The Arctic Winter Millimeter-Wave Radiometric Experiment: Summary, Conclusions, and Recommendations

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Introduction

There has been a concern that existing instruments deployed by the Atmospheric Radiation Measurement (ARM) Program may be inadequate to measure low amounts of total-column precipitable water vapor (PWV). This is especially important because of the possibility of scaling of radiosondes by the water amount. Extremely dry conditions, with PWV less than 3 mm, commonly occur in polar regions during the winter months. Accurate measurements of the PWV during such dry conditions are needed to improve our understanding of the regional radiation energy budgets. Jones and Racette (1998) have shown that the strength associated with the 183 GHz water vapor absorption line makes radiometry in this frequency regime suitable for measuring low amounts of PWV. To evaluate the potential of 183 GHz radiometry, an experiment was conducted at the ARM North Slope of Alaska/Adjacent Arctic Ocean (NSA/AAO) Cloud and Radiation Testbed (CART) site during March 1999. Three papers were presented at the 2000 ARM Science Team Meeting describing the preliminary results of this experiment (Racette et al. 2000; Westwater et al. 2000, and Han et al. 2000). This paper summarizes and extends some of the conclusions of these earlier works.

Simulations of PWV Retrieval Accuracy

It is well known that the microwave brightness temperature (Tb) response to water vapor and temperature varies substantially with atmospheric conditions. For almost all clear conditions in the earth's atmosphere, the response to water vapor around the 20.6 or 23.8 GHz region is independent of height and is insensitive to the temperature profile. These features led ARM to deploy dual-frequency microwave radiometers (MWRs) that operate at 23.8 and 31.4 GHz as a standard instrument at all of the

ARM CART sites, including the NSA/AAO. However, at low concentrations of water vapor, say PWV less than 5 mm, the fractional sensitivity to variations is diminished. At the same time, the sensitivity of Tb to water vapor greatly increases at such low vapor concentrations in the 183 GHz region. This is illustrated in the water vapor weighting functions of Figure 1 and the corresponding temperature weighting functions in Figure 2.

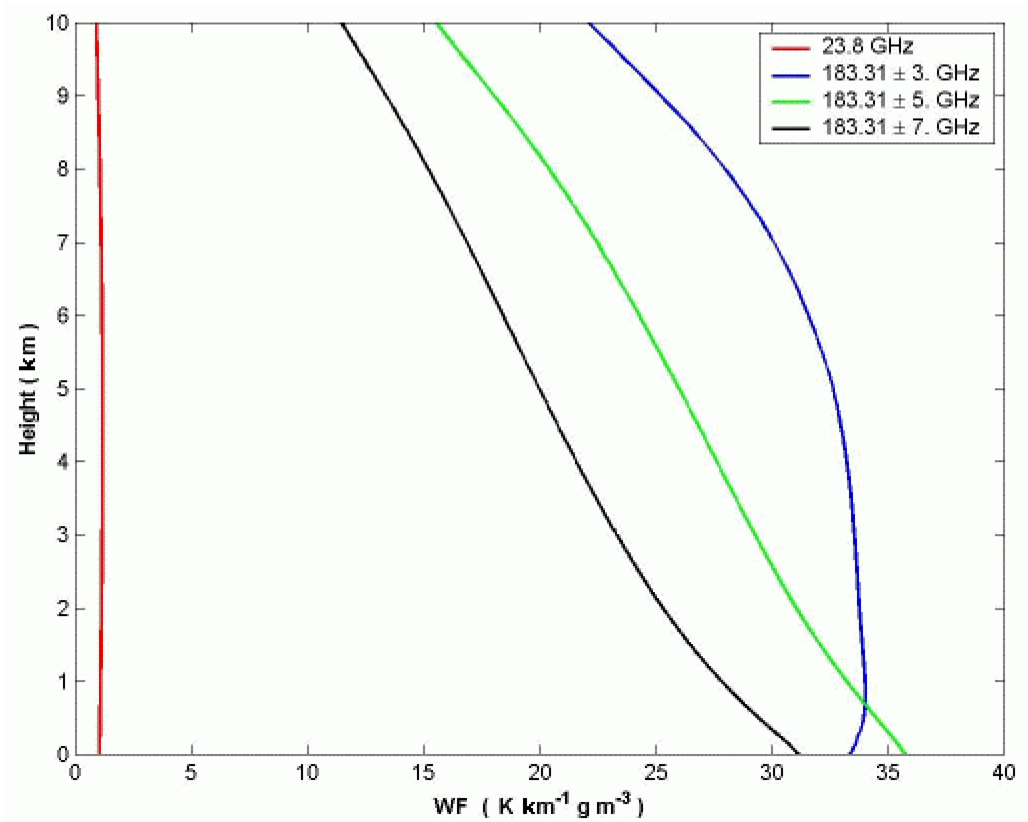

Figure 1. Water vapor weighting functions for conditions of the NSA/AAO for PWV less then 5 mm.

Because the MWR is a standard NSA/AAO instrument, we investigated the addition of Tb measurements near the 183 GHz line as a supplement for the MWR. We performed a set of simulations, in which the vapor-sensitive 23.8 GHz channel was paired with other millimeter-wave channels. These results are shown in Figure 3 and, based on reasonable estimates of instrument noise levels, suggest an accuracy of about 4% over a wide range of PWV amounts during clear conditions. However, retrievals using these frequencies are complicated by the uncertainties in the absorption models and the fact that these frequencies also respond to the vertical temperature distribution as well as to liquid and ice clouds.

The Experiment

The National Aeronautics and Space Administration (NASA) Goddard Space Flight Center and National Oceanic and Atmospheric Administration (NOAA) Environmental Technology Laboratory conducted the Arctic Winter Millimeter-Wave Radiometric Experiment at the ARM NSA/AAO CART site located just outside Barrow, Alaska. NASA and NOAA deployed a suite of radiometers covering 25 channels

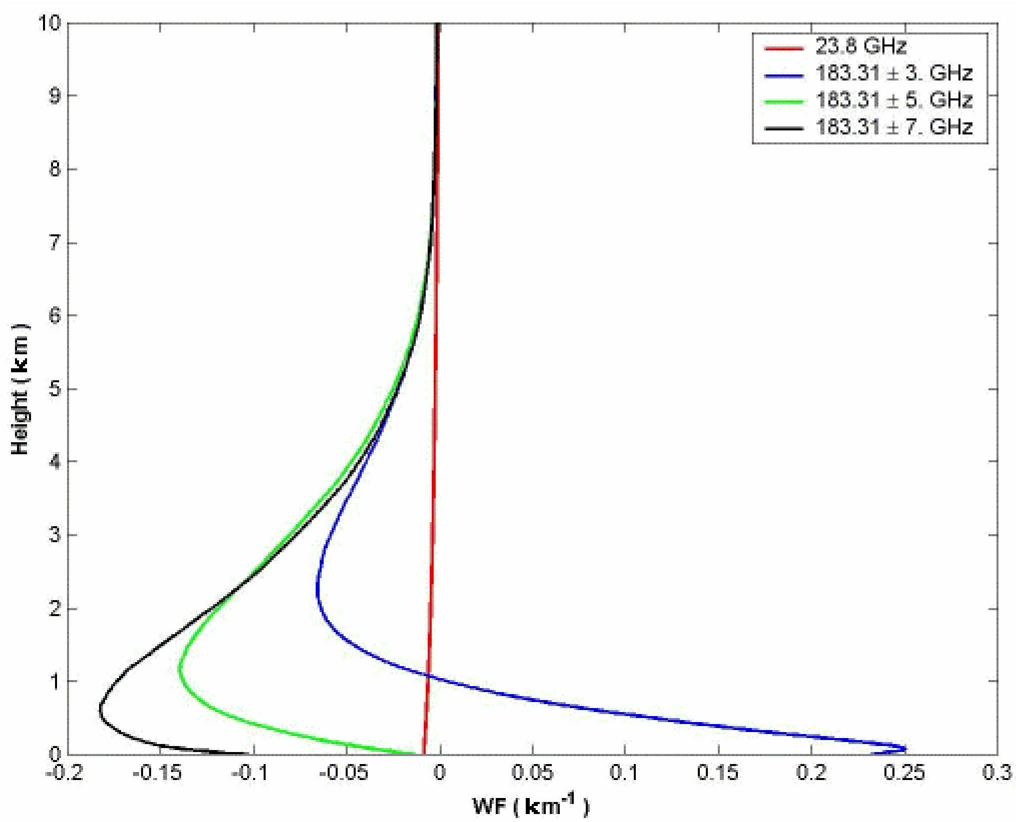

Figure 2. Temperature weighting functions for conditions of the NSA/AAO for PWV less then 5 mm.

in the frequency range of 20 GHz up to 340 GHz including 8 channels around the 183 GHz water vapor absorption line. Redundant measurements were made near 183 and 340 GHz by two instruments, the Millimeter-wave Imaging Radiometer (MIR), and the Circular Scanning Radiometer (CSR). Vaisala RS80 radiosondes were launched daily at the CART site, as well as at the nearby National Weather Service (NWS) site in Barrow, Alaska, where VIZ radiosondes were launched. Data were collected over a 23-day period in March 1999. The experiment benefited from a wide variety of arctic-winter atmospheric conditions ranging from clear, calm skies to blowing snow and heavy multi-layer cloud coverage. Measurements made by the CART site MWR indicate the PWV varied from ~0.9 to ~5.7 mm during the experiment. The near-surface temperature varied between about -40 to -15°C. Over the course of the experiment there were two periods of prevailing clear skies during which time the PWV was about 2 mm or lower. During the first period the surface temperature was ~10°C colder than during the later period though the PWV was about the same. The differing conditions allow us to study how the atmospheric temperature affects PWV retrievals using millimeter wave radiometry. In addition to the three references cited in the Introduction, preliminary results from the experiment are also given by Racette et al. (2000).

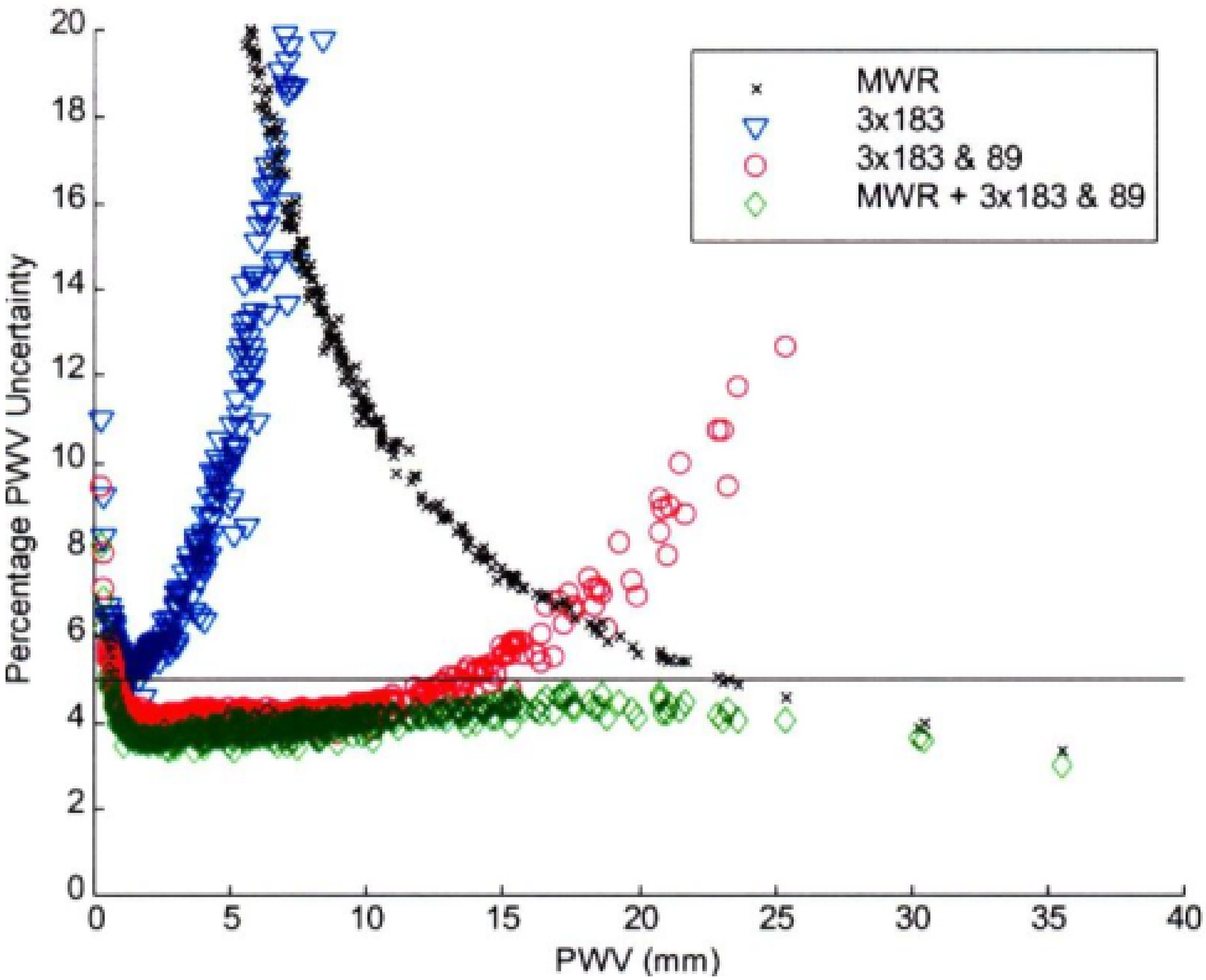

Figure 3. Clear air retrieval uncertainty for four-channel combinations using 400 high-latitude model profiles. Observation uncertainty, σ, for MWR is 1 K, for channels > = 90 GHz, σ = 3 K.

Observations

Figure 4 shows Tbs measurements made by the MIR over the period of the experiment. Overlaid on the measurements are forward-model calculations derived from radiosonde measurements; the NWS radiosondes are from the nearby Barrow NWS station; GWo and GWc are derived, respectively, from the original and corrected “Great White” Vaisala RS-80 radiosondes launched at the NSA/AAO site. Forward-model calculations were made using two absorption models, Liebe 87 (-L87) (Liebe and Layton 1987) and Rosenkranz 98 (-ROS) (Rosenkranz 1998). Significant differences between the forward-modeled Tbs and those measured by the MIR are observed for all the radiosonde calculations.

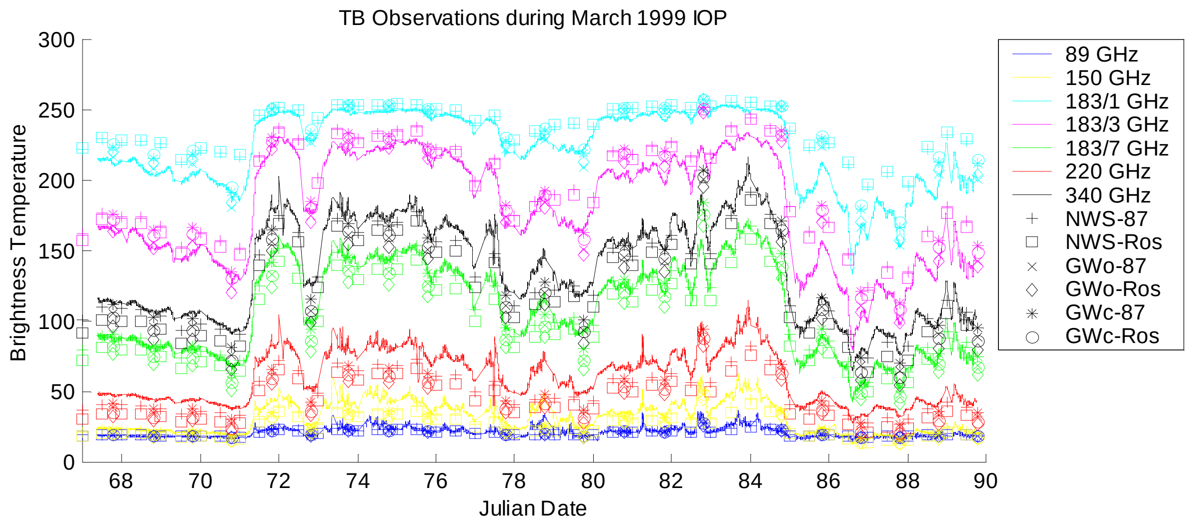

Figure 4. Brightness temperatures measured in Kelvin by the MIR throughout the course of the experiment. Overlaid on the plot are forward-modeled Tbs based upon radiosonde measurements.

The measurements made near the 183 GHz absorption line are generally lower than the forward-modeled Tbs, whereas, in the window regions near 150 GHz, 220 GHz, and 340 GHz the measured Tbs are higher than the forward-modeled Tbs. Thus, the discrepancies between the forward-modeled and measured Tbs cannot be explained by a simple bias of the radiosonde humidity profile.

Even though the MIR and CSR were independently calibrated, good agreement exists between measurements from the two instruments. The MIR used two internal blackbody references to achieve absolute calibration. The CSR used internal references and then tipping-curve calibration to achieve absolute calibration. The average difference between the CSR and MIR brightness temperatures (CSR-MIR) are 2.02, -2.25, 0.18, and 0.45 K for the 183 +/-1, 183 +/- 3, 183 +/- 7, and 340 GHz channels, respectively. The agreement between the two instruments gives a high degree of confidence in the calibration of the radiometer data. However, the consistency between the measurements is not necessarily representative of their absolute error.

Absorption Model Comparisons and Clear-Air Retrievals

Work reported by Westwater et al. (2000) compared radiative transfer modeling for three contemporary absorption models: Liebe and Layton (1987), Liebe et al. (1993), and Rosenkranz (1998). For simplicity, we refer to the measurements as L87, L93, and ROS. Calculations based on a radiosonde launched during very dry and cold conditions (PVW = 0.8 mm) revealed differences as large as 10 K between the three models. In addition to the forward-model studies, single-channel PWV retrievals were derived for six channels of the MIR data. The retrievals were limited for the two periods of predominantly clear conditions. Results using the L87 model are shown in Figure 5. Overlaid on the time series are PWV values derived from the original and corrected RS80 radiosondes. Large discrepancies are observed between the retrieved values. The window channels yield higher values of PWV than those channels near the 183 GHz line. These differences are attributed to a combination of errors in the measured Tbs and uncertainties in the absorption models.

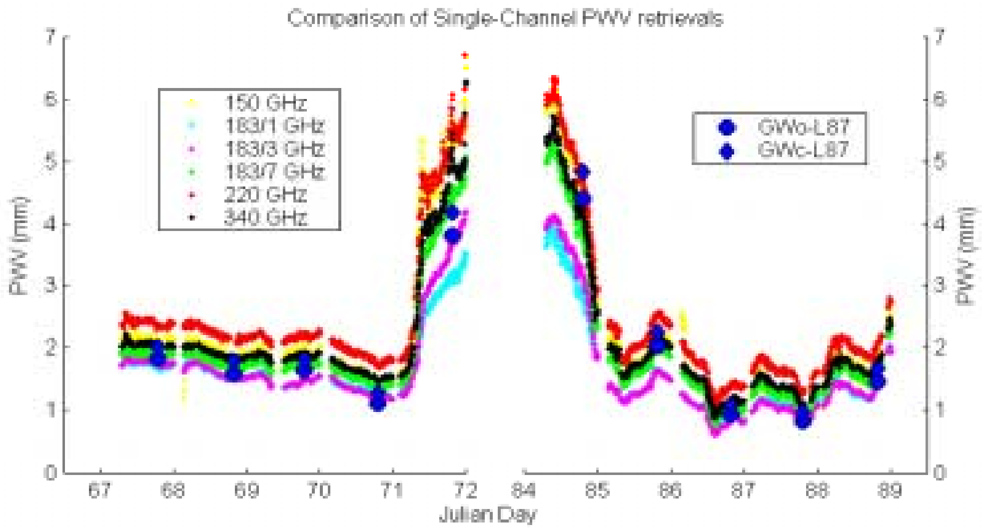

Figure 5. Comparison of single-channel PWV retrievals. Overlaid are PWV measured by Vaisala RS-80 radiosondes.

Conclusions and Recommendations

The theoretical basis of using 183 GHz radiometers to improve MWR retrievals of PWV at low amounts is sound. A variety of simulations and theoretical considerations all suggest that about 4 percent accuracy can be obtained during clear conditions; for PWV, less than about 20 mm. However, retrieval of PWV using millimeter-wave radiometric measurements is complicated by uncertainties that are outlined in the following.

Ground-based measurement experience of 183 GHz brightness temperatures is much less than that in the 22.235 GHz region. Forward-modeled Tbs differ when different absorption models are used. Our calculations showed that substantial (~10 to 15 K) differences existed between the various models at some of the sub-millimeter frequencies. Our estimated radiometric calibration accuracy allowed us to resolve some, but not all, of the problems. For the MWR channels, the Liebe et al. (1993) model agreed with better than 0.1 K bias and a standard deviation of better than 0.2 K root mean square. However, for the millimeter-wave channels, the Liebe et al. (1993) model significantly over predicted Tb by 5.9, 8.8, and 13.3 K. The uncertainties in RAOB measurements of water vapor, coupled with MIR and CSR calibration uncertainties of perhaps 3 K, did not allow us to make a clear choice between the Liebe and Layton (1987) and the Rosenkranz (1998) absorption models. This is not a fundamental limitation of the 183 GHz region, but reflects the fact that a more comprehensive database of Tb and high-quality radiosonde measurements is needed.

Comparisons of NWS radiosondes launched at Barrow with those of ARM launched at the CART site showed agreement in PWV, usually in the range of about 0.05 cm, although simultaneous radiosondes were not available. Because of the long database of NWS radiosondes, and because currently, only one radiosonde per day is launched at the NSA/AAO CART site, a more definitive radiosonde comparison is recommended. Because of the excellent data that is produced by the ARM MWR, perhaps the simultaneous operation of MWRs at the CART site and at the NWS facility could aid in such a study.

It was discovered during the experiment that the initial calibration of the ARM MWR was spurious because of poor thermal control. However, as was shown by Han et al. (2000), much of this problem was overcome when instantaneous, rather that averaged, calibration factors were used. Again, the crucial importance of tipcal was demonstrated.

For window frequencies and channels beyond perhaps ± 5 GHz from the absorption line center, sub-millimeter-wave radiometer calibration can benefit by the tipcal method. Unfortunately for the MIR radiometer during our experiment, two-sided tipcals were not possible, and hence some residual uncertainties existed. Again, this is not a fundamental limitation, but one that can be overcome by equipment design.

A companion poster by Leuski and Westwater (2001) indicates that excellent temperature profiles can be derived from a scanning 5-mm radiometer if a radiosonde temperature profile is used for an initial guess. The availability of such data can improve sub-millimeter-wave measurement-based retrievals in two ways: the derived profiles can be used to determine real-time mean radiating temperatures for tipcals. Second, the derived profiles can be scaled by MWR PWV measurements to provide a high-quality first guess for 183 GHz radiometers.

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