Enhancement of ARM 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 that were performed in conjunction with the first Water Vapor 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. Two Raman lidars, two Atmospheric Emitted Radiance Interferometers, (AERIs), and a suite of 13 microwave radiometers were assembled at the CART site during the IOP, and 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 and relative humidity 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 the IOP and to determine if instrument failure or drift occurred during the IOP.

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 relative humidity measurements so that sensor drift or calibration errors may be detected. These modifications to the observation and calibration strategy led to improvements in the continuous routine measurements at the ARM CART site.

1. Introduction

This paper describes the temperature (T) calibrations and the relative humidity (RH) intercomparisons that were performed at the Oklahoma Mesonet (Brock et al. 1993; Crawford et al. 1992) using the T and RH chambers developed there. In addition, in situ measurements made during the IOP will be compared with radiosonde measurements as well as raman lidar. This work was done in conjunction with the first Water Vapor (WV) Intensive Observation Period (IOP) (American Meteorological Society 1997) that took place at the Atmospheric Radiation Measurement (ARM) Program Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site during September of 1996 (Stokes and Schwarts 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 numer-

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ous 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 Atmospheric Emitted Radiance Interferometers (AERIs, Feltz et al. 1997), a Twin Otter aircraft equipped with chilled mirror sensors, CART microwave radiometers, and CART in situ sensors located at the surface and on a 60-m tower.

The purpose of this work was to provide the National Institute of Standards and Technology (NIST) traceability to the in situ T and RH measurements made at the SGP CART site Central Facility. Prior to this work, sensors were calibrated by the manufacturer, and data from the CART site suggested calibration errors. This study was designed to verify this finding by testing the in situ temperature and moisture sensors both before and after the IOP in order to detect instrument problems or drift.

The Oklahoma Mesonet (Brock et al. 1993) relative humidity and temperature calibration chambers (Richardson 1995) were used for this work. The relative humidity chamber is a small enclosure, about a liter in volume, capable of calibrating up to six Vaisala HMP 35 or similar probes simultaneously. The calibration ''standard'' is a General Eastern D2 chilled mirror dewpoint hygrometer with an NIST traceable inaccuracy of $\pm 0.2°C$. The temperature calibration facility is approximately a liter in volume and is enclosed in a temperature controllable environment. The temperature reference is 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 ''transfer standards'' to the SGP CART relative humidity sensors located at 25 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) before the IOP. The sensors that were used as transfer standards were Vaisala HMP 35C temperature and relative humidity 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 adjacent to existing CART instrumentation during the IOP on the 60-m tower (at both the 25- and 60-m levels) and at the SMOS site (surface). These instruments were neither more accurate nor more stable than the CART instrumentation but did provide a second measure of temperature and relative humidity to detect drift or biases in the CART sensors. Relative humidity errors in excess of 3% RH and temperature errors of approximately 0.5°C could be detected using the sensors calibrated in the Mesonet laboratory.

The results from the pre- and post-IOP intercomparisons revealed several findings. First, the two chilled mirror sensors used (the Oklahoma Mesonet standard and a dewpoint sensor that was flown on the Twin Otter aircraft during the IOP) agreed within about 0.5°C above 0°C or roughly 1%–2% relative humidity. A second finding was that the CART temperature and relative humidity sensor used at the Balloon Borne Sounding System (BBSS) launch site had a 2%–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 that the relative humidity sensors on the CART 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. This latter finding was particularly significant because these sensors were used to characterize the lowest 1 km of the atmosphere as well as to compare with sonde and aircraft measurements.

a. *Motivation*

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

Accurate T and RH measurements at 60 m on the tower were required to aid calibration of the raman lidar located at the SGP CART site. In addition, evidence suggested (Lesht and Liljegren 1997) 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. In order 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 tower and SMOS instrumentation.

b. *Sensors included in intercomparisons*

Table 1 provides a description of the abbreviated name that will be used to refer to each sensor along with sensor accuracy, approximate response time, and range. Data given are manufacturer specifications whenever possible; however, data was not available for some of the sensors. In these cases, the given data are marked with an asterisk (*). The response time of the GE M2 differed from that given by the manufacturer because an air filter was used that damped the high-frequency response of the instrument. The manufacturer did not

TABLE 1. Sensor specifications and abbreviated names used to refer to sensors. Asterisks (*) indicate data are not manufacturer specifications either because they did not apply because of the system design or because specifications were not provided by the manufacturer. See text for details.

Sensor	Sensor accuracy	Approximate sensor response time	Sensor range	Description
GE M2	+0.2°C	Approx. 30 s as configured with filter*	−35 to +25 at 25°C	General Eastern M2 chilled mirror sensor. Used as laboratory standard for six years for Mesonet RH calibrations.
GE 1011B	±0.2°C	Approx. 30 s as configured with filter*	−35 to +25 at 25°C	General Eastern 1011B chilled mirror sensor. Flown on the twin Otter aircraft to measure dewpoint.
Meteolabor 1	±0.25°C	2–4 s	−30° to +50°C	Meteolabor chilled mirror dewpoint thermometer TP3-ST with T-Preamplifier. This sensor was used on the tethersonde during the IOP.
Meteolabor 2	±0.25°C	2–4 s	−30° to +50°C	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	RH: ±1%–3% RH T: ±0.2°C	15 s for both T and RH	0%–100% RH −40° to 80°C	Vaisala HMP 233 temperature and relative humidity sensor. This sensor was located at the BBSS site during the IOP.
BBSS launch site sensor 2	RH: ±1%–3% RH T: ±0.2°C	15 s for both T and RH	0%–100% RH −40° to 80°C	Vaisala HMP 233 temperature and relative humidity sensor. This sensor was sued during the IOP to check the operation of the BBSS sensor and the SMOS sensors.
60-m Mesonet	±2%–3% RH ±0.5°C	RH: 15 s T: approx. 15+ s*	−30° to +50°C	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	±2%–3% RH ±0.5°C	RH: 15 s T: approx. 15+ s*	−30° to +50°C	Vaisala HMP 35C temperature and relative humidity sensor. This sensor was located at the 60-m level and housed in an R. M. Young aspirated radiation shield.
25-m Mesonet	±2%–3% RH ±0.5°C	RH: 15 s T: approx. 15+ s*	−30° to +50°C	Vaisala HMP 35C temperature and relative humidity sensor. This sensor was located at the 25-m level and housed in an aspirator.
SMOS Mesonet	±2%–3% RH ±0.5°C	RH: 15 s T: approx. 15+ s*	−30° to +50°C	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	T: ± 0.5°C	5 s	−30° to +50°C	YSI 44203 temperature sensor. This sensor was located in the same shield as the Vaisala HMP 35C sensor but had a faster response and smaller radiational heating error.
25-m Mesonet Fast T	±0.5°C	5 s	−30° to +50°C	Same as 60-m Mesonet Fast T but located at 25 m on the 60-m tower.
SMOS Mesonet Fast T	±0.5°C	5 s	−30° to +50°C	Same as 60-m Mesonet Fast T but located at the SMOS site.
SMOS CART	±2%–3% RH ±0.5°C	RH: 15 s T: approx. 15+ s*	−30° to +50°C	Vaisala HMP 35C temperature and relative humidity sensor located at the CART SMOS site about 200 m east of the CART 60-m tower.
60-m CART 1	±2%–3% RH	15 s	0% to 100% RH	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	±2%–3% RH	15 s	0% to 100% RH	Qualimetrics 5120-E relative humidity sensor. This sensor was located at the 60-m level on the tower before the IOP began.

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 and RH sensors	Yes (four sensors)	Yes (three sensors)
60-m CART sensors	No	Yes (two sensors)
Meteolabor 1 and 2	No	Yes

give a time constant for the HMP 35C, but experience indicates it to be in excess of 15 s in modest wind speeds (5+ m s^{-1}; Richardson et al. 1998).

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 relative humidity; the GE 1011B only measured dewpoint. The two BBSS launch site sensors were new and had not been used prior to the IOP. The four Mesonet temperature and relative humidity 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 faster response sensors (e.g., approximately 10 s with a 1 m s^{-1} aspiration rate) than the Vaisala T sensor. These sensors were also part of the Mobile Mesonet Research Facility and were used in conjunction with the Vaisala HMP 35C temperature and relative humidity sensor. This sensor was used during the IOP to remove large relative humidity errors (as large as 8% RH during the IOP) that occur with the Vaisala HMP 35C because of a temperature lag and radiational heating errors associated with the HMP 35C sensor. These errors were infrequent (occurring only with rapid temperature fluctuations) and could be minimized by using a sufficiently large averaging interval. For a complete discussion of this issue, see Richardson et al. (1998).

All of the RH sensors had inaccuracies of 2%–3% RH, while the temperature sensors had inaccuracies of $\pm$0.3°C or better. Accuracy specifications for the chilled mirror sensors are discussed in section 3a(1).

Some sensors were included in both the pre- and post-IOP relative humidity intercomparisons, while others were available for only one or the other. This is summarized in Table 2. The temperature calibrations were only performed during the post-IOP due to time constraints. The sensors that were included in the temperature calibration were the Vaisala HMP 35C's, the Mesonet fast response sensors, and the BBSS launch site sensor 1.

The Meteolabor chilled mirror sensors were new and had not been used prior to the IOP. These sensors consisted of a small mirror and an air temperature sensor. It was only possible to include the Meteolabor sensors in the post-IOP tests.

2. Laboratory facilities

The Mesonet calibration/intercomparison facilities have been described in Richardson (1995). A brief description of the temperature and relative humidity calibration/intercomparison chambers will be given below as well as any modifications that were made to accommodate the different instrumentation used during the IOP.

a. Relative humidity intercomparison

A schematic of the RH intercomparison setup is shown in Fig. 1. Moist and dry air were combined at various ratios to produce air with different relative humidities. The moist and dry air combined as it entered the relative humidity chamber where the test sensors were located. The chamber was completely sealed so that air could only exit the chamber through a tube leading to the chilled mirror sensors. Special Teflon tubing was used for the sampling lines to avoid condensation, adsorption, or absorption in the tubing leading from the RH chamber to the chilled mirror devices. Therefore, dewpoint could be calculated with knowledge of the air temperature and relative humidity or that RH could be calculated from knowledge of air temperature and dewpoint (note that care should be used when performing this calculation at low RH; see Richardson et al. 1998).

The relative humidity chamber was capable of producing relative humidities ranging from near 0% to near 100% RH. There was no independent temperature control for the relative humidity chamber so tests were performed at room temperature (between 22° and 23°C, temperature variations inside the chamber were less that 1°C). The GE M2 had an NIST traceable calibration, although it had not been recalibrated for several years. For this reason, the term relative humidity *intercomparison* is used here instead of *calibration*.

Relative humidity was varied from near 100% RH to near 0% RH in steps of 5%–10% RH followed by steps back up to 100% RH. This variation of RH with time will be referred to as an RH ''ramp''; Fig. 2 shows the RH ramp determined from the GE M2 temperature and dewpoint. Figure 3 is the variation of dewpoint with time inside the chamber. All tests were performed with the ramps shown in Figs. 2 and 3.

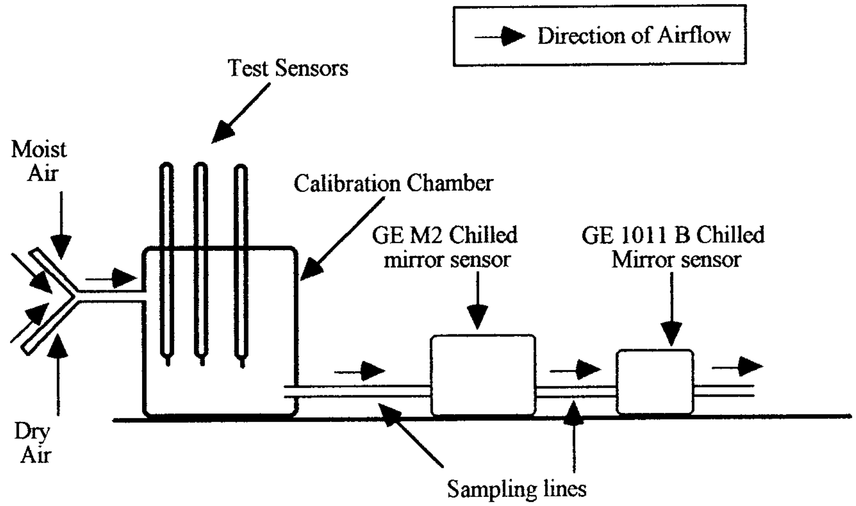

FIG. 1. Schematic of the relative humidity intercomparison facility.

b. Temperature calibration

The term calibration is used to describe the temperature intercomparison process because a very stable and accurate temperature standard was used (NIST traceable precision Resistance Temperature Detector, Azonics model A1011). The probe had an rms inaccuracy of ±0.03°C. The temperature calibration was similar to that described in Richardson (1995) except that an air bath was used instead of a water or antifreeze solution. The temperature calibration chamber consisted of a chest freezer with heaters used to produce temperatures above room temperature. Sensors could be exposed to temperatures ranging from −25° to +50°C. Temperature inside the chamber was varied slowly to allow sensors to equilibrate. Figure 4 shows a schematic of the temperature calibration apparatus. The test sensors were inside an additional enclosure within the freezer and a fan was used to stir the air. Additional fans were used inside the freezer to further circulate air around the secondary enclosure (not shown in Fig. 4).

3. Laboratory test results

a. Relative humidity intercomparison results

For these intercomparison tests, the GE M2 was chosen as the reference dewpoint sensor because the GE 1011B could not be included in the post-IOP tests. The GE 1011B sensor was calibrated prior to this experiment at Sandia National Laboratories Primary Standards Lab but this sensor was not designed to measure very large dewpoint depressions (G. Senum 1997, personal com-

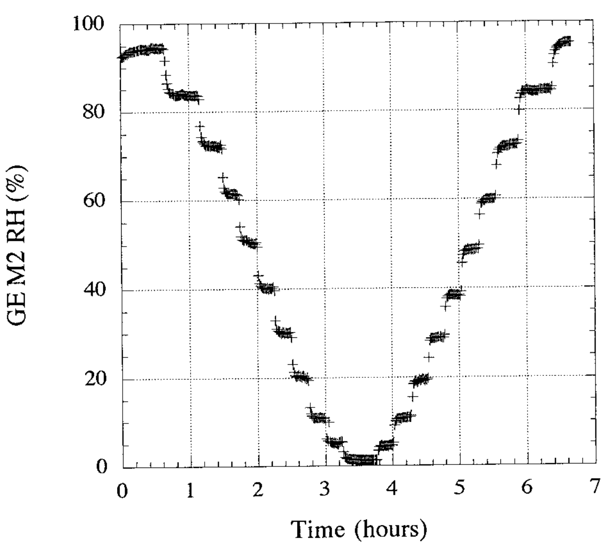

FIG. 2. Variation of relative humidity inside the RH chamber as determined by the GE M2 dewpoint and air temperature sensors.

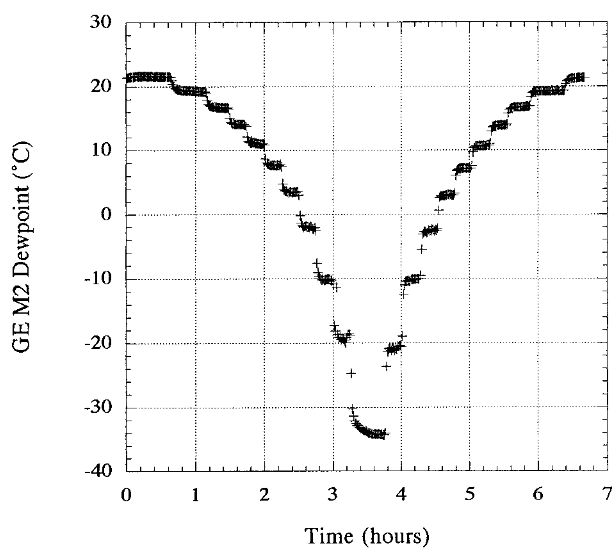

FIG. 3. Same as Fig. 2 but for dewpoint.

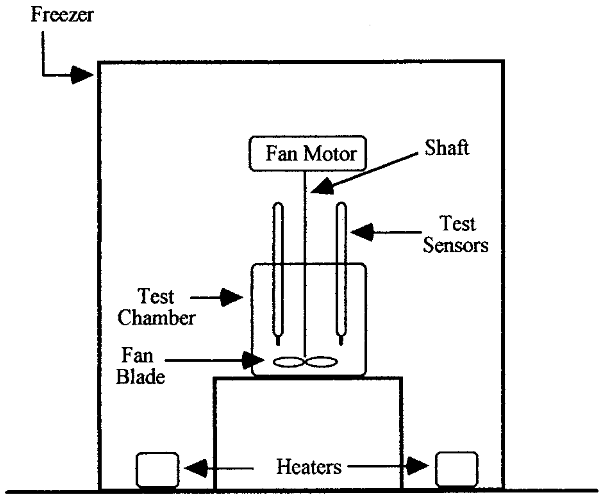

FIG. 4. Schematic of the temperature calibration facility.

munication) nor did it have a temperature sensor to facilitate calculation of RH. Thus, the GE 1011B was used as a transfer standard for checking the operation of the GE M2 during the pre-IOP tests.

1) CHILLED MIRROR DEWPOINT SENSORS: GE M2 AND GE 1011B

Results from the calibration of the GE 1011B were obtained from Sandia National Laboratories and the output of the 1011B was adjusted accordingly. The adjustments to the raw output were small, between 0.0°

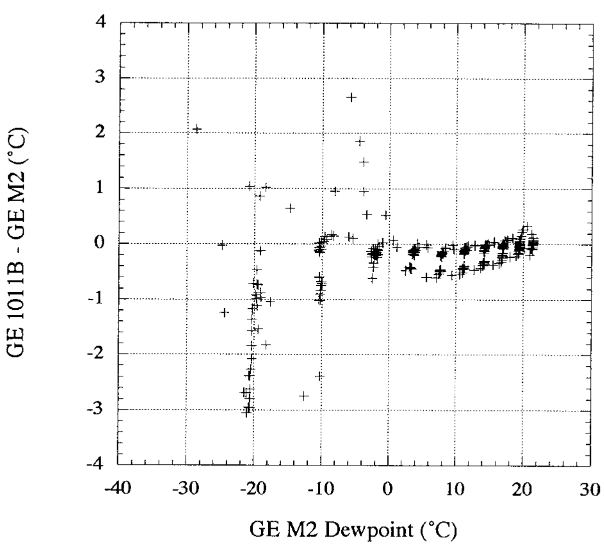

FIG. 5. Difference between the GE 1011B and the GE M2 chilled mirror sensors as a function of chamber dewpoint. Some of the larger errors were due to the response time of the sensors; i.e., the mirror temperature was equilibrating after a change in RH inside the chamber. In addition, below 0°C it is possible for either dew or frost to be on the mirror and this introduces additional uncertainty (see the text for details).

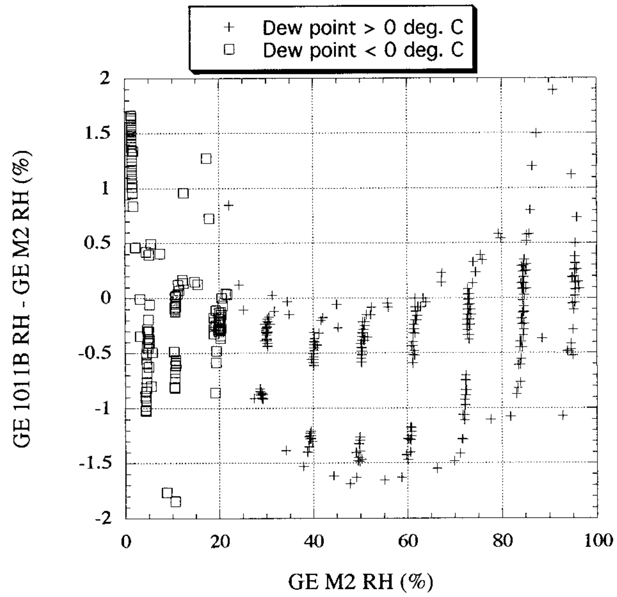

FIG. 6. The same data as Fig. 5 except converted to relative humidity. The errors were generally less than 2% RH, which was adequate for verifying the accuracy of the sensors listed in Table 1.

and 0.3°C. Whenever GE 1011B data are shown, the calibration has been applied. The certificate of calibration stated that when the corrections were applied, the inaccuracy of the hygrometer was estimated not to exceed ±0.5°C for the dewpoint temperatures tested (−20° to +20°C). It was noted that in the temperature range of 0° to −20°C, either dew or frost may exist on the dewpoint mirror and that an additional uncertainty of 2°C dewpoint temperature may be introduced. Note that the minimum dewpoint temperature during the 21-day IOP was 7°C.

Figures 5 and 6 show the difference between the two chilled mirror sensors; Fig. 5 is the difference in measured dewpoint as a function of dewpoint, and Fig. 6 is the difference in calculated relative humidity as a function of relative humidity (using the GE M2 temperature sensor). Both figures show what appears to be a hysteresis error; however, this was an artifact of the RH chamber design and subsequent modifications have significantly reduced it. The chamber air is now continuously mixed using a fan inside the chamber like the one in the temperature calibration chamber (section 2b). The fan reduced the differences shown in Fig. 6 from 1% RH to less that 0.5% RH. The GE 1011B and GE M2 agree within approximately ±0.5°C and 2% RH over the entire range. The manufacturer specifications for both units were approximately ±0.2°C, although the recalibration of the GE 1011B was good only to ±0.5°C. Thus, the two dewpoint devices appear to have been operating within calibration uncertainty.

2) LABORATORY RESULTS

Relative humidity as measured by all eight sensors during a pre-IOP intercomparison is shown in Fig. 7.

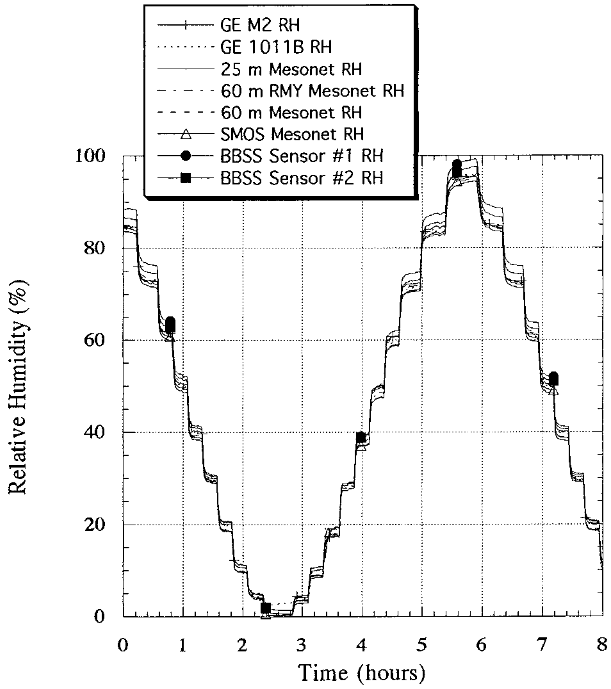

FIG. 7. Relative humidity measured by all eight sensors included in the pre-IOP intercomparison.

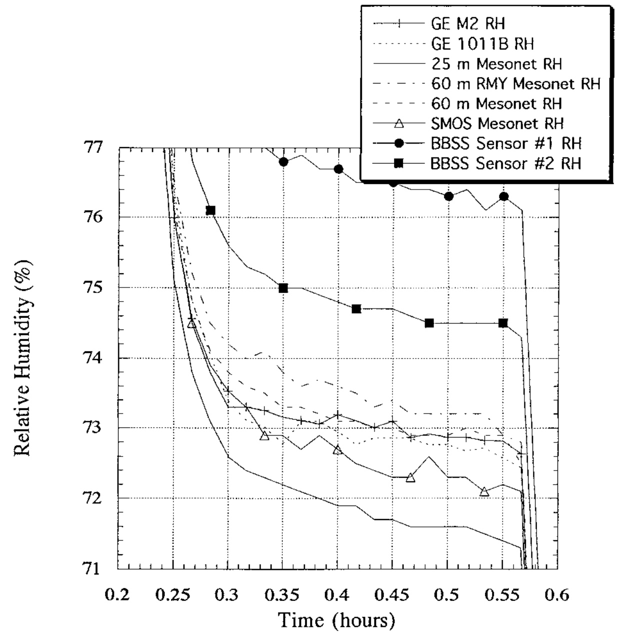

FIG. 8. Blowup of part of Fig. 7. Note the BBSS sensors appear to be 2%–4% high. The agreement between the remaining six sensors is very good and within ±1% RH.

This plot is meant to show the general agreement between all the sensors. Figure 8 shows an enlargement of Fig. 7 at the 70% RH level. The GE M2 and GE 1011B measured dewpoint 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 ±1%. The BBSS launch site sensors appear to be biased high by 2% to 4%.

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

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 and it was returned to the manufacturer.

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

Test results from the Meteolabor 1 and 2 sensors are shown in Fig. 9. It is evident that these sensors were unable to measure large dewpoint depressions (manufacturer specifications state a maximum mirror cooling of approximately of 40°C). Above 0°C the agreement of the two sensors with the GE M2 reference sensor and with each other was very good, less than ±0.6°C. Either dew or frost can be on the mirror surfaces for dewpoints below 0°C and this can introduce errors.

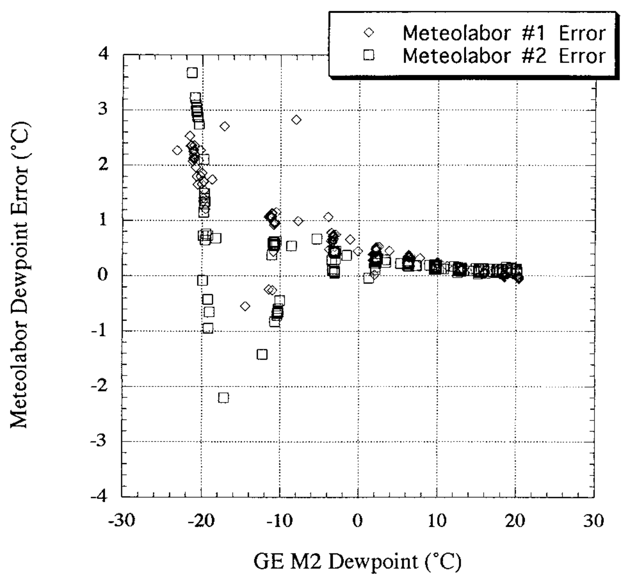

FIG. 9. Dewpoint errors for the two Meteolabor chilled mirror sensors. Below 0°C either dew or frost can be on the mirror surface and this leads to uncertainty in the measured dewpoint (see the text for details).

b. Temperature calibration results

To test the probes over the range of temperatures experienced during the IOP, the temperature calibrations were performed over the temperature range 0°–30°C. In general, all sensors were within ±0.3°C of the reference sensor.

4. Field intercomparisons

As stated in section 1a, one goal of this project was to determine the cause for the discrepancy between radiosonde measurements of relative humidity and the CART tower and SMOS in situ measurements. This was done by collocating sensors that were checked in the laboratory with existing CART SMOS and tower sensors.

The sensors that were collocated with the CART sensors were housed in aspirated radiation shields designed and developed for use in the VORTEX field project (Rasmussen et al. 1994). The shields, which will be referred to as VORTEX shields, were constructed from 3-in. PVC tubing and were designed to protect the sensors from rain and mechanical damage (e.g., hail).

To summarize the results that were obtained, it was found that the Qualimetrics sensors on the tower (at both 25 and 60 m) were reporting values of relative humidity ranging from 5% to 20% RH too high. The SMOS relative humidity also appeared to be in error; data indicated that it was biased approximately 9% RH high. Comparison of all temperature sensors indicated that air temperatures measured at all locations agreed within less than ±0.5°C.

During the daylight hours the sensors in the VORTEX aspirator (Vaisala and Fast temperature sensors) were about 0.5°–0.7°C warmer than the SMOS temperature. In general, the shield that produces the lowest daytime temperatures is considered more accurate because environmental factors tend to cause an overestimation of air temperature. The radiational heating error associated with the VORTEX shields was not unexpected because this shield was constructed for use on mobile observing platforms, that is, mounted on cars, and had large surface area compared to the small diameter tubing used in other aspirated radiation shields. Note that although T and RH were effected by radiational heating errors, combining T and RH from a given sensor will still provide an accurate estimate of dewpoint or mixing ratio assuming moisture conservation.

5. 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 were expected. The following were two systems in which the tower measurements provided a useful source of data for instrument verification efforts.

a. Radiosonde comparisons

The following section discusses radiosonde accuracy as it pertains to the findings in the first WV IOP. More detailed information regarding the uncertainty in radiosonde measurements of temperature and relative humidity estimated from dual-sonde soundings made during the first WV IOP can be found in Lesht (1998).

Discrepancies between model-calculated spectral radiances in the longwave region (based on input from radiosondes) and that measured by an infrared interferometer at the SGP CART site provided some of the impetus to define the atmospheric state with higher accuracy, particularly water vapor. Use of the in situ tower sensors was one method used to help identify variances observed in radiosonde relative humidity calibrations. Radiosondes were launched every 3 h from the SGP CART Central Facility for the 21 days of the IOP. Approximately half of these launches contained two radiosonde packages.

Vaisala RS-80H sondes from two different calibration lots (June 1996 and August 1996) were used during the IOP. Sondes from these lots were flown individually and in pairs. Sondes were arranged during the paired soundings to examine both the within-batch and between-batch variability. Based on comparisons both of the relative humidity at the surface measured by sondes in the dual soundings and of the precipitable water vapor (PWV) obtained by integrating the sonde profiles, we found that the sondes calibrated in June 1996 were significantly drier than those calibrated in August.

The differences between the two batches were originally attributed to calibration variability (it happened that the manufacturing calibration system was itself recalibrated in July). Examination of the calibration system by the manufacturer, however, was unable to discover any change that would account for such a large difference. As a result of our findings and of others suggesting that RS-80H sondes may have a dry bias, Vaisala subsequently determined that contamination of the humidity sensor might be possible during storage. This contamination would have the effect of inhibiting the absorption of water vapor to the humidity sensor membrane. Although the issue is still under investigation, preliminary corrections procedures have been developed and are being tested (A. Paukkunen 1998, personal communication). At present, these procedures are proprietary but are based on the theory that contamination of the humidity sensor will increase with sonde age. We were supplied with a preliminary version of the correction algorithm and applied it to the data from the paired soundings.

The results (Fig. 10) show that much of the difference

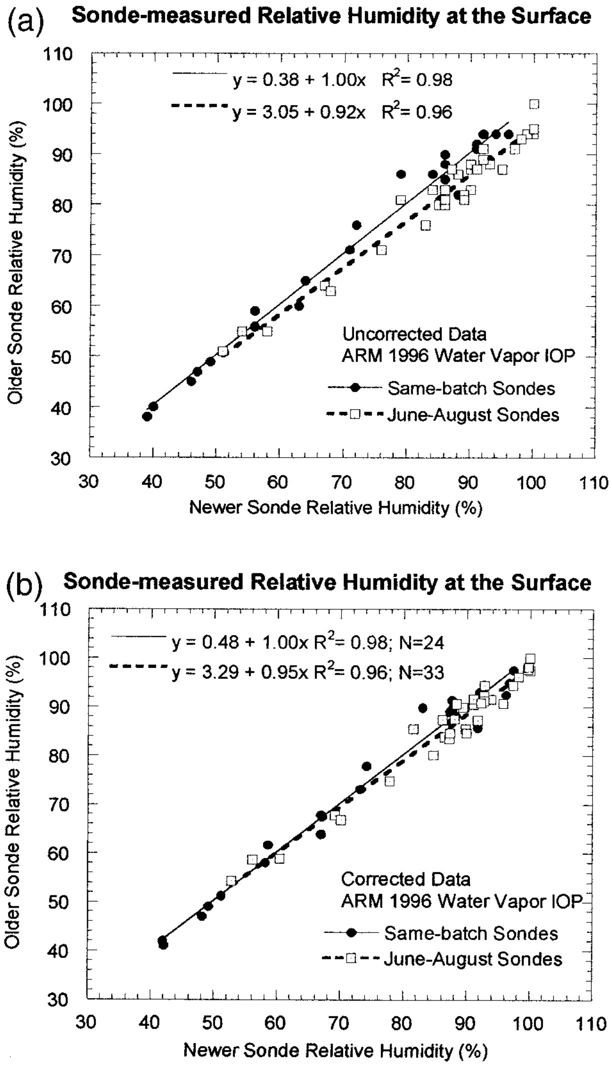

FIG. 10. Sonde-measured relative humidity at the surface. Shown in (a) is the uncorrected data for the same-batch and Jun–Aug sondes; note the slope in the latter, which is significantly different from that of the same-batch sondes. The corrected data (as described in the text) is shown in (b); the slope of the Jun–Aug sondes is closer to unity and no longer significantly different from the same-batch sondes.

between the two-sonde batches can be accounted for by age-dependent changes in the humidity response of the sondes. The RH measured at the surface was examined and there was no significant difference (at the 1% level) between the RH measured by same-batch sondes before or after the correction was applied (Fig. 10a). However, sondes from different batches were significantly different before the correction was applied but not significantly different after the correction was applied (Fig. 10b). This supports the hypothesis that the dry bias in the older sondes results from contamination and can be corrected by the Vaisala algorithm.

Similar analysis was performed using PWV calculated from dual sonde launches (Fig. 11). The old-sonde

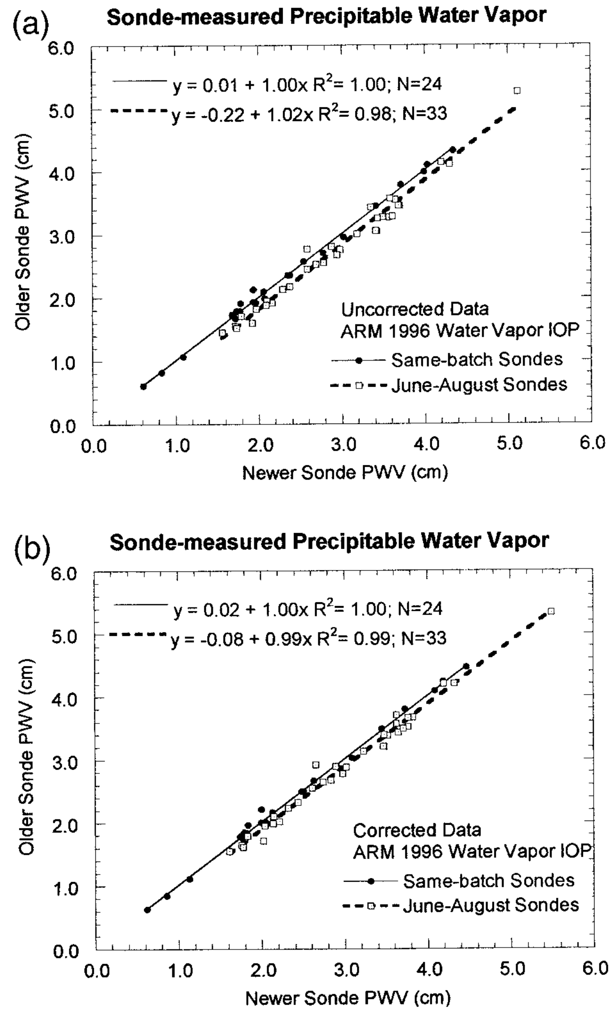

FIG. 11. Similar to Fig. 10 but for precipitable water vapor calculated from radiosondes. Uncorrected data are shown in (a), while (b) shows the data after the correction was applied. The difference between the intercepts in the uncorrected data is significant while it is not in the corrected data.

dry bias appears as an offset in the uncorrected data (Fig. 11a). The corrected data show a significantly different (and closer to zero) intercept, again supporting the hypothesis that the older sondes have a dry bias.

b. Raman lidar comparisons

The CART Raman lidar, anticipated to provide water vapor mixing ratio measurements with high temporal and vertical resolution, required a high-accuracy calibration during the Water Vapor IOP. Potential calibration sources for the IOP period included both in situ and remote instrumentation. Chilled mirror sensors flown on tethersondes (up to 1 km) and aircraft could provide high-accuracy samples at altitudes greater than the 60-m tower. Microwave radiometers were used to provide a high-accuracy estimate of the columnar water vapor.

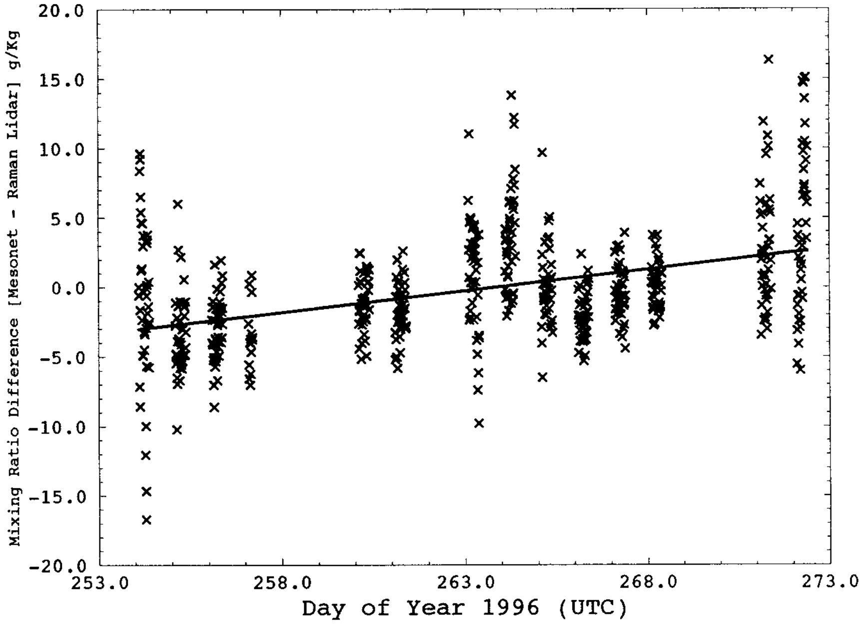

FIG. 12. Comparison of Raman lidar mixing ratio at 58 m and mixing ratio calculated from the Mesonet RH and the CART T at 60 m. Note the possible drift between the two throughout the IOP.

The Mesonet sensors were able to provide NIST traceable estimates of the water vapor mixing ratio at the 60-m level for a nearly continuous 21-day period. The Raman lidar's lowest estimate is available at 58 m, though this lowest range gate data are assumed not to be ideal for data comparisons to other instrumentation.

The difference between the Raman lidar mixing ratio at 58 m and the Mesonet sensors at 60 m were 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 Fig. 12 is the apparent drift between systems during the 21-day IOP. The linear fit to the data shows a change of approximately 5% in the mixing ratio differences, which is approximately equivalent to a 8% RH difference. The accuracy of the Mesonet sensors was ±2%–3% and laboratory comparison before and after the IOP did not indicate detectable drift. Thus, it is unlikely that the Mesonet sensor uncertainty can explain this behavior and seems to indicate that the Raman lidar measurements may have drifted over the 21-day IOP. It is not known whether this possible drift in the Raman lidar is a phenomenon only at the lower gate, or whether it extends to throughout the lidar profile. The importance of using high accuracy and stable sensors for the in situ measuring systems *and* conducting intercomparisons before and after the field experiment are shown in this example.

6. Concluding remarks

The first water vapor Intensive Operation Period 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 was accurate in situ measurements. Although every effort has been made by the ARM Program to maintain high data quality, the measurements of relative humidity on the 60-m tower at the CART site showed signs of errors prior to the IOP. Thus, additional sensors were, after careful laboratory calibration, mounted adjacent to the existing CART RH sensors. Ideally, the CART sensors would have been included in the laboratory 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 and 60 m on the tower. Upon detailed analysis, it was determined that the sensor errors resulted from inadequate manufacturer calibration methods.

Laboratory calibrations/intercomparisons showed that most instruments were operating within their manufacturer specifications. In general, relative humidity measurements should be accurate to within ±2%–3% RH, while temperature measurements should be accurate to within ±1°C or better. The laboratory tests provided additional confidence in the in situ moisture measurements 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 that were launched during the IOP.

The dual-sonde experiment proved that the older sondes were dryer than the newer ones; the newer ones also agreed better with the other instruments. The hypothesis that the dry bias in the older sondes results from contamination (and can be corrected by the Vaisala algorithm) is supported by the IPO data. Without the correction, sondes from the same batches give the same results (this shows that the within batch variability is small) but sondes from different batches do not (the bias appears in the slope in Fig. 10 and in the offset in Fig. 11). When the correction is applied, there are no statistically significant differences between batches.

The work described here resulted in modifications to the calibration procedures, that is, the sensors are now calibrated every six months by an independent calibration facility. In addition, there are now redundant temperature and relative humidity measurements at both levels on the tower so that sensor drift or calibration errors may be detected. These modifications to the observation and calibration strategy led to improvements in the continuous routine measurements at the ARM CART Site.

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