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Observations of integrated water vapor and cloud liquid water at the SHEBA ice station

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Abstract-Water vapor and clouds play a critical role in moderating the Arctic climate. During the field phase of the Surface Heat Budget of the Arctic (SHEBA) project, continuous measurements of integrated water vapor and integrated cloud liquid water were obtained from a station in the Arctic ice pack over a 12-month period using a dual-channel microwave radiometer. The integrated water vapor measurements are shown to compare well with co-located radiosondes. Measured brightness temperatures support the water vapor absorption model from Liebe and Layton [7] but reveal improved agreement when the Rosenkranz [11] oxygen absorption model is substituted for that in Liebe and Layton. Comparisons of the integrated cloud liquid water with *in situ* data from the NCAR C-130 aircraft exhibit varying agreement that appears to reflect the spatial variation of the clouds.

1. INTRODUCTION

In the Arctic water vapor and clouds influence the surface radiation balance to a greater extent than at lower latitudes. Because the integrated water vapor is often less than 5 mm, substantial radiative cooling occurs in the 20 μm infrared region whereas this region is normally opaque at lower latitudes having greater water vapor amounts. The relatively thin Arctic liquid water clouds also significantly affect the surface radiation balance. Accurate measurements of water vapor and liquid water amounts are therefore necessary for understanding and modeling the surface radiation budget in the Arctic.

The Surface Heat Budget of the Arctic (SHEBA) program [1] carried out a year-long field effort to acquire comprehensive measurements of atmospheric, oceanic and sea-ice processes in order to better understand their interactions and to improve the treatment of these processes in models used to investigate potential effects of climate change. Integrated water vapor and integrated cloud liquid water were measured continuously at the SHEBA ice station over a 12-month period beginning in October 1997 with a dual-channel microwave radiometer. An overview of these measurements is presented in this paper.

2. THE MICROWAVE RADIOMETER

The microwave radiometer (MWR) deployed at SHEBA is a dual-channel instrument built by Radiometrics Corporation, Boulder, Colorado, USA that operates at 23.8 and 31.4 GHz. It was among the suite of instruments deployed at SHEBA by the U. S. Department of Energy's Atmospheric Radiation Measurement (ARM) Program [2]. It is identical to the microwave radiometers deployed by the ARM Program at its facilities in Oklahoma, Kansas, Alaska and on islands in the tropical Pacific Ocean [3].

2.1 Calibration

Beginning in December 1997, the MWR was operated in a continuous elevation angle-scanning (or "tipping") mode in order to ensure that sufficient calibration data were obtained. The range of angles scanned by the radiometer was constrained by its location on the deck of the Canadian icebreaker *Des Groseilliers* to ±45° of zenith at 5° intervals. The radiometer required two minutes to scan all 20 angles, including a second zenith measurement at the completion of the scan. The calibration algorithms applied *a posteriori* to the SHEBA microwave radiometer were essentially identical to those developed for continuous real-time calibration of other ARM microwave radiometers [4]. The calibration is based on the 2000 most recent cloud-free scans (or "tip curves"). The resulting brightness temperature calibration is believed to be accurate to ±0.2 K.

2.2 Retrieval Algorithms

The integrated water vapor (IWV) and the integrated liquid water (ILW) from clouds were determined from the microwave brightness temperatures using a statistical retrieval [5] stratified into monthly retrieval coefficients. Radiosonde data from Barrow, Alaska for 1990-1995 were used to drive the NOAA/ETL microwave radiation transfer software [6], which implements the Liebe-87 [7] absorption model, in order to generate the *a priori* data set for the retrieval. For a 0.2 K root-mean-square (RMS) error in the measured brightness temperatures, the expected RMS error in the retrieval IWV ranged from 0.1(January) to 0.25 mm (July); the RMS ILW retrieval error ranged from 0.01 mm (10 g/m^2) in January to 0.03 mm (30 g/m^2) in July.

3. GENERAL RESULTS

The hourly record of integrated water vapor (IWV), integrated liquid water (ILW), and surface air temperature at the SHEBA ice station is presented in Fig. 1. The IWV ranged from 0.1 cm during the winter to more than 2.0 cm during the summer.

The dramatic changes that occur once the surface temperature reaches 0 °C are particularly interesting. When the surface air temperature is below freezing the IWV and ILW are generally small and variations in IWV correlate well with variations in the

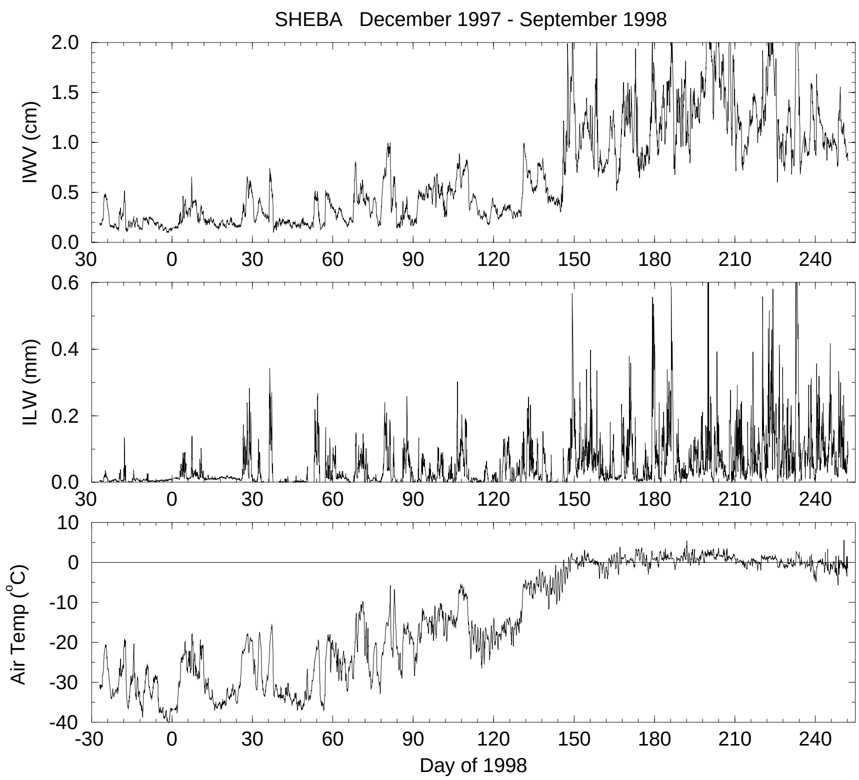

Figure 1. Hourly-averaged integrated water vapor (top), integrated liquid water (middle) and surface air temperature (bottom) for December 1997 - September 1998 at SHEBA. Note the dramatic increase in IWV and ILW when the air temperature reaches 0 °C.

surface air temperature as warmer (and more moist) air masses move through the region. However, once the surface air temperature reaches 0 °C, the net radiation no longer goes to heating the air but rather to melting snow and evaporating water. Once this happens, melt ponds begin to develop and the IWV (and ILW) dramatically increase. Subsequently they are no longer correlated with the surface air temperature. Low clouds and fog occurred frequently during this period.

It is also interesting that substantial amounts of liquid water are evident even when the surface air temperatures are substantially below freezing. The DABUL dual polarization lidar operated by NOAA/ETL confirmed that these were liquid water clouds. The occurrence of liquid water clouds is due in part to the strong surface temperature inversions that occur during the polar night (due to the radiative cooling in the 10 and 20 μm window regions). It is also likely that low concentrations of cloud condensation nuclei permitted super-cooled clouds to occur frequently.

4. WATER VAPOR COMPARISONS

4.1 Radiosonde Comparison

Radiosondes were normally launched twice per day at SHEBA. During the NASA FIRE IFO [8] periods sondes were launched four times per day. These were Vaisala RS-80 sondes with the H-Humicap relative humidity sensor. The comparison of IWV derived from radiosondes with IWV from the microwave radiometer is presented in Fig. 2 for clear sky conditions. The limited number of data points for IWV > 1.0 cm is due to the predominantly cloudy conditions that prevailed once the air temperature reached 0 °C.

The agreement between the MWR and the radiosondes is very good down to 1 mm of IWV. The calibration correction recently developed by Vaisala for the Humicap relative humidity sensors was not applied. For such low water vapor amounts the correction would not be expected to be significant [9].

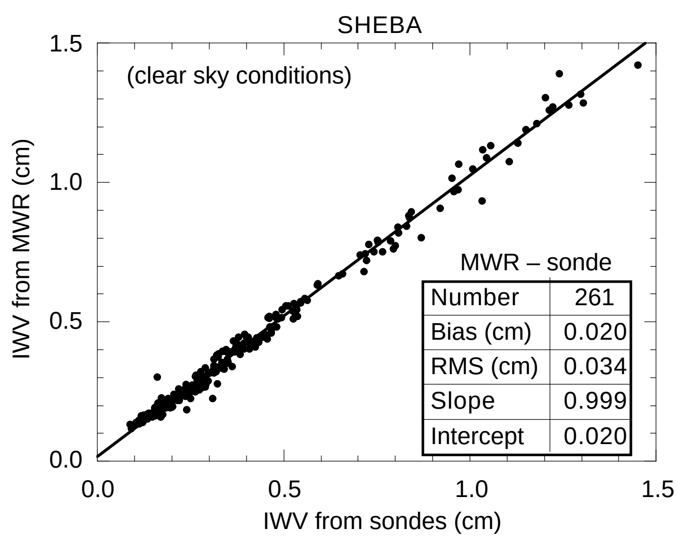

Figure 2. Integrated water vapor (IWV) from Vaisala radiosondes compared with 30-minute averaged values from the microwave radiometer (MWR) during clear sky conditions for December 1997 - September 1998.

4.2 Model Comparison

The SHEBA MWR measurements permit the examination of model performance in the limit of low water vapor where the microwave signal is dominated by oxygen emission. In Fig. 3 brightness temperatures measured with the MWR during clear-sky conditions for the period December 1997 - September 1998 are compared with calculations based on the Liebe-Layton [7] ("Liebe 87") absorption model. Although the similar values for the slopes of the regression lines suggest that the water vapor absorption model appears correct, the significant difference in the intercepts suggests that the oxygen absorption model in Liebe-87 under-predicts.

When the oxygen absorption model due to Rosenkranz [10, 11] is substituted ("Liebe 87 R93"), the calculated brightness temperatures increase such that the regression slopes are unchanged but the difference in the intercepts (MWR-model) is substantially reduced. Using the Rosenkranz oxygen model reduces the median (MWR-model) difference from 0.65 K to 0.30 K at 23.8 GHz, and from 0.75 K to 0.30 K at 31.4 GHz.

Because the IWV retrieval is based on the difference between the two channels, and

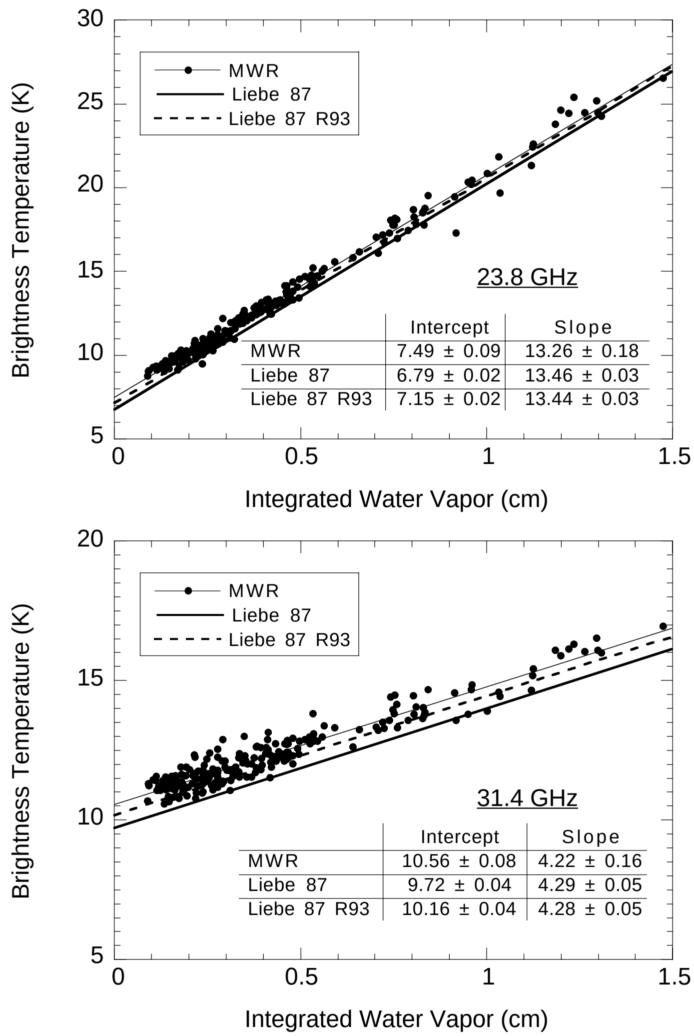

Figure 3. 30-minute averaged brightness temperatures at 23.8 and 31.4 GHz measured with the MWR compared with calculations using the Liebe-Layton ("Liebe 87") absorption model [7] for both water vapor and oxygen, and the Liebe-87 water vapor absorption model with the Rosenkranz oxygen absorption model [11] ("Liebe 87 R93"). The calculations used the same radiosondes as in Fig. 2 for clear sky conditions during December 1997 - September 1998. The integrated water vapor along the abscissa is derived from the radiosondes. The slopes and intercepts of the regression of T_B on IWV are tabulated along with their 95% confidence intervals.

because the brightness temperature biases have the same sign, they essentially cancel each other, which is why the retrieved IWV exhibits good agreement with the radiosondes despite the under prediction of oxygen absorption.

5. LIQUID WATER COMPARISONS

During the FIRE IFO periods several research aircraft flew over the SHEBA ice camp. Among them, the NCAR C-130 was equipped with both King hot-wire and Gerber particle volume monitor (PVM) liquid water content probes. Integrated liquid water from the MWR and ILW from the King and PVM probes are presented in Fig. 4 for three cases in May 1998.

For the May 4 case, the PVM indicates greater ILW than the King probe due to the presence of ice in the clouds. For the 15 and 18 May cases, the PWV and King probes give nearly identical results. The agreement between the aircraft probes and the MWR

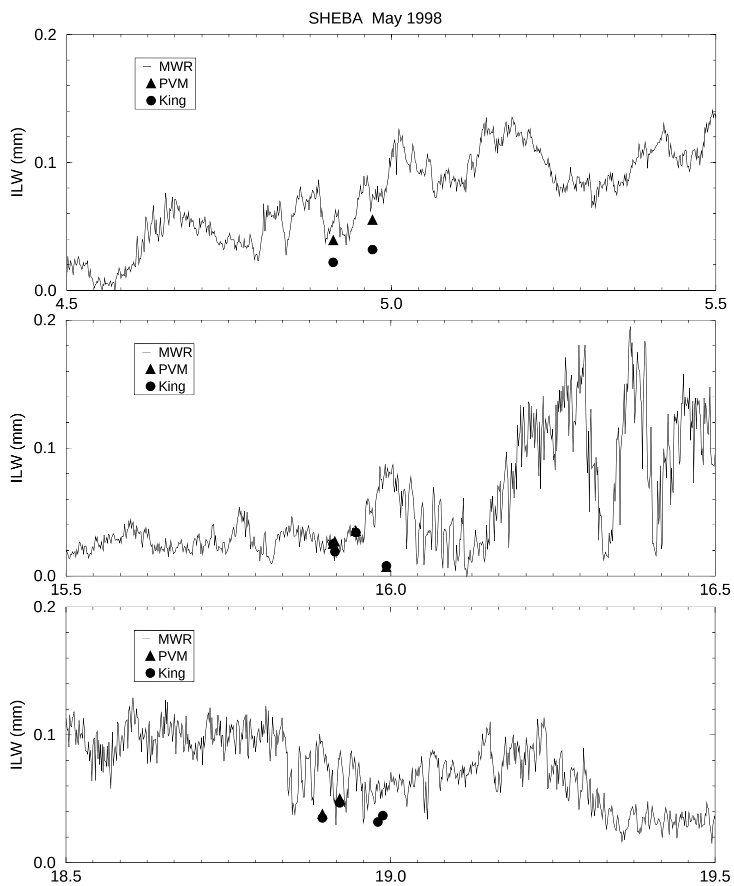

Figure 4. Time series of integrated liquid water (ILW) from the microwave radiometer for days when the NCAR C-130 aircraft with the PVM and King liquid water probes flew over the site.

vary from case to case. One possible explanation for the variable agreement is that the statistical retrieval may be inadequate. For example, the mass absorption coefficient of liquid water depends exponentially on the temperature of the liquid water. In the statistical retrieval for ILW the liquid water temperature, and thus the mass absorption coefficient, is implicitly held constant at the monthly mean value. For clouds that are warmer or colder than this mean value, the retrieved ILW would be in error. To examine this, a retrieval that explicitly accounts for the cloud temperature [12] was applied to several cases. For each case the liquid-weighted cloud temperature was calculated based on the temperature profiles from radiosondes weighted by the cloud radar reflectivity [13]. Although at times the difference in the ILW between the two retrievals exceeded 10%, during the periods when the aircraft were present the agreement between the retrievals was generally within 5%. This does not appear to explain the differences between MWR and aircraft measurements.

It appears that the agreement between the ILW from the MWR and the aircraft is better when there is less temporal variation in the ILW from the MWR, and thus less spatial variation in the clouds. Under these conditions the clouds sampled by the aircraft would be more likely to be representative of the clouds that advected through the field of view of the MWR. To examine the spatial variability and representativeness of the aircraft measurements, the difference between the median ILW measured with the MWR for 2-hour periods centered on the time of the aircraft measurement and the ILW from the King probe are plotted in Fig. 5 as a function of the inter-quartile range (75^{th} percentile - 25^{th} precentile) of a) the zenith ILW from the MWR, and b) the difference in ILW measured at 45° on either side of zenith over the same time. (The median and inter-quartile range statistics are used instead of the mean and standard deviation because the ILW does not generally follow a symmetric distribution; however, the trends are the same.) Figure 5a indicates that the difference in ILW measured by the MWR and King probes increases as the temporal variation in ILW increases. Figure 5b indicates that the difference between the MWR and King probe ILW also increases as the spatial variability in ILW increases. The agreement between the MWR and the aircraft generally improves as the spatial variability of ILW decreases.

6. CONCLUSIONS

The ARM microwave radiometer provided a continuous 12-month record of integrated water vapor and liquid water at SHEBA. The integrated water vapor measurements (down to 1 mm) were in very good agreement with radiosondes. Comparisons of measured brightness temperatures with model calculations suggest that the Rosenkranz absorption model for oxygen [11] is a significant improvement over that in the Liebe-87 model [7]. Integrated liquid water measurements exhibited varying agreement with the King and PVM probes on the NCAR C-130 aircraft, probably due to the spatial variations of liquid water in the clouds.

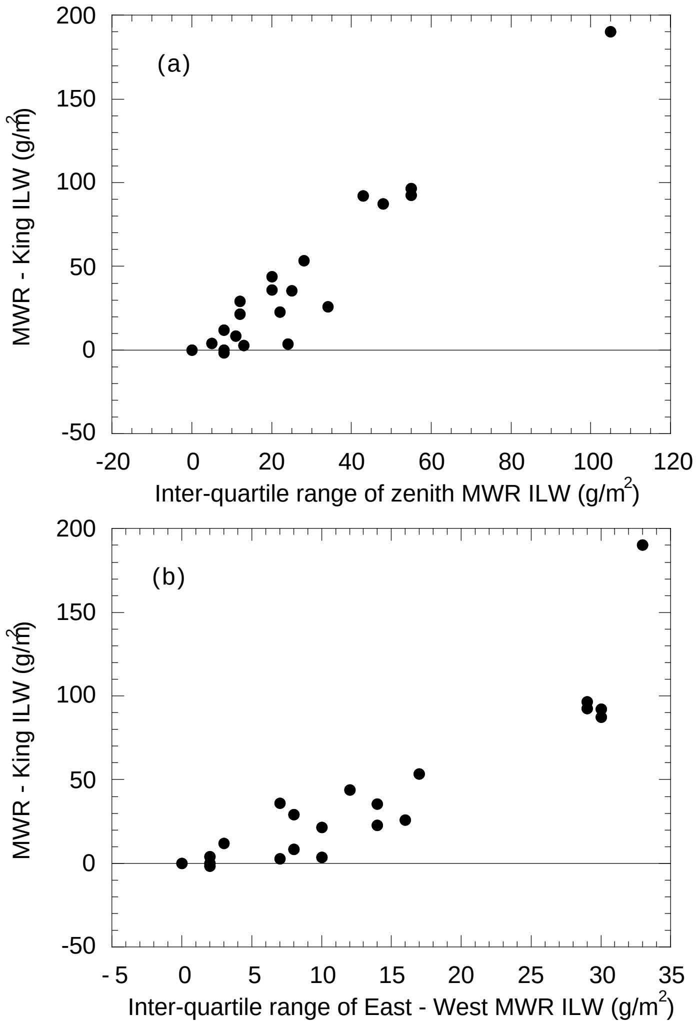

Figure 6. Differences in integrated liquid water (ILW) from the microwave radiometer (MWR) and the King probe on the NCAR C-130 plotted against (a) the temporal variation in ILW from the MWR described by the inter-quartile range (75^{th} percentile – 25% percentile) of ILW; (b) the spatial variation in ILW described by the inter-quartile range of the difference in ILW measured at 45° angles on either side of zenith.

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