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AND/ER/CP-93862
CONF-980121--

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and Relative Humidity Estimated from Dual-Sonde Soundings
made During the September 1996 ARM Water Vapor IOP

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UNCERTAINTY IN RADIOSONDE MEASUREMENTS OF
TEMPERATURE AND RELATIVE HUMIDITY ESTIMATED
FROM DUAL-SONDE SOUNDINGS MADE DURING THE
SEPTEMBER 1996 ARM WATER VAPOR IOP

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1. INTRODUCTION

Studies of radiosonde accuracy have tended to involve intercomparisons among different radiosonde types (see, for example, Schmidlin, 1993; Nash et al., 1995). One goal of these intercomparisons has been to quantify biases or other systematic errors related to the kinds of sensors employed. Little apparent attention has been paid, however, to the operational uncertainty associated with a single sensor type. The U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) Program has used a single radiosonde type (Vaisala RS-80H) since beginning field operations in 1992 at its Cloud and Radiation Testbed (CART) site. Because of the dependence of ARM Science Team experiments on measurements of the atmospheric state, considerable interest exists within the program in quantifying the uncertainty associated with radiosonde measurements. The September 1996 Water Vapor Intensive Operations Period (WVIOP) provided an excellent opportunity to investigate further the operational performance of the radiosondes used by ARM.

Although many instruments were intercompared during the WVIOP, including Raman lidar, microwave, and chilled-mirror sensors, the lack of an accepted absolute standard makes evaluation of the results difficult. By focusing on information obtained from the radiosondes themselves, with minimal reference to external instruments, we hope to eliminate much of the uncertainty associated with comparing different measurement systems.

2. BACKGROUND

Studies of the operational performance of the radiosondes are an ongoing part of the data quality procedures in ARM. Previous work, based on analysis of ground checks and of the ascending and descending phases of individual soundings, provided some quantitative estimates of the uncertainty associated with ARM radiosonde

temperature and relative humidity values (Lesht, 1995). The ground check analysis, in which radiosonde readings of temperature (T) and relative humidity (RH) made in a small desiccated chamber were compared with reference values of RH and T, showed that the sonde RH values are accurate to within $\pm 1\%$ RH at very low RH values when the sonde is at surface ambient temperature and pressure. We also found that the sonde T values are accurate to within $\pm 0.3^\circ\text{C}$, again at very low RH and at surface ambient pressure.

The ground check analysis provides information about the low-RH performance of the sondes across a fairly limited temperature range (surface ambient). In an attempt to extend the analysis to measurements made aloft, we compared data obtained during ascending and descending phases of the same sounding -- assuming that the atmospheric state would not change substantially during the time interval between upward and downward sonde passage. The analysis of these pseudo-replicates (ascending vs. descending) showed that the precision of the RH measurement (estimated by the average difference) aloft is 3% RH (median correlation coefficient of 0.73), and that the precision of the T measurement aloft is 0.4°C (median correlation coefficient of 0.99).

Finally, although both the ground check and the ascending-descending analysis suggested that the radiosonde measurement precision levels are within the manufacturer's specifications, a separate analysis, comparing precipitable water vapor obtained from the CART microwave radiometers with that calculated from the radiosondes, showed that the accuracy of the sonde RH could be batch dependent and that a large batch of radiosondes used by ARM was incorrectly calibrated (Lesht and Liljegren, 1996). This batch-lot dependence of radiosonde accuracy had not been reported in any previous intercomparison study. The experiments we conducted during the WVIOP were intended, in part, to examine further the magnitude and significance of this batch-dependent radiosonde calibration.

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3. PROCEDURES

We conducted several experiments during the WVIOP to confirm and extend our previous work. Our primary objective was to improve the characterization of CART radiosonde performance with minimal reference to other sensors. The results shown here are based only on comparisons of sondes with sondes and of sondes with independently calibrated surface sensors.

We added new operational procedures during the WVIOP both to provide data needed for the analysis and to improve the response of the radiosondes during the earliest part of the sounding. Improving the measurement of water vapor in the lowest few hundred meters was a goal. The new procedures included adding a pseudo-ground-check procedure to determine how well the sondes measured T and RH at a known point (0% RH, ambient temperature). We term this a "pseudo" check because the operators (rather than the system) had to judge the point at which the sondes reached equilibrium. Thus, some additional uncertainty due to operator effects is expected relative to the ground check analysis reported by Lesht (1995).

We placed the sondes in an aspirated chamber before launch to minimize the effects of solar heating and to improve the sampling of the near-surface air. We also installed calibrated sensors (Vaisala HMP233 and PTB201) to measure pressure, T, and RH independently at the sonde launch point. The temperature and humidity sensors were housed in an aspirated shield located within 2 m of the sonde balloon launcher. Data from these sensors were recorded by the operators along with the corresponding sonde readings just before launch to provide a second "known" point in RH-T space.

Most importantly, half of the soundings done during the WVIOP were made by flying two radiosondes on a single balloon. Sondes from two different calibration months were used during the WVIOP. The dual soundings included both sondes from the same batch flown together (to determine within-batch precision) and sondes from different batches flown together (to assess between-batch differences). Sondes used in the dual soundings were tuned to different transmitting frequencies, at least 1 MHz apart, and taped together before being attached to the balloon.

4. RESULTS AND DISCUSSION

4.1 Sounding Statistics during the WVIOP

Sounding operations during the WVIOP began on September 6, 1996 (23:30 UTC), and continued through September 30, 1996 (23:30 UTC). During this time we flew 257 Vaisala RS-

80H-L radiosondes. Other points of interest are the following:

- The calibrated surface sensors were deployed on September 10, 1996 (20:30 UTC).
- The radiosonde aspiration chamber was deployed on September 11, 1996 (20:30 UTC).
- A total of 172 soundings (8 per day) were conducted, of which
 - 87 soundings used a single sonde and
 - 85 soundings used two sondes.
- Of the 85 dual-sonde soundings,
 - 46 were mixed calibration lots,
 - 28 were August calibration lots (serial numbers 63XXXXXXX), and
 - 11 were June calibration lots (serial numbers 62XXXXXXX).

4.2 Comparisons at the Surface

Comparison of the radiosonde measurements with known reference values provided an estimate of the absolute accuracy of the sensors. Figure 1 shows the results of the pseudo-ground-check analysis in which the sonde values of T and RH were compared with ambient T measured by using a certified mercury thermometer and an assumed 0% RH. The pseudo-ground-check test showed that the RH accuracy of the overall population of sondes used was within specifications ($\pm 2\%$ RH) at very low humidity at surface ambient temperatures. This result agrees with our previous work. The scatter in the results was somewhat greater, however, than in the formal ground checks performed in 1993-1994. This additional scatter is most likely due to depending on the operators' subjective judgment to determine when the sonde has equilibrated in the ground check chamber.

We also compared the sonde RH and T values just before launch with RH and T values measured by the co-located surface sensors. This comparison was intended to provide a second reference point in RH-T space (ambient conditions) in addition to the point provided by the pseudo-ground-check analyses. The surface sensor (Vaisala HMP233) had been calibrated recently by the manufacturer and was housed in an aspirated shield located very close to the aspirated chamber in which the radiosonde was placed before launch. The results (Fig. 2) show somewhat more scatter in RH than expected and a tendency for the radiosonde RH to be lower than the HMP233 RH at higher RH values.

Figure 1. Distributions of the differences between radiosonde and reference RH (top panel) and T (bottom panel) obtained from pseudo-ground-check procedures.

Figure 2. RH (top panel) and T (bottom panel) measured by radiosondes before launch, compared with simultaneous measurements obtained from the surface sensor (HMP233).

Some further insight into the uncertainty of the sonde RH and T measurements may be gained by comparing the surface readings obtained from the pairs of sondes used in the dual soundings. Because the sondes are sampling identical air, differences in measurement must be related to variations in the calibrations of the two sensors. Although these comparisons do not provide information on the absolute accuracy, they do make it possible to quantify the operational precision of the measurements. We found that sondes from the same calibration batch showed virtually no differences in surface RH before launch. Sondes from different calibration batches, however, did show differences, with the June sondes being drier (lower RH) than the August sondes (Fig. 3).

Figure 3. Comparison of RH measured simultaneously by two radiosondes before launch. Results are grouped by calibration batch type (mixed or same).

4.3 Comparisons Aloft

The question of how uncertainty in measurement of RH translates into uncertainty in the estimation of the water vapor density profile can be examined by comparing estimates of column-integrated precipitable water vapor (PWV) obtained from the sondes used in the dual soundings. These estimates are of particular interest because of the dependence that ARM places on measurements of PWV obtained from microwave radiometers (MWRs). Figure 4 shows that sondes from the same calibration batch (either June or August) used in dual soundings measured almost identical PWV values. On the basis of average observed PWV, mixed-batch flights showed that June sondes measured approximately 8% less PWV than did August sondes. Note that these results do not speak to the absolute accuracy of the estimates but do confirm a calibration batch dependence in the measurement of RH or T or both.

Figure 4. Comparison of PWV measured simultaneously by two radiosondes in dual soundings. Results are grouped by calibration batch type (mixed or same).

5. CONCLUSIONS AND RECOMMENDATIONS

The September 1996 WVIOP was the first of several that are planned. We expect to continue to evaluate the performance of ARM radiosondes as part of these studies. Our results indicate the following:

- Batch-to-batch calibration differences in RH may be significant at the level of accuracy required by ARM. This finding follows from analysis of the pseudo-ground-check results (which showed batch differences), from comparison of dual-sonde readings before launch, and from comparison of the PWV calculated from dual-sonde pairs.
- Within-batch variation of both T and RH measurements, however, is consistent with previous results and with the manufacturer's specifications. When compared to known values at the surface, the sondes were within 2% RH and 0.3°C. This observation may require a reevaluation of whether the level of accuracy required by ARM can be met by current sensors.
- Operational problems contribute to the overall observed uncertainty. More rigorous procedures are needed to minimize operator effects on the pseudo-ground-check results. Also requiring resolution are suggestions obtained by analysis of detailed profile plots (not shown) that telemetry interference due to the close proximity of the two sonde transmitters contributes to uncertainty in measurements aloft.
- We are working with the sonde manufacturer to determine whether the calibration differences we observe between some batches can be characterized and reduced or eliminated.

5. ACKNOWLEDGMENT

This work was supported by the Environmental Sciences Division, U.S. Department of Energy, Office of Energy Research, Office of Biological and Environmental Research, under contract W-31-109-Eng-38, as part of the Atmospheric Radiation Measurement Program.

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