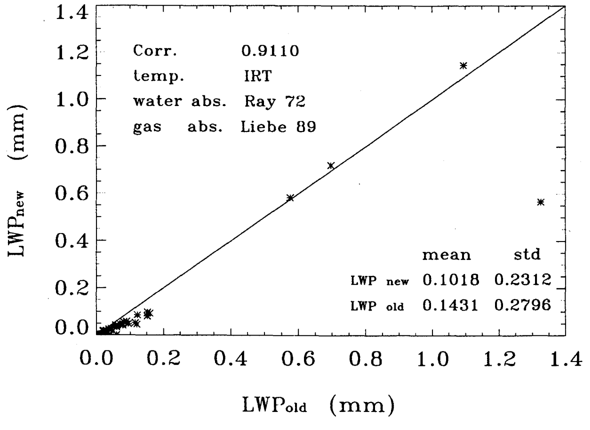

Figure 2. Comparison of *LWP* from surface MWR data using standard ARM technique (OLD) and current method (NEW) during FIRE ACE for all clouds.

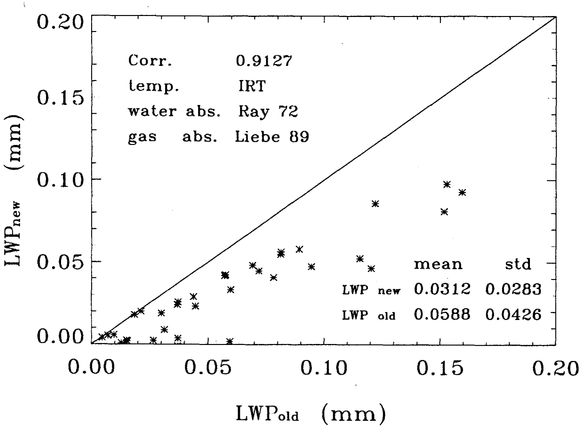

Figure 3. Same as Figure 2, except for non-precipitating clouds only.

The *LWP* values from the current retrieval are compared to the PVM measurements in Figure 4 for small-to-moderate *LWP*

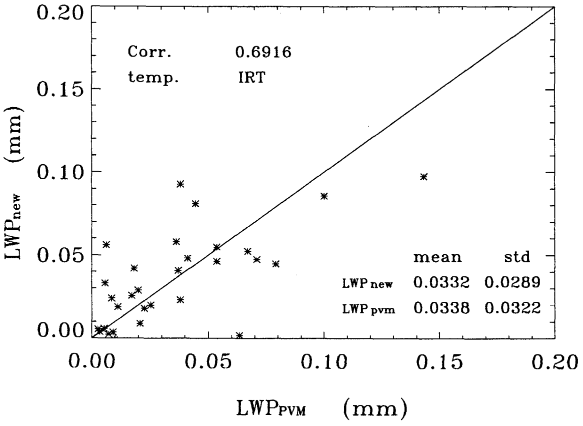

Figure 4. Same as Figure 1, except using current method (NEW) for MWR retrieval.

cases. The mean and standard deviation of the differences between the in situ and MWR *LWP* data are –0.0005 and 0.0242 mm, respectively. The correlation coefficient is about 0.7, which is substantially above the 95% confidence level. The root mean square (rms) difference of 0.024 mm between the new MWR and PVM *LWP* estimates is larger than the uncertainties in the retrieval algorithm. Spatial and temporal mismatches between the aircraft and surface observations, as well as the uncertainty in the conversion from liquid water content to *LWP* in the in situ data, probably contribute significantly to the large rms differences. The large variations of cloud water amounts in aircraft measurements obtained during the short flight legs support this hypothesis. Comparison of the current results with the King measurements produced essentially the same differences as those found using the PVM data.

When the possible precipitation cases are included, the correlation is still significant with r ~0.65 and the resulting mean MWR *LWP* of ~0.1 mm, exceeds the aircraft mean of ~0.05 mm; these differences may be a result of the in situ probes not responding to the larger droplets in those clouds.

Values for *LWP* were also derived with the current algorithm using the aircraft-measured cloud water temperature for *Tc* and adjusting *LWP* and *CWV* until the MWRTM simulation was consistent with MWR-measured *Tb* values. There is excellent correlation (~0.95) between the *LWP* retrievals using *Tc* from the aircraft and IRT. The two retrievals are also very close (bias of –0.006 mm and standard deviation of 0.014 mm). The mean *LWP* retrieved from the IRT is slightly smaller than that from the aircraft *Tc* and is likely due to the small underestimation of *Tc* using IR measurements of the low polar water clouds. The rms difference between the two kinds of retrievals from the same MWRTM is comparable to the errors estimated in previous section, strongly indicating the importance of cloud temperature on MWR retrievals.

5. Conclusions

An algorithm adopted from the satellite remote sensing method of *Lin et al.* [1998] was used to retrieve *LWP* and *CWV* simultaneously from ground-based MW measurements in a polar environment. The results show that this technique yields estimates of *LWP* that are much closer to in situ *LWP* observations than the standard ARM *LWP* products which are based on a different set of absorption coefficients. Because the current method is more generalized, it should be applicable to clouds in any location. For physically-based MW retrieval algorithms, water vapor absorption (including vapor amount and absorption coefficient) and cloud water temperature are critical for obtaining the accuracy seen here. Thus, this method could be easily adapted for use at all of the ARM sites in the southern Great Plains and tropical western Pacific, as well as at any other site where the requisite instrumentation is available. An improvement in the estimate of cloud water temperature may be realized by using the ARM cloud radars together with a sounding to better determine the cloud radiating height (temperature). Increased accuracy of the *LWP* above these sites is necessary both for monitoring cloud properties above the site and for validating satellite retrievals of cloud properties.

Although the current retrieval method accounts for all of the major physical factors of atmospheric microwave absorption and emission and will work well for general use, some uncertainties remain in the computation of microwave radiative transfer through water vapor and liquid water. For example, for very humid tropical weather, the MPM89 or *Rosenkranz* [1998] model may need some improvements for vapor absorption, as indicated by *Rosenkranz* [1998]. The discrepancy (~5K) between model-predicted and measured brightness temperatures at high frequencies (> 85GHz) could not be explained by instrumental errors. Furthermore, there are some uncertainties in the water absorption coefficients, especially for temperature < –15°C. Thus, further improvement of the retrievals will require more accurate information on the vapor continuum and supercooled water absorptions.

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