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4.7 IMPROVED RETRIEVALS OF TEMPERATURE AND WATER VAPOR PROFILES WITH A TWELVE-CHANNEL RADIOMETER

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1. INTRODUCTION

The Atmospheric Radiation Measurement (ARM) Program has operated a twelve-channel microwave radiometer profiler (MWRP; Solheim et al 1998a) since February 2000. Although the MWRP is currently deployed at the ARM Southern Great Plains (SGP) central facility near Lamont, OK, it has also been successfully operated at the ARM North Slope of Alaska facility at Barrow, AK.

The MWRP provides 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, at approximately 5-minute intervals. Figure 1 shows a frontal passage (~12:00 UTC on 2 April 2002) captured by the MWRP. In contrast to radiosondes, the MWRP provides substantially improved temporal resolution but coarser vertical spatial resolution, which declines in proportion to the height above ground level. In this regard the MWRP more closely matches the temporal and spatial resolution of numerical weather forecast models.

In evaluating the MWRP for the ARM Program, Liljegren (2002) demonstrated significant biases in the water vapor and temperature profiles retrieved from the MWRP with the artificial neural network algorithms supplied by the manufacturer (Solheim et al. 1998b), in comparison with radiosonde data. This finding is in agreement with a previous evaluation of the MWRP by Gueldner and Spaenkuch (2001).

In this paper the retrieval biases are shown to arise from systematic differences between the observed brightness temperatures and the values calculated at the five measurement frequencies between 22-30 GHz with the microwave absorption model used to develop the retrieval algorithms. Replacing the value for the air-broadened half-width of the 22-GHz water vapor line (Liebe and Dillon 1969) used in the absorption model with the half-width from the HITRAN compilation (Rothman et al. 1992), which is 5% smaller, largely eliminates the systematic differences in brightness temperatures.

An *a priori* statistical retrieval based on the revised model yielded significant improvements in the accuracy and vertical resolution of the retrieved temperature and water vapor profiles. Additional improvements were demonstrated by combining the MWRP retrievals with those from the GOES-8 sounder and by incorporating brightness temperature measurements at off-zenith angles in the retrievals.

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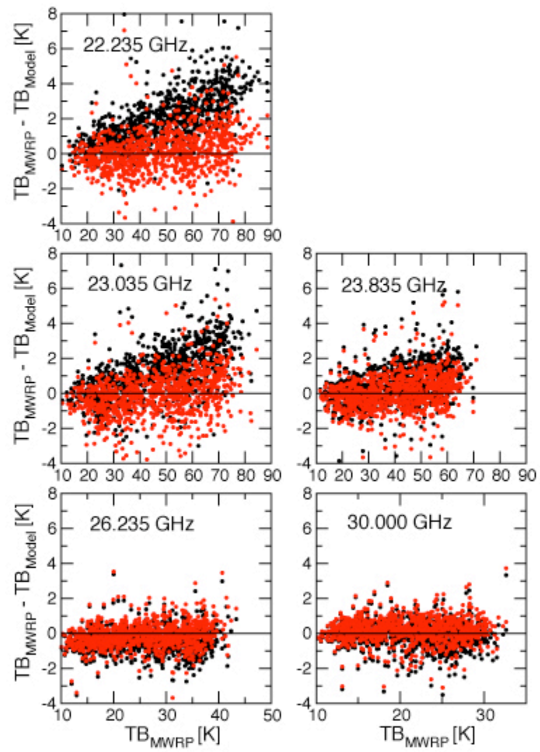

Figure 2. Differences between measured and modeled brightness temperatures for the Liebe and Dillon (1969) half-width (black) and the half-width from HITRAN (red).

2. REVISED ABSORPTION MODEL

Brightness temperatures measured in the five K-band channels (22.235, 23.035, 23.835, 26.235, and 30.0 GHz) that span the water vapor resonance centered at 22.235 GHz were compared with calculations based on the Rosenkranz (1998) water vapor absorption model. To ensure that any dry bias in the radiosondes used in the model calculations did not affect the brightness temperature comparison, ARM's scaled radiosonde product (sgplssondeC1.c1) was used. In this product the relative humidity of the radiosonde is linearly scaled so that the integrated precipitable water vapor (PWV) matches the PWV reported by a collocated two-channel microwave radiometer operating at 23.8 and 31.4 GHz.

The results, presented in Figure 2, show that the measured minus modeled brightness temperature differences are about 5% too large at 22.235 GHz but that the differences decline with increasing frequency separation from the line center. S. A. Clough (personal communication) pointed out that this trend results

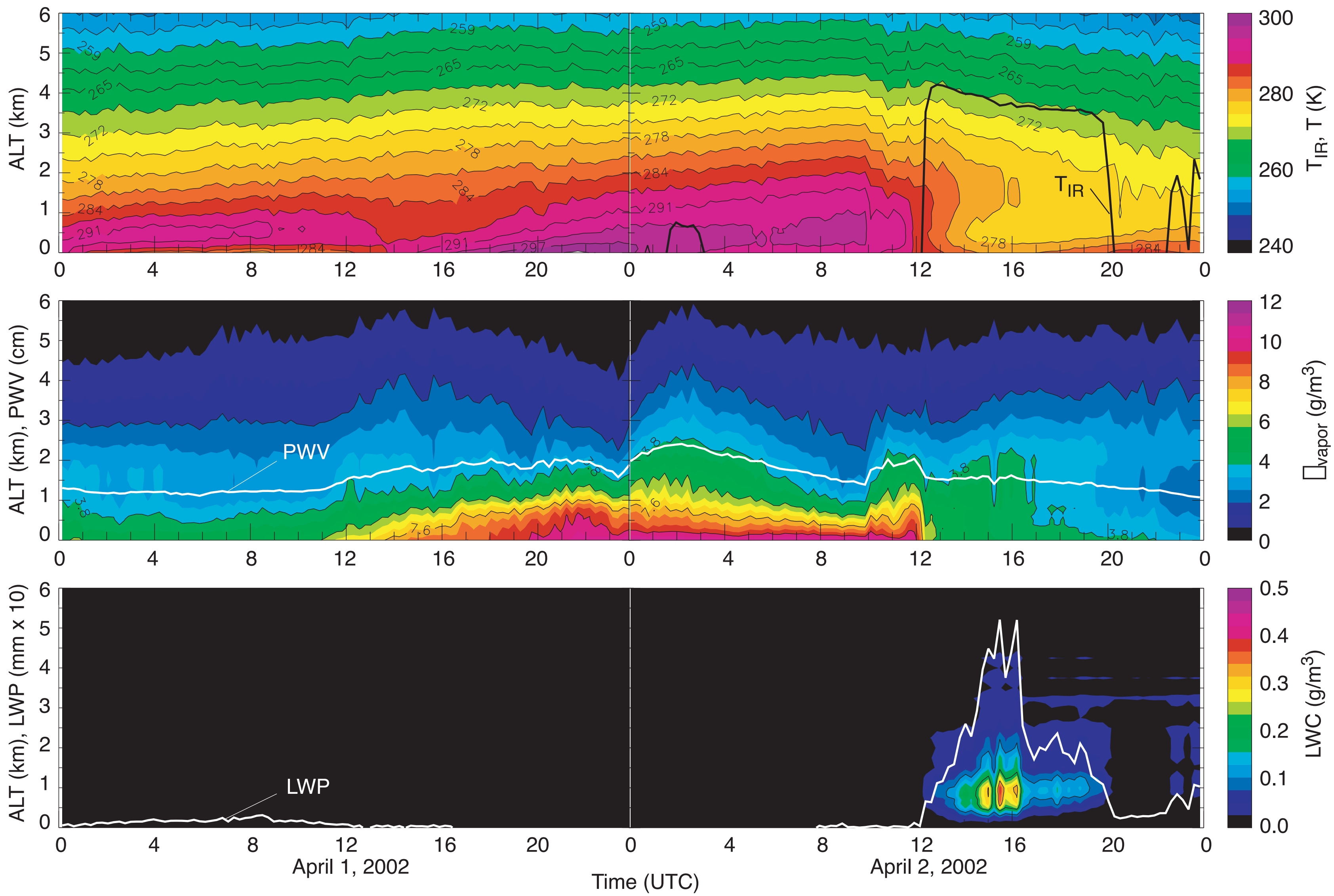

Figure 1. Time-height contours of temperature (top), water vapor density (middle), and cloud liquid water content (bottom) for 1-2 April 2002 at the ARM SGP site near Lamont, OK. The heavy black line in the top panel indicates the sky temperature reported by the infrared thermometer (IRT). The heavy white lines in the middle and bottom panels indicate the precipitable water vapor (PWV) and liquid water path (LWP), respectively.

because the line width in the Rosenkranz model is 5% too large; the air-broadened half-width given by Rosenkranz (1998) is 0.00281 GHz/kPa at 300 K, whereas the value from HITRAN database (Rothman et al. 1992) is 0.002656 GHz/kPa at 300 K, about 5% less than the Rosenkranz value. When the HITRAN value for the line width is substituted in the calculations, the agreement with the measured brightness temperatures improves dramatically, as shown in Figure 2.

3. CORRECTED TEMPERATURE AND WATER VAPOR RETRIEVALS

A priori statistical retrievals of temperature and water vapor profiles based on the Rosenkranz absorption model with the reduced 22-GHz line width were developed for three-month periods (spring, summer, fall, and winter) by using 9041 radiosonde soundings from the SGP central facility launched in 1994–2000. These retrievals were applied to brightness temperatures measured with the MWRP at the SGP in July 2001–September 2002. The differences between the retrieved profiles of temperature and water vapor and those measured by 955 co-temporal (unscaled) RS-90 radiosonde soundings were calculated. The mean (bias) and standard deviation of these differences are presented in Figure 3, along with a comparison of the original neural network retrievals developed by the

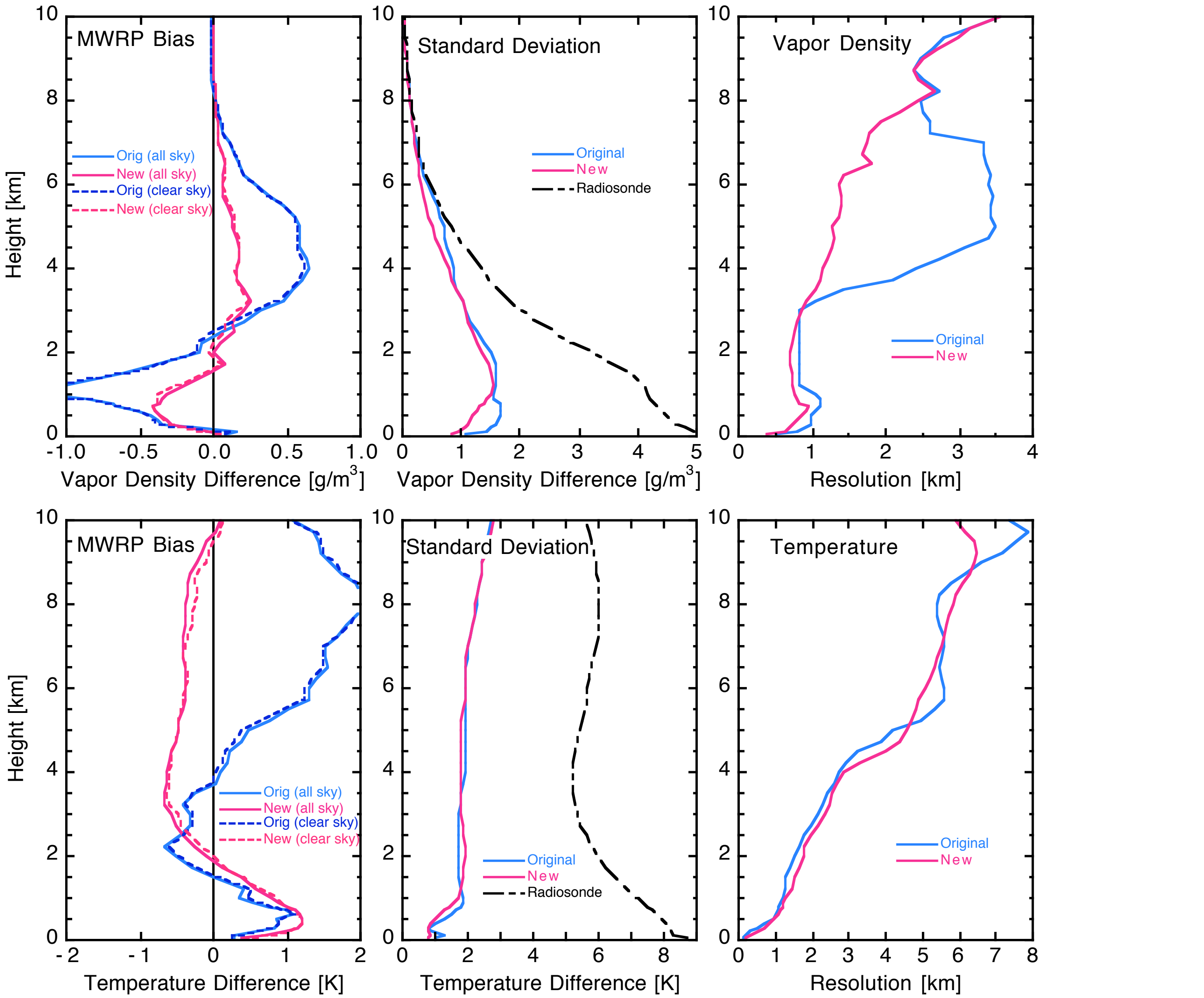

Figure 3. Mean (bias) and standard deviation of the MWRP-radiosonde differences in the water vapor and temperature profiles for the original neural network retrievals (blue) based on the Rosenkranz (1998) absorption model and the new statistical retrievals (magenta) based on the modified Rosenkranz model with the HITRAN value for the half-width of the 22-GHz water line. The standard deviation of the ensemble of radiosonde soundings about the mean of the ensemble (black) is provided for reference. The vertical resolutions of the original (blue) and new (magenta) water vapor and temperature retrievals are also shown.

manufacturer, Radiometrics Corporation (Solheim et al. 1998b), which were based on the unmodified Rosenkranz absorption model. The bias in the retrieved water vapor profiles in the lower and middle troposphere is substantially reduced with the new statistical retrieval based on the HITRAN line half-width. The standard deviation is also slightly reduced. The large temperature bias in the upper troposphere is also substantially reduced with the new retrieval. The upper tropospheric temperature retrieval is dominated by the brightness temperatures at 51.25 and 52.28 GHz, which have significant contributions from water vapor and therefore are sensitive to errors in the water vapor absorption model.

Figure 3 also presents calculations of the vertical resolution of the temperature and water vapor retrievals and the improvement in resolution, particularly for water vapor, due to the statistical retrievals with the HITRAN half-width. The vertical resolution of the retrieved temperature and water vapor profiles from the MWRP was determined by following Smith et al. (1999) with the inter-level error covariance $C(z_0,z)$ defined as

$$C(z_0,z)=\frac{\langle[Y(z_0)-Y_{sonde}(z_0)][Y(z)-Y_{sonde}(z)]\rangle}{\sqrt{\langle[Y(z_0)-Y_{sonde}(z_0)]^2\rangle\langle[Y(z)-Y_{sonde}(z)]^2\rangle}}. \quad (1)$$

Here z_0 is the height for which the resolution is to be determined, Y is the retrieved temperature or water vapor, Y_{sonde} is the value measured by the radiosonde,

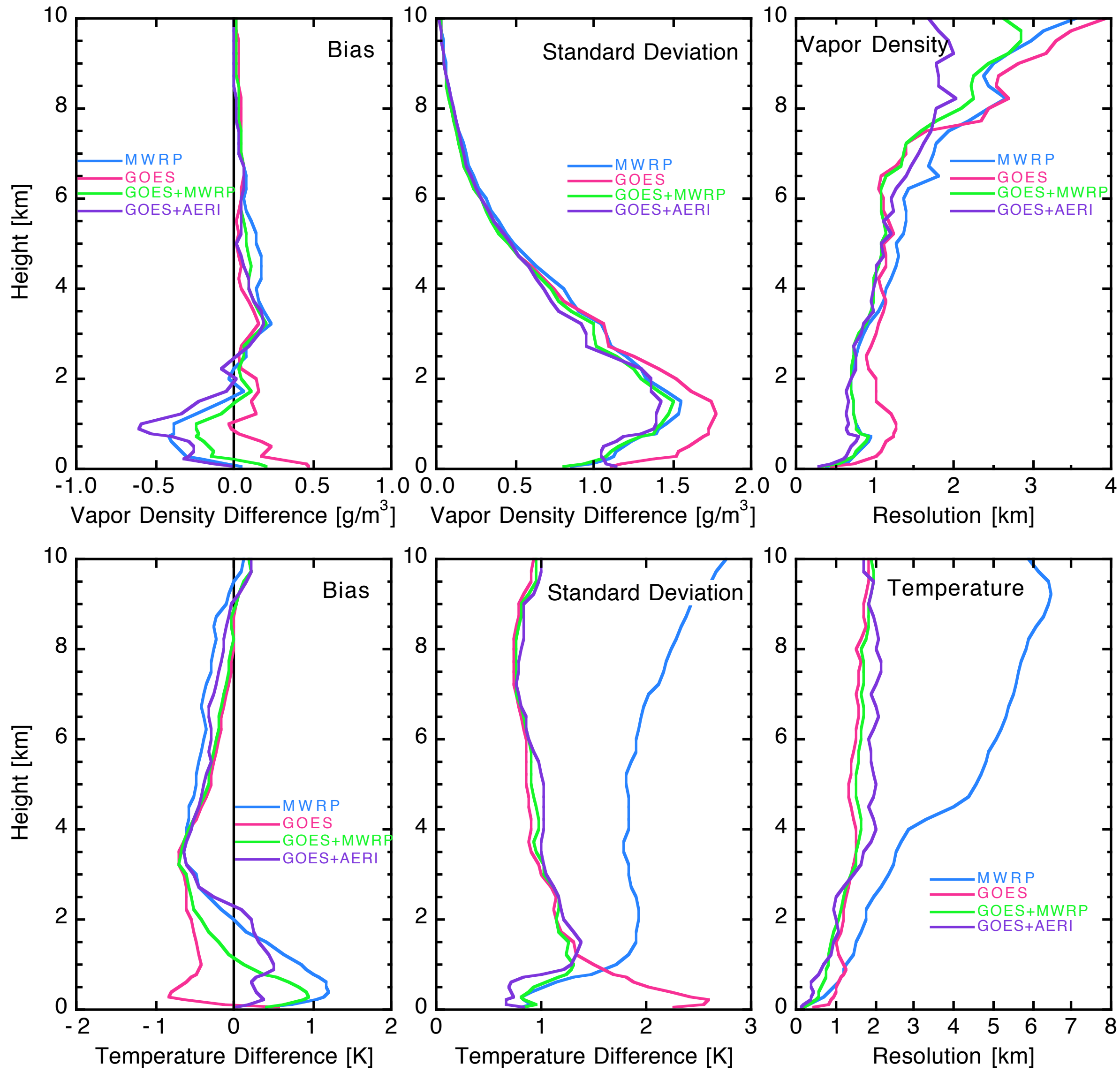

Figure 4. Mean (bias) and standard deviation of the retrieval-radiosonde differences for water vapor and temperature profiles derived from the MWRP alone (blue), GOES-8 sounder alone (magenta), GOES+MWRP (green), and GOES+AERI (purple). Vertical resolution for water vapor and temperature profiles is also shown. Vertical resolution is defined as the distance between the heights where the inter-level error covariance for each level falls to 0.5.

and the summations are over all profiles in the ensemble. Noting that $C(z_0, z=z_0) = 1$, the resolution at z_0 is defined as the distance between the heights z where $C = 0.5$. This is the method used by Smith et al. (1999) to calculate the vertical resolution of temperature and water vapor profiles derived from the Atmospherically Emitted Radiance Interferometer (AERI) spectrometer and also by Gueldner and Spaenkuch (2001) in their analysis of the MWRP neural network retrievals. Smith et al. (1999) noted that the resolution defined in this way represents a lower limit because of the limited number of levels in the retrieval and the vertically correlated errors in the rapidly ascending radiosonde measurements.

4. COMBINED MWRP AND GOES-8 RETRIEVALS

Temperature and water vapor profiles retrieved independently from the MWRP and GOES-8 (ARM product sgpg8profC1.a1) were combined by using the inverse covariance weighting technique:

$$Y(z) = \frac{Y_1(z)\sigma_1^{-2}(z) + Y_2(z)\sigma_2^{-2}(z)}{\sigma_1^{-2}(z) + \sigma_2^{-2}(z)}. \qquad (2)$$

Here Y is the temperature or water vapor density profile, z is the altitude, subscripts 1 and 2 indicate the two independent measurements of Y to be combined, and σ^2 is the error covariance, taken to be the square of the standard deviation of the difference between the retrieved profiles and collocated radiosonde soundings.

The results of the inverse covariance weighting are presented in Figure 4, along with results from the GOES+AERI retrieval (ARM product sgpgaeriprofC1.c1) for reference. For temperature, bias of the combined system is reduced relative to that of the separate retrievals below 1 km. Above 1 km, the GOES retrieval dominates because of its significantly lower standard deviation, so the combined bias tends toward the GOES-only bias. The vertical temperature resolution of the combined system is also improved relative to the separate systems. For water vapor, the benefit of the combination is not as dramatic, because the standard deviations of the GOES retrieval errors are greater than or equal to the MWRP retrieval error standard deviation below 4 km. Above this the vertical resolution does benefit noticeably. One limitation of the combined MWRP+GOES profiles (which is also applicable to the AERI+GOES retrievals) is that the infrared systems (GOES and AERI) are restricted to clear-sky conditions.

5. MULTI-ANGLE RETRIEVALS

To test whether the vertical resolution of the retrieved temperature and water vapor profiles could be improved further by incorporating off-zenith brightness temperature measurements, a retrieval was developed that used measurements at an elevation angle of 15° (i.e., the lowest angle in the tipping curve calibration scan) in addition to zenith. The resolution of this multi-angle retrieval was evaluated by applying it to simulated brightness temperature measurements computed by adding 0.5 K root-mean-square noise to model-calculated brightness temperatures and then computing the inter-level error covariances between the retrieved profiles and the input radiosonde profiles. The results are shown in Figure 5.

The results indicate that an improvement in resolution would be achieved in the water vapor density profile but not in the temperature profile. To achieve an improvement in the resolution of the temperature profile may require measurements at lower elevation angles. A systematic study of the optimal frequency-angle combinations for each retrieval height is necessary.

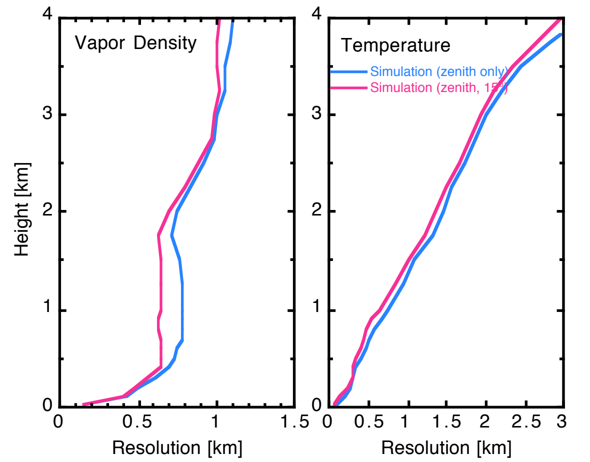

Figure 5. Resolution of retrieved temperature and water vapor profiles for simulated measurements in the zenith only (blue), and in the zenith and 15° elevation angle (magenta).

6. CONCLUSIONS

Biases in the temperature and water vapor profiles retrieved with the twelve-channel MWRP have been attributed to the half-width of the 22-GHz water vapor line used in the Rosenkranz model, which is 5% too large. Retrievals based on the value for the half-width in the HITRAN database exhibited a temperature bias of less than 1 K and a water vapor bias of less than 0.5 g/m^3. The reduced line half-width also improved the vertical resolution of the temperature and water vapor retrievals significantly.

Combining the ground-based MWRP retrievals with those from the GOES-8 sounder dramatically improved upper tropospheric temperature resolution.

Incorporating off-zenith brightness temperature measurements at 15° elevation into the retrievals improved water vapor profile resolution, which suggests that further study of the optimal combination of angles and frequencies for each height in the retrieval is warranted.

ACKNOWLEDGEMENTS

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