Nauru 99: Scaling of Radiosondes by Microwave Radiometers

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

B. B. Stankov and J. A. Shaw
National Oceanic and Atmospheric Administration
Environmental Technology Laboratory
Boulder, Colorado

D. Cimini
University of L' Aquila
L' Aquila, Italy

B. M. Lesht
Argonne National Laboratory
Chicago, Illinois

Introduction

Previous experience, both in the Tropical Western Pacific (TWP) during the Prototype Radiation Observation Experiment (Westwater et al. 1999), at the Atmospheric Radiation Measurement (ARM) Program's Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site (Lesht 1999), and during Nauru 99 (Westwater et al. 2000) indicated the need for adjustments to Vaisala Humicap RS80 humidity soundings. The need for such corrections was identified by comparisons of measurements of precipitable water vapor (PWV) by microwave radiometers (MWR) and by radiosonde observations (RAOBs). As suggested by Clough et al. 1996, radiosonde humidity soundings can be scaled by MWR-derived PWV and used in calculations of their line-by-line radiative transfer model (LBLRTM). For many ARM CART sites, the radiance measured by the Atmospheric Emitted Radiance Interferometer (AERI) is in better agreement with calculations based on the scaled RAOBs. However, several issues arise when deriving PWV from MWRs; these include calibration of the radiometer, the forward model used in the retrieval, and the retrieval method. In this work, we examine the first two issues for data taken during Nauru 99.

Calibration of the MWR

Many of our comparisons rely on the accuracy and consistency of the ARCS-2 MWR. During this experiment, the radiometer was run in a nearly continuous tip cal mode. When the sky conditions were favorable, as determined by symmetry of radiometer scans, the radiometer continued scanning at angles corresponding to the air masses 1, 1.5, 2.0, and 2.5 (elevation angles of 90, 41.8, 30, and 23.6 degrees). When clouds were present, angular symmetry was destroyed, and the radiometer went into a zenith-observing mode. Since we cannot calculate brightness temperatures (Tbs) from RAOBs during cloudy conditions, we will focus on clear conditions only; another reason for focusing on clear conditions is that during these conditions, calibration can be done on a nearly continuous basis. The operational ARM calibration algorithm (Liljegren 2000) was used and excellent data were obtained. We also applied the Environmental Technology Laboratory (ETL) calibration method (Han and Westwater 2000) to the same tip cal data, and nearly identical results were obtained. Our results, requiring beam width and angular-dependent mean radiating temperatures, use the standard deviation (F) equivalent zenith Tbs (EZTB) as a measure of calibration quality. We compute this dispersion for each scan. A 24-h time series of F of this EZTB is shown in Figure 1. Note that the F values were frequently better than 0.3 K, indicating a high degree of atmospheric stratification and antenna beam symmetry. In Figure 2, we compare data taken with the ETL tip curve method with the original ARM line-of-sight (LOS) data (these zenith values are both the result of tip curve calibration). We note that except for occasional excursions (mainly due to clouds) the data are in close agreement. Because our major objective here was to compare data taken during clear conditions, we restrict our data to those when the ETL tip cal procedure yields F less than 0.3 K. Under these restrictions, the high-quality, clear data of Figure 3 results. It is apparent that the absolute calibration of the MWR, as determined by the two methods, was in excellent agreement. As reported last year (Westwater et al. 2000) we also performed a liquid nitrogen (LN2) calibration experiment, in which a blackbody reference target (or load) was filled with LN2 and placed over the MWR. The measured Tbs during this experiment showed that the MWR was accurate to within ±1K. This single-target calibration measurement, together with the continuous high quality of tip cals, indicated that the MWR could be used as a comparison standard for the experiment.

Correction/Scaling Algorithms for the Vaisalsa Radiosondes

The manufacturers of Vaisala RAOBs have developed a proprietary algorithm to correct for the dry bias problem (Lesht 1999; Miller et al. 1999). We have used a version of the algorithm that bases the correction only on the age of the RAOB; a preliminary evaluation of this algorithm for the Nauru 99 data was reported by Westwater et al. 2000. This work showed that usually some of the dry bias was removed, but at times, good data were degraded.

We have also developed scaling algorithms for the Vaisala RAOBs that are based on MWR data. Because we wanted to test the accuracy of these algorithms on AERI data, we focused our efforts on clear data. This focus has several advantages: we can use only the high-quality, instantaneous tip cal data with F values of EZTB less than 0.3 K, and both single-frequency and dual-frequency algorithms

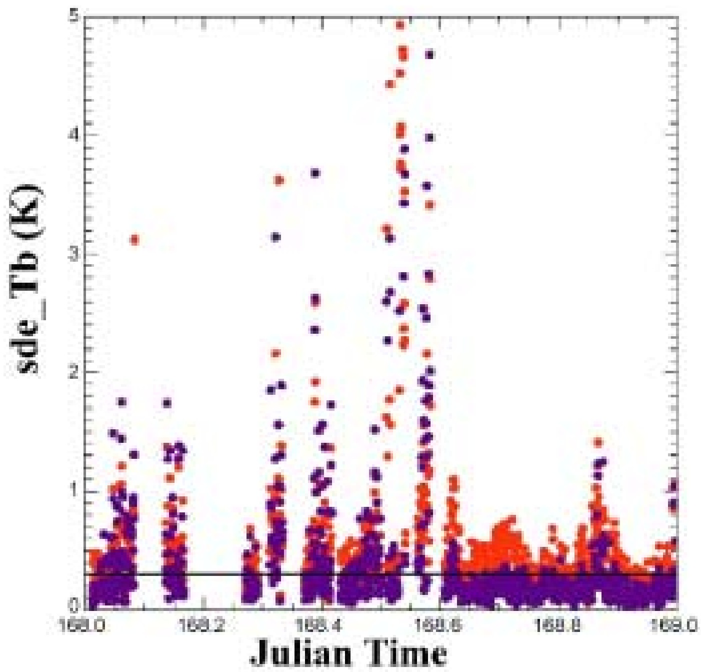

Figure 1. 24-hr time series of the sde of equivalent zenith Tb at 23.8 (red) and 31.4 (purple) GHz for Nauru 99. The quality control threshold of 0.3 K is indicated with the solid line.

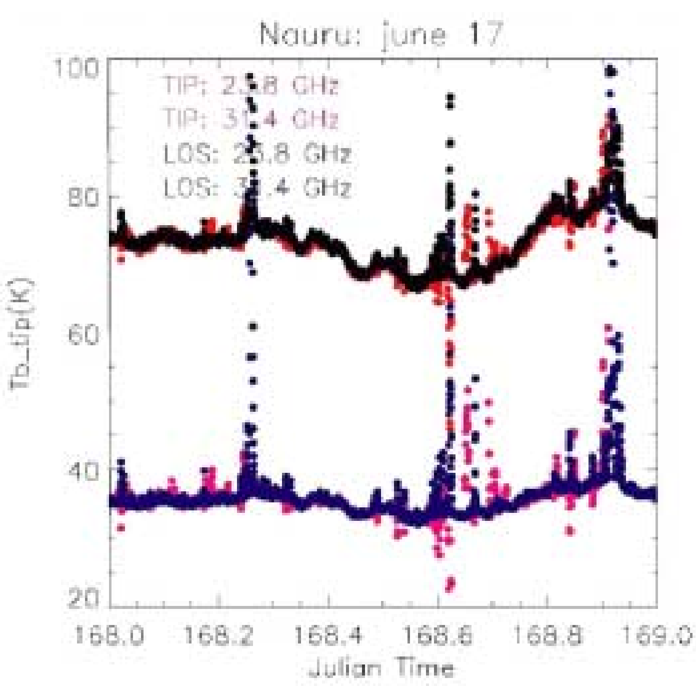

Figure 2. 24-hr time series of the Tb at 23.8 and 31.4 GHz for Nauru 99. The ETL data were determined from the tip cal method of Han and Westwater et al. (2000) and the ARM line-of-sight (LOS) data from the tip cal method of Liljegren (2000).

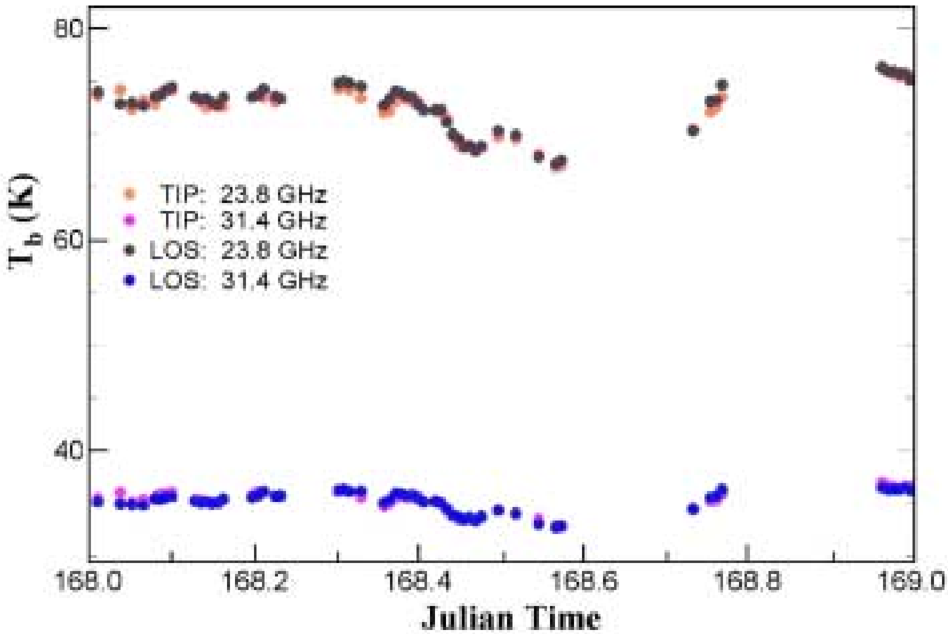

Figure 3. 24-hr time series of the 10-min-averaged Tb at 23.8 and 31.4 GHz for Nauru 99. The ETL data were determined from the tip cal method of Han and Westwater (2000) and the ARM LOS data from the tip cal method of Liljegren(2000). Only data that passed the EZTB quality-control threshold of 0.3 K sde are shown.

can be developed. In addition, because temperature variation is small at Nauru, the difference between statistical and physical retrieval algorithms is small. Our algorithms use the standard technique of deriving optical depth J from Tb by use of a mean radiating temperature Tm,

$$\tau = \ln\left(\frac{Tm - Tc}{Tm - Tb}\right)$$

where Tc is the cosmic “big bang” contribution of 2.75 K. We developed dual-frequency and single-frequency algorithms to derive PWV from J as follows:

a. dual-frequency algorithm over a clear + cloudy ensemble of profiles

b. dual-frequency algorithm over an ensemble of clear profiles

c. single-frequency algorithm over an ensemble of clear profiles, using 23.8 GHz Tb

d. single-frequency algorithm over an ensemble of clear profiles using 31.4 GHz Tb.

Further, each of the algorithms (a) through (d) were developed for the absorption models (1) Liebe and Layton 1987; Liebe 1989, (2) Rosenkranz 1998, and (3) Liebe et al. 1993. For simplicity in notation, we use L87, ROS, and L93 for (1), (2), and (3), respectively. Our a priori ensemble of profiles was developed from several ocean stations of data taken during Tropical Ocean Global Atmosphere-Coupled

Ocean Atmosphere Response Experiment (TOGA-COARE), and we used a radiometric noise level of 0.3 K root mean square (rms). Results of retrievals of PWV are shown in Figure 4. We note that retrievals using L87 (also used in ARM operational algorithm) and ROS are quite similar. It is also evident that the difference between the dual-channel cloudy versus clear algorithms is very small. We note that there is a large dispersion between all of the retrievals using the L93 model, indicating possible inconsistencies in the absorption calculations at 23.8 and 31.4 GHz. We also note large differences between the original RAOBs and that the Vaisala correction algorithm improves comparisons with the MWR. Occasionally, however, the Vaisala correction degrades the comparison with the MWR.

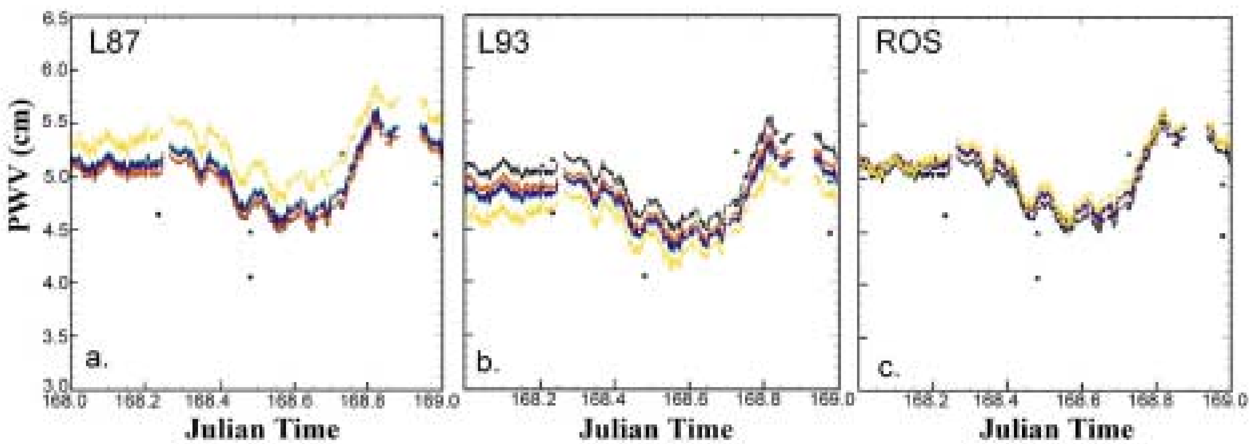

Figure 4. 24-h time series of the PWV (10-min averages) at Nauru Island, showing the original ARM LOS data and the retrievals of methods (a) to (d) described in the text. Retrieval algorithms: (a) L87, (b) L93, and (c) ROS. Only data that passed the EZTB quality-control threshold of sde = 0.3 K are shown.

Comparisons with Mirai Radiosondes

For three days in June, the research vessel (R/V) *Mirai* was located immediately adjacent to Nauru Yoneyama 2000. The *Mirai* RAOBs were again RS80 RAOBs, but were newer than those used on Nauru. In figure 5 we compare the measured and calculated Tbs and PWV. For these comparisons, we show only the comparisons using the ROS model. It is quite evident that the agreement with the MWR data, using the *Mirai* RAOBs, is excellent, and that deficiencies in both the original and corrected Vaisala data are clearly shown.

Comparisons with AERI Measurements

We had another independent measurement to compare corrected and uncorrected RAOBs; the AERI data from ARCS-2. For a portion of the measurement period (July 3-15), a Fourier Transform Infrared Radiometer (Shaw et al. 1991) was operated by ETL on the R/V *Ronald H. Brown*. We made

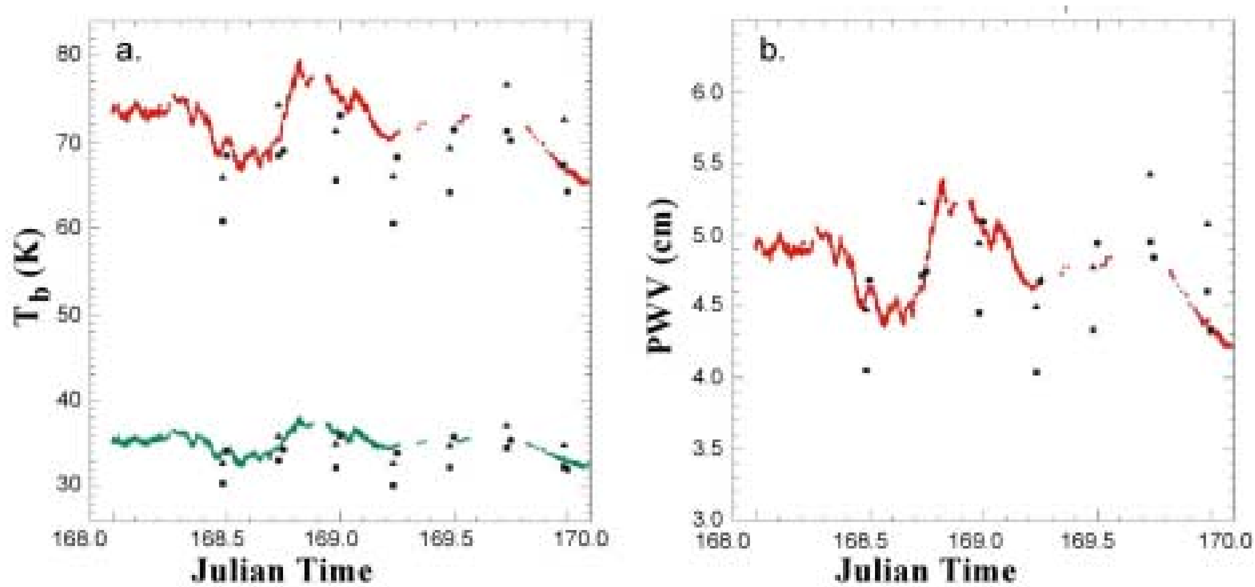

Figure 5. (a) 48-h time series of the Tb at 23.8 and 31.4 GHz (10-min-averaged data) showing the MWR data processed by the ETL tip cal method, using the Rosenkranz98 Forward model, black squares—original ARCS-2 radiosondes; black triangles—corrected ARCS-2 radiosondes; black circles—Mirai radiosondes. Nauru 99. (b). 48-hr time series of the PWV retrieved from the MWR data. Same notation as in (a).

several intercomparisons of the data between the two instruments during times when both the ceilometers at ARCS-2 and the *Ronald H. Brown* indicated clear conditions. These comparisons indicated that both completely independent instruments were well calibrated. We show AERI spectra in Figure 6; here we also indicate the portion of the window region where we make detailed comparisons of measurements and calculations. Our infrared spectral calculations are based on the LBLRTM model of Clough et al. (1996). Figure 7 shows a comparison between measurements and calculations based on original, corrected, and scaled RAOBs, as well as a new radiosonde from the *Ronald H. Brown*. It is clearly evident that the calculations from the MWR-scaled RAOB, the *Ronald H. Brown* RAOB, and the AERI data are in excellent agreement. Another example is shown in Figure 8, where this time the corrected ARCS-2 RAOB and the MWR-scaled RAOB agree well with the measured AERI data.

We also computed statistics between AERI measurements and original and corrected radiosonde data. Figure 9 shows comparisons between original, Vaisala-corrected, and MWR-scaled RAOBs. It is apparent that the original ARCS-2 RAOBs also have a dry bias relative to the AERI measurements and that the corrected data agree better with the AERI. Also, there is a slight difference in bias between the Vaisala-corrected and MWR-scaled RAOBs, but less scatter with the MWR-scaled data. In Figure 10, we compare AERI measurements with all three of the absorption models. It is evident that the L87 (the ARM operational model) and the ROS models give similar results, and both are closer to the AERI measurements than L93.

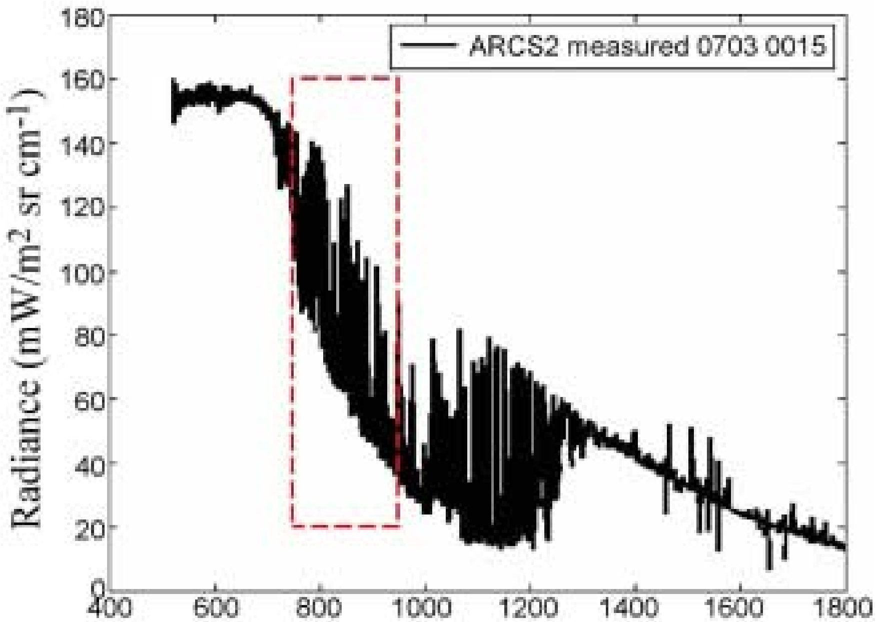

Figure 6. Infrared radiance spectrum measured by the AERI on ARCS-2 during Nauru 99 in clear conditions. The portion enclosed in red indicates the portion of the transparency window that we analyze in subsequent figures.

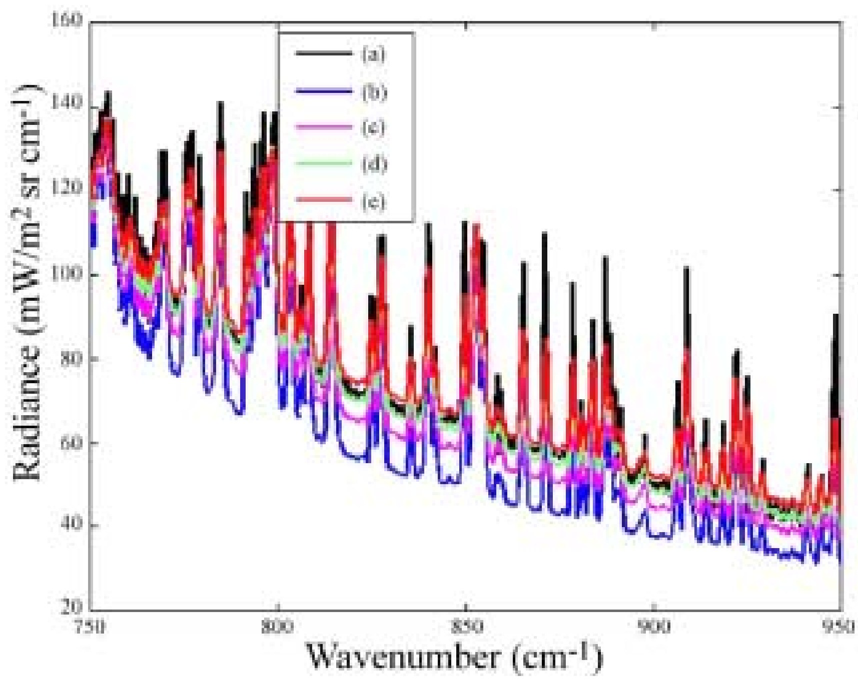

Figure 7. Measured spectral radiance compared with calculated radiance using a variety of original, corrected, and scaled radiosondes. (a) Measured by MWR, (b) calculated from original ARCS-2 radiosonde, (c) calculated from the corrected ARCS-2 radiosonde, (d) scaled by MWR PWV measurements, and (e) calculated from the original *Ronald H. Brown* radiosonde.

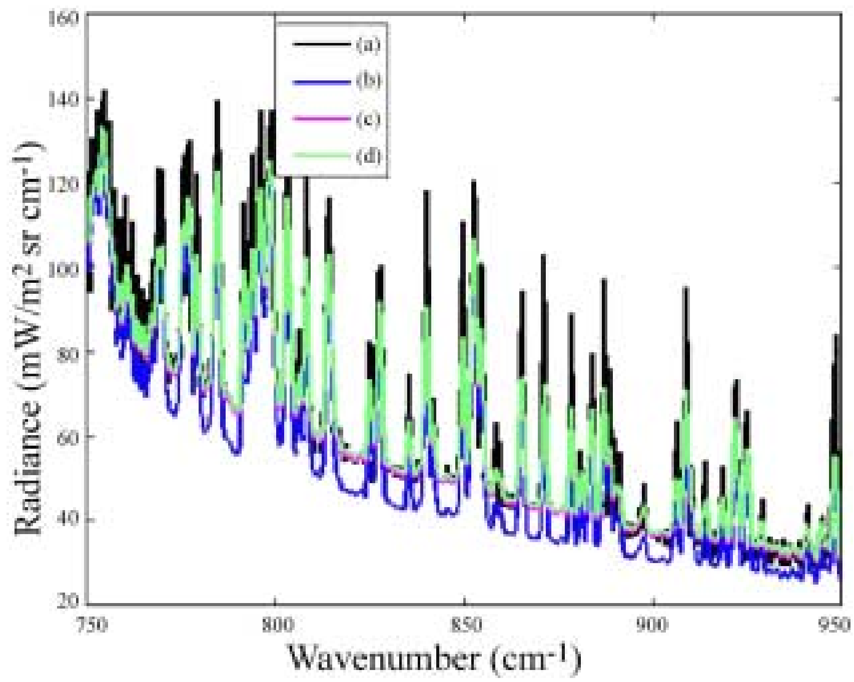

Figure 8. Measured and calculated spectral radiance using a variety of original, corrected, and scaled radiosondes. (a), (b), (c), and (d) as in Figure 7.

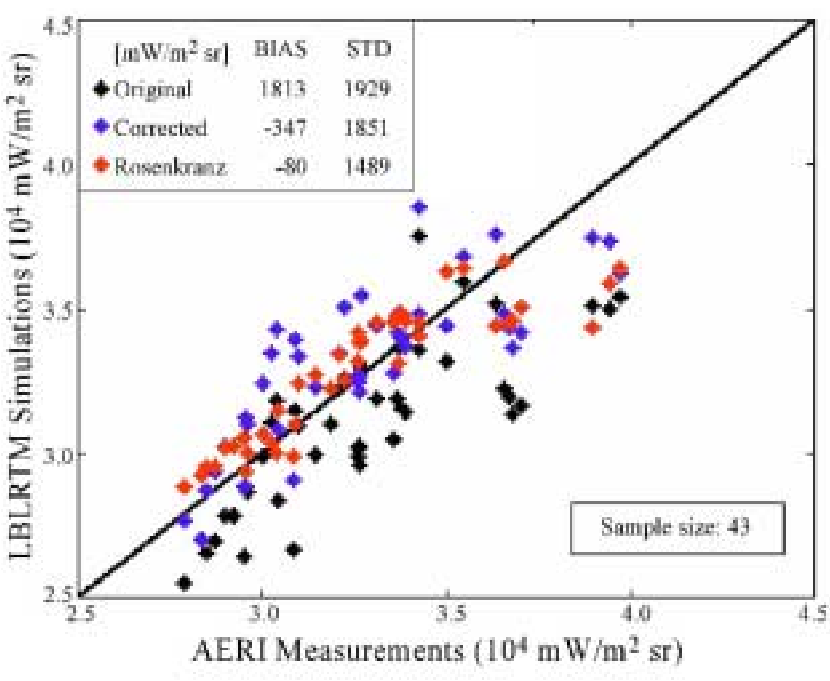

Figure 9. Scatter plot of calculated and AERI-measured spectral radiance using ARCS-2 original radiosondes, corrected ARCS-2 radiosondes, and ARCS-2 radiosondes that were scaled by PWV derived from the ARCS-2 MWR and the Rosenkranz98 forward model in the retrieval.

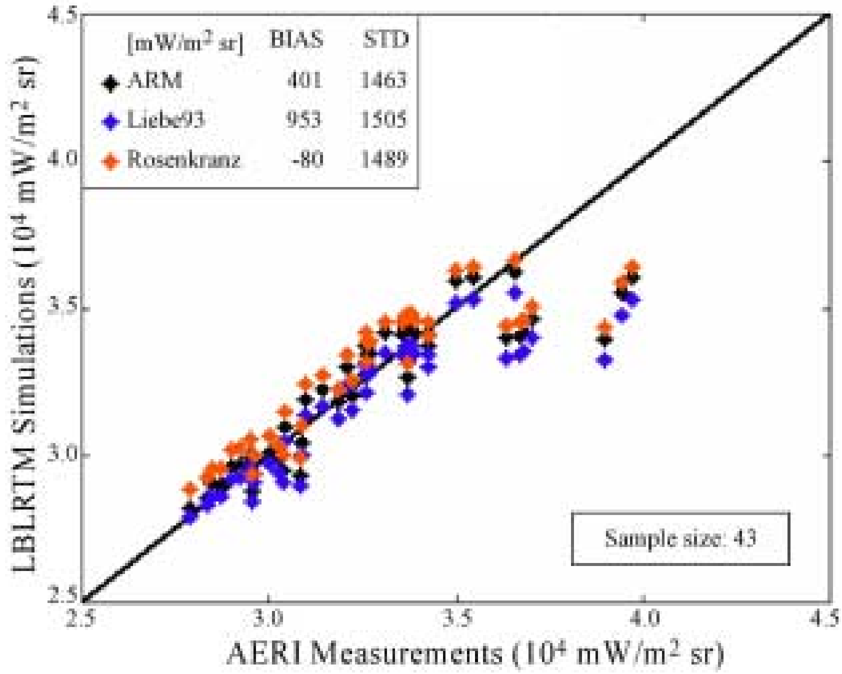

Figure 10. Scatter plot of calculated and AERI-measured spectral radiance using ARCS-2 original radiosondes, scaled by retrievals using the indicated forward models. The ARM-scaled retrievals use L87.

Conclusions and Discussion

The ARM MWR operating at the ARCS-2 provided an excellent data set for the entire Nauru 99 experiment. The calibration accuracy was verified by a LN2 blackbody target experiment and by consistent high-quality tip cals throughout the experiment. The data thus provide an excellent baseline for evaluation of the quality and consistency of Vaisala RAOBs that were launched from ARCS-2. Our results confirm that substantial errors, sometimes of the order of 20 percent in calculated Tb, occurred with the uncorrected RAOBs. When the Vaisala correction algorithm was applied to the RAOBs, better agreement with the MWR was obtained. When we scaled the RAOBs with the MWR-derived PWV, better agreement with *Mirai* RAOBs and with AERI data were obtained. The Liebe87 (the ARM operational model) and the Rosenkranz98 models were closer to the AERI measurements than Liebe93.

Corresponding Author

Dr. Ed R. Westwater, Ed.R.Westwater@noaa.gov, (303) 497-6527

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