

An Interpretation of Radiosonde Errors in the Atmospheric Boundary Layer

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ABSTRACT

The authors review sources of error in radiosonde measurements in the atmospheric boundary layer and analyze errors of two radiosonde models manufactured by Atmospheric Instrumentation Research, Inc. The authors focus on temperature and humidity lag errors and wind errors. Errors in measurement of azimuth and elevation angles and pressure over short time intervals and at higher altitudes introduce wind vector errors greater than 5 m s^{-1} . Mean temperature and humidity lag errors were small, and collectively, these lag errors had little effect on the calculation of the vertically integrated water vapor content. However, individual large lag errors occurred with dramatic changes in the environment, such as near the surface or at the top of the boundary layer. Dual-sonde flights showed mean instrument error comparable to lag error and had little effect on the calculation of the columnar water vapor content. A hypothetical consistent error of 5% in the measurement of relative humidity in a dry environment could introduce error in the calculation of columnar water vapor content up to 1 kg m^{-2} .

1. Introduction

Routine radiosonde observations continue to be a basic source of information for forecasting the behavior of the atmosphere. Schwartz and Doswell (1991) point out that the "radiosonde's capability for resolving details of the thermodynamic structure in the vertical has yet to be duplicated by any of the new remote-sensing systems." Radiosonde observations are important in the development of satellite techniques to retrieve temperature and humidity profiles (Finger and Schmidlin 1991; Garand et al. 1992). In addition to routine use for weather forecasting, radiosonde observations are taken by the U.S. Department of Defense, by the National Center for Atmospheric Research (NCAR) (Finger and Schmidlin 1991), and by research groups at universities and other government agencies. Some recent efforts have focused on using radiosonde measurements to estimate broad area evaporation (Abdulmumin et al. 1987; Sugita and Brutsaert 1990a, 1991; and Munley and Hippias 1991).

The National Weather Service (NWS) flies radiosondes made by VIZ Manufacturing Co. and the Space Data Corporation, and the characteristics of these

sondes have been examined by the Test and Evaluation Branch of the NWS (NWS 1991). Another sonde manufactured by Atmospheric Instrumentation Research Inc., the Airsonde, and the focus of this paper has been used in experiments to estimate broad area evaporation (Sugita and Brutsaert 1990a; Munley and Hippias 1991; Smith et al. 1991) by application of similarity theory, bulk boundary layer theory, and Bowen ratio concepts. Wooldridge et al. (1991) has also used this sonde to look at profiles of vertically integrated water vapor content (VIWVC) in attempts to identify evapotranspiration and horizontal advection of water vapor. Since the Airsonde is not widely used operationally but is frequently used in atmospheric boundary layer investigations, a further look into its characteristics is desirable.

In this paper, we review the sources of error in radiosonde measurements and analyze the errors in two sets of soundings from different mountainous sites (Wyoming, elevation 3200 m, and Pennsylvania, elevation 700 m). We use information gathered from previous intercomparisons (Kaimal et al. 1979; Richner and Phillips 1982) and information on sensor characteristics and data reporting practices to analyze error limits in the Airsondes (AIR, Inc.). We focus on temperature and humidity lag errors and wind errors.

Lag errors are a function of the instrument time constant, the ascent rate of the package, and of the vertical gradient of the variable being measured. Brut-

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saert and Kustas (1985) and Sugita and Brutsaert (1990b) accounted for different time constants of sensors by adjusting the temperature and humidity data to an appropriate pressure level in the atmosphere. We felt this method was questionable and evaluate the lag error here in a formal manner.

One of the driving forces behind this paper is the application of the results to boundary layer measurements for evaporation studies. The boundary layer is of primary interest, and the error analysis is limited to below 4000 m AGL (400 mb in Wyoming and 650 mb in Pennsylvania). Aside from this, the Airsonde has shown greater discrepancy in measurements performed above 300 mb in previous sonde intercomparisons (Richner and Phillips 1982; Kaimal et al. 1979). In a study of annual cycles of tropospheric water vapor, Gaffen et al. (1992) did not use humidity data above 500 mb because of the known poor performance of the radiosonde hygrometers in cold, dry environments.

In boundary layer studies, higher vertical spatial data resolution than that usually obtained by NWS soundings is often necessary. We noted increased variation in collecting wind data at a higher resolution and wanted to identify and quantify sources of error. Overall, error limits are examined for their influence on the detection of boundary layer features and calculation of VIWVC in a series of radiosonde flights.

2. Airsonde instrumentation

Atmospheric Instrumentation Research (AIR), Inc. of Boulder, Colorado manufactures and supports the atmospheric data acquisition system (ADAS). The system is used in conjunction with an optical theodolite and data recorder, such as a computer or tape recorder, to track, receive, and process telemetered meteorological data from the Airsonde package (AIR 1986).

Two Airsonde models are examined here: the helicoid-shaped sonde, which uses a wet-bulb sensor for humidity measurement and the box-type model, which uses a carbon hygrometer for humidity. In both models, the temperature is measured by a white-coated bead thermistor and pressure is measured by an absolute barometric, electronic aneroid capacitance sensor, with a thermistor connected to the sensor to provide temperature-compensated data. The manufacturer states the temperature is accurate to 0.5°C over the range of -40°C to +40°C with a 3–5-s time constant, and the pressure is accurate to 3 mb over the range of 1000–300 mb.

The accuracy of the wet-bulb temperature in the helicoid sonde is the same as the temperature sensor but has a 15-s time constant. The wet-bulb humidity measurement is sensitive over the range of 10%–100%, ($\pm 3\%$). For the Airsonde model, where humidity is measured by the carbon hygrometer, the accuracy is reported to be 5% over the range of 20%–100% RH. Ap-

parently, the range and accuracy of the humidity measurement can be improved by using a "premium" sensor (M. Freedman 1991, personal communication, VIZ Manufacturing Corporation) and an appropriate transfer equation (Wade 1991).

When used as a system in the sonde, measurement discrepancies have been reported for these systems, which appear to exceed the manufacturers specifications for the individual sensors [Boulder Low Level Intercomparison Experiment (BLIE) (Kaimal et al. 1979) and radiosonde intercomparison SONDEX, (Richner and Phillips 1982)]. In SONDEX, the Airsonde system underestimated pressures above an altitude of 700 mb, compared to the mean pressure from all other sensors, reaching a difference of -5 mb at 300 mb (Richner and Phillips 1982). Also in the SONDEX study, the Airsonde temperature mean was smaller than the mean of all sensors above the 800-mb altitude, reaching a difference of 1.25°C at 300 mb. The difference between the actual ascent rate used and the manufacturer's prescribed ascent rate was thought to contribute to the temperature differences.

During BLIE, the average temperature, which the Airsonde recorded, was 0.1°C higher than mean temperatures on the nearby tower on which data were taken at heights ranging from 10 to 300 m above the surface. The average temperature of the Airsonde was 0.35°C higher than the average of all sondes used for the height range of 10 m to 3 km, but the correlation of Airsonde temperature data with tower data and overall mean sonde data were $r = 0.95$ and 1.00. Solar radiation effects were thought to contribute to differences in temperature noted during BLIE (Kaimal et al. 1979) for the helicoid sensor housing, and the sonde was subsequently modified to correct for this: the thermistor was coated with a white reflective paint and the insides of the measuring ducts were painted black.

The comparison of humidity data in SONDEX produced large discrepancies between different types of sensors used. For the wet-bulb sensor, little could be done to correct for humidity inaccuracies when the air temperatures were below freezing and the sensors froze. Also, errors in pressure were not accounted for when using the psychrometric equation to calculate RH. The carbon element used in another sonde (VIZ 1392) is now used to sense humidity in the AIR box-type radiosonde. This sensor element showed very small deviations from the common mean of the other sensors up to 100 mb in altitude. This sensor is described as the regular hygrometer and is used in the VIZB sondes employed by the NWS.

3. Error assessment

Radiosonde errors have been attributed to 1) systematic errors related to the characteristics of the sonde being used, 2) instrumental errors, which persist

throughout a sounding but may vary from one sounding to the next, and 3) random errors of observation (World Meteorological Organization 1971). Hooper (1975) defined systematic error as the departure from "truth" of the data mean from sondes made to a common design and distinguished it from sonde error and random error. Sonde error is the departure of averaged data of individual sondes from a population of sondes, while random error is the departure of individual measurements from the mean of a single sonde (Hooper 1975). Systematic errors can be determined by knowledge of the physical characteristics of the sensors and their measurement capabilities.

The WMO (1971) suggested that the assessment of errors related to 1) and 2) above proceed by comparing data from a series of soundings with two sondes attached to the same balloon. Hooper (1975) discussed both laboratory evaluation of sonde performance as it relates to calibration stability and simulated flights and of actual twin-sonde comparisons and successive flight of single-sonde ascents flown close together in time. Hoehne (1980) describes the standardized procedures for determining the functional precision of the radiosondes used by the NWS. As Hooper (1975) pointed out, the atmosphere cannot be fully simulated for laboratory measurements, and there are many uncertainties in comparing actual flight measurements. Examination of laboratory calibration information, theoretical evaluation of errors for single-sonde ascents, and twin-sonde comparisons will increase our knowledge of performance.

a. Temperature

Systematic errors in temperature measurements can be attributed to radiation effects and to the response lag of the instrument in relation to its ascent through the environment. The temperature lag error is a function of its time constant, the ascent rate of the balloon and instrument package, and the vertical gradient of environmental temperature. It can be represented by (WMO 1971)

$$\delta T = -\lambda V \frac{\Delta T}{\Delta z} \quad (1)$$

where δT is the temperature error, λ the time constant, V the ascent rate of balloon and instrument package, and $\Delta T/\Delta z$ the vertical temperature gradient.

The time constant for temperature depends primarily on pressure p and ventilation velocity u and can be satisfactorily represented by (Richner and Phillips 1981)

$$\lambda = \lambda_o \left(\frac{p_o}{p} \right)^{0.5} \left(\frac{u_o}{u} \right)^{0.5} \quad (2)$$

where the subscript o represents the value of the parameters at a reference level.

The magnitude of solar radiation effects are influenced by the intensity of solar radiation, height in the atmosphere, the physical characteristics of the temperature sensor, the ventilation of the sensor, the heat conduction, convection and radiation between the sensor, the environment, the body of the sonde, and the physical characteristics of the balloon and its distance to the sonde (Hooper 1975).

Talbot (1972) looked at radiation influences on a white-coated thermistor and found a 0.2°C amplitude of diurnal temperature variation at midtropospheric levels. Luers (1990) addressed the radiosonde temperature error as a function of altitude under different environmental conditions. He found that solar radiation errors were the least below the 10-km elevation because the increased radiation path length significantly decreases the solar irradiance of the thermistor. Cloud cover, surface and cloud temperatures, and solar elevation angles affect the solar irradiance of the thermistor and individually account for temperature errors of 0.5°–1°C (Luers 1990).

Teifenau and Gebbeken (1989) examine the influence of meteorological balloons on radiosonde temperature measurements. Their work focused mainly on influences above the troposphere because within the troposphere, the balloon expansion and subsequent adiabatic cooling of the gas has an almost negligible effect on the temperature measurements made within the wake of the balloon since the natural atmospheric temperature gradient is nearly adiabatic.

b. Humidity

The errors associated with humidity measurement are principally attributed to the lag of the sensor as it moves through a changing environment. An expression similar to that used for calculating temperature errors in (1) can be used for calculating RH errors:

$$\delta RH = -\lambda V \frac{\Delta RH}{\Delta z} \quad (3)$$

The humidity time constant for a radiosonde depends not only on pressure and ventilation velocity, but also is a function of absolute temperature and water vapor pressure (Richner and Phillips 1981). The response characteristics of the sensor indicate fast initial response, increasing response times with decreasing temperatures, and variations in response time due to a hysteresis effect (Stine 1963; Marchgraber and Grote 1963). The hysteresis effect of the carbon element affects its time constant in a manner that increases the response time when the sensor encounters a drier environment and has a shorter response time when the sensor encounters a moister environment.

In dry environments, Wade and Wolfe (1989) and Brousaides (1973) showed that many of the problems encountered at low humidities have been due to the

misrepresentation of transfer equations. The box-type Airsonde uses the VIZ carbon hygistor, which outputs a measured resistance that is converted to RH. The ADAS system incorporates a transfer equation supplied by VIZ in which a different set of coefficients is used for relative humidities above and below 20%. Wade (1991) suggests that the same set of coefficients used for RH data above 20% be applied to data below 20% to alleviate this problem.

The wet-bulb sensor does not exhibit the hysteresis effect, but of particular concern in the use of this sensor is its slow response time.

c. Winds

One hundred-gram balloons were inflated with helium and used to carry the instrument package. For dual-sonde flights, 200-g balloons were used to carry the instrument packages. The Airsondes were suspended approximately 10 m below the balloon on a cord. For dual-sonde flights, the packages were flown one above the other and separated by approximately 5 m to minimize coupling of radiosonde frequencies (after Hooper 1975). Vertical distances were calculated by the hypsometric equation for successive pressure measurements. Height was determined by summing the vertical distances. Wind speed and direction were determined by trigonometric relations based on the angular position of the balloon from one time frame to the next.

Errors in the calculated values of wind speed and direction reflect errors in the azimuth and elevation readings or errors in the determination of height from errors in pressure measurements. Assessment of the wind vector error δV can be expressed (WMO 1971)

$$(\delta V)^2 = \frac{2}{\Delta t^2} [(\Delta h)^2 Q^2 + (\Delta \alpha)^2 H^2 (Q^2 + 1)^2 + (\Delta \phi)^2 H^2 Q^2] \quad (4)$$

where Δt is the time interval between observations, Δh the error in height, $Q = \bar{V}/\bar{v}$, $\bar{v}$ the mean balloon ascent rate up to height H , $\bar{V}$ the magnitude of mean wind vector up to height H , and $\Delta \alpha$, $\Delta \phi$ the errors in measurement of elevation and azimuth.

Each of the components of error can alternatively be expressed (Singer 1957)

$$\begin{aligned} \delta V_p &= \left(\frac{R_d}{g} \right) \frac{T_v \cot \alpha \Delta p}{\Delta t}, \\ \delta V_\alpha &= \frac{H \csc^2 \alpha \Delta \alpha}{\Delta t}, \\ \delta V_\phi &= \frac{H \cot \alpha \Delta \phi}{\Delta t}, \\ \delta V &= \delta V_p + \delta V_\alpha + \delta V_\phi \end{aligned} \quad (5)$$

where R_d is the dry-air gas constant, g the acceleration due to gravity, T_v the virtual temperature, Δp the random error in pressure, P the pressure, α , ϕ the elevation and azimuth angles, respectively. The subscripts on δV denote error due to the individual components of pressure, elevation, and azimuth angles. The dependence of the error on the elevation angle and the sampling rate imply that the greatest error will be introduced when measuring at low elevation angles and when sampling at higher frequencies.

4. Methods

Errors were determined for temperature, humidity, and wind measurements taken at two different sites: a high-elevation mountainous area in Wyoming (41°22'N, 106°15'W, elevation 3200 m) and a lower-elevation site in a mountainous area in Pennsylvania (40°50'N, 78°7'W, elevation 700 m). A total of 108 flights were evaluated individually, of which 23 were measured by the helicoid sonde and 85 were measured by the box-type sonde. A limited number of dual flights, where two sondes were suspended on a single balloon (after Hooper 1975), were analyzed. The majority of the sounding flights were made at the Wyoming site (95) while only 13 flights were made in Pennsylvania.

Temperature and humidity lag errors were estimated by (1) and (3) for each of the sample data points of a sonde flight as the instrument ascended through the air. The time constant for temperature was calculated by (2), and the temperature gradient and ascent rate of the balloon were approximated by finite differences. For calculations involving the use of (2), the reference pressure p_o was taken as the surface pressure and the reference velocity u_o was taken as the manufacturer's recommended ventilation velocity (1 m s⁻¹ for the spin-type sonde and 3 m s⁻¹ for the box-type sonde). The reference time constant for temperature was taken as the manufacturer's time constant (3 s).

Equation (2) was used to calculate the humidity time constant. For the wet-bulb sensor, the reference humidity time constant was taken as the manufacturer's time constant (12 s). Using graphical information presented by Marchgraber and Grote (1963) for a carbon hygistor encountering a drier environment, we fit a simple exponential equation to represent the dependency of the time constant upon temperature:

$$\lambda_o = \exp\left(\frac{6.89 - T}{11.27}\right) \quad (6)$$

This expression serves as the reference used in (2) for determining the time constant for humidity used in (3). Before humidity data measured by the carbon hygistor were analyzed, the correct transfer equation was applied (AIR 1986):

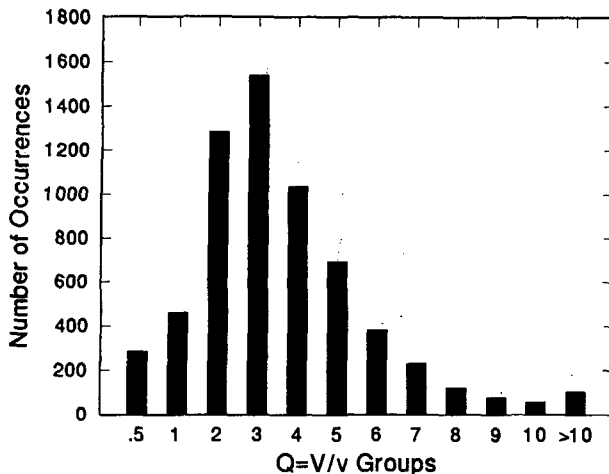


FIG. 1. Frequency of occurrence of values of $Q = V/v$ (horizontal wind/ascent rate of the balloon) over all sonde flights. (Ranges: 0.5 = 0–0.5, 1 = 0.6–1, 2 = 1.1–2, etc.)

$$RH = A - \frac{69}{\sum_{k=0}^4 D_k [f(R_s)]^k} \quad (7)$$

where RH is the percent relative humidity, $f(R_s) = f(t) \ln(R_s/R_{33})$, R_s the humidity sensor lock-in resistance, R_{33} the humidity sensor lock-in resistance at 33% RH and 25°C, $f(t) = \sum_{k=0}^3 C_k(t)^k$ the temperature coefficient of the humidity sensor, and A , D_k , and C_k are constants supplied by the manufacturer for a particular lot of sensors.

To apply the equation, the measured resistance must be known. The ADAS system in use at the time the measurements were made was not set up to output measured resistance from the hygistor. Therefore, we used Wade's (1991) proposal that resistance values could be determined iteratively from sonde data already collected if the lock-in resistance at 33% humidity were known. In this manner, the resistance values for all datasets, which used the hygistor for humidity measurements, were determined, and the appropriate transfer equation was applied before humidity lag error calculations were performed.

Solar radiation errors are the least below 10 km (Luers 1990). The thermistor coated with white reflective paint used in the Airsondes will experience a small, diurnal temperature variation error due to exposure (Talbot 1972). But since the sondes were flown under similar clear to partly cloudy daylight conditions, which minimized diurnal temperature variations, and the focus of data collection was below 4 km (approaching 400 mb at the Wyoming site and 650 mb at the Pennsylvania site), radiation errors were not evaluated here. Care was taken before launch of the sensor package to ensure that it was kept out of direct sunlight and ventilated as well as possible. When this was not done,

particularly when there was inadequate ventilation of the sensor, temperature jumps of 1°–2°C were observed.

Wind data from full sonde flights were initially evaluated by (4) and (5), resulting in large errors. As was stated in a previous section, the balloons carrying the sondes were visually tracked from the ground by a theodolite. In some cases, the azimuth and elevation angles were recorded visually, and in other cases, the angles were recorded automatically by the ADAS system. In either situation, the tracking was performed manually and human error could readily be introduced. In view of this, a general sensitivity approach was taken to quantify the occurrence of significant errors.

Data from all sonde flights were used to determine the frequency of occurrence of elevation angle ranges (i.e., 0°–5°, 5.1°–10°, 10.1°–15°, etc.) and the Q value (i.e., 0–0.5, 0.6–1, 1.1–2, etc.) in (4). Distinct elevation angles (5°, 10°, 15°, ..., 90°) and Q values (0.5, 1, 2, ..., 10) were used as input to (4) and (5) for a systematic evaluation of the theoretical wind errors. Levels were chosen in 100-m increments from the surface to 1000 m above the surface and increments of 500 m from 1000 up to 4000 m above the surface. Time intervals used were 5, 10, 15, 30, and 60 s. The 5-s time interval was the shortest measuring interval on the ADAS system.

The dual-sonde measurements of temperature and humidity were evaluated for functional precision by determining the difference between measured values at 100-m-level increments. Data were linearly interpolated to these levels. Hoehne (1980) suggests that a bias is introduced in the comparison process when one sonde is flown above the other. In these cases, the bias is defined as the mean difference and the functional precision is obtained from the standard deviation.

5. Results

a. Wind errors

The frequency of elevation angles measured and the occurrence of the calculated value $Q = \bar{V}/\bar{v}$ over all sonde flights, including both windy and calm conditions, are shown in Figs. 1 and 2. An average balloon rise rate ($\bar{v}$) over all soundings was 3.1 m s⁻¹ with a standard deviation of 1.3. The most frequently occurring values of $Q = \bar{V}/\bar{v}$ lie between 1.1 and 5 (Fig. 1), and the most frequent elevation angle measurements fell in the 10°–30° range (Fig. 2). Even though the Pennsylvania data comprised a smaller sample, they exhibited the same frequency patterns when viewed as a separate subset (not shown).

The theoretical wind vector errors (4) at distinct heights for the most frequent intervals of Q (2, 3, 4) assuming a 0.1° error in azimuth and elevation angles and a 1-mb pressure error are shown in Figs. 3a, 3b, and 3c. The predicted error is significant for a time

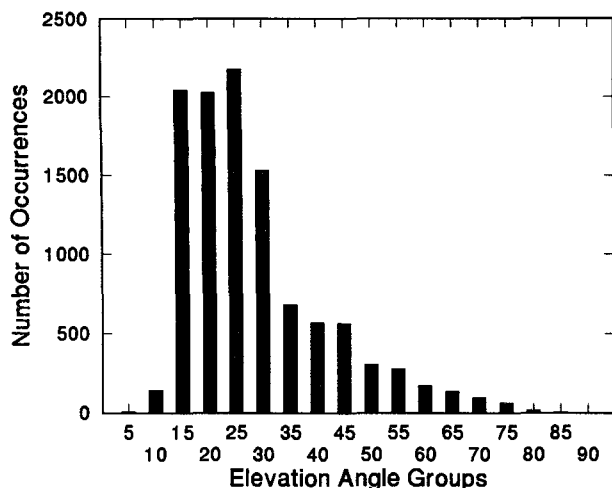


FIG. 2. Frequency of occurrence of elevation angles ($^{\circ}$) over all sonde flights. (Ranges: 5 = 0–5, 10 = 5.1–10, 15 = 10.1–15, etc.)

step of 10 s (Fig. 3a) and less for time steps of 30 and 60 s (Figs. 3b and 3c).

If the error in the azimuth and elevation angles were assumed to be 0.5° , errors of measurements made near the surface would remain relatively unchanged, while errors at 500 m above the surface would increase by 35% for $Q = 2$ and by 80% for $Q = 4$. At 1000 m above the surface the wind error potential would increase by 100% for $Q = 2$ and by 180% for $Q = 4$. For values of Q greater than 4, which indicate strong horizontal winds, the error increases dramatically with height.

Calculations of theoretical vector error at distinct heights for each component of (5) (δV_p , δV_{α} , δV_{ϕ}) for the most frequently occurring elevation-angle intervals (15, 25, 35) with 0.1° azimuth- and elevation-angle errors and a 1-mb pressure error are shown in Figs. 4a, 4b, and 4c. From Fig. 4, the greatest predicted error below 2000 m will arise from pressure error. Above 2000 m, errors in the measurement of elevation angles will have a greater influence on the calculation of the wind speed. For a 0.5° assumed error in the azimuth and elevation readings, the angle errors would contribute 18%–25% more to the wind error near the surface and 120%–160% more at 1000 m above the surface (not shown).

A combination of the errors contributed by the three separate components in (5) are shown in Fig. 4d. As with the wind vector errors calculated by (4) for a 10-s time interval, the potential theoretical wind errors can be significant near the surface and increase dramatically with height above the surface. The errors decrease as the time step is increased (not shown).

In the above analysis, the values used to represent error in measurement of height and of elevation and azimuth angles were very conservative. The 0.1° angle error represents a data resolution for automated read-

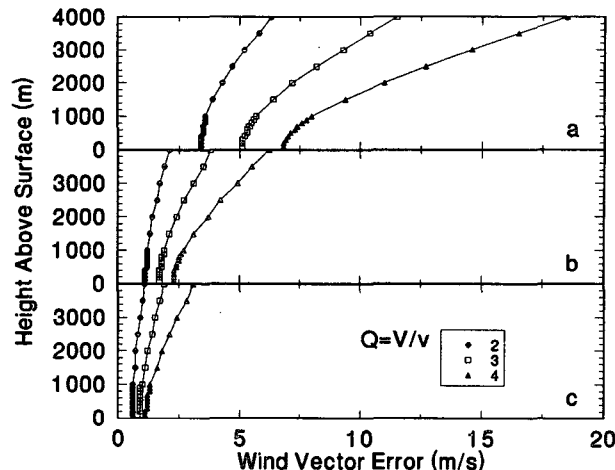


FIG. 3. Theoretical wind errors calculated by Eq. (4), assuming 0.1° error in measurement of azimuth and elevation angles and a 1-mb error in height for time intervals between observations of (a) 10 s, (b) 30 s, and (c) 60 s. Calculations made for the most frequent values of Q (2, 3, 4) at distinct heights.

ings; the precision of the readings and the human error in tracking the sonde package is likely to be considerably larger than this. The 1-mb error in height is, likewise, a conservative value, as the precision of the sensor is 3 mb and the influence of the error in potential temperature [see (5)] upon the pressure error has not been taken into account.

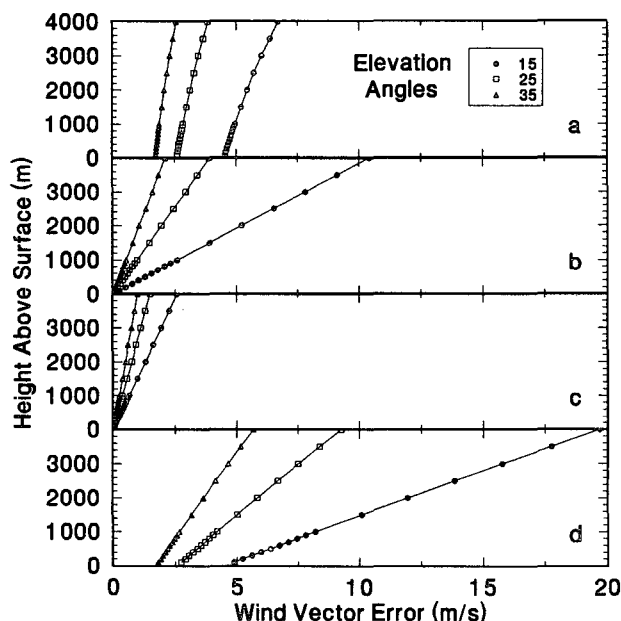


FIG. 4. Components of wind error calculated by Eq. (5) at distinct heights and elevation angles with assumed 0.1° error in measurement of angles and a 1-mb error in height for (a) δV_p , (b) δV_{α} , (c) δV_{ϕ} , and (d) $\delta V = \delta V_p + \delta V_{\alpha} + \delta V_{\phi}$. Measurement frequency was set to 10 s.

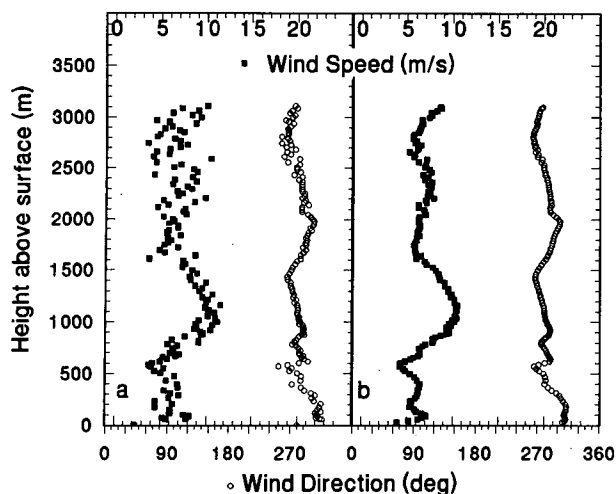


FIG. 5. Example sounding taken at the Wyoming site, 1000 MST 2 August 1991 for (a) wind data collected at 10-s intervals and (b) wind data smoothed with a five-point running average.

Taking frequent measurements of the wind profile by theodolite will give a more detailed picture of the atmosphere but will include some of the errors mentioned above. For example, Fig. 5a depicts wind data taken at 10-s intervals. The data contain considerable scatter, especially above 1500 m. The average rise rate of the balloon for this sounding was 2.5 m s^{-1} , resulting in calculated Q values between 2 and 6, which as noted above, results in increased error potential. Our experience suggests that the theoretical errors are not unreasonable. Visual tracking of the balloon and package by theodolite under strong winds is as challenging as a computer game; sometimes the position of the target is overestimated, sometimes it is underestimated.

Let us think of the wind profile in terms of spectral components and focus interest on the mean wind, which is contained in the low-frequency end of the spectrum. The high-frequency end of the spectrum contains turbulence and spurious errors (Armendariz and Rachele 1967). Smoothing by the five-point binomial weighted filter will remove some, but not all, of the high-frequency data (Panofsky and Brier 1968). This results in a profile, which better estimates the mean wind and leads to easier interpretation for wind profile classification (e.g., Fig. 5b).

b. Temperature and humidity errors

1) SINGLE-SONDE FLIGHTS

Theoretical temperature lag errors were calculated using (1) for all datasets. Over all soundings, the mean temperature lag error was 0.1°C with a standard deviation of 0.1. No lag errors were found larger than $\pm 1.5^\circ\text{C}$; the largest temperature lag errors occurred in elevated inversions. A smaller mean temperature lag

error and standard deviation were noted for soundings made in Pennsylvania, but additional analysis revealed that the smaller mean and standard deviation applied to measurements made with the helicoid sonde (see Table 1). On the helicoid sonde, the temperature sensor is mounted in a duct on one of the arms; on the box-type sonde, the sensor is exposed to the atmosphere directly. We believe that the sensor exposure is the main reason for the differences in lag error.

Humidity lag errors were analyzed separately for the wet-bulb (helicoid sonde) and carbon hygistor (box sonde) sensors. The large time constant of the wet-bulb sensor and the increasing time constant with decreasing temperatures for the hygistor sensor resulted in significant RH lag errors for both types of measurements. The occurrence of the errors within the atmospheric boundary layer profile were different between the two sensors and in many instances reflected the characteristics of the profile being measured.

Twenty-three profiles were measured with the wet-bulb sensor. Ten of the soundings were taken at the Wyoming site, the other 13 soundings were measured at the Pennsylvania site. Relative humidity was calculated for the duration of the flight or until the wet-bulb sensor froze, which for our soundings ranged from -4° to -10°C . Of the 23 flights, 13 terminated measurements close to 2000 m AGL; the other flights terminated measurements close to 3000 m AGL.

Over the wet-bulb soundings (Table 1), the mean theoretical humidity lag error was 0.1% with a standard deviation of 2.3. Values ranged from -18% to 19% with the average maximum value of 10% and the average minimum value of -5.8% . An example of a RH profile measured by a wet-bulb sensor for a sounding in Pennsylvania and the calculated lag errors is presented in Figs. 6a and 6b. As with the temperature lag errors, the largest errors occurred at the top of the boundary layer (1100 m above the surface), distinguished by an elevated inversion and dramatic moisture change. For the whole wet-bulb dataset, the slightly higher occurrence of large, positive humidity lag errors

TABLE 1. The means, absolute maximums, and standard deviations for theoretical lag error ($^\circ\text{C}$), humidity lag error (%), and vertically integrated water vapor content (VIWVC) difference (actual minus lag corrected) for the helicoid sonde (wet-bulb sensor) and box sonde (carbon hygistor sensor).

		Mean	Abs (max)	Std dev
Temperature lag error ($^\circ\text{C}$)	helicoid sonde (wet bulb)	0.02	0.35	0.05
	box sonde (carbon hygistor)	0.08	1.55	0.13
Humidity lag error (%RH)	wet-bulb sensor	0.12	19	2.20
	carbon hygistor sensor	0.08	20	1.71
VIWVC different (kg m^{-2})	wet-bulb sensor	0.002	0.05	0.01
	carbon hygistor sensor	0.04	0.10	0.01

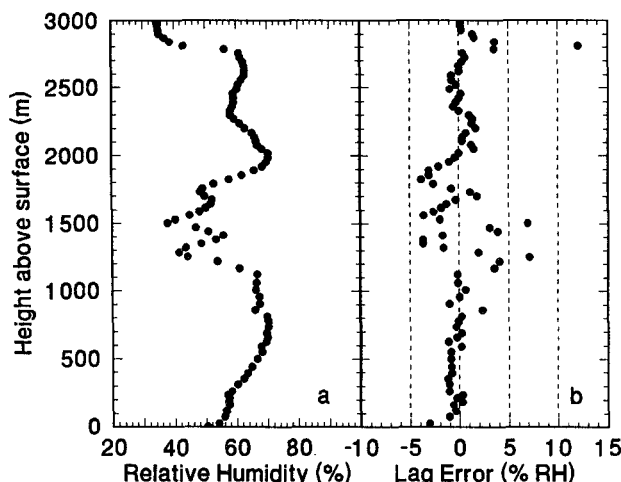


FIG. 6. Example (a) RH profile measured by a wet-bulb sensor and (b) lag errors calculated by Eq. (3) for a sounding made in Pennsylvania, 1230 EST 28 May 1990.

over the negative lag errors indicate that conditions most often encountered were a drier atmosphere above the boundary layer.

All the soundings that used the carbon hygistor were taken at the Wyoming site. Approximately two-thirds of the soundings had measurements that extended up to or above 3500 m AGL. The mean humidity lag error for these soundings was 0.1% RH, with a standard deviation of 1.7% (Table 1). Figures 7a–d show two examples of RH measured by the carbon hygistor sensor and the theoretical humidity lag error in a dry climate.

The data for Figs. 7a and 7b depict a dry morning sounding in September with specific humidity averaging 3.5 g kg^{-1} in the mixed layer and averaging 1.5 g kg^{-1} above the mixed layer. The abrupt change in moisture at the top of the boundary layer is an area where the theoretical lag error is high, reaching 10% RH. The data for Figs. 7c and 7d depict a morning sounding with specific humidity varying throughout the profile from 7 g kg^{-1} near the surface to 2 g kg^{-1} above. Due to the increasing response time of the sensor under decreasing temperatures, the same changes in RH near the surface have lower theoretical lag errors than at 3000 m above the surface.

The theoretical lag errors resulting from the use of the carbon hygistor below the 3000-m altitude were generally less than those resulting from the use of the wet-bulb sensor. Most errors calculated below 3500 m in elevation ranged between -20% and $+20\%$ RH. At higher altitudes, where humidity changed abruptly and temperatures were low ($< -10^\circ\text{C}$), humidity lag errors as great as 30% were calculated. This was not a surprising effect and mainly reflects the characteristics of the sensor an increasing time constant with decreasing temperatures.

The humidity lag errors accentuated dramatic changes in the atmospheric profile such as a surface-layer inversion, different moisture layers in the atmosphere, and the boundary layer top (z_i). The errors were smaller in the lower portion of the atmosphere, below 3500 m, and were larger in the upper part of the atmosphere. The delayed response of either the wet-bulb or carbon hygistor sensor had the effect of smoothing over layers of different humidities within the atmosphere. Even with our method of estimating lag errors it is difficult to estimate the actual error in measurement due to the sensor's delayed response.

The humidity values, measured by both the wet-bulb sensor and carbon hygistor, were corrected for lag errors to determine the effects on the calculated VIWVC. Even though large individual lag errors were estimated, the average correction tended to be small (0.1% RH) and no significant changes were noted in the calculation of the VIWVC. Table 1 presents the summary statistics for differences (actual minus lag corrected) in VIWVC for measurements made by the wet-bulb sensor and the carbon hygistor sensors. The maximum difference over all points was 0.1 kg m^{-2} . Differences were slightly larger for the carbon hygistor measurements, reflecting that more measurements were made at higher altitudes where larger lag errors were observed; wet-bulb measurements were not used when the sensor froze (-4° to -10°C).

2) DUAL-SONDE FLIGHTS

Even though precautions had been taken to minimize data problems caused by the close radio frequen-

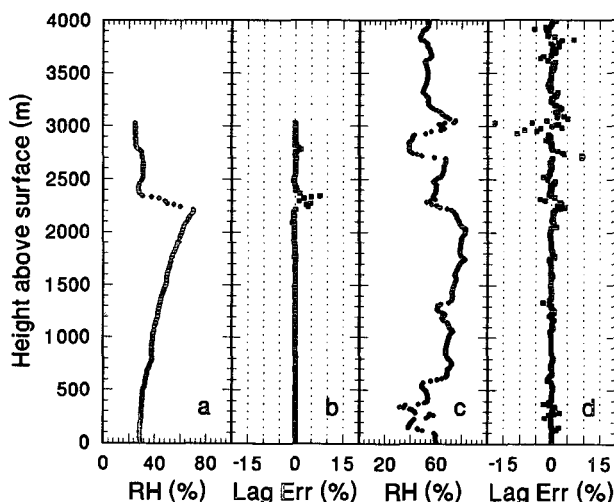


FIG. 7. Examples relating to humidity measurement by carbon hygistor for (a) RH profile, 0900 MST 12 September 1990 and (b) associated lag errors calculated by Eq. (3), (c) RH profile, 0800 MST 2 August 1991, and (d) associated lag errors calculated by Eq. (3). Soundings were made in Wyoming.

cies of the dual flights, noise was introduced into the signal. Therefore, after lag corrections had been applied, a five-point running weighted average was used to smooth both the temperature and RH data before looking at differences between the two measurements.

The precision statistics for temperature and humidity difference data are presented in Table 2. Sounding "A" was flown above sounding "B." The temperature differences between soundings were calculated: A minus B. Hoehne (1980) suggests that a bias is introduced in the comparison process when one sonde is flown above the other. In these instances, the mean difference is interpreted as the bias and the standard deviation is interpreted as the functional precision.

The overall temperature bias calculated for these sondes is -0.4°C with a temperature precision of 0.3°C . The T values computed for each set of temperature differences show that the biases, ranging from -0.2° to -0.7°C , were significant. Hoehne (1980) showed the functional precision of temperature for an NWS radiosonde, determined by comparison of data at the same height, to be $\pm 0.8^{\circ}\text{C}$ with a bias of -0.2°C (Hoehne 1980). In this NWS evaluation by Hoehne, data were evaluated for 50 flights and the comparisons were made at 300-m increments up to 10 mb.

A visual inspection of our temperature data showed that the differences increased slightly with height. The 0900 MST sounding, which showed the largest bias, depicted a persistent stable layer from the previous evening, being slowly eroded away near the surface by heating. The 1130 and 1330 MST soundings taken later in the day depicted a mixed layer extending up 800 m and overlaid with a stable atmosphere. The 1000 MST sounding taken the next day indicated that a shallow surface adiabatic layer (200 m) was below a deeper "residual" adiabatic layer. The largest differences occurred for the sounding with the strongest temperature gradients. This is also where the largest lag errors occur.

Relative humidity differences between the paired soundings showed mixed results. The overall bias was -0.6% RH with a precision of 1.6% . The scatter of both negative and positive humidity differences for the 0900 and 1300 MST soundings produced t values indicating the biases were not different from 0 at the 20% level. The t values for the other soundings showed that

the biases were significant ($p < 0.001$). The functional precision of RH for the NWS VIZB radiosonde determined by comparison of data at the same pressure was $\pm 2.3\%$ RH (NWS 1991).

The Wyoming site has a typical dry continental climate. To put this into perspective, Gaffen and Elliot (1993) computed seasonal and annual averages of surface to a 400-mb columnar water vapor content for 15 Northern Hemisphere rawinsonde stations. Moist areas such as Singapore averaged 51.6 kg m^{-2} for the year without regard to cloudiness, while the drier climate of Oakland, California, averaged 13.8 kg m^{-2} for clear skies over the year.

The temperature and humidity data for the B flights were corrected for bias and the difference between flights A and B calculated for the VIWVC. Over the four flights, the average difference ranged from -0.06 to 0.07 kg m^{-2} with the maximum difference ranging from -0.11 to 0.11 kg m^{-2} . This difference is comparable to that resulting from the lag response of the sensor.

The results from the dual-sonde flights are encouraging and show that the precision of the temperature and humidity measurements are comparable to those obtained by NWS sondes. However, this is a small sample size and further testing of the sonde would be desirable both by itself and compared with other sondes used by the NWS.

In our own experiences of correcting the RH measurements for the proper transfer equation, we realized that a change of a couple hundred ohms in the 33% lock-in resistance would produce a noticeable change in the humidity output. Wade (1994) mentions that the lock-in resistance for the hygistor is determined as the average resistance for a given production lot. He examined the lock-in resistance values for a small sample of hygistors, which indicated that individual values differed from the lot average by several hundred ohms. Above 60% RH, the effect of lock-in error was less than 2% RH at 25°C , becoming negligible for colder temperatures. At 33% RH and 25°C , a 3% RH error is produced by a 600Ω error. Below 33% RH, errors larger than 3% RH could be produced by errors larger than 600Ω (Wade 1994).

TABLE 2. Summary statistics for temperature and relative humidity differences for dual-sonde flights.
[Flight—yy jdy hh (year, julian day, hour).]

Flight	Temperature differences ($^{\circ}\text{C}$)				Relative humidity differences (%)			
	Min	Max	Bias	Precision	Min	Max	Bias	Precision
9121909	-1.4	-0.2	-0.7	0.3	-5.5	3.1	0.4	1.7
9121911	-0.7	0.1	-0.2	0.2	-3.8	-0.1	-1.9	0.9
9121913	-0.5	0.5	-0.2	0.3	-7.2	1.7	-0.5	1.9
9122010	-0.7	0.0	-0.4	0.2	-2.5	1.6	-0.8	0.8

The accuracy of the regular hygistor is reported to be 5% RH. In making frequent sonde measurements throughout the day, one wonders what the effect of a consistent error of $\pm 5\%$ RH would have on the calculation of the columnar water vapor content. Figure 8a depicts a Wyoming profile of integrated water vapor content with error lines to show the effect of a consistent error in RH of $\pm 5\%$. At 3800 m above the surface, the consistent error produces a difference in the VIWVC of 1.1 kg m^{-2} . In light of the discussion on errors due to lock-in resistances and our own results of precision for humidity measurements, a consistent error of $\pm 2\%$ RH for our soundings is highly probable. Figure 8a shows the effect of this difference on the columnar water vapor content ($\pm 0.6 \text{ kg m}^{-2}$ at 3800 m).

Figure 8b depicts a hypothetical sounding derived from the August monthly mean upper-air data representing a tropical oceanic humidity regime (Gaffen et al. 1992). Although RH errors of 2% or less are more probable for this environment due to errors in the lock-in resistance, the effect of a consistent error of 2% and 5% RH on the calculation of the columnar water vapor content is shown. For a 2% error in RH, there is a potential for error of 1 kg m^{-2} in the columnar water vapor content; for a 5% error in RH, there is a potential for error of 3 kg m^{-2} in the columnar water vapor content.

Figure 8c depicts a series of profiles taken throughout the day from the Wyoming site. The differences in the profiles from one time frame to the next ranged from -0.8 to 1.4 kg m^{-2} (Fig. 8d). An increase or decrease of water vapor content in the profile throughout the day could be attributed to a number of factors: evaporation from the surface, entrainment from above the boundary layer, or from horizontal advection. From the errors examined so far, the systematic and instrumental errors could account for some, but not all, of the differences observed. From the results of the dual-sonde measurements, a difference of less than 0.1 kg m^{-2} could be attributed to sensor inaccuracies; a very conservative evaluation would result in differences up to 1 kg m^{-2} based on the accuracy of the sensor. Thus, to use radiosonde measurements, particularly humidity, in the study of surface evaporation, entrainment, or advection careful handling of the sonde package and baselining of the RH at 33% should be undertaken before the sonde is released to ensure that the measurements are as accurate as possible.

6. Conclusions

Overall, sonde errors increase with height for the measurement of winds, temperature, and relative humidity. In the examples presented here, balloons were tracked manually with a theodolite, and coordinates were either recorded automatically or logged manually and used to determine winds. Errors in measurement

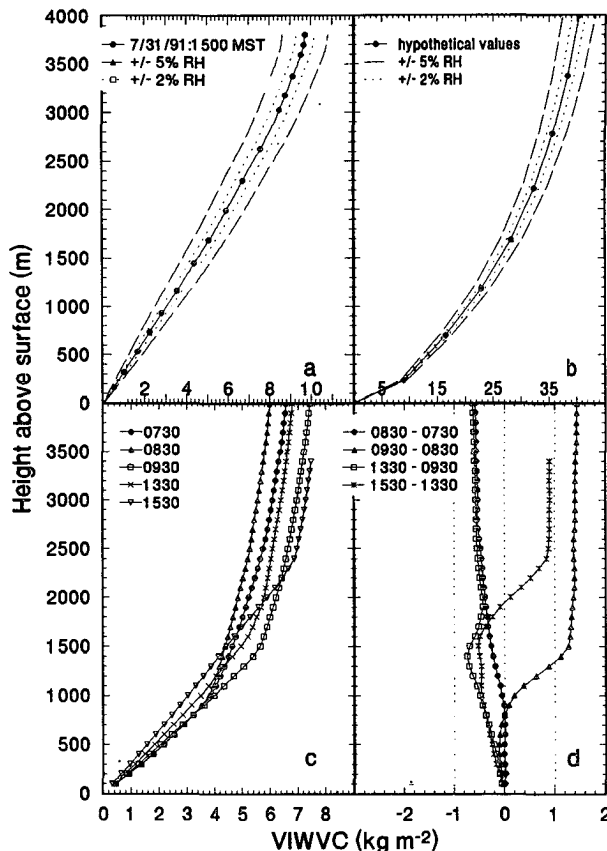


FIG. 8. (a) Differences in the calculation of vertically integrated water vapor content (VIWVC) for consistent errors of $\pm 5\%$ RH for the sounding taken 1500 MST 31 July 1991. (b) Differences in the calculation of VIWVC for consistent errors of $\pm 5\%$ RH for a hypothetical sounding representing a tropical oceanic humidity regime in August. (c) Profiles of VIWVC taken throughout the day for the Glacier site in Wyoming on 23 August 1989. (d) Differences in the VIWVC for successive time frames for the profiles represented in (c).

of azimuth and elevation angles and pressure over short time intervals and at higher altitudes introduce theoretical wind vector errors greater than 5 m s^{-1} , particularly when the horizontal winds were strong ($> 10 \text{ m s}^{-1}$) or when the ratio of horizontal wind speed to rise rate of the balloon was greater than 2.

Although most radiosonde balloons are no longer tracked manually, there are many operations that obtain their information in this manner. There is also interest in detailed vertical information on a smaller scale than that obtained from NWS soundings. The nature of (4) and (5) imply that collecting data at a higher resolution will introduce error. It is important to be aware of sources of error such as this in the data, particularly if there is a need to compare different datasets.

Frequent wind measurements collected at 10-s intervals and smoothed with a binomial weighted filter attenuate the high-frequency turbulent wind compo-

nents and spurious errors to provide a better estimate of the mean wind profile.

The mean theoretical systematic lag errors of the temperature and humidity measurements were small (means of 0.1°C for temperature and 0.1% for RH). Individual large lag errors in temperature ($\pm 1.5^{\circ}\text{C}$) and humidity ($\pm 18\%$) occurred with dramatic changes in the environment, such as near the surface or at the top of the boundary layer. Theoretical RH lag errors resulting from the use of the wet-bulb sensor were larger throughout the entire profile than those from the carbon hygistor sensor, which also showed large lag errors in the upper portions of the profile. Varying atmospheric stability also contributed to lag errors. Geographic location (Pennsylvania or Wyoming) had no detectable effect on the measurements.

Collectively, the lag errors had little effect on the calculation of the VIWVC within the atmosphere ($<0.1 \text{ kg m}^{-2}$).

Comparison of dual-sonde flights showed functional precision differences of 0.3°C for temperature and 1.6% RH. These errors also had little effect on the calculation of the VIWVC ($\leq 0.1 \text{ kg m}^{-2}$). The accuracy of the wet-bulb and carbon hygistor measurements is 3% – 5% RH. Wade (1994) shows that improper baselining of RH data could produce negligible errors up to 2% RH error for measurements above 60% RH and errors greater than 6% RH for low-humidity measurements. A sample calculation of a consistent error in measurement of 5% humidity at the dry Wyoming site resulted in a difference of 1.1 kg m^{-2} for integrated water vapor content at 3800 m above the surface. An evaluation of the error in the columnar water vapor content for a hypothetical, tropical humid sounding resulted in a 1 kg m^{-2} potential error for a consistent 2% RH error and a 3 kg m^{-2} potential error for a consistent 5% RH error.

Errors of 1 kg m^{-2} can be very significant in an analysis when dealing with total values of 10 kg m^{-2} representing a dry environment, than when dealing with total values of 40 – 50 kg m^{-2} representing a humid environment. If the data are baselined properly, this will not be a problem and a lesser error limit will apply.

Differences between the columnar water vapor content were determined for a series of profiles taken throughout a day in August for the Wyoming site. Sources of error mentioned within this paper could account for some, but not all, of the measured differences and indicate that humidity measurements can be used reliably in further research efforts.

Overall, this assessment of errors has provided a framework to determine the range of expected deviations of measurements for wind and humidity for the AIR, Inc. sounding system. Further evaluation of dual-sonde flights and comparisons with a reference sonde

will help to quantify actual errors in the radiosonde systems.

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