On the Utility of Radiosonde Humidity Archives for Climate Studies

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Abstract

This paper considers the use of upper-air data from radiosondes in long-term climate studies. The accuracy and precision of radiosonde humidity measurements, including temperature and pressure measurements used in calculating them, and their effects on the precision of reported and derived variables are estimated. Focusing on the U.S. radiosonde system, we outline the history of changes in instruments and reporting practices and attempt to assess the implications of such changes for studies of temporal variations in lower-tropospheric water vapor. Changes in biases in the data are highlighted, as these can lead to misinterpretation of climate change. We conclude that the upper-air data record for the United States is not homogeneous, especially before 1973. Because of problems with the humidity data in cold, dry conditions, the water vapor climatology in the upper troposphere, nominally above the 500-mb level, is not well known.

1. Introduction

Meteorological data, particularly upper-air data, are taken largely for weather forecasting purposes, not to study the climate. Instruments change as improved technology makes better observations possible; reporting practices and algorithms for processing the signals and deriving quantities change with improvements in data-handling techniques. These changes, no matter how beneficial to weather forecasting, can be the bane of those studying climate change. That different nations use different instruments and practices aggravates the problems.

With increased interest in climate research, the utility of archived meteorological data is becoming an issue of concern. Surface temperature and precipitation are the most conspicuous of the climate variables and have received the most scrutiny, at least partly because long records of them exist. Upper-air data, although only available for the last four or five decades, are also receiving increased attention. Among the variables deserving more examination is atmospheric moisture, since much of the projected temperature increase calculated to accompany an enhanced greenhouse effect comes from a concomitant increase in water vapor (e.g., Meehl and Washington 1990). We have undertaken studies of the climatology of water vapor and its variability in the region of the atmosphere accessible to radiosonde humidity instruments (Elliott et al. 1991; Gaffen et al. 1991). This has led us to examine the data archives and to become sensitive to changes in humidity instruments and reporting procedures.

Compared with surface weather data, upper-air data records are brief. While there are some upper-air data prior to 1940, they are of questionable quality and too sparse to allow a global climatology. As we will discuss later, the useful record of moisture data is shorter than the post-WW II period, unless substantial adjustments can be made. One effect of the brevity of the record is that there are fewer station moves with which to contend than is the case with surface data. Effects of station moves and urban heat islands on upper-air data should be minimal, except for the near-surface data. Despite the relative brevity of the record, there have been substantial changes in U.S. radiosonde humidity instrumentation and practices that influence the archived humidity values. Table 1 lists those known to us, and we discuss the effects of some of these changes in subsequent sections. In addition, there are U.S. practices that have not changed recently, but which are different from the practices of other nations and so could suggest spurious horizontal humidity gradients.

Our purpose in this paper is to describe some of the characteristics of the archived radiosonde humidity data. Pratt (1985) and Bosart (1990) have reviewed some of the problems with radiosonde temperature and humidity data, but a comprehensive treatment focusing on the problem of detecting climate variations has not yet been made. Some of the material has been presented before (Angell et al. 1984; Elliott et al. 1991; Gaffen et al. 1991), but in this paper we draw together all the information and analysis of which we are aware for the benefit of users of radiosonde data. We treat specific problems associated with using conventional radiosonde data to establish a climatology of tropospheric water vapor and its changes with time. Because information on U.S. National Weather Service (NWS) radiosonde instruments and practices is most readily available to us, we concentrate on the U.S. data. Radiosonde stations using U.S. instru-

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TABLE 1. A chronology of known changes in the U.S. radiosonde network.

Date	Change and Source of Information
1943	Lithium chloride humidity element replaced hair hygrometer (U.S. Weather Bureau 1964).
1943	Ceramic temperature element, operating on resistance principle, replaced glass tubes with electrolytic temperature elements. Color was dark (Jenne and McKee 1985).
1948	Began computing all relative humidities using saturation values with respect to water. Prior computations involved saturation with respect to ice for temperatures below 0°C (U.S. Weather Bureau 1964; Lott 1976). Changed observation times from 2300 and 1100 UTC to 0300 and 1500 UTC (Hosler 1961).
1949	Smaller ceramic temperature element introduced to decrease instrument response time (Jenne and McKee 1985).
1950	Introduced correction to temperature data between 400 and 10 mb for daytime soundings whenever solar elevation angle was equal to or greater than –2.5°. Such corrections, which adjusted for radiation effects on the instrument, were discontinued with the introduction of white thermistors (Jenne and McKee 1985).
1957	Observation time changed from 0300 and 1500 UTC to 0000 and 1200 UTC (Lott 1976).
1960	Introduced white-coated temperature elements (Jenne and McKee 1985).
1965	Introduced carbon humidity element. Began reporting low relative humidity measurements. (Earlier practice with lithium chloride sensor was not to report low values when the instrument was said to be "motorboating.") (Mathews 1963; Lott 1976)
1969	Changed from completely manual system to a time-share computer system for calculating upper-air data (Facundo, personal communication).
1972	Redesigned relative humidity ducts introduced to reduce insolation effects on instrument, which were responsible for low biases in humidity measurements for some daytime soundings (Friedman 1972).
1973	Introduced current practice of considering measured relative humidities less than 20% as "motorboating" and reporting all lower RH values as 19% (Wade and Wolfe 1989).
1974	Introduced semi-automatic mini-computer-based system (Facundo, personal communication).
1980	New carbon hygristors introduced. Relative humidity transfer equation changed for the new sensor (Richner and Phillips 1982).
1985	Introduced fully automatic mini-computer-based system (Facundo, personal communication).
1988	Precalibrated hygristor replaced type requiring individual preflight calibration (Ahnert, personal communication).
late 1988	Introduced new VIZ sonde with new humidity duct (Ahnert 1989).
1989	Introduced fully automatic micro-computer-based system (Facundo, personal communication).

ments and practices are not confined to the United States proper. Many stations in the western Pacific are run with U.S. help and practices, and some western hemisphere countries follow U.S. procedures. Thus, a significant area of the globe is affected by changes in U.S. techniques.

We review the accuracy and precision of the basic measurements in section 2. Section 3 considers the effects of instrument changes, section 4 the effects of procedural changes. Section 5 addresses some issues involved in the use of archived moisture data, including the need to use care with mean monthly data. The final section will summarize the changes and their implications for upper-air humidity variability and climatology. We pay particular attention to biases, as changes in a bias are more apt to produce erroneous indications of changes in climate than improvements in precision of the basic measurements. Our findings suggest caution is appropriate when using the humidity archives or interpreting existing water vapor climatologies so that changes in climate not be confounded by nonclimate changes.

2. Precision of radiosonde data

a. Instrument performance

The radiosonde humidity sensor transmits a signal that is proportional to the relative humidity, but is also affected by the temperature of the hygristor. Thus, the radiosonde temperature is needed both to correct the reading of the hygristor and to convert the relative humidity to measures of water vapor content. (The reported and archived humidity data often have been converted to dewpoint or dewpoint depression, so to recover the relative humidity may require another conversion.) The temperature and relative humidity sensors, as well as the pressure sensor, are subject to error. The World Meteorological Organization (WMO) has set accuracy requirements and performance limits for upper-air measurements (WMO 1983), and recent field intercomparisons have evaluated the actual performance of contemporary instruments (Nash and Schmidlin 1987). The WMO requirements vary according to intended use of the data (e.g., synoptic meteorology or climatology) and pressure level, but the strictest requirements for the lower troposphere are that pressure be measured to an accuracy of ±1 mb (1 mb = 1 hPa), temperature to an accuracy of ±0.5°C, and relative humidity to an accuracy of ±5%.

In field tests, measurement precision, or reproducibility, is more readily evaluated than accuracy, which requires knowledge of true values. Tests of the radiosonde system in use in the United States in 1978 showed the measurement precision (defined as one standard deviation) to be about ±1.9 mb for pressure, ±0.67°C for temperature, and ±3.67°C for dewpoint (Hoehne 1980). A more recent analysis of several models of radiosondes used in the United States in the 1980s (Ahnert 1989) showed some improvements. Typical precision of pressure, temperature, dewpoint, and relative humidity was reported as about ±2 mb, ±0.3°C, ±2.5° to 3.5°C, and ±2%, respectively. Recent WMO-sponsored intercomparison tests (Nash and Schmidlin 1987) determined time constants, relative biases, precision, and effects of variable atmospheric conditions for radiosondes from several major manufacturers flown by different nations. Of the instruments tested, most had comparable precision, with the exception of the Indian sonde, which carries a lithium chloride hygristor and which had lower reproducibility than other sondes. Without delving into the idiosyncracies of each instrument type, it is reasonably safe to say that most radiosondes tested measure temperature with a precision of about ±0.2°C and relative humidity with a precision of about ±3.5%. Because instrument response depends on the number of water molecules present, measurement quality degrades in cold, dry conditions.

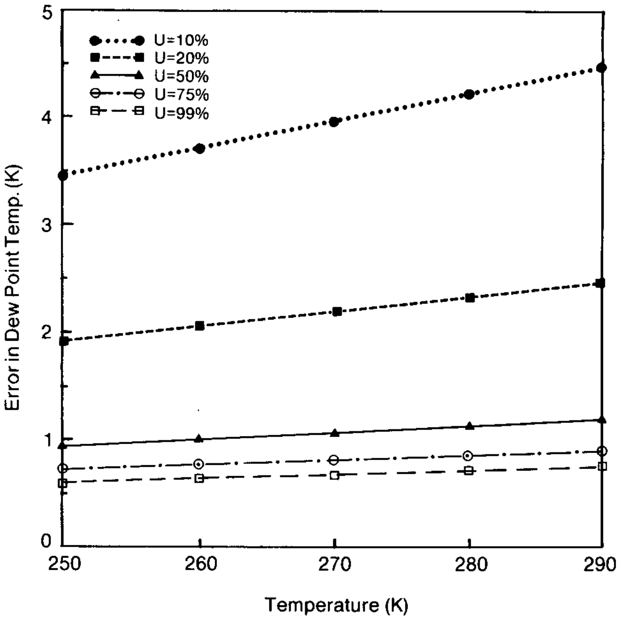

FIG. 1. Standard deviations of computed values of errors in dewpoint (E_{T_d}) as a function of temperature, *T*, and relative humidity, *U*.

b. Estimates of random errors in moisture variables as derived from radiosonde measurements

Radiosondes carry temperature (T), pressure (p), and relative humidity (U) sensors, and the finite precision of their measurements leads to imprecision in the values of variables computed from them. Assuming that random errors in measurements are normally distributed, and using values from the literature for their magnitude, we have made theoretical estimates of the resulting errors in derived variables. Mathematical details are presented in the Appendix.

Random errors in the reported dew point (E_{T_d}) depend on random errors in U and T as well as the values of U and T themselves. As a measure of the expected typical magnitude of E_{T_d}, we present the standard deviations of the computed values of E_{T_d} as a function of U and T in Fig. 1. At very low U (<10%), the standard deviation of the errors in the reported dewpoint (T_d) is of order 5 K but decreases rapidly with increasing U, and for $U > 20\%$ the standard deviation of the errors in T_d is about 2 K or less. The mean values of the error in T_d (not shown) are less than 0.15 K and are estimates of the bias in T_d due to random errors in U and T.

The reported T_d and T can be used to calculate a value of relative humidity (RH, to distinguish it from the measured value U). The error in RH, E_{RH}, depends on T and T_d as well as their random errors. The computed standard deviation of E_{RH} is shown in Fig. 2. The error increases with T_d for a given T but decreases with T. At high RH ($T - T_d$ small), the standard deviation of E_{RH}

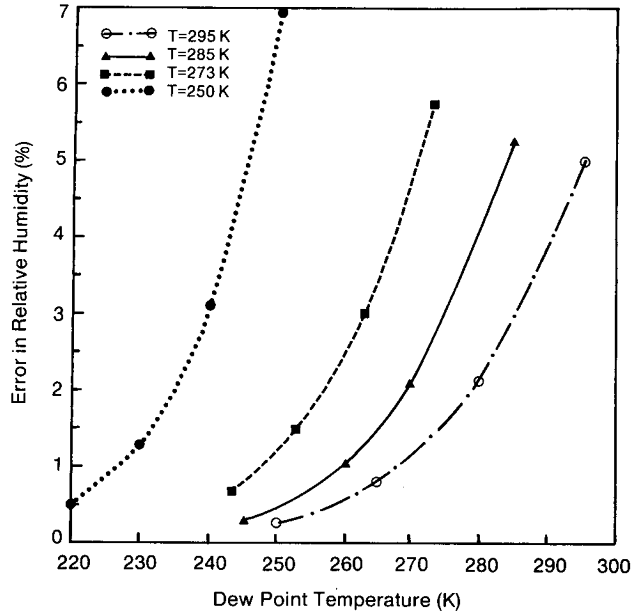

FIG. 2. Standard deviations of computed values of errors in relative humidity (E_{RH}) as a function of temperature, T, and dewpoint, T_d.

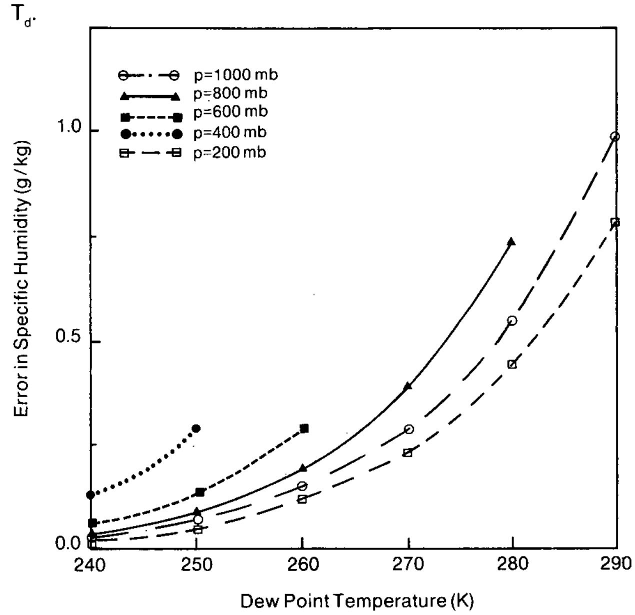

FIG. 3. Standard deviations of computed values of errors in specific humidity (E_q) as a function of dewpoint, T_d, and pressure, p.

can approach 7%. The mean value of E_{RH}, not shown, is generally less than 1%.

Lastly, we consider the random error in computed specific humidity, E_q. The standard deviation in E_q as a function of T_d and p is shown in Fig. 3. The standard deviation of E_q can approach 1 g kg^{-1}, but for most tropospheric temperatures and pressures, standard deviations are less than 0.5 g kg^{-1}. The error increases with decreasing pressure and increasing dewpoint, but so does specific humidity (q) itself. The resulting percentage error in q is much less variable—6% to 8%.

c. Precision of radiosonde reports

The coding and transmission of the radiosonde report introduces another source of imprecision. Because the coded message allows only five characters for temperature and dewpoint (three for temperature and two for dewpoint depression, $D = T-T_d$), the precision of coded upper-air data is limited. Temperature is given to the nearest 0.1°C; D is in tenths of °C if $D \leq$ 5.0°C, but D is reported to the nearest whole degree whenever $D >$ 5.0°C. (Temperature data taken directly from the global telecommunications system transmissions are reported to the nearest 0.2°C.) The effect is that D reports are less precise at lower relative humidity (D = 5.0°C occurs at about 75% RH for high temperatures to about 60% for the lowest temperatures). While this practice is consistent with the known pattern of instrument performance (lower accuracy at low humidity), it introduces an additional random error, whose maximum value is 0.5°C.

In summary:

- Most contemporary radiosonde instruments measure temperature and relative humidity with precisions of about 0.2°C and 3.5%, respectively. Performance is worst in cold, dry regions.
- The expected value of random errors in reported dewpoint due to random errors in measured temperature and relative humidity errors is small, and the standard deviation is greatest at very low humidity and increases slightly with temperature. For relative humidity greater than 20%, the standard deviation of errors in dewpoint tends to be less than 2 K.
- Calculated relative humidity values are influenced by errors in reported temperature and dewpoint. The relative humidity errors are greatest at high humidity and low temperature, where the standard deviation of the errors can be as large as 7%.
- Calculated specific humidity values contain errors due to errors in reported pressure and dewpoint. The standard deviation of specific humidity errors is largest at low pressure and high dewpoint, where it approachs 1 g kg^{-1}, although values less than 0.5 g kg^{-1} are more typical.
- Transmitted radiosonde reports have a precision unto themselves. Temperature is given to the nearest 0.2°C, and dewpoint depression (D) reports are in tenths of degrees for $D <$ 5.0°C and in whole degrees otherwise.

3. Instrument changes

Three major changes in U.S. humidity-measuring systems influence the data archive (see Table 1). These were 1) the replacement of the hair hygrometer

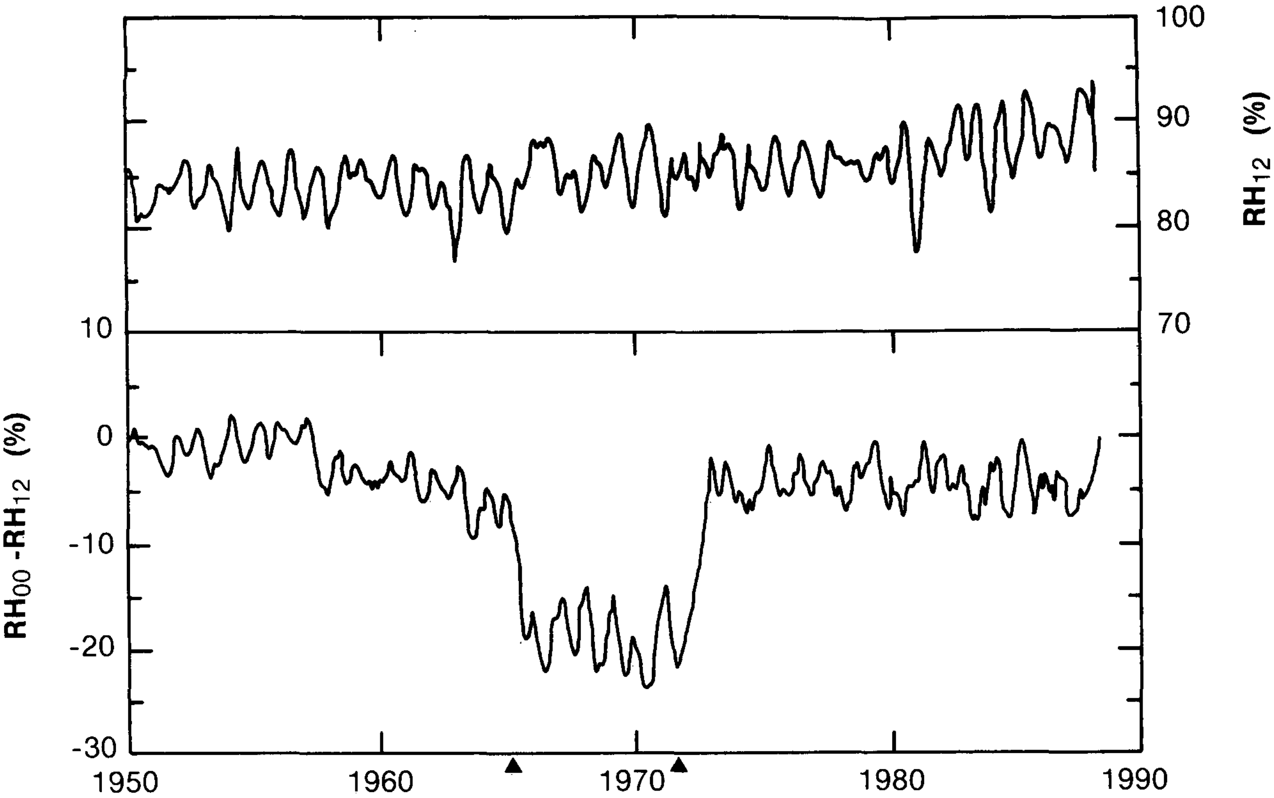

FIG. 4. Top panel: Mean monthly 850-mb-level relative humidity (RH) measured at Hilo, Hawaii, from 1950 to 1988. These measurements were taken at 1200 UTC (local nighttime). Bottom panel: Difference between mean monthly 850-mb RH from 1200 UTC and 0000 UTC. (Before 1957, soundings were taken at 0300 and 1500 UTC, but these are plotted here as 0000 and 1200 UTC data.)

by the lithium chloride strip in 1943, 2) the replacement of the lithium chloride strip by the carbon hygristor in 1965, and 3) the change in the housing that shields the hygristor in 1973.

The introduction of the lithium chloride instrument represented an improvement over the older hair hygrometers, which suffer from a very long lag, particularly at cold temperatures (Middleton 1947). The lag increases with decreasing temperatures, becoming essentially infinite at –40°C, and many consider the values almost useless at temperatures below 0°C (Showalter 1965). Since relative humidity tends to decrease with height, the hair hygrometer would tend to indicate higher values than a faster-responding instrument. [An improved hair hygrometer, using a "rolled" hair, was used by some nations well into the 1970s (Richner and Phillips 1982.)]

The carbon hygristor replaced the lithium chloride sensor about 1965, mainly because the former has a faster response, particularly at low temperatures. It still left much to be desired, however, for it would not register humidities below 40% at temperatures below –40°C (Showalter 1965). There is some evidence that the lithium chloride sensor created a small temperature increase in the enclosure, due to an exothermic reaction, and thus indicated a slightly lower relative humidity than the ambient air (Mathews 1965). A new housing design accompanied the new humidity element. (Humidity-reporting procedures also changed about 1965, and we discuss this change in section 4.) Because these three changes—a new element in a new housing and a different reporting procedure—occurred about the same time, it is difficult to separate their effects.

The new housing permitted the entry of sunlight, which warmed the walls and the air inside, thereby lowering the humidity the element experienced (Morrissey and Brousaides 1970; Teweles 1970). This led to large day–night differences in reported humidity at some stations, as demonstrated in Fig. 4. The top panel shows the monthly mean relative humidity at the 850-mb surface above Hilo, Hawaii, for the 1200 UTC (about 0200 local time) soundings. The lower panel shows the difference between the monthly mean 0000 UTC (about 1400 local time) and the 1200 UTC monthly mean RH. (In this analysis, the period preceding 1957 includes 0300 and 1500 UTC data. See section 4b.) Clearly, there is an apparent decrease of

10%-20% in RH during the period from February 1965, when the new sensor was introduced at Hilo, to May 1973 when a new housing design was adopted. Studies showed that this radiation effect increased with increasing sonde elevation and was greatest at high sun elevations (Ruprecht 1975). In the 48 contiguous states, the observation times, 0000 and 1200 UTC, are morning and evening hours, so the effect is less noticeable, except possibly on the west coast. In the central and western Pacific, however, the observations are taken closer to midday and midnight so the effect is more obvious there. Unfortunately, a number of the stations in the western Pacific take observations only at 0000 UTC, i.e., in the daytime, so these are all suspect during the 1965-1973 period.

There were other sources of error in the design of the radiosonde housing prior to 1973 that were corrected, or at least improved, in the new design. However, there still remain problems, in that the thermal lag of the hygristor leads to lower-than-actual humidity reports whenever the temperature decreases with height (Pratt 1985). Williams and Acheson (1976) suggest adjusting the apparent RH by estimating the true temperature of the hygristor from the measured conditions and empirically determined thermal lag constants of the hygristors, but this method has not been adopted for routine use.

Another source of bias in the records results from the procedures used to transfer the output of the sonde to relative humidity. A slide-wheel device was used originally to calculate relative humidity but there was also an analytical transfer function that was used in the computer program that processed the signal. It was found that these did not always give the same value, the slide-wheel giving a higher value, mainly at low temperatures and high humidities. Richner and Phillips (1981) discuss this problem and feel the slide-wheel values were more nearly correct. The introduction of the new hygristor in 1980 necessitated a new algorithm and slide wheel and there appears to be no discrepancy between them now. However, the new algorithm also eliminated the possibility of reports of humidities greater than 100% but ensured that humidities of 100% cannot be reported in cold temperatures. The overall effects of these changes is difficult to ascertain. The new algorithm should have led to higher reported humidities compared to the older algorithm, but the elimination of reports of very high values at cold temperatures would act in the opposite sense.

We note the recent work of Schwartz (1990) demonstrating that a change in NWS radiosonde data-collection and analysis methods has affected the data archive. Specifically, introduction of the computer-based Automatic Radiotheodolite System (ARTS) coincided with an increase in missing reports and obvious errors in the data for the ARTS period, 1986-1990. In addition, the recent effort on the part of the NWS to avoid reliance on a single supplier of instruments has led to the introduction of sondes from a second manufacturer at several stations in the southwest United States and in Alaska (NWS, internal memorandum). Ahnert (1989) compares the two sondes now in use and reports that differences between the two sondes could be several percent relative humidity. The apparent cause is that the paint on the inside of the duct of the newly introduced sonde retains moisture after passing through a cloud. The manufacturer is testing a new duct paint. (Ahnert reports some differences in temperature between the two sondes, as well.)

In summary:

- U.S. radiosondes carried hair hygrometers, whose performance was poor at temperatures below freezing, until 1943.
- The tropospheric water vapor estimates derived from U.S. radiosonde data are biased toward the low side in the period 1965–1972 compared to later values, mainly because of a problem with the instrument housing. This is particularly noticeable in the daytime soundings. Since only daytime soundings are available from many of the western Pacific stations, U.S. data are suspect for this region during that time.
- There was a complicated change in procedures for processing radiosonde signals around 1980 whose effects are difficult to estimate.
- Radiosondes from a second supplier were introduced at some stations in 1989, which may introduce spurious horizontal humidity gradients.

4. Effects of reporting practices

a. Changes in low-humidity reports

Substantial changes in reporting practices occurred in 1948, 1965, and 1973 (Table 1). In 1948, saturation over water replaced saturation over ice for computing relative humidity at below-freezing temperatures, which makes a difference in the computed vapor pressure and relative humidity. At −50°C the saturated vapor pressure over ice, e_s' is only 0.62 that over water, e_s; at −30°C, $e_s'/e_s = 0.75$; at −10°C, $e_s'/e_s = 0.91$; and at −5°C, $e_s'/e_s = 0.95$. There would be an apparent increase in water vapor over the United States from 1947 to 1948 due to this change in computation alone.

When the carbon hygristor replaced the lithium chloride element in the middle 1960s, changes were also adopted in the reporting of moisture. Prior to 1965, dewpoints were reported as "motorboating" when the relative humidity fell below 20%. The archived data show these as missing. The new element produced greater confidence, at least for a while, and values of RH between 10% and 20% were recorded with the appropriate dewpoints. With the correction of the duct work in 1973, a new practice was begun in which RH below 20% is reported as "dry" (Nordahl 1982). Our experience with those post-1973 archives in which RH is reported shows that 19% indicated "dry," although current instructions (NWS 1988) imply that 20% would now be used, and we do not know when the change occurred. Current NWS practice is to report the dewpoint depression as 30 in these conditions (NWS 1988).

These changes, particularly the reporting of low humidities begun in 1965, had a substantial effect on the recorded data, as shown by Angell et al. (1984) in their study of upper-air humidity data from Brownsville, Texas, and Great Falls, Montana. After the introduction of the new reporting practice in 1965, the number of missing moisture observations at 500 mb dropped from about 35% at Great Falls and 50% at Brownsville to practically zero at both stations. At the same time, the number of observations of RH < 20% in the 500- to 400-mb layer rose sharply from 0% to about 20% at Great Falls and 35% at Brownsville, respectively. At lower levels the effect is less dramatic but still significant. Clearly most of the reports of "missing" before 1965 came from the exclusion of low values of RH. In Fig. 5 (adapted from Angell et al. 1984) the effect of this change can be clearly seen. There the 500-mb annual average RH expressed as deviations from long-term means is shown. The apparent dramatic drop in RH in 1965 is due almost entirely to the inclusion of the drier reports; the difference can be as much as 15% at this level. The effect was apparent even at 850 mb, although much less. Calculations of mixing ratio and precipitable water between the surface and 500 mb were noticeably lower after 1965.

As mentioned above, in 1973, the NWS began reporting humidities below 20% as 19%. Figure 5 suggests an increase in RH after about 1973 that could be related to the change in reporting practice or the newly designed housing. (At these stations the 0000 UTC and 1200 UTC observations are taken about 0600 and 1800, and 0700 and 1900 local time, respectively, so the effects of sunlight on the instruments should have been fairly small.)

b. Effect of change in observation time

Currently, radiosonde launches are made at 0000 and 1200 UTC; however, between 1948 and 1957, observation times were 0300 and 1500 UTC. (Prior to 1948, balloons were released at 2300 and 1100 UTC.) It is likely that this change affects the record for some stations. A possible example is the Hilo record (Fig. 4). The difference between the night and day soundings seems to change about 1957 and the effect apparently is a result of the air at 850 mb being drier at 1400 local time than at 1700 local. Whether this was a result of a change in climate or the change in observing time is not certain. The effect would be different at different stations, depending on the local topography, proximity to water bodies, etc., as well as the local sun time. Furthermore, if either temperature or humidity instruments were affected by solar elevation angle, climatologies based on data from pre- and post-1957 might be systematically different.

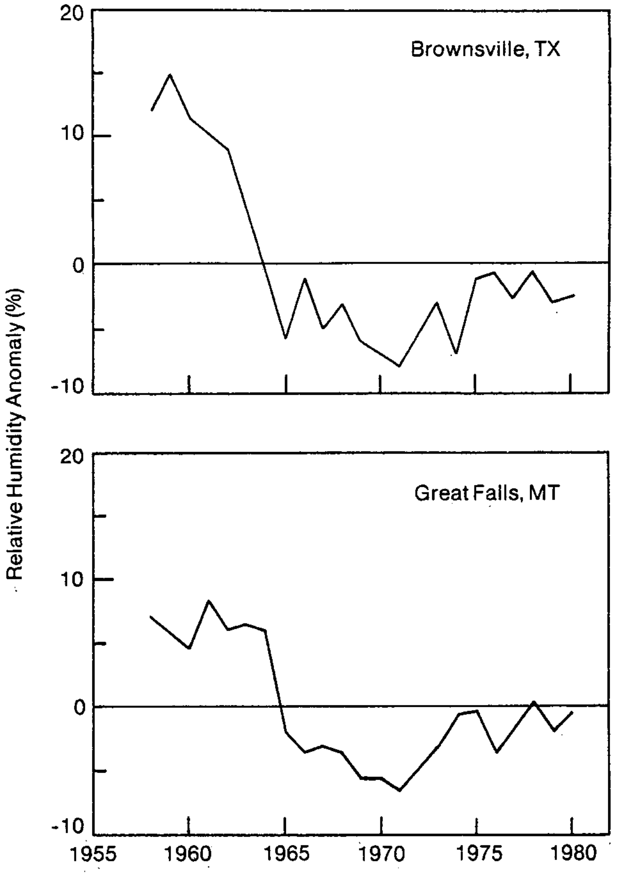

FIG. 5. Variation in annual average RH at the 500-mb level from 1957 to 1980, expressed as a deviation from the long-term mean at Brownsville, Texas, and Great Falls, Montana. The high RH values at the beginning of the record result from the practice of reporting observations with RH less than 20% as missing. (Adapted from Angell et al. 1984.)

c. Effect of U.S. low-temperature cutoff

Current NWS practice is to report dewpoint depression as missing whenever the temperature is less than –40°C. Accepting the data as so reported would introduce a moist bias into the averages of specific humidity, since the coldest, hence driest, soundings would be excluded. To assess the effect of this U.S.

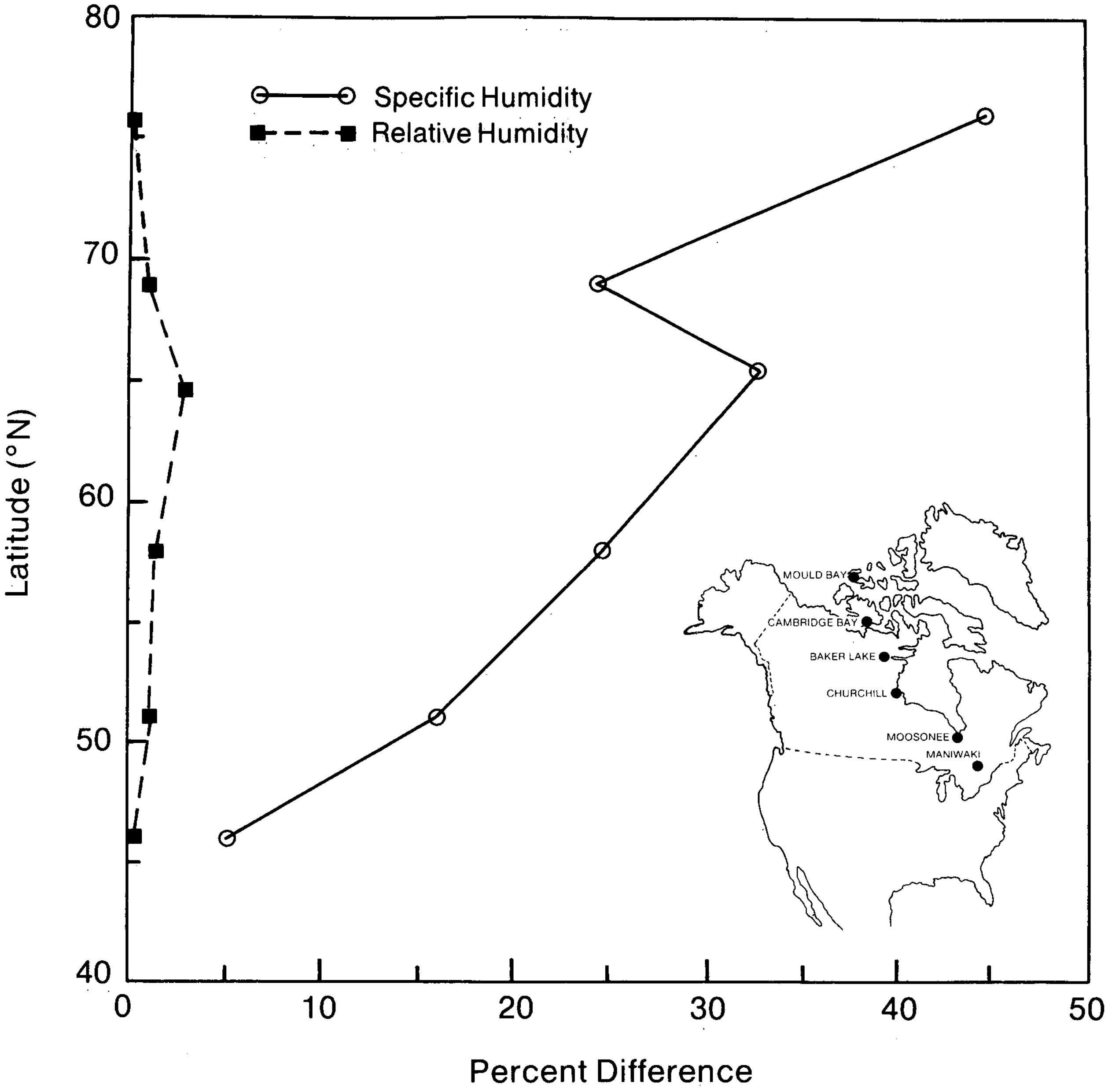

FIG. 6. Differences between values of mean moisture variables calculated from all observations and from only those with temperatures above −40°C, expressed as a percentage of the former. Shown are 500-mb specific humidity (solid line) and relative humidity (dashed line) differences for the cold months of 1989 at the Canadian stations identified in the insert.

reporting practice, we analyzed Canadian radiosonde data, supposedly taken with the same instrument type as is used in the United States but which are not treated the same way at low temperature and humidity. With data from the six Canadian stations shown in the insert to Fig. 6, we used each observation of temperature and dewpoint depression in 1989 to compute specific and relative humidity for the 1000-, 850-, 700-, 500-, and 400-mb levels, in two ways. The first was to take the data as reported ("Canadian rules"), the second was to eliminate all reports in which the temperature was less than −40°C ("U.S. rules"). We computed mean humidity values for each station and pressure level for January, February, November, and December.

During these four cold months, over half the 500-mb observations at Mould Bay at 76°N had temperatures below −40°C, and at 400 mb only 3 temperatures, out of 221 observations, were above −40°C. As far south as Maniwaki at 46°N, 6% of the 500-mb and over half the 400-mb observations were below −40°C. The mean relative humidity, using Canadian rules, always decreased with height, as did the mean specific humidity, but U.S. rules could produce an appar-

TABLE 2. Saturation Vapor Pressure Formulas

Wexler	$e_s(T) = 0.01 \exp[-2991.2729 \times T^{-2} - 6017.0128 \times T^{-1} + 18.87643854 - 0.028354721 \times T + 0.17838301 \times 10^{-4} \times T^2 - 0.84150417 \times 10^{-9} \times T^3 + 0.44412543 \times 10^{-12} \times T^4 + 2.858487 \times \ln(T)]$ T = Temperature in Celsius + 273.15
Goff–Gratch	$\log_{10}(e_s(T)) = -7.90298 \times (373.16/T - 1) + 5.02808 \times \log_{10}(373.16/T) + (-1.3816 \times 10^{-7}) \times (10^{11.344 \times (1 - T/373.16)} - 1) + 8.1328 \times 10^{-3} \times (10^{-3.49149 \times (373.16/T - 1)} - 1) + \log_{10}(1013.246)$ T = Temperature in Celsius + 273.16
Buck 1	$e_s(T) = 6.1121 \times \exp[(17.502 \times T)(T + 240.97)^{-1}]$ T in Celsius
Buck 4	$e_s(T) = 6.1121 \times \exp\{[(18.729 - T/227.3) \times T](T + 257.87)^{-1}\}$ T in Celsius
Tetens	$e_s(T) = 6.11 \times 10^{(7.5 \times T)/(T + 237.3)}$ T in Celsius

ent increase between 500 and 400 mb for both measures of moisture. Because temperatures below –40°C rarely occur at or below 700 mb, average humidity values at those levels are minimally affected by U.S. rules.

In the mean, the relative humidity of the below –40°C cases was only slightly lower than the RH of the warmer cases, so the effect of excluding the colder cases raised the apparent RH only slightly (but enough sometimes to reverse the vertical gradient). The effect of U.S. rules on specific humidity is considerable, however. Figure 6 shows the percent differences of both specific humidity and relative humidity at 500 mb for the six Canadian stations; at 400 mb the effect is, of course, even larger. The effect is greatest at high latitudes but not negligible at lower latitudes. The absolute amounts of water vapor at these cold temperatures is very low, so excluding them has little effect on estimates of total water. Nevertheless, it would be almost impossible to generate a valid climatology of the moisture content or fluxes at these levels using U.S. rules.

In summary:

- Reporting practices for low relative humidity situations introduce moist biases in the U.S. radiosonde data before 1965 and, to a lesser extent, from 1973 to present.
- A change in the operational launch times from 0300 and 1500 UTC to 0000 and 1200 UTC in 1957 probably introduced bias in the U.S. data, especially at stations near the international dateline.
- The U.S. practice of not reporting dewpoint depression when temperatures are below –40°C introduces a moist bias into the record.

5. Issues involving use of archived data

a. Converting relative humidity to dewpoint depression

The current formula used by NWS to convert the relative humidity signal to dewpoint depression is

$$D = (14.55 + .114T)\,U1 + (2.5 + .007\,T)^3\,U1^3 + (15.9 + .117T)\,U1^{14}, \qquad (1)$$

where D is the dewpoint depression, T the temperature in Celsius, and $U1 = 1 - U$, U being the measured relative humidity expressed as a decimal (NWS 1988). This equation is used if $1.0 > U > 0.20$. If $U = 1.0$, D is set equal to 0; if $U \leq 0.20$, U is set to 0.20 and D is set to 30. (Note that D = 30°C is not equivalent to RH = 20%, except near T = 55°C; at lower temperatures, D = 30°C would imply a much lower RH.) We do not know when this algorithm came into use or what algorithm preceded it.

b. Saturation vapor pressure

To convert RH to T_d (and subsequently to other moisture quantities, such as specific humidity or mixing ratio) requires the calculation of saturated vapor pressure e_s at the appropriate temperature. For a pure vapor in equilibrium with a pure liquid or solid, e_s is a function of T only (the Clausius–Clapeyron relation). There are several semi-empirical approximations to this equation. The Goff–Gratch relations were employed in constructing the widely used Smithsonian Tables (List 1949). Later experimental work led A. Wexler at the National Bureau of Standards to present

TABLE 3. A comparison of different formulae for saturation vapor pressure e_s (mb) as a function of temperature.

	WEXLER	GOFF–GRATCH		BUCK 1		BUCK 4		TETENS	
T(°C)	e_s	e_s	% diff.	e_s	% diff.	e_s	% diff.	e_s	% diff.
–80	0.1192E–02	0.1072E–02	–10.11	0.1020E–02	–14.44	0.1146E–02	–3.89	0.9369E–03	–21.41
–70	0.5194E–02	0.4919E–02	–5.28	0.4722E–02	–9.08	0.5078E–02	–2.23	0.4446E–02	–14.40
–60	0.0195	0.0199	–2.72	0.0185	–5.40	0.0193	–1.19	0.0177	–9.26
–50	0.0645	0.0636	–1.38	0.0625	–2.98	0.0641	–0.57	0.0608	–5.66
–40	0.1905	0.1891	–0.70	0.1876	–1.49	0.1900	–0.23	0.1843	–3.24
–30	0.5106	0.5088	–0.35	0.5074	–0.63	0.5103	–0.07	0.5019	–1.69
–20	1.256	1.254	–0.18	1.254	–0.20	1.256	0.00	1.247	–0.77
–10	2.866	2.863	–0.10	2.865	–0.03	2.866	0.01	2.858	–0.26
0	6.112	6.108	–0.07	6.112	0.00	6.112	0.00	6.110	–0.03
10	12.28	12.27	–0.06	12.28	–0.03	12.28	–0.01	12.28	0.03
20	23.39	23.37	–0.05	23.37	–0.05	23.38	–0.01	23.39	0.02
30	42.45	42.43	–0.05	42.44	–0.04	42.45	0.00	42.44	–0.02
40	73.81	73.78	–0.05	73.84	0.04	73.82	0.02	73.77	–0.05

new vapor pressure formulations (Wexler 1976, 1977). Based on the Wexler formulations, Buck (1981) gives coefficients for use in some of the simpler equations that approximate the complicated empirical equations.

Table 2 gives five versions of the temperature-saturation vapor pressure formulas including: the Wexler equation given in Buck (1981); the Goff–Gratch formula (List 1949); Buck's optimization of Tetens's formula

$$e_w = a \exp\left(\frac{bT}{T + C}\right) \tag{2}$$

for the temperature range –20°C to 50°C (Buck 1); Buck's optimization of

$$e_w = a \exp\left[\frac{(b - T/d)T}{T + C}\right] \tag{3}$$

for temperatures between –40°C and 50°C (Buck 4); and Tetens's original formula, which is used in some older works. The coefficients for the Wexler, Buck 1, and Buck 4 are given by Buck (1981); the Goff–Gratch coefficients are in List (1949); the Tetens coefficients are from Saucier (1955).

Sonntag (1990) presents vapor pressure formulations based on the 1986 set of fundamental constants and the new International Practical Temperature Scale, ITS-90. The vapor pressure values in this formulation are, over the range of temperatures encountered in the troposphere, virtually identical, to three to four significant figures, to the Wexler values.

Table 3 compares these versions as a function of temperature and gives the percent differences between the Wexler values and each of the other formulas. Each of the formulas underestimates the Wexler curve over most of the temperature range, but only at low temperatures is the departure greater than 1%. The Tetens coefficients do produce significantly larger discrepancies than the others at temperatures below 0°C. Above –20°C the departures of the two Buck equations are less than 0.1%, like the Goff–Gratch equation above –10°C. These discrepancies from Wexler are, over most of the range shown, less than the deviation that would result from a 0.01°C error in the temperature itself. Thus, except at very low temperatures, the differences among most of these equations for e_s are negligible, particularly for use with radiosonde data. Analysis of upper tropospheric and stratospheric humidities, however, requires consideration of these differences.

In computing the saturation vapor pressure of moist air, rather than that of pure water vapor, it is customary to multiply the latter by the empirically determined enhancement factor, *f*, which is a weak function of both temperature and pressure (see List 1949 for a discussion). Neglecting this factor will result in about a 0.3% underestimate of e_s at 500 mb and about a 0.5%–0.6% underestimate at 1000 mb. The Smithsonian Tables of saturated mixing ratio include this factor, and Buck (1981) gives an approximation of *f* as a function of pressure only. Sonntag (1990) also gives an approximation of *f* that is slightly higher than Buck's, by less than 0.1%.

c. Approximations of variables describing moisture content

There are two other computations that we will mention in passing, although they are not strictly associated with the archive. One is the use of approximations for variables describing the total amount of moisture in the air.

$$q = \frac{\varepsilon e}{p-(1-\varepsilon)e} \approx w = \frac{\varepsilon e}{p-e} \approx \frac{\varepsilon e}{p} \quad . \tag{4}$$

The mixing ratio w, can be 2%–3% greater than specific humidity q, and $\varepsilon e (p)^{-1}$ is 1%–2% less than q at $T_d > 20$°C. This could make a noticeable difference in calculating precipitable water, the vertical integral of q, in the tropics.

The second issue is the definition of relative humidity. Most texts define RH as e/e_s and that is the definition used by the NWS as well as the WMO. On the other hand, List (1949) gives w/w_s, where w_s is the mixing ratio at saturation, and some texts also give this definition. The difference is greatest at a nominal RH of 50%. For example, at a $T = 30$°C and $T_d = 11$°C, $e/e_s = 0.52$ and $w/w_s = 0.51$ (at 1000 mb). The discrepancy is less at lower temperatures and slightly greater at lower pressures.

d. The use of mean monthly data

Some archived radiosonde data are in the form of mean monthly values of T_d or RH as well as the temperature. It is tempting to use these mean values to derive mean monthly values of other moisture variables, such as vapor pressure and specific humidity. There are pitfalls in this practice, however, as the conversions are not linear.

Consider first the case in which mean monthly dewpoint is given and mean vapor pressure is desired. Using a Taylor's series expansion of the relationship $e = e(T_d)$, dropping the higher order terms and taking monthly averages yields an expression for the error, Δ_e

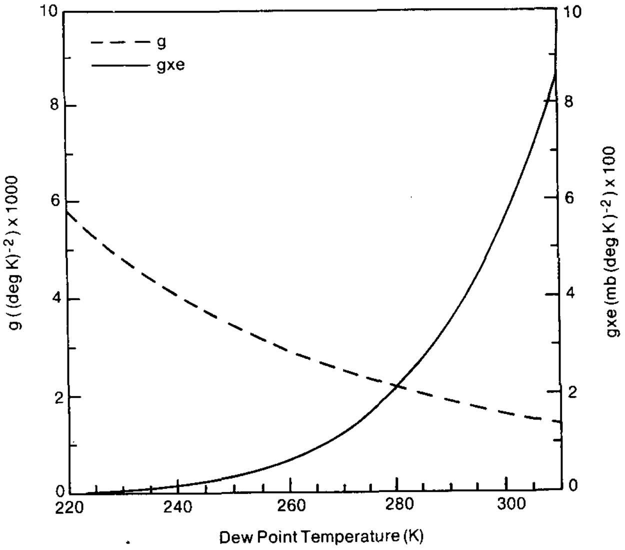

FIG. 7. The functions, $g(T_d)$, and $g(T_d)$ x e as defined in the text, section 5d.

$$e\overline{(T_d)} - \overline{e(T_d)} \equiv \Delta_e \approx (1/2)\sigma^2(T_d)\frac{\partial^2 e}{\partial T_d^{\,2}}, \tag{5}$$

where $\sigma^2(T_d)$ is the variance of T_d during the month, and an overbar denotes a monthly mean value. The second derivative term can be evaluated using the Clausius–Clapeyron equation with the latent heat considered constant. Thus,

$$\Delta_e/e = (1/2)(L/T_d^{\,3}R_v)(L/R_vT_d - 2)\sigma^2(T_d) \equiv g(T_d)\sigma^2(T_d). \tag{6}$$

The functions $g(T_d)$ and e x $g(T_d)$ are shown in Fig. 7. These can be multiplied by the variance of T_d to obtain the relative error, $g(T_d)$ x σ^2, and the absolute error, $g(T_d)$ x σ^2 x e, respectively. Since $\sigma^2(T_d)$ can range from about 1 K^2 to $10^2 K^2$ appreciable errors are possible—tens of percent at low dewpoints and several mb at high dewpoints. Thus, if mean monthly T_d is used to estimate mean monthly vapor pressure, the latter will be underestimated and the amount of the underestimation increases with the variability of T_d during the month. Furthermore, the lower T_d the greater the relative error, and the higher T_d the greater the absolute error. It would be possible to have a change in mean vapor pressure if the variability of T_d changed but its mean value remained the same.

The situation is more complicated if T and RH are used instead of T_d. For $e = e_s(T)$ x RH, the Taylor's series expansion involves two variables. Carrying out the expansion and averaging as above, we arrive at

$$\Delta_e/e = g(T)\sigma^2(T) + (L/R_vT^2)(1/\mathrm{RH})\sigma(T)\sigma(\mathrm{RH})r(T,\mathrm{RH}), \tag{7}$$

where $\sigma(T)$ and σ (RH) are the standard deviations of the T and RH, and $r(T,\text{RH})$ is the correlation between temperature and relative humidity during the month. The sign of the second term on the right is determined by the sign of the correlation. If T and RH are negatively correlated, as seems often to be the case (Gaffen et al. 1991), it is possible the error could be less than that with T_d alone or even of opposite sign. In any case the magnitude of that term is greatest in cold, dry conditions. In using the mean RH rather than the mean T_d, the variation of the RH comes in only if there is a non-zero correlation between RH and T. Otherwise, better results are obtained using mean T and RH because of the poorer precision of the T_d data.

In summary:

- Different formulas for saturation vapor pressure yield similar results, except at very low temperature.
- Using approximations for mixing ratio and specific humidity can introduce errors of 1%–3%.
- Care must be taken in converting mean monthly data to other variables because of the nonlinear relations between moisture variables and temperature.

6. Discussion and conclusion

We have examined and analyzed U.S. radiosonde precision, instrument changes, and reporting practices as they affect studies of changes in tropospheric humidity. We have also noted some effects of data treatment on the records and their interpretation. The introduction of a new sensor is an obvious potential source of spurious indications of climate change but so are more mundane adjustments such as changes in shape of the instrument case and its paint. An equally important source of bias are changes in data-handling practices. Changes in signal-processing algorithms and changes in the reporting of low humidities are examples. Furthermore, current practices are not immutable. Indeed, there is discussion of reporting humidity data at lower temperatures and humidities than is now the case, in part because of recent findings that the carbon hygristor performs more reliably at low humidity (Wade and Wolfe 1989).

The record of water vapor from the U.S. radiosonde archives is not homogeneous, particularly before 1973. Since then, the changes that have been made have had less obvious impacts, but the effects of the 1980 changes may deserve further attention. To extend the record before 1973 will require adjustments of the data. We also feel that the data above 500 mb, with the possible exception of the tropics, are not reliable enough to draw conclusions about upper-level humidity. Even 500-mb data may be unreliable at high latitudes; the combination of poorer sensor response in low temperatures and lower accuracy, in addition to the variety of ways of treating cold, dry conditions, make determining a water vapor climatology there problematical. Finally, it should be noted that the archived records contain some bad data, many probably the result of transmission errors. Also, one cannot assume that all bad observations have been eliminated by quality assurance practices. We occasionally find impossible temperatures, dewpoint depressions, surface pressures, and heights of mandatory levels.

To establish a global water vapor climatology will require information about other nations' instruments and practices similar to this for the United States. Toward that end, the WMO has appointed one of us (DG) as Rapporteur for Historical Changes in Radiosonde Instruments and Practices. A questionnaire has been circulated to all WMO members to help establish a history of upper-air practices that affect the humidity (and temperature) records. In the meantime, the authors would appreciate any information the reader can contribute regarding U.S. practices and instruments that we have left out and the history of other nations' upper-air measurements. We intend to make all such information readily available.

The changes in radiosondes and practices discussed here were made to improve the accuracy and precision of the weather data, and so to improve weather forecasts, or at least to reduce their cost. Had homogeneity of climate records been the only criterion, we might still be using hair hygrometers attached to kites. Climatologists will always be faced with reconciling data records taken for different purposes and with techniques that change over time. However, great importance is now attached to climate change and the implications for public policy if changes are deemed caused by human activity. It behooves the community to assist in separating changes in climate from changes in methods of observing the weather. In compiling this record we have received the cooperation of many in the U.S. National Weather Service and other components of the National Oceanic and Atmospheric Administration. Nevertheless, we are not sure we have identified all the important changes. We would encourage, actually plead, for attention to maintaining good records of all improvements in instrumentation, changes in procedures, conversion algorithms, reporting practices, and the like. These should be kept in a central, easily-accessed location.

When new instruments, algorithms, etc., are to be put into service, a careful comparison with the "old" method should be made so records can be adjusted if necessary. The development of a "Reference Radiosonde" as described by Finger and Schmidlin (1991), for example, is very desirable. Barring this, it would be very helpful if some upper-air stations could be established whose primary purpose is the maintenance of climate data and where the old ways are continued along with the new until such time as we know how to maintain a homogeneous record. At one time or another, we have all complained of our predecessors failure to fully document their data; let us minimize our successors' complaints of our own efforts.

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Appendix

In section 2b we noted that the finite precision of radiosonde measurements of atmospheric temperature and moisture content leads to random errors in estimates of measured, reported, and derived variables. This appendix outlines the mathematical analysis of the problem. We begin with the following equations.

$$\mathrm{RH} = e/e_s \qquad (A1)$$

$$e_s = e_0 \exp[(L/R_v)(1/T_0 - 1/T)] \qquad (A2)$$

$$e = e_s(T_d) \qquad (A3)$$

$$q = \frac{\varepsilon\, e}{p + e\,(\varepsilon - 1)} \qquad (A4)$$

where the variables used are:

RH – relative humidity
e – vapor pressure
e_s – saturation vapor pressure
$e_0 = e_s(T_0) = 6.11$ mb
L – latent heat of vaporization = 2.5×10^6 J kg^{-1}
R_v – gas constant for water vapor = 461 J (deg kg)$^{-1}$
T – temperature
$T_0 = 273$ K
T_d – dew point temperature
p – pressure
q – specific humidity
ε – ratio of molecular weight of water vapor to that of dry air = 0.622

Using Taylor's series expansion, an expression for the error in any dependent variable as a function of errors in independent variables can be written. Let F be a function of independent variables x, y, and z. If x, y, and z take the values of x_0, y_0, and z_0 with associated errors of Δx, Δy, and Δz, respectively, then, retaining only terms of order Δx, Δy, Δz, and larger, the overall error, E, can be expressed as:

$$E \equiv F(x_0 + \Delta x, y_0 + \Delta y, z_0 + \Delta z) - F(x_0, y_0, z_0) \approx \Delta x(\partial F/\partial x) + \Delta y(\partial F/\partial y) + \Delta z(\partial F/\partial z). \qquad (A5)$$

We are interested in the estimated error in reported T_d due to random errors in measured T, p and relative humidity U (to distinguish it from the calculated value, RH) as well as the errors in calculated RH and specific humidity, q. After some manipulation of equations A1-A4, we obtain:

$$T_d = \frac{1}{1/T - R_v/L\,[\ln(U)]} \qquad (A6)$$

$$\mathrm{RH} = \exp[(L/R_v)(1/T - 1/T_d)] \qquad (A7)$$

Carrying out the operations required in Eq. A5 leads to the following expressions for the errors in dewpoint (E_{Td}), relative humidity (E_{RH}), and specific humidity (E_q) in terms of either measured or reported quantities.

$$q = \frac{\varepsilon\, e_0 \exp\left[\frac{L}{R_v}\left(\frac{1}{T_0} - \frac{1}{T_d}\right)\right]}{p - e_0(\varepsilon - 1)\exp\left[\frac{L}{R_v}\left(\frac{1}{T_0} - \frac{1}{T_d}\right)\right]} \qquad (A8)$$

$$E_{T_d} = \left(\frac{1}{T} - \frac{R_v}{L}\ln(U)\right)^{-2}\left[\frac{\Delta T}{T^2} + \left(\frac{\Delta U\, R_v}{L\, U}\right)\right] \qquad (A9)$$

$$E_{RH} = \frac{L}{R_v}\exp\left[\frac{L}{R_v}\left(\frac{1}{T} - \frac{1}{T_d}\right)\right]\left[\frac{\Delta T_d}{T_d{}^2} - \frac{\Delta T}{T^2}\right] \qquad (A10)$$

$$E_q = \frac{-\varepsilon\, e_0 \exp\left[\frac{L}{R_v}\left(\frac{1}{T_0} - \frac{1}{T_d}\right)\right]\left(\frac{\Delta T_d p L}{R_v T_d{}^2} + \Delta p\right)}{\left(p - e_0(\varepsilon - 1)\exp\left[\frac{L}{R_v}\left(\frac{1}{T_0} - \frac{1}{T_d}\right)\right]\right)^2}. \qquad (A11)$$

The technique used to estimate these errors is described using the error in reported T_d, as expressed in Eq. (A9), as an example. The error E_{Td} depends on the values of T and U as well as their associated errors, ΔT and ΔU. Numerical estimates of E_{Td}, as a function of T and U, can be made by assuming the statistical distribution of ΔT and ΔU. For this analysis, ΔT and ΔU are assumed to be uncorrelated and normally distributed, with mean zero and standard deviations as determined by field tests of radiosonde instruments, 0.2 K and 3.5%, respectively (Nash and Schmidlin 1987). Two uncorrelated sets of random numbers with normal distributions, mean zero and unit standard deviation, having 1000 samples each, were generated to simulate ΔT and ΔU. These were then used to calculate 1000 values of E_{Td} for fixed T and U, and the mean and standard deviation of the resulting distribution were calculated. This procedure was repeated for a representative selection of $T-U$ pairs.

The error in computed RH, E_{RH}, is estimated in the same fashion as E_{Td}. To computer E_{RH} we take 1.0 K as the standard deviation of ΔT_d, and the standard deviation of ΔT as 0.2 K, as before. Finally, the error in computed specific humidity depends on errors T_d and p. We take their standard deviations as 1.0 K and 1.9 mb (Hoehne 1980), respectively, to estimate E_q.

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