Review of Radiosonde Humidity and Temperature Errors

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31 July 1984 and 3 January 1985

ABSTRACT

An attempt is made to provide a brief but comprehensive summary of sources of error in National Weather Service upper air data, and a guide to the relevant literature. Error analysis must be tailored for particular applications. Temperature errors are generally 1°C or less, but reports of relative humidity can be low by 20–30% under unfavorable conditions, especially at very low temperatures.

1. Introduction

Although atmospheric science research frequently relies on archived National Weather Service (NWS) upper air data, a complete error analysis does not exist. Different properties of the system are important for each application. For example, Danielson's (1959) study of stable laminae required an understanding of temperature errors and the vertical resolution of operational soundings. Constant changes in instruments and operating procedures are other obstacles to comprehensive documentation, yet case studies or climate calculations depend on the data quality for a particular time period.

This summary grew from a study of clear air layers that are supersaturated with respect to ice, using radiosonde humidity data (Detwiler and Pratt, 1984). Humidity is still the most difficult of the upper air measurements, and in that study time response and both random and nonrandom humidity errors were crucial, especially for low temperatures. This summary and guide to the literature is a starting point for assessing the quality of radiosonde data. For some applications it will be necessary to seek relevant unpublished literature or undocumented work.

Discussion is limited to the era of the carbon hygistor, used by the NWS since about 1970 (somewhat earlier by the military). The lithium chloride hygistor previously used had slower response, greater hysteresis, and was influenced more by the presence of water on its surface (Marchgraber and Grote, 1965). Hodge and Harmantas (1965) compared measurements from the two sensor types.

General characteristics of carbon hygristors based on laboratory tests are given by Marchgraber and Grote (1965) and Stine (1965). National Weather Service radiosondes (VIZ Manufacturing Corporation, Philadelphia, PA) have been compared in the field with European sondes in SONDEX (Phillips *et al.*, 1981; Ri-

chner and Phillips, 1982). Similar comparisons have been reported by the World Meteorological Organization (Hooper, 1975).

2. Hygistor and thermistor performance

The VIZ radiosonde hygistor consists of a thin carbon coating applied to a plastic strip. The electrical resistance of the carbon varies in response to relative humidity (as well as temperature), producing a voltage that is converted to relative humidity.

The NWS requires that hygistor error be within 5% relative humidity (RH) with respect to water above 30% RH, and within 7% below 30% RH (Nordahl, 1982). Brousaides (1975) describes a humidity chamber test that involves stepping humidity up from low to high levels and down again, leaving sufficient time at each step for the hygistor to reach equilibrium. Similar tests are made at the factory for quality control, and at the National Bureau of Standards (NBS) at the request of the NWS or other agencies.

The tests by Brousaides (1975) explored the poor low-humidity sensitivity of the carbon hygistor, but also illustrated hysteresis that may be an important source of error. Indicated RH remains several percent higher than actual when RH is lowered from its highest value, a property also observed above 85% RH in production tests (L. Potts, personal communication, 1982), and in NBS tests supplied to the author by J. Facundo (personal communication, 1982) of the NWS.

A related property is revealed by some of the NBS tests in which humidity is cycled up and down more than once (at constant temperature). The carbon hygistor exhibits aging, whereby indicated humidities on subsequent cycles differ from those on the first. The test samples examined suggested this process could produce errors exceeding the $\pm 5\%$ specification, especially at low temperature.

J. Facundo (personal communication, 1982) has

rightly pointed out that such laboratory tests are designed to investigate specific properties of the hygistor, and are not necessarily indicative of performance in the field. The important point is that observed properties of the hygistor (hysteresis and aging) suggest the possibility of significant bias in indicated RH, for instance as the ascending sonde leaves the upper edge of a single moist layer or penetrates multiple moist layers.

The assessment of hygistor accuracy is complicated by changes in the method used to convert hygistor voltage output to RH. A slide wheel calculator was used until the 1970s when NWS offices acquired computers. Discussions of disagreement between the two methods of calculation (slide wheel and programmed equations) can be found in Brousailles (1975), Richner and Phillips (1981) and Phillips *et al.* (1981). There have been various minor changes in the transfer equations that could especially affect humidities reported near 100% (L. Potts, personal communication, 1982; J. Facundo, personal communication, 1982). The most pronounced change is associated with a change in the manufacturing process around 1980, and resulted in a reduced frequency or absence of recorded humidities of 100%, especially at low temperatures (Nordahl, 1982). In summary, the transfer equations and slide wheel have had a changing influence on humidity data that is confusing and difficult to document. Most important for humidities near 100% and at low temperatures, the influence seems to be comparable to or less than the design accuracy.

Finally, the time response of the carbon hygistor to changes in humidity at constant temperature has been investigated by Marchgraber and Grote (1965) using a military version of the hygistor (ML-476). They found a complicated, nonexponential time response that was slower at temperatures below 0°C, and different responses for increasing than for decreasing humidity. While these qualitative characteristics also apply to the NWS hygistor, very little is published about its quantitative characteristics. Richner and Phillips (1981) summarize tests which mainly confirm the qualitative results of Marchgraber and Grote. Based on their summary, limited NBS test results supplied by J. Facundo, (personal communication, 1982), and comments by the manufacturer (L. Potts, personal communication, 1982), the hygistor will register at least 90% of a step change in humidity in 1–3 s, above 0°C.

At lower temperatures response is much slower. For example, the time necessary to respond to 90% of the change between 40 and 60% RH in a different NBS test (Hixon, personal communication, 1982) averaged about 2 min at –40°C. Extrapolation from this test at –40° and –50°C suggests that 90% response time would not exceed 30 s for temperatures above –30°C. This is consistent with sounding strip chart traces examined by the author. At the design balloon ascent rate of 5 m s^{–1}, 30 s implies a minimum vertical resolution for humidity of 150 m.

3. Performance in the sonde case

Around 1970 it became widely recognized that serious errors in humidity data (typically 20–50%) resulted from a difference between the temperature of the hygistor and that of the ambient air (Bunker, 1953; Holland, 1970; Teweles, 1970). This resulted either from the time lag of the hygistor in adjusting to temperature changes of the ambient air, or from heating of the hygistor and the adjacent layer of air by solar radiation. This discovery prompted testing to correct specific data sets (e.g., Ostapoff *et al.*, 1970). Redesigning the radiosonde case to reduce radiative heating (Morrissey and Brousailles, 1970) and to increase ventilation of the hygistor led to significant improvements (Friedman, 1972; Brousailles and Morrissey, 1971; Shinnars *et al.*, 1971; Betts *et al.*, 1974), but the two effects are still a source of some error. Although the improved sondes were available as early as 1972 (Riehl and Betts, 1972), it would be difficult to determine exactly when they came into use at a particular upper air station.

Detailed corrections for these errors in the current sonde design have been documented by Brousailles and Morrissey (1974). Table 1 gives maximum mean corrections, which reflect the variation in ventilation efficiency with height. Insolation error causes higher than actual humidity reports, but only in daylight. The overestimates for it in Table 1 are averages over various solar elevations, and may be less if the sonde is shaded by higher clouds. The thermal lag of the hygistor leads to higher than actual humidity reports whenever temperature decreases with height, and lower than actual in inversions. Table 1 gives the overestimate corresponding to average tropospheric lapse rate; adjustments based on instantaneous lapse rate could be made as described by Brousailles and Morrissey (1974).

An unusual field verification of the effect of errors discussed so far is described by Jahnson *et al.* (1974). Using aircraft observations of liquid water and ice crystal types in tropical clouds coincident with several radiosonde ascents, they established the average values of reported relative humidity that corresponded to water and ice saturation. The reported relative humidities

TABLE 1. Mean relative humidity errors due to insolation and thermal lag (Brousailles and Morrissey, 1974).

Level (mb)	Error (%)		Total
	Insolation (daytime only)	Thermal lag	
1013			
700	3	3	6
500	6	4	10
350	9	6	15
250	14	9	23

were too low by an average of 19% at 350 mb and 5% at 500 mb. These (daytime) corrections are consistent with Table 1, allowing for the likelihood that insolation was reduced in the lower levels of the deep convective clouds.

Thermal lag and insolation problems for the thermistor are less serious than for the hygistor, but are poorly documented. Based on laboratory tests, Richner and Phillips (1981) give a thermal lag "time constant" of 3 s at 1000 mb, which they extrapolate to about 7 s at 200 mb. These imply steady state temperature errors of about 0.5°C or less at the dry adiabatic lapse rate. McInturff *et al.* (1979) found evidence of insolation error in the VIZ sonde, as did Phillips *et al.* (1981) and Richner and Phillips (1981) when comparing the VIZ sonde with European models. A table in the latter study indicates insolation errors of less than 1°C below 100 mb. By comparison, the thermistor accuracy specified by the manufacturer (at constant temperature) is within 0.4°C rms in the range +40°C to -70°C (Richner and Phillips, 1981).

Both the hygistor and the thermistor are affected by the presence of water, but the design change of 1972 minimized raindrop influence on the humidity measurement except in very heavy precipitation (Brousaides, 1973). Laboratory tests by Richner and Phillips (1981) show the psychrometer effect (cooling of the thermistor by evaporation of water or ice that has accumulated on it in cloud) could lower indicated temperature at least several tenths of a degree. Water on the thermistor can also suddenly freeze, producing latent heat and a spike in the temperature sounding (Pietrowicz and Schiermeier, 1978).

Since the hygistor and thermistor have different time responses, it can be difficult to assess errors in derived quantities that depend on both outputs, such as mixing ratio or lifting condensation level (Betts, 1976). They would depend on the vertical rates of change of temperature and RH as well as the absolute temperature and pressure. Although the calculation of humidity from hygistor output depends on temperature, temperature errors are generally less than 1°C, and the resulting humidity error (less than 1% RH) is insignificant compared to others.

4. Data reduction

The sonde alternately transmits the thermistor and hygistor outputs, switching rapidly after an interval that corresponds to about 95 m of ascent near the surface and increases upward. A single pen traces the signal on a strip chart, limiting precise definition of shallow temperature or humidity layers (Richner and Phillips, 1981).

The raw data are reduced and entered into the collection network by procedures described in Federal Meteorological Handbook No. 3, *Radiosonde Observations* (U.S. Department of Commerce). Significant level criteria specify pressure levels other than standard

for which temperature and humidity are to be reported—in the troposphere, deviations from straight lines connecting reported points on the chart are to be within $\pm 1^\circ\text{C}$ or $\pm 10\%$ RH respectively. Relative humidities evaluated over 100% are recorded as 100%, etc.

By the late 1970s, most NWS stations were processing and transmitting data with minicomputers. The operator selects and enters data at a number of levels sufficient to meet the significant level criteria; the computer selects and transmits only those necessary to meet the criteria. However, printouts of all entered data are sent to the National Climatic Center. Hence, archived soundings that have been computer processed contain more detail than those processed manually or than operationally transmitted soundings, a factor important for case studies.

5. Precision

Atmospheric variations in time and space make determinations of precision or reproducibility difficult. A recent attempt to determine this property for the VIZ sonde (Richner and Phillips, 1981) involved ascents of pairs of instruments on a single balloon. They concluded that with careful calibration, reproducibility is within the manufacturing specifications for accuracies—0.4°C rms for temperature, and $\pm 5\%$ RH for humidity.

Data reported from similar "functional" precision tests by the NWS (Hoehne, 1980) imply a similar value for relative humidity. Dew point temperature differences for pairs of sondes were within about 2°C for 54% of the ascents (Hoehne, 1980, Fig. 3). A 2°C dew-point depression corresponds to about 7% RH at 0°C, a value also estimated for humidity precision by Brousaides (1973). Functional precision tests of the newer hygistor in use since 1980 have also been undertaken (Facundo, personal communication, 1982). An unrelated dual-measurement test program for temperature and pressure has been reported by Schmidlin *et al.* (1982).

6. Summary

Sources of error, especially nonrandom error, must be evaluated carefully with respect to a particular application. Relative humidity reports are usually biased downward, by several to as much as about 20%, as a result of thermal (ventilation) lag and warming by sunlight. The time lag of the hygistor or its tendency to exhibit hysteresis can temporarily lead to comparable errors, especially at low temperatures, where humidity changes rapidly at cloud or moist layer boundaries. The thermistor is subject to similar effects, but the resulting temperature error is generally less than 1°C.

Acknowledgments. This work was supported by Grant ATM7920767 from the National Science Foundation and Grant DE-ACO2-80ER10691 from the U.S.

Department of Energy. Andy Detwiler was an essential source of advice, and the cooperation of Joseph Falcundo of the NWS, Luken Potts of the VIZ Corp., the Albany, New York, NWS office, and R. Hixon of the Pacific Missile Test Center is appreciated.

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