Atmospheric Microwave Radiative Models Study Based on Ground-Based Multichannel Radiometer Observations in the 20-60 GHz Band

C. Cimini, F. S. Marzano, and P. Ciotti
Center of Excellence CETEMPS
Universita' dell'Aquila
L'Aquila, Italy

D. Cimini
Science and Technology Corporation
Hampton, Virginia

E. R. Westwater
Cooperative Institute for Research in Environmental Sciences
University of Colorado
National Oceanic and Atmospheric Administration
Environmental Technology Laboratory
Boulder, Colorado

Y. Han
National Oceanic and Atmospheric Administration
National Environmental Satellite, Data, and Information Service
Office of Research and Application
Camp Springs, Maryland

S. J. Keihm
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

R. Ware
Radiometrics Co. and
University Consortium for Atmospheric Research
Boulder, Colorado

Introduction

We present recent results from the study of different atmospheric microwave absorption models available in literature. Recent experiments have shown an excellent calibration accuracy for ground-based microwave radiometers (MWRs). On the other hand, uncertainty related to the radiative properties of the atmosphere is the main limiting factor for the retrieval of atmospheric water vapor. Differences in brightness temperature (Tb), as computed using a variety of microwave absorption models, depend on frequency and atmospheric water vapor content and can exceed 4 K in the 20-60 GHz for a humid environment. The four atmospheric microwave absorption models considered in this study are available in literature, and hereafter referred to as LIEBE87 (Liebe and Layton 1987), LIEBE93 (Liebe et al. 1993), ROSEN98 (Rosenkranz 1998), and MONORTM (Delamere et al. 2002). We computed model predictions in the spectral range from 20 to 60 GHz, which is commonly used for ground-based estimates of atmospheric temperature and water vapor content by MWRs. The input dataset for the models was provided by atmospheric thermodynamic profiles measured by balloon-borne sensors, Vaisala RS90, which substantially reduced the so-called "dry-bias" (Cimini et al. 2003a). The sensors were launched 4 to 6 times daily. Simultaneously, empirical measurements were collected during two observational periods by four independent radiometers for a total of 19 channels, from 20.6 to 58.8 GHz. Thus, we compare model predictions with observations, and we discuss the impact of the differences found.

Instruments, Observations, and Simulations

Empirical data were collected during the water vapor intensive operational period (WVIOP), held in September/October 2000 at the Atmospheric Radiation Measurement (ARM) Program Southern Great Plains (SGP) site. Three MWR units were deployed, with a total of seven channels from 20.6 to 31.65 GHz. These units are the ARM central facility dual-channel (23.8, 31.4 GHz), the NASA/JPL three-channel radiometer (20.7, 22.2, 31.4 GHz), and the NOAA/ETL dual-channel circulating scanning radiometer (20.6, 31.65 GHz), hereafter referred as CF, JPL, and CSR, respectively. During the WVIOP2000, the three MWR units run for about a month, scanning continuously in the east-west direction. Thus, it was possible to apply the tip curve method to refine calibration (Han and Westwater 2000), and, therefore, show a calibration accuracy of the order of 0.5 K during clear-sky (Cimini et al. 2003a). In addition, there were three-hourly radiosonde launches, deploying two different kinds of sensors, the RS80 and the RS90, both from Vaisala. During the WVIOP2000, RS90 sensors substantially reduced the “dry-bias” affecting the RS80, as described in Cimini et al. (2003a). In Figure 1, we show the Tb spectrum from 20 to 32 GHz computed using the four absorption models (solid lines) from tropospheric profiles of pressure, humidity, and temperature measured by an RS90 radiosonde (launched at 2000/10/01 05:28:00 UTC). We also plot ground-based observations from the three MWR units (squares for CSR, triangles for JPL, and circles for ACF), averaged for about 30 minutes after the launch time. By comparing the four lines, we notice that differences in Tb between models’ predictions might exceed 2 K, depending on frequency. Figure 1 refers to just one case, so we should form any

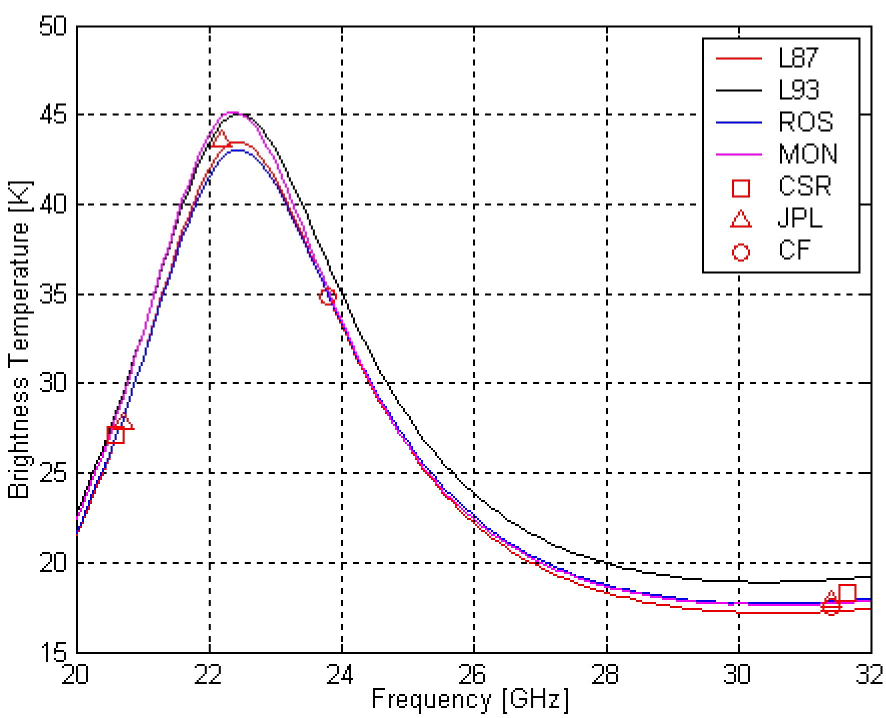

Figure 1. Ground-based Tb observations from three MWR units (squares for CSR, triangles for JPL, and circles for CF) and simulations computed using four absorption models (solid lines) from pressure, humidity and temperature profiles measured by an RS90 radiosonde (2000/10/01 05:28:00 UTC).

conclusions based on it. However, it shows that model differences are sometimes larger than the MWR accuracy, and, thus, might be studied and possibly corrected according to measurements. To extend the frequency range under examination, we have later considered radiometric observation from the radiometrics multi-channel microwave radiometer profiler (MWRP), deployed at the ARM SGP since May 2002. The MWRP observes radiation at 12 channels in the 20-60 GHz range (22.235, 23.035, 23.835, 30.0, 51.25, 52.25, 52.280, 53.850, 54.94, 56.66, 57.29, and 58.8 GHz), that were selected by eigenvalue analysis (Solheim et al. 1998). The MWRP absolute calibration relies on a combination of internal ambient target, noise diode, and tipping curve, when applicable. During the deployment of the MWRP at the ARM SGP, 6-hourly launches of RS90 were performed routinely. Similar to Figure 1, Figure 2 shows the Tb spectrum from 22 to 60 GHz computed using the four absorption models (solid lines) from tropospheric profiles of pressure, humidity, and temperature measured by an RS90 radiosonde (launched at 2002/05/31 23:25:00 UTC). Due to the large Tb range, the differences caused by different absorption models are not evident in this figure. For this reason, in Figure 3, we plot the same case of Figure 2, focusing on the 22-31 (a) and the 50-60 (b) GHz ranges. Now the differences in simulated Tb caused by the different models are evident, and it is also clear that observations might help to resolve some of the uncertainties related to absorption models. Although, as already said, one case is not enough to draw a conclusion.

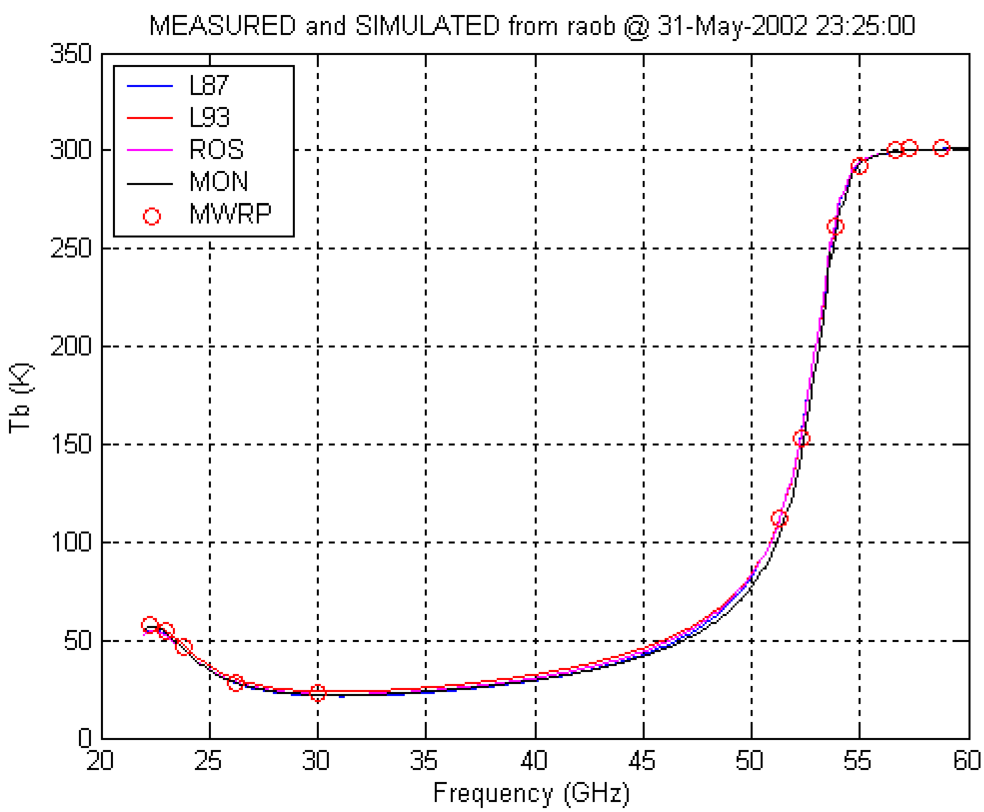

Figure 2. Ground-based Tb observations from the MWRP (circles) and simulations computed using four absorption models (solid lines) from pressure, humidity, and temperature profiles measured by an RS90 radiosonde (2002/05/31 23:25:00 UTC).

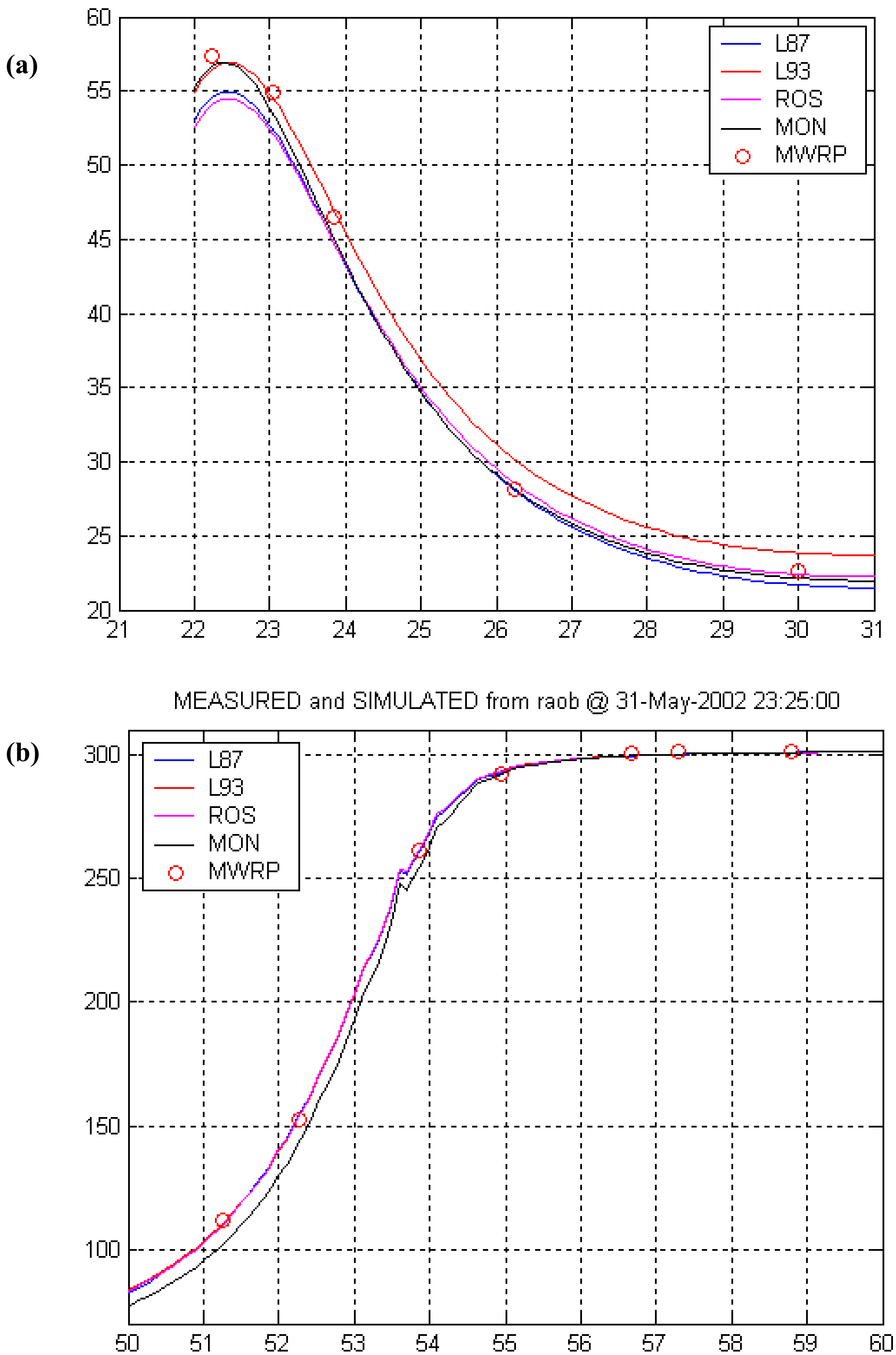

Figure 3. Same as Figure 2, but with (a) enlarged resolution for the 20-30 GHz range and (b) 50-60 GHz range (b).

Data Analysis

Following the results of the previous section, a statistical analysis based on a larger set of cases was performed. The result is a set of 34 atmospheric profiles for the WVIOP2000. This is accomplished by taking the whole set of radiosondes launched during the experiment (288), and, considering only the RS90 (55), screening out measurements in cloudy conditions. To compare simulations with empirical observations for each of these profiles, we computed the synthetic Tb with the four absorption models, at every frequency available during the experiment. Mean value (BIAS) of the difference between observations (Tb(MWR)) and simulations based on RS90 profiles (Tb(RS90/FM)), i.e., ΔTb = Tb(MWR)-Tb(RS90/FM), have been grouped in Figure 4 for each frequency and each model. Each group of bars corresponds to a different channel available during the WVIOP2000, while each color within the group corresponds to a different absorption model in the set under evaluation. Note that in this figure, there are two channels at the same frequency (31.4 GHz) belonging to two independent instruments (the JPL and the CF units). It might be disappointing to see quite different results from two equivalent channels, but we have to remember that the MWR measurements are not always coexistent, and, due to the relatively poor sample of radiosondes (34), the statistics are sensitive to that. Figure 4 suggests some considerations. The LIEBE93 model gives brightness temperatures consistently warmer than measurements. This is especially true in the proximity of the so-called "hinge points"

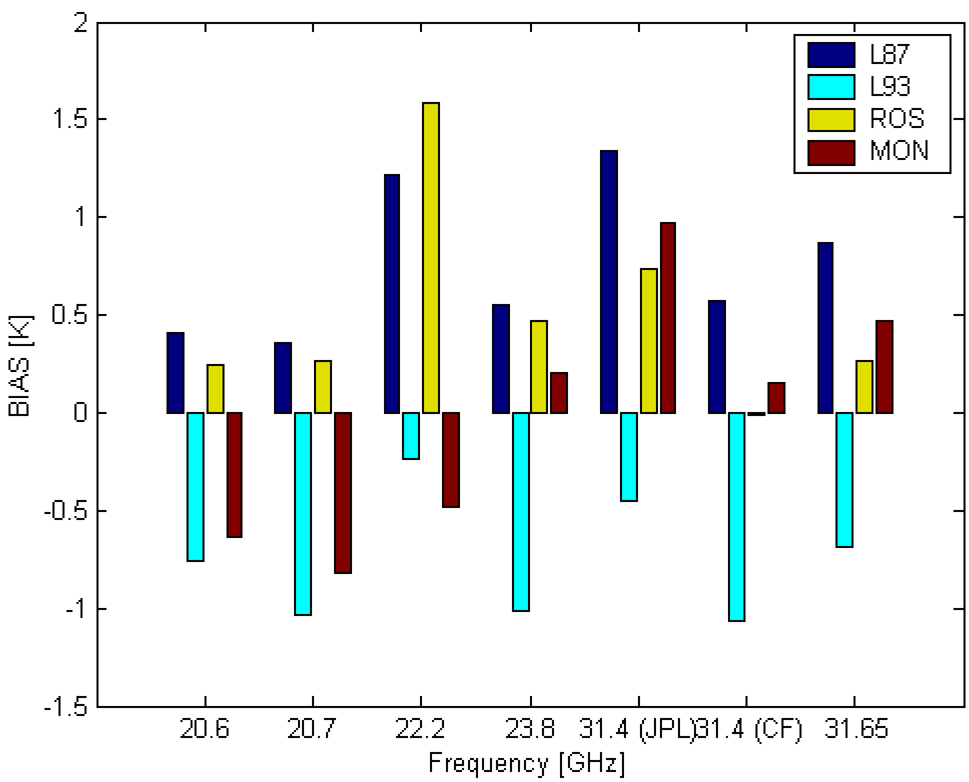

Figure 4. Mean value (BIAS) of the difference between observations and simulation based on RS90 atmospheric profiles, i.e., ΔTb = Tb(MWR)-Tb(RS90/FM) as introduced in the text. Each group of bars corresponds to a different channel available during the WVIOP2000, while each color within the group corresponds to a different absorption model.

(Cimini et al. 2003b), at 20.7 and 23.8 GHz. Although, it seems to give the best results in the center of the line at 22.2 GHz, but LIEBE87 and ROS98 are slightly, but consistently, colder than measurements. In particular, ROS98 absorption model gives good results near the hinge points, but it is off by about 1.5 K in the center of the line. A different behavior is shown by the MONORTM, which switches at 22 GHz from warmer to colder Tb with respect to measurements. Extending our analysis up to 60 GHz, by means of differences between simulations and MWRP observations, we obtain Figure 5. As expected, results in the 20-30 GHz range are fairly consistent with those obtained using WVIOP2000 dataset, but, comparisons in the 50-55 GHz band give quite surprising results. First, we found that the version of MONORTM we were evaluating (v2.10) gave mean differences up to 10 K with respect to other models and measurements. Based on these results, an updated version of MONORTM has been released (v2.11), which was later validated on an independent dataset (Cady-Pereira et al. 2004). Also, the remaining models show a sharp change, from +2 to –2 K, when comparing 51.2 and 52.2 channels with observations. Finally, in the 55-60 GHz band, the models agree very closely with each other, although they show a consistent negative bias of about 1 K with respect to measurements. In such a case, where the models agree so well, there is a concern whether the observations are biased. Our future research will include further analysis to address this issue.

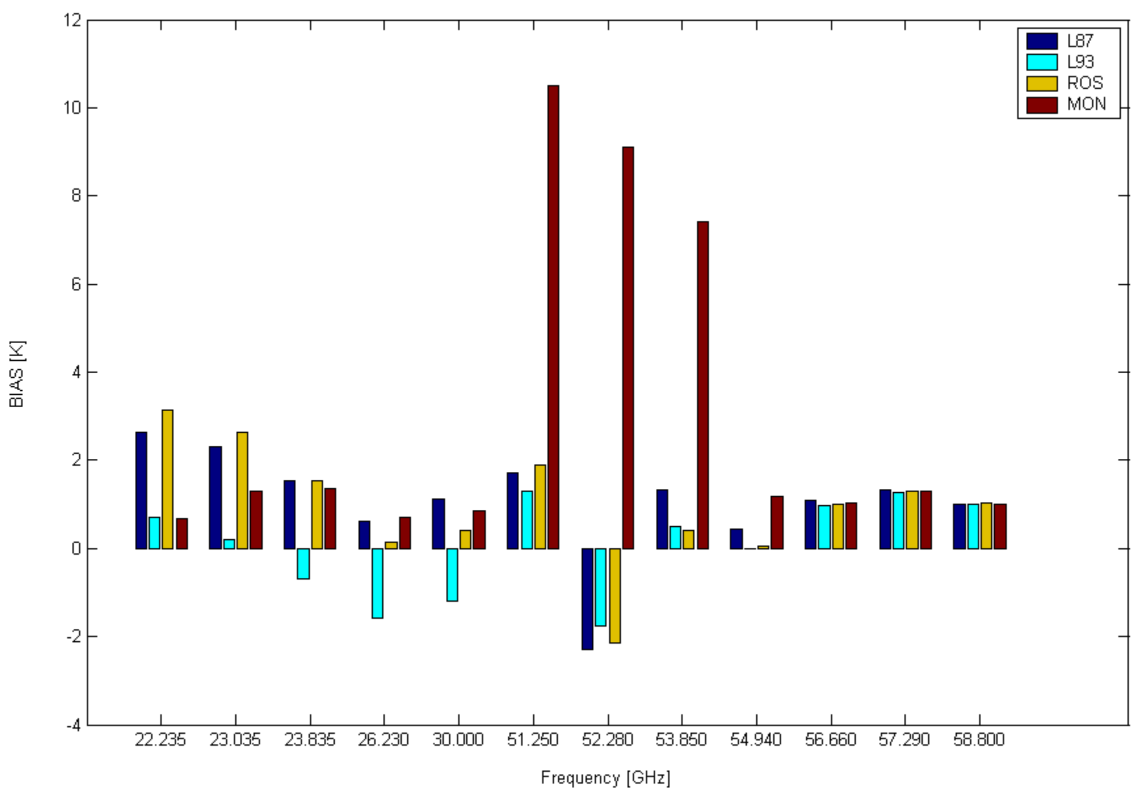

Figure 5. Mean value (BIAS) of ΔTb = Tb(MWR)-Tb(RS90/FM), as in Figure 4, but for measurements and simulations collected during June 2002 by the MWRP and RS90 sondes.

Summary and Conclusion

From our comparison of Tb simulations and observations in the 20-50 GHz range and the analysis of the mean value of ΔTb = Tb(MWR)-Tb(RS90/FM), we can state the following:

1. ROS98 gives the best results at 20.6-20.7 GHz channels.
2. LIEBE93 and MONORTM(v2.10) are preferable when close to 22.2 GHz.
3. Three models (LIEBE87, ROS98, and MONORTM(v2.10)) stay within 0.3 K at 23.8 GHz.
4. ROS98 gives the best results in the atmospheric window (~30 GHz).
5. Large bias, from 8 to10 K, are found in the MONORTM(v2.10) when comparing the 50-55 GHz channels. Based on these results, an updated version of MONORTM, i.e., v2.11, has been released, and later validated to correct for this effect.
6. Three models (LIEBE87, LIEBE93, and ROS98) show a sharp change, from +2 to –2 K, when comparing 51.2 and 52.2 channels with observations.
7. Models are almost equivalent in the 55-60 GHz band, but show a negative bias (~1 K) with respect to radiometric observations.

According to our results, we conclude that there is not a unique forward model among the ones we considered that represents the best empirical data in the whole considered spectral range. This means that the search for a single forward model that represents the best empirical data at any selected frequency in the microwave region is still open. It is also evident that it is not convenient to draw any conclusion looking at one or two channels. Moreover, measurements at other significant frequencies are needed to study forward models in a larger spectral range.

Future Plans

Our future research will focus on two major developments of this work. First, we intend to include other forward models in the set to cover the largest variety possible that is available in literature. Recent developments in forward modeling will be tested as well. For example, the MONORTM v2.11 (Cady-Pereira et al. 2004), and the model proposed by Liljegren (2004) will be considered. In addition, observations collected at other available frequencies will be considered to assess the performances of forward models in the broadest possible range. The Arctic Winter Millimeter Wavelength Radiometric Experiment (Westwater et al. 2004), recently held at the ARM North Slope of Alaska (NSA) site, will provide an excellent source of comparison. In fact, as shown in Table 1, up to 39 channels were deployed during this experiment, with frequencies ranging from 22 to 380 GHz.

Table 1. List of the instruments, channels, and frequencies deployed during the Artic Winter Water Vapor Experiment, held in March 2004 at the ARM NSA. Last column shows the atmospheric parameters related to the correspondent channels.

Instrument	Frequency (GHz)	Parameter
MWR	23.8, 31.4	PWV, ICL
GSR	50.3, 51.76, 52.625, 53.29, 53.845, 54.4, 54.95, 55.52, 56.025, 56.215, 56.325	T(z), ICL
MWRP	22.235, 23.035, 23.835, 26.235, 30.0, 51.25, 52.28, 53.85, 54.94, 56.66, 57.29, 58.8	PWV, ICL, T(z)
GSR	89 H, 89 V	ICL
GSR	183.31 + (±0.5, ±1, ±3, ±5, ±7, ±12, ±15)	PWV
GSR	340 H, 340 V	ICL
GSR	380.2 + (±4, ±9, ±17)	PWV
ICI	8-14 μm	Cloud Images
GSR	10 μm	Cloud presence
GPS		PWV

Acknowledgements

The work presented in this paper was sponsored by the Environmental Sciences Division of the U.S. Department of Energy as a part of their Atmospheric Radiation Measurement Program and by the Science and Technology Corporation (STC Contract No. 45-EANA-0-00055).

Corresponding Author

Domenico Cimini, Nico.Cimini@aquila.infn.it

References

Cady-Pereira et al., 2004: Monochromatic radiative transfer model (Monortm): Recent developments. *Specialist Meeting on Microwave Remote Sensing*, February 24-28, 2004, Rome.

Cimini, D., E. R. Westwater, Y. Han, and S. J. Keihm, 2003a: Ground-based microwave radiometer measurements and radiosondes comparisons during the WVIOP2000 field experiment. *TGRS*, **41**, N. 11, 2605–2615.

Cimini, D., E. R. Westwater, and Y. Han, 2003b: Theoretical analysis of the frequency allocation of the hinge points around 22.235 GHz. In *Proceedings of the Thirteenth Atmospheric Radiation Measurement (ARM) Science Team Meeting*, ARM-CONF-2003. U.S. Department of Energy, Washington, D.C. Available URL: http://www.arm.gov/publications/proceedings/conf13/extended_abs/cimini1-d.pdf.

Delamere, J. S., et al., 2002: An update on radiative tranfer model development at Atmospheric and Environmental Research, Inc. In *Proceedings of the Twelfth Atmospheric Radiation Measurement (ARM) Science Team Meeting*, ARM-CONF-2002. U.S. Department of Energy, Washington, D.C. Available URL: http://www.arm.gov/publications/proceedings/conf12/extended_abs/delamere-js.pdf.

Han, Y., and E. R. Westwater, 2000: Analysis and improvement of tipping calibration for ground-based microwave radiometers. *Trans. Geosci. Rem. Sens.*, **38**(3), 1260–1276.

Liebe, H. J., and D. H. Layton, 1987: *Millimeter Wave Properties of the Atmosphere: Laboratory Studies and Propagation Modeling*, NTIA Report 87-24, p. 74.

Liebe, H. J., et al., 1993: Propagation modeling of moist air and suspended water/ice particles at frequencies below 1000. *AGARD Conf. Proc. 542*, pp. 3.1 to 3.10.

Liljegren, J. C., 2004: The effect of the half-width of the 22-Ghz water vapor line on retrievals of temperature and water vapor profiles with a twelve-channel microwave radiometer. *Specialist Meeting on Microwave Remote Sensing*, February 24-28, 2004, Rome.

Rosenkranz, P. W., 1998: Water vapor microwave continuum absorption: a comparison of measurements and models. *Radio Sciences*, 33(4), 919-928.

Solheim, F., J. Godwin, E. Westwater, Y. Han, S. Keihm, K. Marsh, and R. Ware, 1998: Radiometric profiling of temperature, water vapor, and liquid water using various inversion methods. *Radio Sciences*, **33**, 393-404.

Westwater, E. R., et al., 2004: The 2004 North Slope of Alaska Arctic Winter radiometric experiment. This Proceedings.