

INITIAL EVALUATION OF PROFILES OF TEMPERATURE, WATER VAPOR  
AND CLOUD LIQUID WATER FROM A NEW MICROWAVE RADIOMETER

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## 1. INTRODUCTION

To measure the vertical profiles of temperature and water vapor that are essential for modeling atmospheric processes, the Atmospheric Radiation Measurement (ARM) Program of the U. S. Department of Energy launches approximately 2600 radiosondes each year from its Southern Great Plains (SGP) facilities in Oklahoma and Kansas, USA. The annual cost of this effort exceeds \$500,000 in materials and labor.

Despite this expense, the measured profiles are not as well suited to modeling as might be desired. Radiosondes take about 40 minutes to ascend through the troposphere and about 2 hours to ascend to full height, which limits their temporal resolution. Cost and other practical considerations further limit the temporal sampling interval (i.e. launch frequency) to 3 hours during Intensive Operation Periods (IOPs) and 6-8 hours during routine operations. In contrast, the radiation measurements used for comparison with model calculations have temporal resolutions and reporting intervals of a few minutes at most.

Conversely, radiosondes have a much higher vertical spatial resolution, about 10 meters, than most models can use. Modelers generally reduce the vertical resolution of the soundings by averaging over the vertical layers of the model.

In an attempt to acquire profile measurements with temporal and spatial characteristics similar to the radiation measurements and more appropriate to models, ARM has deployed a variety of ground-based remote sensors. However, none of these remote sensors can provide a complete profile of tropospheric temperature or water vapor over the wide range of sky conditions and with the high reliability of the balloon-borne sounding system (BBSS). Consequently the BBSS remains the primary profiling instrument.

Recently, Radiometrics Corporation has developed a ground-based microwave radiometer capable of providing continuous, real-time vertical profiles of

temperature, water vapor and limited-resolution cloud liquid water from the surface to 10 km in nearly all weather conditions. The microwave radiometer profiler (MWRP) offers a much finer temporal resolution and reporting interval (about 10 minutes) than the BBSS, but a coarser vertical resolution that may be more appropriate for models.

To evaluate the performance of this new instrument and the suitability of its profile measurements for driving typical radiation models, the radiometer was deployed at the ARM SGP central facility from 15 February to 8 August 2000. The initial results of that evaluation are presented here.

## 2. THE RADIOMETER PROFILER

The microwave profiler is comprised of two separate receivers in the same cabinet that share the same antenna and antenna pointing system. A highly stable synthesizer permits tuning to a large number of frequencies within the receiver bandwidth. The temperature-profiling receiver measures the radiometric brightness temperature of the sky at seven frequencies corresponding to a complex of oxygen absorption lines between 51 and 59 GHz. The water vapor-profiling receiver uses five frequencies extending from the center of the water vapor line at 22 GHz out to 30 GHz. Surface meteorological sensors measure air temperature, barometric pressure and relative humidity. To improve the measurement of water vapor and cloud liquid water profiles, cloud base altitude information is obtained with an infrared thermometer. The calibration of the water vapor-profiling receiver is maintained by continuous tipping curves. A liquid nitrogen-cooled blackbody target is used to calibrate the temperature-profiling receiver. Detailed descriptions of the instrument and calibration procedures are given by Solheim *et al.* (1998a).

Profiles of temperature, water vapor and cloud liquid water are obtained at 47 levels: from 0 to 1 km above ground level at 100 m intervals, and from 1 to 10 km at 250 m intervals. The profiles are derived from the measured brightness temperatures with neural network retrieval algorithms. The neural network was trained

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with brightness temperatures calculated using a microwave radiation transfer model for ten years of radiosonde profiles from Oklahoma City for February through August. The neural network retrieval and alternative retrieval methods are discussed by Solheim *et al.* (1998b).

### 3. PROFILE EXAMPLES

MWRP profiles of temperature, water vapor, and cloud liquid from 10 May 2000 are presented as time-height plots in Figure 1. These show that cool, dry air was replaced by warm, moist air, which resulted in an increase in precipitable water vapor (PWV) from about 1.5 cm to 3 cm and in the formation of low clouds. MWRP profiles coincident with the 11:31 UTC (05:31 local) and 23:47 UTC (17:47 local) radiosonde soundings for 10 May are presented in Figures 2 and 3, respectively. These illustrate typical performance for temperature inversion and lapse conditions.

### 4. PROFILE COMPARISONS

The profiles of temperature and water vapor density derived from the MWRP brightness temperatures were compared with routine soundings from the Vaisala Balloon Borne Sounding System (BBSS) using RS-80H radiosondes. The soundings were interpolated to the 47 MWRP levels. MWRP profiles were also compared with boundary layer profiles (up to 3 km) derived from the Atmospherically Emitted Radiance Interferometer (AERI) infrared spectrometer, described by Smith *et al.* (1999). The mean difference ("bias") and the root-mean-square difference ("rms error") between the MWRP or AERI and the BBSS for the cool, dry springtime period from 15 February to 15 May 2000 comparison are presented in Figure 4. The results for the warm, moist summertime period from 15 May to 8 August are presented in Figure 5. The standard deviation about the ensemble mean of the BBSS profiles for each of these periods, often referred to as "climatology", is also plotted as a reference. The nearly all-weather capability of the MWRP allowed for about 37% more valid profiles than AERI during the spring (199 vs. 145) and 20% more during the summer (150 vs. 124).

Both the MWRP and AERI compare well with the BBSS, with rms errors significantly less than the climatology below 4 km. Both the MWRP and AERI have some difficulty resolving sharp temperature and moisture gradients at the top of the mixed layer, as indicated by the rms errors plotted in Figures 4 and 5, and illustrated in Figure 2. However, few models can resolve such gradients either.

The temperature profile comparisons show that the MWRP exhibits a bias relative to the BBSS at altitudes between 0.5 and 2 km. This bias is as large as 1 K during the spring and up to 2 K during the summer. The AERI profiles exhibit a similar, but slightly smaller bias.

If monthly values of the neural net retrieval coefficients had been used instead of a single set for February through August, it is likely that the MWRP bias and rms errors would have been somewhat smaller.

The water vapor density profiles show that the MWRP and AERI exhibit comparable skill (i.e. comparable bias and rms errors) in both spring and summer periods, except that during the summer the MWRP exhibits a bias of about 1 g/m<sup>3</sup> at the ground. The mean difference in surface relative humidity reported by the MWRP and BBSS is about 2% during the summer. Although this is within the expected accuracy of the humidity sensors, at the average summer surface temperature (~300 K) and relative humidity (~72%) a 2% difference in relative humidity results in a 1 g/m<sup>3</sup> difference in water vapor density.

Above about 4 km the water vapor density is very small and the rms error in the MWRP water vapor density profiles is comparable to the standard deviation about the mean of the radiosonde ensemble. This suggests that using the mean spring or summer water vapor density profile would be equally accurate above 4 km. Monthly retrieval coefficients may improve the bias and rmse. Gueldner and Spaenkuch (2000) obtained similar results with an identical MWRP when using a neural net retrieval; they also reported improved results using an alternative, regression-based retrieval.

### 5. MODEL COMPARISONS

To make an initial assessment of the suitability of the MWRP for radiation modeling applications, we used delta two- and four-stream radiative transfer models (Toon *et al.*, 1989; Liou *et al.*, 1988) to compute the downward longwave and shortwave irradiance, respectively. In the radiative transfer calculations gaseous absorption was computed using the k-distribution method and correlated-k tables developed by Kato *et al.* (1999) and Mlawer *et al.* (1997) for shortwave and longwave radiation, respectively. We used the measured water vapor profiles up to 10 km and added the mid-latitude summer standard atmosphere above 10 km. We also used mid-latitude summer standard profiles of ozone, nitrous oxide and methane. Because we were only concerned with the effect of the different temperature and water vapor profiles on the model results, we fixed the solar zenith angle at 60 degrees and the surface albedo at 0.2. No clouds were inserted.

We applied the models to 12 cases (of which AERI profiles were available for only 7) between 10 and 16 May 2000. The results are presented in Figures 6 and 7. The rms errors associated with using the MWRP profiles reach a maximum of 10 W/m<sup>2</sup> at 4 km for the solar flux and 15 W/m<sup>2</sup> at 4 km for the infrared flux, which corresponds to the maximum bias in the water vapor density. In both cases this rms error is less than the variation about the mean of the BBSS-based model results. The bias and rms errors are also less than

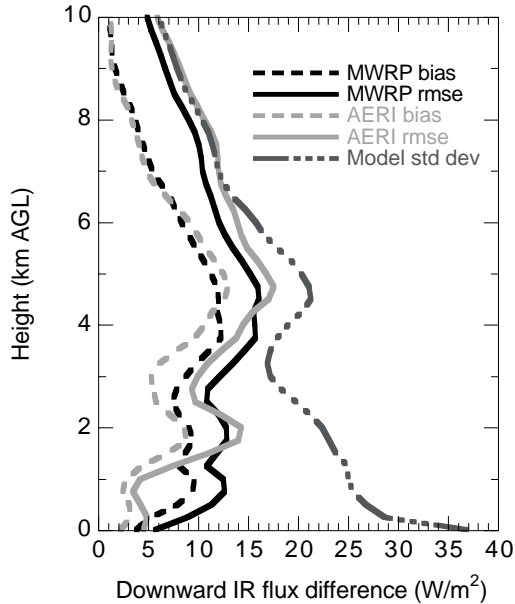


Figure 6. Mean differences (bias) and root mean square differences (rms errors) in downward infrared fluxes calculated using temperature and moisture fluxes from the MWRP or AERI and the BBSS.

those of the pyranometers and pyrgeometers typically used to measure the radiation fluxes.

## 6. CONCLUSIONS

This initial evaluation of the microwave radiometer profiler suggests its accuracy is comparable to the AERI boundary layer profiler, but can operate to greater altitudes and for a wider range of sky conditions than AERI. The vertical resolution of the MWRP profiles, while coarser than the BBSS, appears to be sufficient for solar and infrared flux calculations.

Evaluation of the liquid water profiles will be undertaken once comparable data from combined cloud radar and two-channel microwave radiometer become available.

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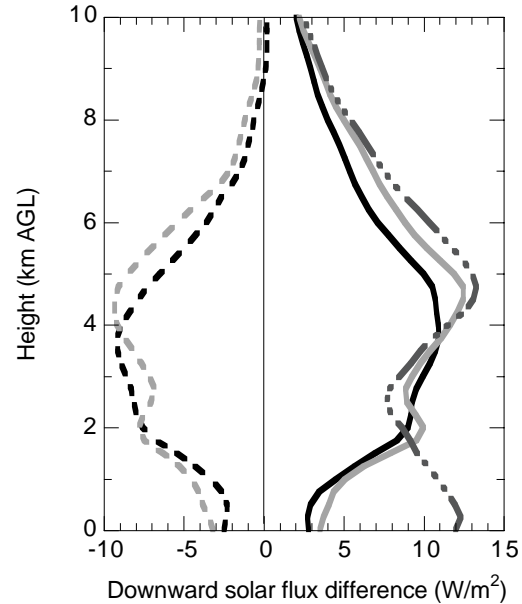


Figure 7. Same as Figure 6 for downward solar fluxes.

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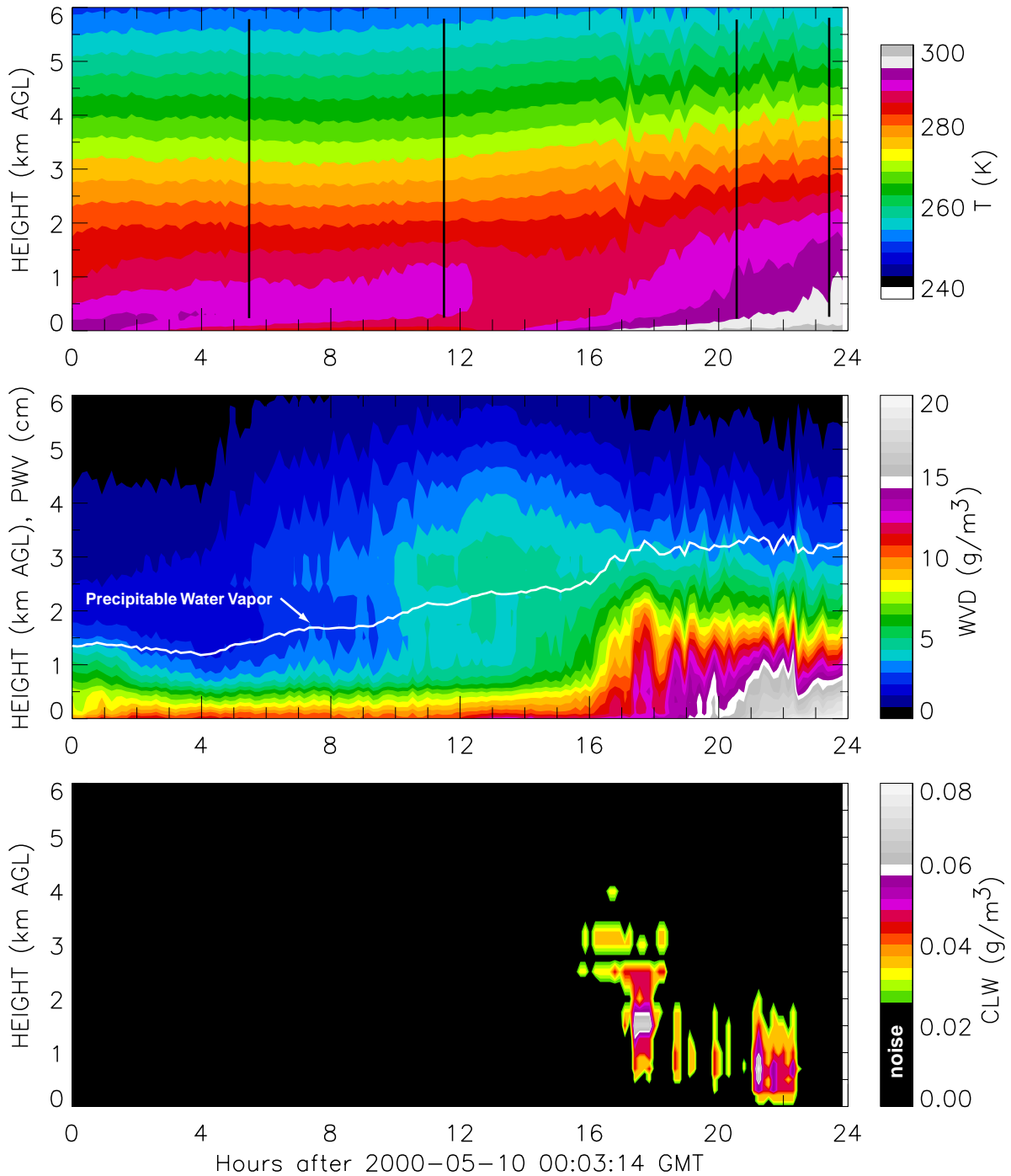


Figure 1. Time-height contours of temperature (top), water vapor (center) and liquid water (bottom) from the microwave radiometer profiler (MWRP) for 10 May 2000. The vertical lines in the top panel indicate the radiosonde launch times for this day. Figures 2 and 3 compare profiles from the MWRP and radiosondes for 11:31 and 23:47 GMT on this day. The white line in the center panel indicates the precipitable water vapor from the MWRP, which doubles in magnitude over the day. In the bottom panel, values of liquid water content less than the instrument sensitivity are set to black.

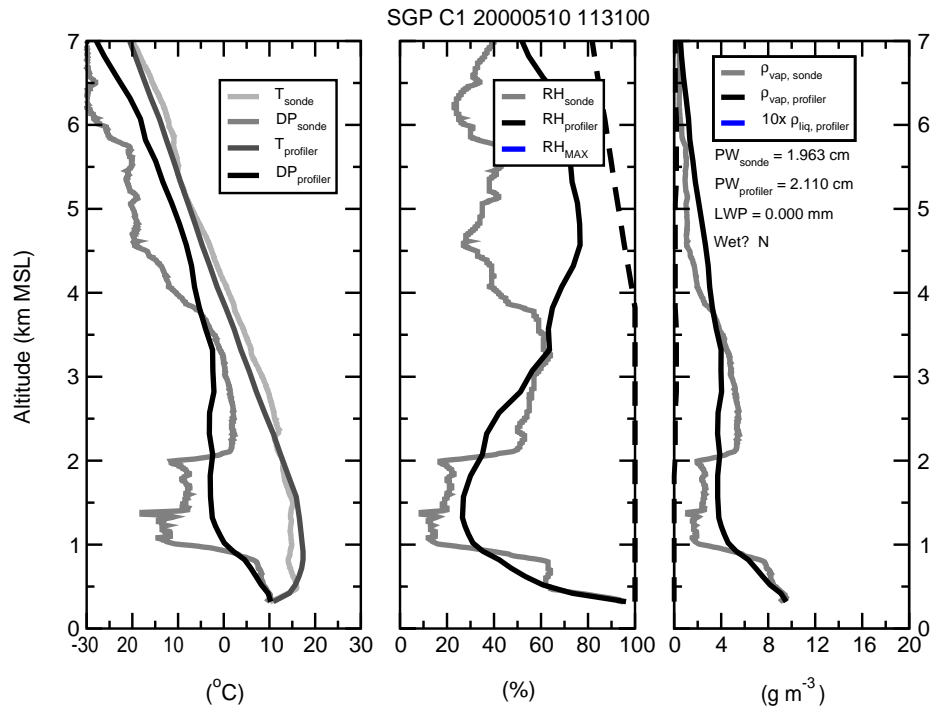


Figure 2. Profiles of temperature and dew point (left panel), relative humidity (center panel) and water vapor and liquid water density (right panel) from the microwave radiometer profiler (MWRP) and balloon-borne soundingsystem (BBSS) for 11:31 UTC (05:31 local time) on 10 May 2000. The dashed line in the center panel indicates the ratio of saturation mixing ratios for ice and liquid water for sub-freezing temperatures. The right panel also lists the precipitable water vapor from both BBSS and MWRP, the liquid water path (LWP) from the MWRP, and the status of the MWRP rain sensor.

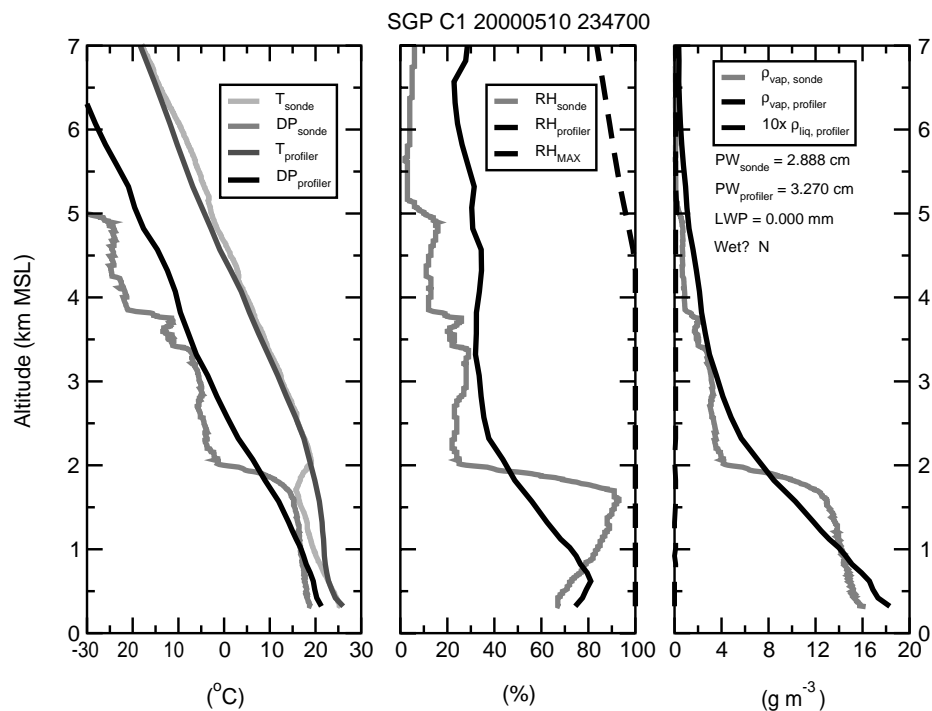


Figure 3. Same as Figure 2 for 23:47 UTC (17:47 local time) on 10 May 2000.

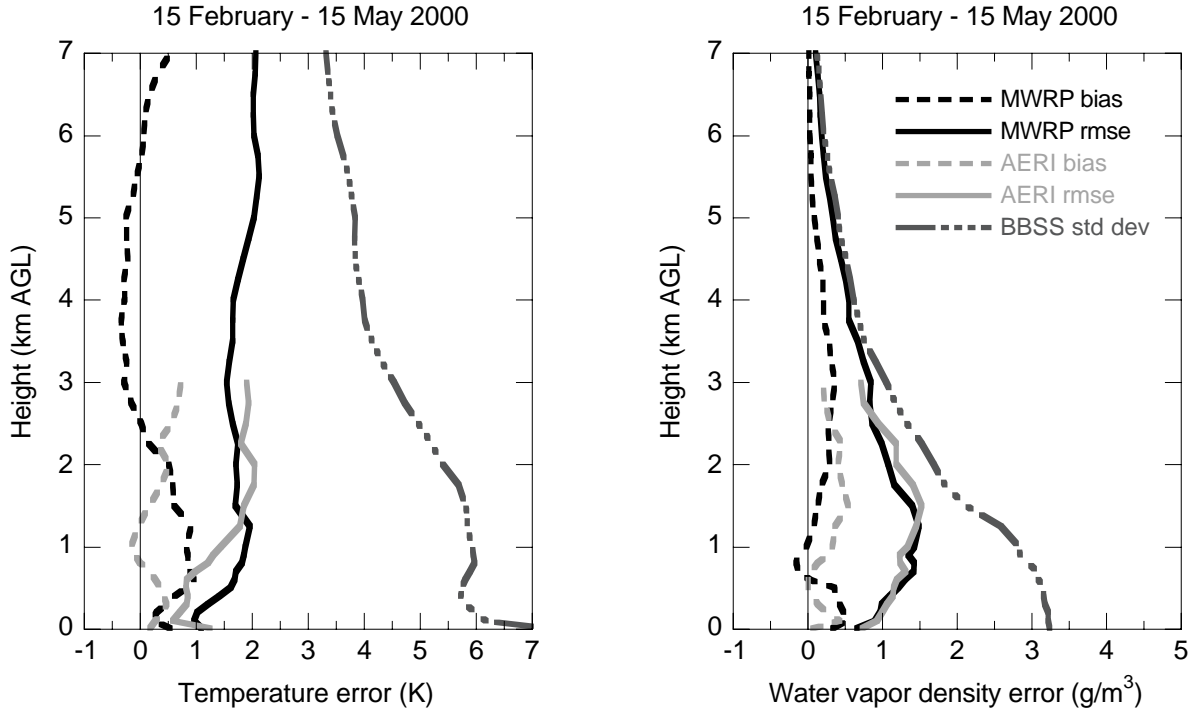


Figure 4. Comparison of temperature and water vapor profiles from microwave radiometer profiler (MWRP) and AERI infrared spectrometer with the Balloon Borne Sounding System (BBSS) for the period 15 February - 15 May 2000. In each plot the dotted lines indicate the mean difference (bias), the solid lines indicate the root-mean-square difference (rms error), and the dot-dashed line indicates the standard deviation about the mean of the radiosonde ensemble (i.e. the "climatology".)

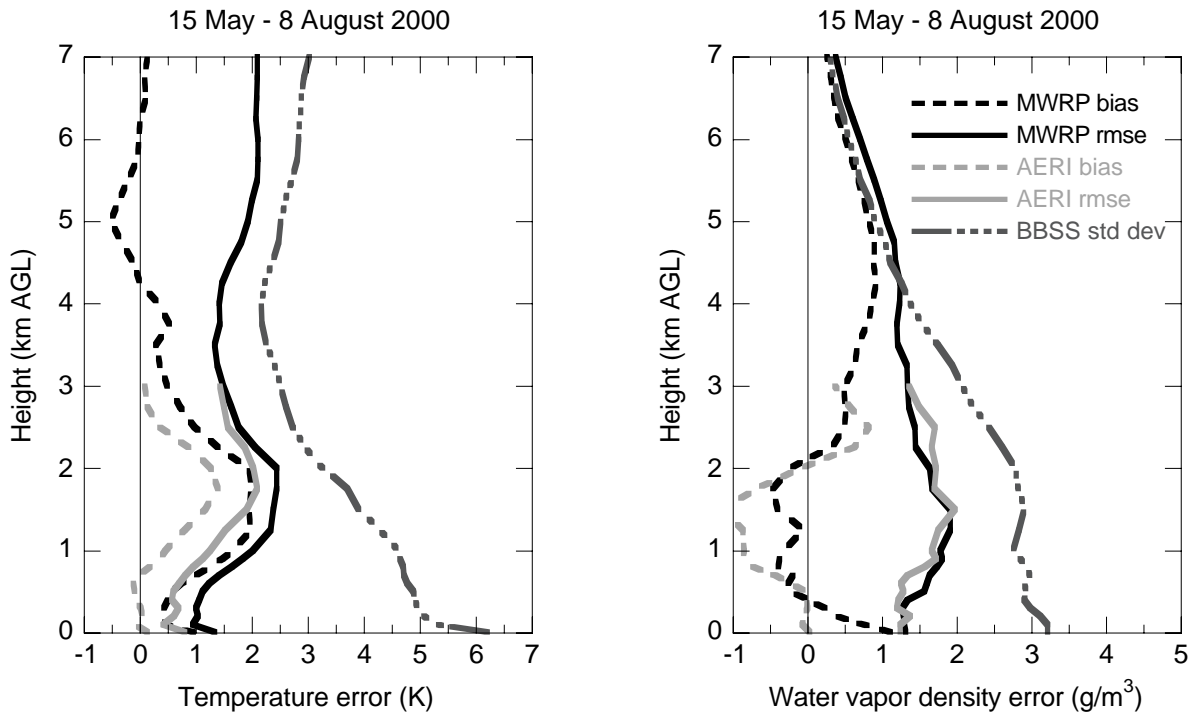


Figure 5. Same as Figure 4, but for the summer period 15 May - 8 August 2000.