Effects on Climate Records of Changes in National Weather Service Humidity Processing Procedures

WILLIAM P. ELLIOTT AND REBECCA J. ROSS

Air Resources Laboratory, Environmental Research Laboratories, NOAA, Silver Spring, Maryland

BARRY SCHWARTZ

Forecast Systems Laboratory, Environmental Research Laboratories, NOAA, Boulder, Colorado

(Manuscript received 29 May 1997, in final form 14 November 1997)

ABSTRACT

The U.S. National Weather Service has recently corrected an error in radiosonde humidity data reduction algorithms, eliminated a sonde that’s processing contained another error, and recently made a further change in the humidity data reduction algorithm. They also introduced new procedures for reporting humidity from radiosondes. These changes will affect the climate records of U.S. upper-air humidity. Because the changes affect observations differently at different temperatures and relative humidities, their impact on monthly mean humidity quantities depends on the frequency with which certain conditions occur. The authors calculated the effects on monthly mean humidity quantities of five specific changes at a representative set of U.S. radiosonde stations. Some of these effects are quite substantial and should be considered in evaluating climate variability.

1. Introduction

Implications of long-term climate change continue to receive attention in scientific circles (Houghton et al. 1996) as well as in the press. This leads to increased scrutiny of climate records upon whose acceptance of climate change by both scientists and the public will ultimately depend. A significant component of climate change would be that of atmospheric moisture. Changes in tropospheric moisture can accompany temperature changes and also be an important cause of climate change, both on the timescale of increasing greenhouse gases and of year-to-year variations. Radiosondes provide the longest record of upper-air humidity, and despite their shortcomings, their records bear study. However, to extract the maximum utility from the records requires understanding the effects of both instrumental and procedural changes over the years of the recorded observations.

Elliott and Gaffen (1991) and Schwartz and Doswell (1991) outlined some problems climatologists encounter with archived radiosonde humidity data, calling particular attention to effects of changes in both instrumentation and data processing on long-term records. Since the publication of those papers, the U.S. National Weather Service (NWS) has corrected some problems with algorithms used in processing the radiosonde humidity signals, modified procedures for reporting humidity, and on 1 June 1997, modified the algorithm used at low humidities (and introduced a new pressure sensor in the radiosonde and new factory calibration procedures that are not considered here). This paper will examine the quantitative effects of these corrections and procedural changes on monthly mean values of relative and specific humidity, dewpoint, and precipitable water. This draws heavily on the work of Wade (1994), who has made a careful study of problems of radiosonde humidity measurements and uncovered some peculiarities in their history. While the emphasis here will be on the climate record, particularly on monthly values, anyone using archived radiosonde humidity data for other research purposes, such as computations of convective parameterizations and satellite moisture retrievals, should be aware of these artifacts. Whether the changes have a serious impact will depend on the particular applications.

It is not difficult to determine the effects of any of these changes on a particular sounding. But because the effects are different at different temperatures and/or humidities, how climate records will be affected depends on how often particular conditions prevail. Thus, the impacts will vary geographically, seasonally, and with elevation. Some will have minimal impact while others can have substantial effects. When these impacts are substantial, they will need to be taken into account in evaluating changes in tropospheric water vapor.
The next section will outline the particular changes examined here. This will involve a brief review of the arcana of translating the atmosphere’s relative humidity into recorded values. We will then discuss the errors and reporting practices now abandoned by NWS, but affect past archived observations, as well as the effect of the recent algorithm change. The quantitative effects of these changes on monthly mean humidity variables will be presented, followed by a discussion including the potential for adjustments.

2. The problems

During 1963–66 the NWS switched from lithium chloride moisture sensors in radiosondes to carbon hygristors, which are still used at most NWS sites. [Schwartz and Wade (1993) give more on the history of U.S. humidity measurements. In 1998 the NWS will begin using Vaisala sondes at the majority of its stations in the lower 48 states.] The carbon hygristor has a plastic strip with metal edges and is coated with a hygroscopic material containing carbon particles in suspension. This coating changes its electrical resistance in response to changes in relative humidity (RH).

A signal proportional to this resistance is transmitted to a ground-based receiver by modulating a carrier signal at an appropriate frequency. Conversion to RH uses the ratio of the sensor’s resistance (R) to the resistance it would have at a relative humidity of 33% (R_{33}). The latter is the so-called lock-in resistance, whose value at 25°C is determined by the manufacturer. An additional fixed resistor is used in the circuit in parallel with the hygristor to facilitate transmitting high-humidity values at cold temperatures.

The receiver converts the frequency signal, including removing the effect of the parallel resistor, to the resistance ratio, R/R_{33}, and this is then converted to relative humidity by applying calibration curves. Because the sensor’s resistance is affected by air temperature as well as RH, temperature corrections are included in the calibration procedure. Until 1 June 1997, NWS used two calibration curves (Wade 1994): one for humidities 20% and above and another set for lower humidities. Both calibration curves are fourth-order polynomials; the coefficients used above 20% RH are referred to as the 1a coefficients and those below 20% are the 1b coefficients (see Fig. 6, section 3e). The NWS now uses only the 1a coefficients for all RH calculations at sites in the 48 contiguous states; this change will be implemented elsewhere at a later date.

Until 1989, the NWS used sondes manufactured by VIZ Manufacturing Company exclusively. Between March 1989 and July 1990, NWS introduced sondes manufactured by the Space Data Division (SDD) of the Orbital Science Corporation at 17 stations in the western United States and Alaska [see NWS (1997) for their comparison of the VIZ and SDD sondes]. These sondes used the same hygristor as VIZ sondes and the same algorithms for calculating RH. The NWS discontinued using SDD sondes between 1994 and 1995. In 1995 NWS introduced sondes manufactured by Vaisala at 25 stations. These use entirely different humidity sensors and none of this paper’s discussion applies to Vaisala sondes. Also, the U.S. military makes radiosonde observations and these may not have the same characteristics as NWS observations so this discussion may not be applicable to military observations, either. We will now lay out the problems that arise in upper-air humidity records.

a. SDD problem

In March 1990, NWS began upgrading the data processing systems at all stations, thus requiring a change to their software. A coding error occurred when the conversion took place at the 17 SDD sites such that after this conversion the temperatures used in the RH algorithm were incorrectly divided by 100. This meant that the value of the temperature used in adjusting the humidity calibrations was effectively 0°C in all situations. The calibration curves are such that using a temperature of essentially 0°C when RH is greater than 33% leads to an underestimate of RH at temperatures above 0°C and an overestimate of RH below that value. If RH is less than 33%, the situation is reversed, that is, RH is overestimated at warm temperatures and underestimated at cold temperatures. The duration of the SDD problem for each of the 17 stations is given in the appendix.

b. Parallel resistor problem

During 1988–89 NWS switched from VIZ type A to VIZ type B radiosonde models (Ahnert 1991). The new model used a slightly different parallel (or shunt) resistor in the humidity circuit but the resistor’s value was not changed in the software. The effect of the incorrect resistor value is to reduce the values at high relative humidities, generally between 1% and 3% but by higher amounts at cold temperature. Wade and Schwartz (1993) describe this problem more thoroughly. This coding error persisted until 1 October 1993 when several changes were made to the ground-station software.

c. Reporting practices: Low temperature cutoff

Because most humidity sensors do not respond well in cold temperatures, NWS policy was to report any humidity as “missing” when the temperature was below −40°C, regardless of the instrument reading. At the request of users, this practice was dropped in 1993 and humidity values are now reported as measured (Canada, which has used basically the same humidity sensor in its radiosondes, has reported RH at temperatures above −65°C since 1983). However, it has not been established that carbon hygristors provide accurate measures at these low temperatures.
Table 1. Practices and errors discussed and their dates.

<table>
<thead>
<tr>
<th>Practice/Error</th>
<th>Start date</th>
<th>End date</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDD error (in temperature correction)</td>
<td>1990</td>
<td>1994–95 (see appendix)</td>
</tr>
<tr>
<td>Parallel resistor error (VIZ Stations)</td>
<td>1988–89</td>
<td>October 1993</td>
</tr>
<tr>
<td>RH = missing if temperature &lt; −40°F</td>
<td>Prior to 1973</td>
<td>October 1993</td>
</tr>
<tr>
<td>RH &lt; 20%: RH = 19% (dewpoint depression = 30°C)</td>
<td>1973</td>
<td>October 1993</td>
</tr>
<tr>
<td>RH &lt; 20%: as observed, with 1b coefficients</td>
<td>October 1993</td>
<td>May 1997</td>
</tr>
<tr>
<td>RH &lt; 20%: as observed, with 1a coefficients</td>
<td>June 1997</td>
<td>continuing</td>
</tr>
</tbody>
</table>

d. Reporting practices: Low humidity cutoff

Before 1965, NWS reported all values of RH less than 20% as missing. When the carbon hygristor was introduced, RH values between 10% and 20% were reported but problems remained at low humidities (see next section). So in 1973, when other changes in the sonde were made, NWS reverted to the policy of not reporting RH if the measured value was less than 20%. The new practice was to record all humidities below 20% as 19% but to transmit a value of 30°C for dewpoint depression over the Global Telecommunication System (Schwartz and Wade 1993). Users unaware that 30 is a fictitious or “dummy” value will usually underestimate the true RH below 20%, whereas 19% will often overestimate the humidity in these dry conditions.

On 1 October 1993, also at the request of data users, NWS dropped this restriction as well and reported RH values at humidities below 20% using the 1b coefficients (dropping this cutoff does not imply that NWS claims data in these conditions are of comparable quality to those in more moist conditions). Thus, after 1 October 1993, there are changes in reported moisture values from U.S. radiosondes that could appear as changes in moisture climate.

e. Low-humidity problem

A problem common to RH measurements below 20% of both SDD and VIZ sondes apparently arose from an error made in the 1960s in the mechanical evaluator used then to convert the radiosonde humidity signal to RH. Wade (1994) describes the error and its subsequent propagation through the years. The 1b coefficients used at RH <20% in the data processing software were designed to reproduce the evaluator’s values at these low humidities. However, tests suggest that the 1a coefficients are better approximations to the sensor response well below 20% (Wade 1994). This problem at low RH evidently led to the practice of ignoring all values less than 20% and also to the perception that the carbon hygristor did not function well in dry conditions. The NWS discontinued use of the 1b coefficients in June 1997.

Table 1 summarizes these practices and errors and give the dates of their occurrences.

3. Comparisons

To determine the effects of these errors and procedural changes on mean monthly values of moisture variables, we compared monthly means calculated from the original reports with those calculated after adjusting each sounding according to the particular problem, as discussed below. The observations were those transmitted over the Global Telecommunication System (GTS) and were obtained from the National Center for Atmospheric Research.

The transmitted humidity data are dewpoint depressions, so we converted these values to RH and to specific humidity using the reported temperatures, and calculated monthly means of relative humidity, specific humidity \( q \), dewpoint \( T_d \), and precipitable water \( W \). The RH, \( q \), and \( T_d \) were calculated for each sounding at the surface and at 850, 700, 500, 400, and 300 mb. We calculated \( W \) between the surface and 850 mb, 850–500 mb, 500–300 mb, and surface to 300 mb, using only values at the five pressure levels. The total precipitable water, \( W_T \), is taken as the surface-to-300 mb value.

To examine the SDD problem we used one year of observations (1991) at three sites: Fairbanks, Alaska, Bismarck, North Dakota, and Del Rio, Texas. These stations span the climate extremes of those that used SDD equipment. We corrected each temperature used in the calibration of the humidity sensor and recomputed the values of the moisture variables. For the other comparisons we used observations at 11 VIZ stations from 1994 and 1995, adjusting the observations to produce values that would have been produced by the practices that prevailed before 1994 or after June 1997. The values for all soundings were averaged for the two Januaries, the two Febuarys, etc. All adjustments used equations and coefficients from Wade (1994). Because reported surface values are not made with the radiosonde instruments and therefore not subject to the radiosonde data reduction procedures, no surface data were adjusted for changes in algorithms. Differences between adjusted and unadjusted monthly means were calculated separately for each observation time; unless otherwise noted, the results shown are for 1200 UTC.

Figure 1 shows the locations of both sets of stations.

To give an idea of the range of conditions these stations represent, Fig. 2 shows the average vertical distribution of relative humidity in January and July during
1994–95 at the VIZ stations and during 1991 at the SDD sites. A decrease with height, up to 500 mb, of RH is evident at most stations. The subtropical sites, especially San Diego, California, show the presence of the trade wind inversion by a very marked fall off of RH near 850 mb. Figure 2 also gives mean values of \( W_T \) at each station. The values range from 0.32 cm at Barrow, Alaska, in January to 5.51 cm at Majuro in July.

**a. SDD error**

All data from the three SDD stations were influenced by the incorrect temperature correction algorithm (section 2a, above). To correct the original reports, temperatures were divided by 100 (to duplicate the software error) and used to find the value of the resistance ratio \( R/R_3 \) by iteration that would give the reported RH to within 0.1%. Using this resistance ratio and the correct temperature in the calibration equations, a corrected value of RH was determined and used to calculate corrected values of \( q, T_\phi, \) and \( W \).

The effects of this error on 1991 monthly means are illustrated in Fig. 3. The left-hand plots show the differences at 850 mb and 500 mb between the mean monthly relative humidities calculated from the erroneous reported values and those calculated using the correct temperatures at the three SDD stations. Positive differences indicate the error resulted in too-high RH values. Except at Del Rio at 500 mb, there is a clear annual cycle, with the largest positive (or least negative) values in the cold season and least positive (or greatest negative) values in the warm season. The largest positive values are at 500 mb at Fairbanks where errors in excess of 6% RH can occur, while the largest negative values are at 850 mb at Del Rio where errors of about −4% RH occur.

The right-hand plots of Fig. 3 show the total precipitable water differences, expressed as a percentage of the monthly mean for each month. The pattern at each station is similar to that of the 850-mb RH differences; at Fairbanks the difference is such that \( W_T \) was overestimated in every month while at Del Rio \( W_T \) was underestimated in every month (the maximum percentage difference at Del Rio, the station with the highest mean \( W_T \), corresponds to about 0.15 cm). At Bismarck the differences were negative in May through September, otherwise they were positive.

The resulting errors in monthly mean specific humidity and dewpoint follow the patterns of RH errors. At Fairbanks, errors in \( q \) rarely were greater than 0.1 g kg\(^{-1}\) and usually much less. In winter these values approach 10% of the monthly mean. Farther south, at Bismarck, the maximum errors in \( q \) reach 0.4 g kg\(^{-1}\) with about the same range of percentage errors as Fairbanks. At Del Rio the error could be 0.6 g kg\(^{-1}\) and percentage errors of \( q \) could be as high as 10% at high levels. None of these stations had \( T_\phi \) errors greater than 1 K and most were less than 0.5 K.

While our focus is differences in monthly means, the largest positive error for an individual sounding at any pressure level in 1991 was about 16% in RH at each of the three stations; the greatest negative errors were −3% (Fairbanks) to −5% (Del Rio). The maximum total precipitable water errors of individual soundings ranged from +0.04 cm (all) to −0.16 cm (Del Rio).

**b. Parallel resistor error (VIZ problem)**

As noted by Wade and Schwartz (1993), the failure to adjust the data-reduction software to reflect the change in the parallel resistor from 1.2 \( \times 10^6 \) to 1.0 ohms meant that observations at high relative humidities were biased low from 1988 to October 1993. Their calculations showed that the correct value could raise the reported RH by about 3% RH at an indicated RH of 94%, and lesser amounts at lower RH. Below RH of about 60% the effect would be negligible (correcting this error still does not allow reports of 100% RH, even in clouds, which remains a known shortcoming of the VIZ RH algorithms).

To evaluate the effect of this error we chose observations from the period after the software had been corrected and recalculated RH using the incorrect resistance. To reproduce the numbers precisely requires exact values of the lock-in resistance, \( R_{13} \), which are not available. In the tests, we used the nominal value of 10 000 ohms for \( R_{13} \). To ensure that our conclusions did not depend greatly on the particular value of \( R_{13} \), we calculated changes assuming \( R_{13} \) equaled 11 000 ohms and 9 000 ohms. The effect was to increase the error slightly for the higher \( R_{13} \), value relative to the nominal value, and to decrease it for the smaller value.

The effect of this error on monthly values is small, smaller than the errors from the SDD problem and will be described without accompanying plots. Only three stations, Annette, Caribou, and International Falls, gave
errors greater than 1% (but less than 2%) in \( W_T \), and these occurred mainly in the colder part of the year. The largest effect was in the 850–500-mb layer but only one month’s error reached 2.4%. Relative humidity errors could be as high as 2% at Annette at 850 and 700 mb but at other stations rarely exceeded 1%. The largest dewpoint error was 0.3 K but, most were less than 0.1 K. The errors were so small at the other stations that it is difficult to characterize an annual cycle except to note that there was a tendency for the monthly mean errors to be larger in the cold seasons.

The maximum error for an individual observation was 8%–10% at the various stations (a portion of these relatively large errors may be attributable to uncertainty
Fig. 3. Differences in RH (left) and \( W_T \) (right) between corrected and uncorrected monthly means for the SDD sites. Positive differences indicate the uncorrected monthly means were higher than the corrected values. The RH differences are shown for 500 mb (solid) and 850 mb (dashed). The \( W_T \) differences are expressed as percent of the monthly mean value.

in the exact value of \( R_{33} \) for each case). The maximum individual errors in \( W \) ranged between 0.06 and 0.12 cm, with the higher values being at the more moist locations.

c. Reporting practices: Low-temperature cutoff

The effect of reporting all humidity values as missing when the temperature was less than \(-40^\circ\)C was discussed by Elliott and Gaffen (1991). They calculated winter mean values of \( q \) and RH reported at Canadian stations, whose sonde used the same hygristor as the NWS but with a \(-65^\circ\)C cutoff, and compared those values with what would have been the means if only observations warmer than \(-40^\circ\)C had been used. They found little difference in relative humidity but differences in specific humidity could be as large as 30%–40% of the monthly mean value.

In this study we calculated the monthly mean values for all observations and for only those warmer than \(-40^\circ\)C. Because we required a minimum of 10 observations per month to calculate a monthly mean, the most pronounced effect of excluding observations below \(-40^\circ\)C was to eliminate most of the monthly mean values at 300 mb even at midlatitudes, except in summer. These restrictions also eliminated cold season monthly \( W \) values at 400 mb at Barrow. When there were at least 10 observations, monthly differences in RH were usu-
ally small, as Elliott and Gaffen (1991) found, only occasionally exceeding 2% RH. On the other hand, monthly overestimates of mean specific humidity could be as high as 60% at 400 mb and 300 mb for the stations in Alaska and the northern contiguous states. Even at 500 mb some stations were affected by the cutoff. At Barrow, in the cold months, differences of 20%–30% in the 500-mb mean $q$ existed and cold season differences up to 8% were found at Caribou, Maine and International Falls, Minnesota. Of course, these percentage differences in $q$ are quite small absolute values: 0.07 g kg$^{-1}$ in Alaska and 0.15 g kg$^{-1}$ at Caribou. At lower latitudes, the 500-mb observations were only occasionally affected by the cutoff, mainly in the colder months and then only by a few percent.

An alternative that we have employed elsewhere, for example, Ross and Elliott (1996), is to substitute values for RH when both the temperature is below $-40^\circ C$ and the dewpoint is reported as missing. Based on analysis of observations below $-40^\circ C$ in Canada, which changed to a $-65^\circ C$ cutoff much earlier, we assumed RH = 35%, 40%, and 50% at the 300-, 400-, and 500-mb levels respectively, in these conditions. The effect of these substitutions is felt only at upper levels and mainly at the higher latitude stations and there differences in monthly mean RH were almost always between $\pm 5\%$, even at 300 mb, and below 300 mb the differences were only a few percent at most. The specific humidity differences were at most 0.02 g kg$^{-1}$ although this could be a percentage change of as much as 20% at 300 mb. Differences

Fig. 4. Percent of observations at 500 mb where the reported RH was less than 20% at 11 VIZ sites. Note differences in vertical scale between the top six and bottom five stations.
in dewpoint were rarely greater than 1 K and these occurred most often at 300 mb. Total precipitable water was hardly affected by the substitution because most of the water vapor is at temperatures warmer than -40°C.

d. Reporting practices: Low-humidity cutoff

The practice of the low-humidity cutoff presents the analyst with a problem. Because observations were considered unreliable below RH = 20%, observations below this value were recorded as 19% or 20% but a dummy value of 30 was transmitted as the dewpoint depression over the GTS network. This situation arises more often than one might think. Figure 4 shows the percentage of “dry” humidities (those less than 20%) at 500 mb during 1994–95 reported by the 11 VIZ stations. At San Diego two-thirds of all the 500-mb relative humidities were less than 20% with over 80% so reported in June. Several months reported dry over 80% of the time at San Juan and Hilo, Hawaii. Fewer of these dry observations appear at 700 mb and still fewer at 850 mb. However, especially at the subtropical stations, months with more than 30% of the observations reported as dry at 700 mb are not uncommon; at San Diego, 69% of the 850-mb RH in the summer months were dry.

The treatment of dewpoint depression reports of 30
will affect monthly mean values. Eliminating all values below 20% (consider them missing) or choosing to use 19% or 20% as the RH value will overestimate the monthly mean RH and therefore the other humidity quantities. On the other hand, assuming the true dewpoint depression is 30°C will result in an underestimate of monthly humidity. Faced with the question of how to treat this dummy number, Ross and Elliott (1996) adopted a relative humidity of 16% for those conditions, again basing their choice on Canadian observations.

We examined the effects of four possible treatments of reported dewpoint depressions of 30: assume them to be missing, take them literally to be 30°C, substitute RH = 19%, or substitute RH = 16%. Figure 5 illustrates the effects of these assumptions at three stations: Caribou, San Diego, (the extreme example in the group of 11), and Majuro. In constructing this diagram, the means based on reported values were subtracted from the values based on the various alternatives. Thus, a positive value in the plots means the particular practice overestimated the monthly mean value. The left-hand diagrams show the changes the four alternatives would produce in RH at 500 mb and those on the right show the effects on \( W_T \) (because so many of the upper-level means of W are missing because of the requirement for 10 observations per month, we do not show \( W_T \) for the 30 = missing alternative).

Clearly, ignoring reported dewpoint depressions of 30 leads to large overestimates of both RH and \( W_T \), even at Caribou, which is fairly typical of most of the mid- and high-latitude stations. At San Diego, the RH overestimate approaches 30% in some months and at Majuro can be above 20%. On the other hand taking 30 as the true dewpoint depression underestimates both RH and \( W_T \), usually by much less than the overestimate from ignoring the observation but still substantial. Using 19% generally reduces the overestimates quite a bit but at San Diego the discrepancy can still be almost 5% (June) in RH and over 10% in \( W_T \). Using 16% produces even less overestimate but again at San Diego it results in a \( W_T \) overestimate of nearly 5% in October. At the northern stations using 16% gives overestimates almost always less than 1% and usually less than 0.5%.

e. Low-humidity problem

As noted previously, the NWS has been aware that there has been a problem in the conversion algorithm at low humidities (Wade 1994) that led to the low-humidity cutoff. When NWS began reporting values below 20% RH in 1993, they were calculated with the 1b coefficients as has been the practice in Canada for some time. To improve low RH values, the NWS dropped the 1b coefficients in June 1997 and began using the 1a coefficients at all RH. For RH below 20% this leads to lower estimates of RH than previously recorded. Nevertheless, there is room for further improvements in this range of RH.

To determine how this could affect monthly mean moisture values, we first calculated the \( R/R_{\text{cal}} \) that gives the observed RH with the 1b coefficients and then used this value to find an adjusted RH using only the 1a coefficients. The process is illustrated by the arrows in Fig. 6, which shows the two calibration curves for \( T = -10^\circ\text{C} \). For a reported RH of 15%, follow the vertical line from 15% to its intersection with the 1b line, then across to the 1a line and read the adjusted RH as 6%. Note that if the 1a coefficients are a reasonable estimate of the true response of the hygristor (see Wade 1994), using 1b coefficients should yield few estimates less than about 14% (or dewpoint depressions greater than 20°–25°C). However, there were reports of dewpoint depressions so large that negative values of RH were calculated with the 1a coefficients. When RH values less than 1% were calculated, we set RH to 1%. This happened more often than might be expected, suggesting there might be problems with individual hygristor calibrations, but further consideration of this is beyond the scope of this study.

The differences between RH means at 500 mb using 1a and 1b coefficients for each month are shown in Fig. 7 and the differences in \( W_T \) in Fig. 8. The pattern of differences reflects the patterns of the fraction of observations that report RH < 20% (Fig. 4), as would be expected. The northern stations have RH overestimates usually less than 3% but the southern stations often show greater values.

These discrepancies in RH can translate into substantial percent differences in \( W_T \), especially at San Diego, which had the lowest mean RH at 850 mb. The average percent difference in \( W_T \) there represents a dif-
ference of about 0.15 cm. Except at San Diego, the estimated amount of water vapor in the surface-to-850-mb layer (not shown) is little affected by the choice of coefficients, rarely exceeding 1%–2%. At San Diego there can be differences of over 6% in the surface-to-850-mb layer’s estimate. In the 850–500-mb layer the differences can be over 25% at San Diego and occasionally approach 10% elsewhere. Because temperatures in the 500–300-mb layer in the Tropics are relatively warm, estimates of W are thought to be most reliable there. However, the number of dry observations can produce percentage differences in this layer up to 30% at San Diego and nearly 20% at Majuro.

4. Summary and discussion

We have looked at the effect on monthly mean values of three different sets of problems that afflict the climate record of U.S. upper-air humidity data. The first set includes the error in the temperature correction of SDD sondes and the use of an erroneous value for the parallel resistor of VIZ sondes. The second set involves the nonreporting of humidities below 2°C and of using 30 to report dewpoint depressions at RH less than 20%. The third set consists of effects of the error in the conversion of the electrical signal to relative humidity in dry conditions.
Within the first set, the SDD error can produce moisture values either too high or too low, depending on the temperature and the RH. Monthly mean values of RH can be in error by over +6% to −4% and $W_T$ errors of +5% to −3% are possible. The parallel-resistor error leads to systematically lower RH but the effect on monthly means is generally quite small, rarely exceeding 1% RH or 1% of $W_T$ and then only at the northern sites.

The second set comprises limitations on reporting data. The cold-temperature cutoff mainly affects values at high levels while the low-humidity cutoff affects observations below RH $= 20\%$, which can occur at any pressure. The effect of the $−40^\circ$C cutoff is to render 300-mb monthly mean moisture data practically useless at high latitudes prior to October 1993. Without observations at temperatures below $−40^\circ$C there is a substantial moist bias in monthly mean values at 400 and 300 mb north of the latitude of Brownsville, except in the warm part of the year. Even at 500 mb monthly moisture data are questionable in winter in climates such as Barrow. Estimates of precipitable water in layers above 500 mb, as well as other moisture quantities, were affected by this cutoff throughout the year and so are suspect, except in the Tropics. The influence of this cutoff was negligible at San Juan, Hilo, and Majuro at all levels.

The lack of information in dry conditions is more...
troublesome. Because the number of observations of RH < 20% can be quite large, as much as 80% at San Diego at 500 mb, this problem can have substantial effects on monthly mean humidity values. The problem could also affect retrospective calculations of stability parameters such as the level of free convection and the convective available potential energy. Faced with an implied dewpoint depression of 30°C, the analyst must decide either to ignore the observation, take it at face value, or substitute some dry value of RH. None of these alternatives is completely satisfactory but the most unsatisfactory one is to reject the observations, as this introduces a large positive bias into the monthly mean values. Substituting a value of 16% for RH produced the smallest bias of those tested but still shows a small positive bias.

The third type of problem is the use of 1b coefficients in calculating RH between October 1993 and June 1997 (and later at sites outside the 48 contiguous states). Although it is an improvement over assigning a fixed value of 30°C (or 19%) when RH < 20%, the coefficients lead to values that are too large. Monthly mean RH at 500 mb can be overestimated by several percent RH at all stations and as high as 8% at the southern sites. Total water, W_{\text{t}}, can be overestimated by as much as 15% at San Diego and some months could be overestimated by up to 8% at other sites.

Because the observed values in dry and cold conditions prior to 1993 were not reported, we are not able to quantify the effects that these changes would have had on trends. Qualitative effects of these changes are summarized in Table 2 where the effects of the errors and practices on monthly mean values are compared to what was reported under procedures used from October 1993 to June 1997. Most of the effects were such that the atmosphere appeared more moist than it was (the exceptions are the parallel-resistor error, some SDD sites in the lower levels, and the substitution of 30 for the dewpoint depression). Thus these changes would contribute a drying tendency to moisture trends at many United States stations after 1993. Because the atmosphere tends to be drier and colder at higher levels, this tendency will be accentuated aloft and so the lapse rate of moisture will appear to steepen. That is, there will be an apparent drying aloft, relative to near-surface conditions.

It would be possible to adjust records for some of these changes. The SDD observations can be readily adjusted using the method we employed to estimate the effect of the error. Since we were interested in monthly means the lack of precision in the GTS transmissions, where dewpoint depression is transmitted only to the nearest kelvin when greater than 5 K, has little effect on the mean. If individual observations are required, it would be best to acquire data to as precise a value as possible. Similarly, the parallel-resistor error can be corrected but one would need values for the individual lock-in resistance to perform the adjustment most precisely. When both these adjustments were made under test conditions (NWS 1997) the SDD and VIZ B sondes gave very similar RH values, with the VIZ B drier by about 0.14% RH.

Data prior to October 1993 cannot be adjusted for the effects of omissions of low-temperature and low-humidity observations because information needed for adjustment is not available. The effect on total precipitable water of the −40°C cutoff can be minimized by using approximate values such as those of Ross and Elliott (1996), allowing retention of soundings that would otherwise be considered missing. Because so little water vapor exists at these low temperatures, the values substituted make little difference in total W but, of course, the upper-layer estimates of RH and q will be very approximate.

The dry reports of the pre-October 1993 data can be brought more in line with the subsequent observations, as Ross and Elliott (1996) did, by substituting a fixed value of RH for RH < 20% but again, the adjustment will be more satisfactory if only monthly means are needed. However, their substitution value of 16% was estimated from data using the 1b coefficients and consequently their estimates could be slightly too moist.

When RH values calculated with 1b coefficients are available, it is not difficult to recalculate values using the 1a coefficients but the surprising number of high

<table>
<thead>
<tr>
<th>Error or practice</th>
<th>Effect</th>
<th>Where</th>
<th>When</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel resistor</td>
<td>Lowered means</td>
<td>Mainly north; at 850 mb</td>
<td>Cold seasons</td>
<td>Not large effect</td>
</tr>
<tr>
<td>SDD error</td>
<td>Raised or lowered means</td>
<td>All sites any elevation</td>
<td>Any season</td>
<td>Sign/size depends on temperature</td>
</tr>
<tr>
<td>−40 cutoff</td>
<td>Raised RH means</td>
<td>High elevations and latitudes</td>
<td>Mainly cold season</td>
<td>Very small effect on W</td>
</tr>
<tr>
<td>Rh &lt; 20%</td>
<td>Raised means</td>
<td>All sites, largest in subtropics</td>
<td>Depends on site</td>
<td>Quite large effect</td>
</tr>
<tr>
<td>Dpd = msg</td>
<td>Lowered means</td>
<td>Same</td>
<td>Same</td>
<td>Large effect</td>
</tr>
<tr>
<td>Rh &lt; 20%</td>
<td>Raised means</td>
<td>Same</td>
<td>Same</td>
<td>Small effect</td>
</tr>
<tr>
<td>Dpd = 30</td>
<td>Raised means</td>
<td>Same</td>
<td>Same</td>
<td>Quite small</td>
</tr>
<tr>
<td>Rh &lt; 20%</td>
<td>Raised means</td>
<td>Same</td>
<td>Same</td>
<td>Can make large difference</td>
</tr>
<tr>
<td>Rh = 16%</td>
<td>Raised means</td>
<td>Same</td>
<td>Same</td>
<td></td>
</tr>
<tr>
<td>Rh &lt; 20%</td>
<td>Raised means</td>
<td>Same</td>
<td>Same</td>
<td></td>
</tr>
<tr>
<td>Use of 1b values</td>
<td>Raised means</td>
<td>Same</td>
<td>Same</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Summary of effects of changes.
dewpoint depressions leading to negative values of RH suggests caution before adjusting the records. It is beyond the scope of this paper to delve into possible reasons for the large number of reports of low RH values seemingly excluded by the $1b$ coefficients. The forthcoming experience with the $1a$ coefficients will provide a guide to any retrospective adjustments that seem desirable. For instance, a new value to substitute for humidities less than 20% could be computed.

It is important to remember that all the changes discussed here were in data reduction algorithms or practices of reporting the observations; none of the changes and corrections involved a change in radiosonde or humidity sensor and any problems with the devices remain. This emphasizes that changes in data processing can have a large effect on data records and must be considered along with changes in instrumentation when climatological time series are examined. It also stresses the need for readily available metadata records that include all changes.

Acknowledgments. William Blackmore and Carl Bower of the National Weather Service provided insights into the measurement processes and valuable comments on the manuscript. Partial support for this work was received from the NOAA Office of Global Programs. Mention of specific manufacturers and products is for information only and does not necessarily indicate endorsements by the authors or NOAA.

APPENDIX

NWS SDD Sonde Stations and the Durations of their Relative Humidity Problem

<table>
<thead>
<tr>
<th>WMO ID No.</th>
<th>Station name</th>
<th>Start</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>70219</td>
<td>Bethel, AK</td>
<td>1 Mar 90</td>
<td>1 Nov 95</td>
</tr>
<tr>
<td>70261</td>
<td>Fairbanks, AK</td>
<td>1 Mar 90</td>
<td>1 Nov 94</td>
</tr>
<tr>
<td>70231</td>
<td>McGrath, AK</td>
<td>1 Mar 90</td>
<td>1 Nov 94</td>
</tr>
<tr>
<td>72764</td>
<td>Bismarck, ND</td>
<td>1 July 90</td>
<td>1 Jun 94</td>
</tr>
<tr>
<td>72476</td>
<td>Grand Junction, CO</td>
<td>1 Mar 90</td>
<td>1 Jun 94</td>
</tr>
<tr>
<td>72363</td>
<td>Amarillo, TX</td>
<td>1 Mar 90</td>
<td>1 Nov 95</td>
</tr>
<tr>
<td>72270</td>
<td>El Paso, TX</td>
<td>1 Mar 90</td>
<td>1 Nov 95</td>
</tr>
<tr>
<td>72261</td>
<td>Del Rio, TX</td>
<td>1 Apr 90</td>
<td>1 Jun 94</td>
</tr>
<tr>
<td>72260</td>
<td>Stephenville, TX</td>
<td>1 Jun 90</td>
<td>1 Jun 94</td>
</tr>
<tr>
<td>72265</td>
<td>Midland, TX</td>
<td>1 Apr 90</td>
<td>1 Nov 94</td>
</tr>
<tr>
<td>72365</td>
<td>Albuquerque, NM</td>
<td>1 Mar 90</td>
<td>1 Jun 94</td>
</tr>
<tr>
<td>72681</td>
<td>Boise, ID</td>
<td>1 Apr 90</td>
<td>1 Nov 95</td>
</tr>
<tr>
<td>72486</td>
<td>Ely, NV</td>
<td>1 Mar 90</td>
<td>1 Jun 94</td>
</tr>
<tr>
<td>72576</td>
<td>Lander, WY</td>
<td>1 Mar 90</td>
<td>1 Nov 94</td>
</tr>
<tr>
<td>72572</td>
<td>Salt Lake City, UT</td>
<td>1 Nov 90</td>
<td>1 Jun 94</td>
</tr>
<tr>
<td>72274</td>
<td>Tucson, AZ</td>
<td>1 Apr 90</td>
<td>1 Nov 95</td>
</tr>
<tr>
<td>72374</td>
<td>Winslow, AZ</td>
<td>1 Apr 90</td>
<td>1 Jun 94</td>
</tr>
</tbody>
</table>

REFERENCES


