Enhancement of Atmospheric Radiation Measurement Surface Meteorological Observations During the Fall 1996 Water Vapor Intensive Observation Period

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Abstract

This work describes in situ moisture sensor comparisons performed in conjunction with the first Water Vapor (WV) Intensive Observation Period (IOP) conducted at the Atmospheric Radiation Measurement (ARM) Program Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site during September of 1996. Numerous remote sensing instruments (e.g., two Raman Lidar, two Atmospheric Emitted Radiance Interferometers [AERI], and a suite of 13 microwave radiometers) were assembled at the CART site during the IOP. The in situ measurements were used for calibration and verification. In addition, this work was meant to help assess the current observing strategy in an effort to make improvements to the routine continuous measurements.

To accomplish these goals, verification of the in situ measurements was required. Therefore, a laboratory intercomparison of the in situ moisture sensors (nine capacitive chip relative humidity sensors and four chilled mirror sensors) was performed at the Oklahoma Mesonet temperature (T) and relative humidity (RH) testing and calibration facility. Tests were conducted both before and after the instruments were used in the IOP, making it possible to detect instrument problems prior to deployment of sensors and to determine if instrument failure or drift occurred during the IOP.

Results from the laboratory comparisons indicate that most of the RH sensors tested were within manufacturer specifications and were capable of measuring RH with an accuracy of 2% to 3% RH; one instrument was not within manufacturer specifications prior to the IOP and apparently drifted during the IOP. The chilled mirror sensors proved to be accurate in the laboratory, with agreement generally $\pm 0.5°C$ for dewpoints above $0°C$.

Preliminary results comparing in situ moisture measurements with remotely sensed atmospheric moisture will be presented and additional applications will be discussed.

As a consequence of this work, modifications were made to the ARM CART calibration procedures, and there are now redundant temperature and RH measurements so that sensor drift or calibration errors can be detected. These modifications to the observation and calibration strategy led to improvements in the continuous routine measurements at the ARM CART Site.

Introduction

This paper describes the temperature calibrations and the RH intercomparisons performed at the Oklahoma Mesonet using the temperature and RH chambers developed there. This work was done in conjunction with the first WV IOP (Amer. Meteor. Soc. 1997) that took place at the ARM Program SGP CART site during September of 1996 (Stokes and Schwartz 1994)

The WV IOP was designed to reduce the uncertainty in the specification of the vertical water vapor profile derived from various state-of-the-science moisture-measuring devices, including both in situ and remote sensing instrumentation. Reducing observational errors of in situ sensors is integral to the characterization of the spectral radiative state of the atmosphere and the subsequent use in radiative transfer studies. Although measurements were made throughout the depth of the troposphere, the primary goal of the first WV IOP was to characterize the lowest 1 km of the atmosphere (which contains a significant fraction of the columnar water vapor) by concentrating the majority of the observations in this region.

Measurements of water vapor were made using numerous instruments including balloon soundings, the CART Raman Lidar (Goldsmith et al. 1997) (CART instruments refer to those sensors or instruments that have been installed at the ARM CART site and are considered permanent project equipment), the NASA Goddard Raman Lidar, two AERIs (Smith et al. 1997; Feltz et al. 1997), a Twin Otter aircraft using chilled mirror sensors, the CART microwave radiometers, and the CART in situ sensors located at the surface and on a 60-m tower.

The purpose of this work was to provide National Institute of Standards and Technology (NIST) traceability to the in situ temperature and RH measurements made at the SGP CART site central facility. Prior to this work, sensors were calibrated by the manufacturer; data from the CART site suggested this may not have been sufficiently accurate. This study was designed to verify this finding by testing some of the in situ temperature and moisture sensors in a laboratory before and after the IOP for an intercomparison. Testing was performed before and after the IOP in order to detect instrument problems before sensor deployment and also to determine if instrument failure or drift occurred during the IOP.

The Oklahoma Mesonet (Brock et al. 1993; Crawford et al. 1992) RH and temperature calibration chambers (Richardson 1995) were used for this work. The RH calibration "standard" was a General Eastern D2 chilled mirror dewpoint hygrometer with a stated inaccuracy of $\pm 0.2°C$. The temperature calibration reference was an Azonics model A1011 precision resistance temperature detector with an RMS inaccuracy of $0.03°C$.

A secondary goal of this project was to bring a "transfer standard" to the SGP CART RH sensors located at 25 m and 60 m on a tower and at the Surface Meteorological Observation System (SMOS) site. This was done because these instruments could not be removed from the CART site (for data collection reasons) for the required period to be included in the laboratory intercomparison. The sensors that were used as "transfer standards" were Vaisala HMP 35C temperature and RH sensors from the University of Oklahoma's Mobile Mesonet Research Facility (Straka et al. 1996). These sensors were included in the intercomparison process before and after the IOP and then mounted near the existing instrumentation during the IOP on the 60-m tower (at both the 25-m and 60-m levels) and at the SMOS site (surface). These instruments were not more accurate or more stable than the CART instrumentation, but they did provide a second measure of temperature and RH and could detect drift or biases in the existing sensors. RH errors in excess of 3% RH and temperature errors of approximately $0.5°C$ were detectable using the sensors calibrated in the Mesonet laboratory.

The results from the pre- and post-IOP intercomparisons revealed several interesting findings. First, the two chilled mirror sensors used (the Oklahoma Mesonet standard and a dewpoint sensor that was flown on the Twin Otter aircraft) agreed within about $0.5°C$ above $0°C$ or roughly 1% to 2% RH during the intercomparisons. A second finding was that the CART temperature and RH sensor used at the Balloon Borne Sounding System (BBSS) launch site had a 2% to 4% RH error before the IOP, and the sensor apparently drifted during the IOP; errors as large as 6% RH were detected during the post-IOP intercomparison. In addition, there had been speculation during the IOP that the RH sensors on the tower needed recalibration, and this was confirmed by including the tower sensors in the post-IOP intercomparison. Finally, two chilled mirror sensors that were flown on a tethersonde during the IOP were tested and proved to be accurate within $\pm 0.6°C$ above $0°C$.

Motivation

A major motivating factor for this work was the fact that there were discrepancies between the RH measured by radiosondes that were launched at the SGP CART facility (located approximately 250 m from the base of the 60-m tower) and RH measurements made on the tower. There were also differences between the tower measurements and AERI retrievals (Smith et al. 1997; Feltz et al. 1997) of temperature and RH at 25 m and 60 m. Additional in situ temperature and RH sensors were used during the IOP to verify the accuracy of the existing CART tower sensors.

Accurate tower and SMOS temperature and RH measurements were required to aid calibration of the Raman Lidar located at the SGP CART site, and moisture measurements at 60 m on the tower provide a calibration point. In addition, evidence suggested (Lesht and Liljegren 1996) that Vaisala RS 80 radiosondes from different calibration lots (i.e., calibrated at different times by Vaisala) show variability when compared with microwave radiometer measurements of atmospheric water content. To assess the magnitude of this variability in calibration lots and to verify that this was not an artifact of errors in the SMOS or tower sensors, the laboratory-calibrated sensors were collocated with the existing instrumentation tower and SMOS instrumentation.

Sensors Included in Intercomparisons

Table 1 provides a description of the abbreviated name that will be used to refer to each sensor. Two of the chilled mirror dewpoint sensors included in the intercomparison were manufactured by General Eastern (GE) and two were manufactured by Meteolabor AG. The GE M2 and the Meteolabor sensors had air temperature sensors that could be used in conjunction with the dewpoint measurement to determine RH; the GE 1011B has only a dewpoint sensor.

Table 1. Abbreviated names used to refer to sensors.

Sensor	Description
GE M2	General Eastern M2 chilled mirror sensor. Used as a laboratory standard for Mesonet RH calibrations.
GE 1011B	General Eastern 1011B chilled mirror sensor. Flown on the twin Otter aircraft to measure dewpoint.
Meteolabor #1	Meteolabor chilled mirror dewpoint thermometer TP3-ST with T-Preamplifier. This sensor was used on the tethersonde during the IOP.
Meteolabor #2	Meteolabor chilled mirror dewpoint thermometer TP3-ST with T-Preamplifier. This sensor was used on the tethersonde during the IOP.
BBSS-launch-site sensor #1	Vaisala HMP 233 temperature and relative humidity sensor. This sensor was located at the BBSS site during the IOP.
BBSS-launch-site sensor #2	Vaisala HMP 233 temperature and relative humidity sensor. This sensor was used during the IOP to check the operation of the BBSS sensor and the SMOS sensors.
60 m Mesonet	Vaisala HMP 35C temperature and relative humidity sensor. This sensor was located at the 60-m level and housed in an aspirator.
60 m RMY Mesonet	Vaisala HMP 35C temperature and relative humidity sensor. This sensor was located at the 60-m level and housed in an R. M. Young aspirator.
25 m Mesonet	Vaisala HMP 35C temperature and relative humidity sensor. This sensor was located at the 25-m level and housed in an aspirator.
SMOS Mesonet	Vaisala HMP 35C temperature and relative humidity sensor. This sensor was located at the SMOS site at approximately 1.5 m agl and housed in an aspirator.
60 m Mesonet Fast T	YSI 44203 temperature sensor. This sensor was located in the same shield as the Vaisala HMP 35C sensor and had a faster response.
25 m Mesonet Fast T	YSI 44203 temperature sensor. This sensor was located in the same shield as the Vaisala HMP 35C sensor and had a faster response.
SMOS Mesonet Fast T	YSI 44203 temperature sensor. This sensor was located in the same shield as the Vaisala HMP 35C sensor and had a faster response.
SMOS CART	Vaisala HMP 35C temperature and relative humidity sensor located at the CART SMOS site about 100 m east of the CART 60-m tower.
60 m CART #1	Qualimetrics 5120-E relative humidity sensor. This sensor was located at the 60-m level on the tower during the IOP.
60 m CART #2	Qualimetrics 5120-E relative humidity sensor. This sensor was located at the 60-m level on the tower before the IOP began.

The two sensors from the BBSS launch site were new and had not been used prior to the IOP. The four Mesonet temperature and RH sensors, as stated previously, were part of the University of Oklahoma's Mobile Mesonet Research Facility.

Included in Table 1 are “Mesonet Fast T” sensors, which were fast response sensors (e.g., 10 seconds with a 1 ms $^{-1}$ aspiration rate) consisting of a YSI 44203 thermistor component with a 44018 thermistor composite and a 44303 resistor composite and a type 705 probe. These sensors were also part of the Mobile Mesonet Research Facility and were used in conjunction with the Vaisala HMP 35C temperature and RH sensor. This sensor was used during the IOP to remove large RH errors (as large as 8% RH during the IOP) that occur with the Vaisala HMP 35C because of a temperature lag associated with the HMP 35C sensor. These errors are infrequent (occurring only with rapid temperature fluctuations) and can be minimized by using a sufficiently large averaging interval. For a complete discussion of this issue, see Richardson et al. (1997).

Some sensors were included in both the pre- and post-IOP RH intercomparisons, while others were available for only one or the other (see Table 2). The temperature calibrations were performed only during the post-IOP because of time constraints before the IOP. The sensors included in the temperature calibration were the Vaisala HMP 35C's, the Mesonet fast response sensors, and sensor #1 from the BBSS launch site.

Table 2. Sensors included in the IOP relative humidity intercomparison.		
Sensor	**Included in Pre-IOP Tests**	**Included in Post-IOP Tests**
GE M2	Yes	Yes
GE 1011B	Yes	No
BBSS Launch Site Sensors	Yes (two sensors)	Yes (one sensor)
Mesonet T & RH Sensors	Yes (four sensors)	Yes (three sensors)
60 m CART Sensors	No	Yes (two sensors
Meteolabor #1 and #2	No	Yes

Only one of the BBSS sensors was included in the post-IOP tests because the other was required for routine data collection at the BBSS location. One of the Mesonet sensors apparently failed during the IOP. Fortunately, it was the 60-m RMY sensor, which was a redundant sensor and not crucial to the experiment. The Qualimetrics sensors (routine CART sensors) were not available for testing prior to the IOP.

The Meteolabor chilled mirror sensors were new and had never been used prior to the IOP. These sensors consisted of a small mirror and an air temperature sensor. Because of technical difficulties encountered prior to the IOP, it was possible to include the Meteolabor sensors only in the post-IOP tests. An additional Meteolabor TP3-ST sensor was obtained from the National Center for Atmospheric Research (NCAR). This sensor is used by NCAR as a reference for radiosonde measurements and was used during the IOP to verify the operation of the (new) Meteolabor #1 and #2 sensors. It was not possible to include this sensor in any of the lab tests performed.

Laboratory Test Results

Relative Humidity Intercomparison Results

For these intercomparison tests, the GE M2 was chosen as the reference dewpoint sensor and the GE 1011B, having been recently calibrated, was used as a transfer standard for checking the operation of the GE M2 during the pre-IOP tests. The GE 1011B and GE M2 agree within approximately $\pm 0.5°$ C and 2% RH over the entire range. The manufacturer specifications for both units are approximately $\pm 0.2°$ C, although the recalibration of the GE 1011B was good only to $\pm 0.5°$ C. Thus, the two dewpoint devices appear to have been operating within specifications.

Laboratory Results

The RH, as measured by all eight sensors during a pre-IOP intercomparison, is shown in Figure 1. This plot is meant to show the general agreement between all the sensors. Figure 2 is an enlargement of Figure 1 at the 70% RH level. The GE M2- and GE 1011B-measured dewpoints combined with the chamber temperature produce equivalent measures of RH. The four Mesonet sensors also agree with the chilled mirror sensors, all six of these sensors indicating an RH within $\pm 1\%$. The sensors from the BBSS launch site appear to be biased high by 2% to 4%.

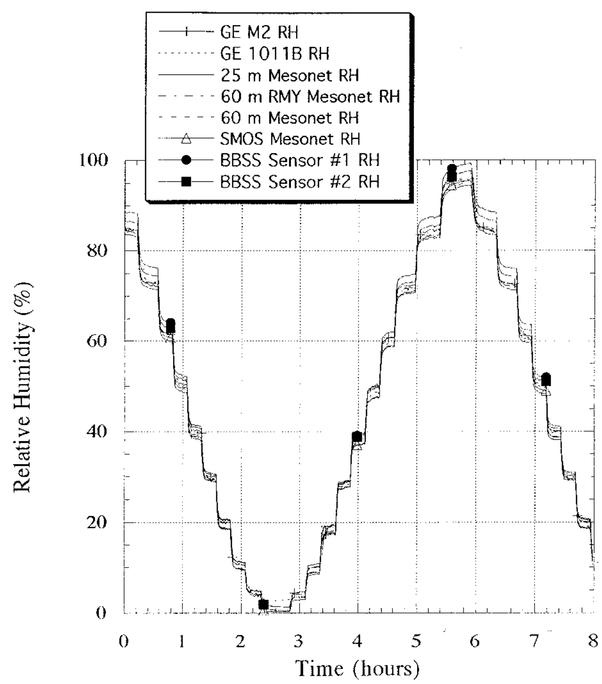

Figure 1. Relative humidity measured by all eight sensors included in the pre-IOP intercomparison.

In general, the pre-IOP and the post-IOP intercomparisons showed that all sensors included in these intercomparisons (see Table 2), except sensor BBSS #1, were within manufacturer specification, i.e., RH errors were less than 2% to 3% RH over the range ~ 0% to ~ 100% RH before and after the IOP.

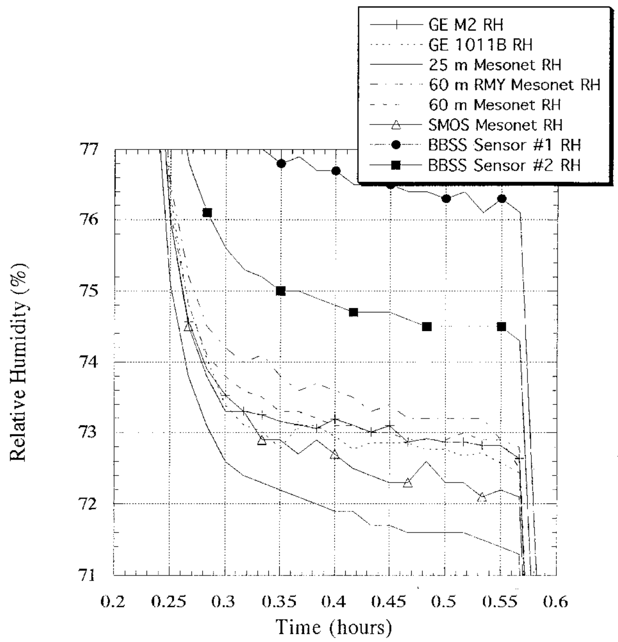

Figure 2. Blowup of part of Figure 1. Note the BBSS sensors appear to be 2-4% high. The agreement between the remaining six sensors is very good and within ±1% RH.

The BBSS #1 sensor showed errors of approximately 4% RH above 80% RH before the IOP and errors approaching 6% RH after the IOP. Thus, this sensor was not within manufacturer specifications prior to the IOP and apparently drifted during the IOP. The cause of these errors is unknown; the sensor was returned to the manufacturer for recalibration.

Evaluation of data received during the IOP from the 60-m CART #1 sensor (the Qualimetrics RH sensor located at 60 m on the tower during the IOP) suggested this sensor may be biased; post-IOP tests confirmed this. A slope- type error was detected, and a correction was determined. In addition, before being returned to the SGP site for field use, the sensor was recalibrated at another facility.

Agreement of the two Meteolabor sensors with the GE M2 reference sensor and with each other was very good, better than $\pm 0.5°$ C.

Temperature Calibration Results

A true temperature calibration could be performed using the Mesonet facilities because a high quality standard was available that was approximately an order of magnitude more accurate than the sensors being calibrated. To test the probes over the range of temperatures experienced during the IOP, the temperature calibrations were performed over the temperature range 0° C to 30° C. In general, all sensors were within $\pm 0.3°$ C of the reference.

Field Intercomparisons

As stated earlier, one goal of this project was to determine the cause for the discrepancy between radiosonde measurements of RH and the tower and SMOS in situ measurements. This was done by collocating sensors that were checked in the laboratory during the pre-IOP tests with existing CART SMOS and tower sensors.

To summarize, it was found that the sensors on the tower (at both 25 m and 60 m) were reporting high values of RH ranging from 5% to 20%. The SMOS RH also appeared to have a bias of approximately 9%. Comparison of all sensors indicated that air temperatures measured at all locations agree within approximately $\pm 0.5°$ C.

Application of In-Situ Measurements to the Field Experiment

The effort to provide NIST-traceable measurements of water vapor was motivated by the need to verify measurements from various instruments operated at the ARM SGP CART Site during the Water Vapor IOP. Validation of other in situ measurements as well as remote sensing instrumentation was expected. The following are two systems in which the tower measurements provided a useful source of data for instrument verification efforts.

Radiosonde Comparisons

Sondes were received from Vaisala from two different calibration lots: one lot calibrated in June of 1996 and the other in August of 1996. In between the two calibration lots, Vaisala recalibrated their calibration chambers. Comparisons of RH were shown to vary between the two radiosonde calibration lots used (each lot having a separate calibration history). Figure 3 shows the intercomparison of the RH in which the radiosonde data were normalized by the Mesonet values.

The difference between radiosonde lots was on the order of 7%, greater than the sensor uncertainties of the tower RH probes. This RH lot dependency results in approximately the same percent difference in mixing ratios between lots.

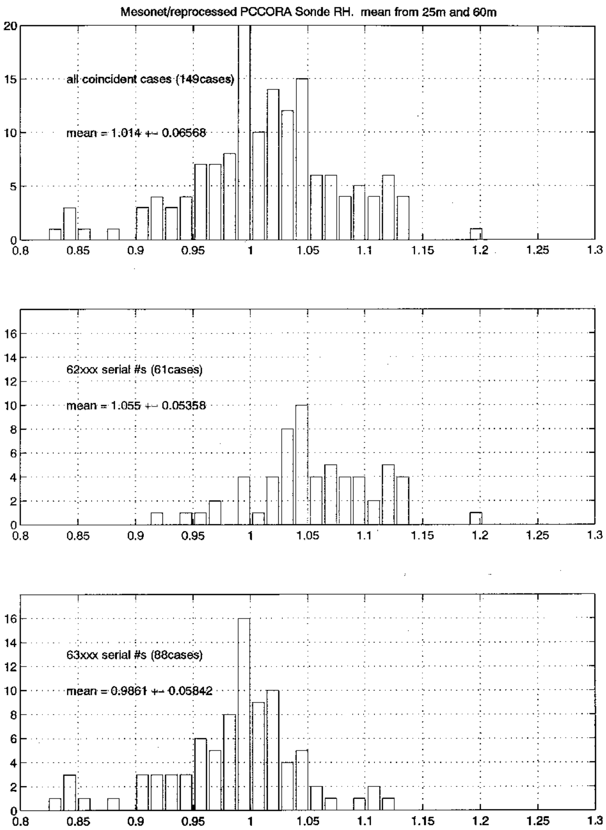

Figure 3. Radiosonde relative humidity normalized by the Mesonet RH.

The radiosonde temperatures were not shown to change significantly between lots. Note that sondes from the two different calibration lots were randomly mixed throughout the IOP. These findings were consistent with those obtained when columnar water vapor estimates from the radiosondes were compared with values from microwave radiometers.

Raman Lidar Comparisons

The difference between the Raman Lidar mixing ratio at 58 m (note the lowest range gate data are not ideal for data comparisons to other instrumentation) and the Mesonet sensors at 60 m was monitored for the course of the IOP. The calibration chosen for the Raman Lidar was based on scaling the Raman Lidar to the CART microwave radiometer (23.8 GHz/31.4 GHz).

The outstanding feature shown in Figure 4 is the apparent drift between systems during the 21-day IOP. The linear fit

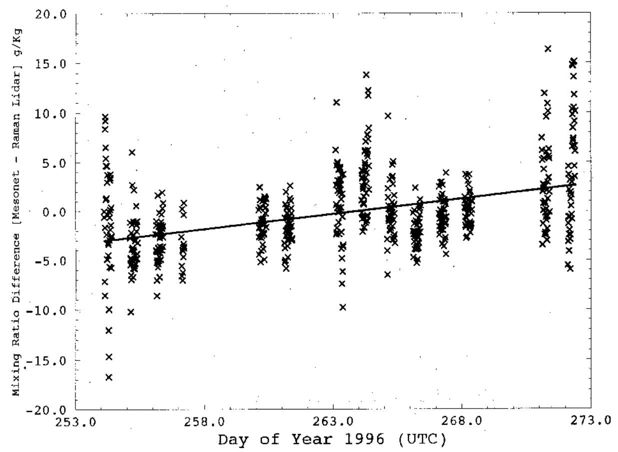

Figure 4. Comparison of Raman Lidar mixing ratio at 58 m and mixing ratio calculated from the Mesonet RH and the CART T at 60 m. Note the possible drift between the two throughout the IOP.

to the data shows a change of approximately 5% in the mixing ratio differences. The accuracy of the Mesonet sensors is estimated to be about +/- 2%, and the drift could be considered insignificant. However, the laboratory comparison of the Mesonet sensors before and after the IOP did not indicate detectable drift. Thus, it is unlikely that the Mesonet sensor uncertainties could explain this behavior and seems to indicate that the Raman Lidar measurements may have drifted over the 21-day IOP. It is unknown whether this possible drift in the Raman Lidar is a phenomenon only at the lower gate or whether it extends throughout the Lidar profile. The importance of using high-accuracy comparison standards for the in situ measuring systems and of conducting intercomparisons before and after the field experiment is shown in this example.

Concluding Remarks

The first WV IOP, conducted during the fall of 1996 at the ARM SGP CART site, brought together numerous atmospheric sensing instruments, both remote and in situ. Some sensors brought to the CART site were new and required calibration or verification (e.g., Raman Lidar). Central to the field calibration were accurate in situ measurements. Although the ARM Program has made every effort to maintain high data quality, the measurements of RH on the 60-m tower at the CART site showed signs of errors prior to the IOP. Thus, after careful laboratory calibration, additional sensors were mounted adjacent to existing CART RH sensors. Ideally, the CART sensors would have been included in the lab calibrations prior to the

IOP, but this was not logistically possible. The extra sensors (called the Mesonet sensors here) showed that, indeed, there was a calibration error in the RH sensors at 25 m and 60 m on the tower. The sensor errors were a result of inadequate manufacturer calibration methods.

As a result of the laboratory calibrations and inter-comparisons, calibration procedures were modified—the sensors are now calibrated every 6 months by an independent calibration facility. In addition, there are now redundant temperature and RH measurements at both levels on the tower so that sensor drift or calibration errors can be detected. These modifications to the observation and calibration strategy led to improvements in the continuous routine measurements at the ARM CART Site.

Laboratory calibrations/intercomparisons showed that most instruments were operating within their manufacturer's specifications. An exception to this was a new temperature and RH probe that was returned to the manufacturer for recalibration. In general, RH measurements should be accurate to within $\pm 2-3\%$ RH while temperature measurements should be accurate to within $\pm 1°$ C or better. The laboratory tests provided additional confidence in the in situ measurements of moisture not only on the tower and at the SMOS site, but on the tethersonde and on the aircraft as well. The tower data proved to be useful in examining the stability of the Raman Lidar as well as examining the accuracy of the radiosondes launched during the IOP. This latter issue, the sonde-to-sonde and lot-to-lot sonde variability, is currently being examined in more detail and additional work will be done during the next water vapor IOP scheduled for fall of 1997.

The calibration procedures followed during the first water vapor IOP at the ARM CART central facility served multiple purposes and accomplished several goals. First, the pre-IOP and post-IOP RH intercomparisons performed at the Oklahoma Mesonet calibration facilities helped identify subtle problems with field instruments, which resulted from inadequate manufacturer calibration procedures. With the identification of this problem, improvements were made in the calibration and maintenance schedule of some CART RH sensors. Finally, this work helped ensure that quality RH measurements were ultimately available, not only during the IOP but at all times.

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