## P1.6 COMPLETING INSTRUMENT METADATA AND ADJUSTING BIASES IN THE RADIOSONDE RECORD TO ALLOW DETERMINATION OF GLOBAL PRECIPITABLE WATER TRENDS

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### 1. INTRODUCTION

The global radiosonde record is the primary tool for determining climatic variations of temperature, moisture, and wind above the surface, but instrument and data processing changes have caused all long-term trends to be questioned. This paper describes initial stages of an effort to adjust radiosonde observations to a common hypothetical "reference instrument" to determine unbiased global precipitable water trends starting 1973.

There are two primary outputs of this research:

(1) Metadata listing all stations with valid soundings and their elevations and instrument types, to be released through the Comprehensive Aerological Reference Data Set (CARDS, possibly to be called postCARDS soon), and

(2) Soundings with temperatures and dew points adjusted for the instrument differences, to be equivalent to the "reference instrument." Since there is no operational reference instrument, the data is adjusted to be equivalent to the average of certain VIZ and Vaisala models. Strictly speaking, the adjustments are not "corrections" since the true state of the atmosphere is not known.

The first output should be useful to researchers who are pursuing their own instrument corrections, or who are comparing radiosondes with other data sources such as satellites. While beyond the scope of this project, satellite retrievals should differ from radiosonde data at individual stations in systematic ways according to the radiosonde instruments in use. Studies of satellite versus radiosonde differences should help confirm the accuracy of the inferred instrument metadata. A long homogeneous radiosonde record should help verify the calibration of different satellites used for climate studies, whether the satellites overlap or not.

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This paper focuses on the techniques used to identify instrument transitions at each station, the specific instrument types involved (not just that a transition occurred), common characteristics of each instrument type, differences from a "reference" instrument, and production of a data base containing observations adjusted forinstrument changes. A companion paper (Schroeder 2003) describes the processes of developing grids and averages from the grids, the resulting trends obtained from adjusted or unadjusted observations, and the magnitude of the adjustments.

### 2. BASIC ASSUMPTIONS

The basic approach to produce instrument adjustments is to infer instrument changes at each station so the metadata is complete, to use station transitions to determine differences between instrument types, and to use the instrument differences to statistically adjust each observation to be equivalent to an observation taken by the "reference" instrument. This approach depends on the validity of several assumptions:

Assumption 1: Some recent models are good enough to be used as a "reference," even though there is no operational reference instrument and the true state of the atmosphere is unknown. As in Nash and Schmidlin (1987), the reference instrument here is defined as the average of certain VIZ (now Sippican) models with carbon sensors and Vaisala models with capacitive sensors.

Assumption 2: Each reported temperature and dew point is adjusted to be statistically equivalent to the reference instrument. The adjustment is viewed as an "absolute" rather than a "relative" adjustment (statistically equivalent to the use of the hypothetical reference instrument) even though it is not known if the reference instrument is correct. Each instrument type is assumed to have common characteristics, so adjustments are developed for each instrument, not each station.

Assumption 3: Adjustments for each instrument type are obtained from the shortest "chain" of comparisons leading to a reference instrument, such as from "Type A" to "Type B" to a reference instrument. Data to compare each pair of models is from transitions between the instrument types at a group of stations, or simultaneous use of the different types at nearby stations.

Assumption 4: The adjustment from one instrument type to another is equal to the difference in the statistical distribution of variables at all stations in the comparison. Different environments are accounted for by considering temperatures at different pressures, or by considering dew points at different pressures and temperatures.

Assumption 5: Each instrument type is adjusted to be statistically equivalent to the reference by applying adjustments in the sequence of the "chain" of comparisons, regardless of the sequence of transitions at any particular station. A reference instrument still needs one correction to the mean of the reference instruments.

## 3. DATA PROCESSING STEPS

The steps to produce complete inferred metadata and an adjusted sounding data base are described in detail here. The input data is archived in Data Set 353.4 at the National Center for Atmospheric Research (NCAR), and starts in 1973. Each month's data is usually available for downloading a few weeks after the end of the month.

The steps are not followed strictly in sequence, and some steps may be repeated, partially or completely, to incorporate new information. Steps (11) to (16), which determine averages and trends of precipitable water, are described in more detail in Schroeder (2003).

### 3.1 *Preprocess data*

Step 1: Preprocess archived data to obtain files containing individual soundings and indicators of usability. Over 30 tests are performed on each sounding to reject unrealistic values, large inversions or superadiabatic lapse rates (often typographical errors), bad surface pressures, and very incomplete observations. Some frequently-occurring errors, such as miscoded heights (a 1000-mb height of 0 meters is often reported as 500 meters) and some reversed temperature signs, can be fixed in an automated way, and some observations have been fixed manually.

This step also checks the reported surface elevation by hydrostatically computing from the first above-surface height to the surface pressure. Published station lists have many errors in the elevation used as the surface level, with a few errors as large as 100 to over 200 meters. Although the surface pressure is reported only to the nearest millibar, it is usually possible to detect the exact observation of an elevation change of 5 meters or more, and a 1-meter change usually can be detected within a month. It is not possible to directly check a station move that does not change the elevation. Ships report an elevation of 0 meters, but their surface elevation usually computes to 5 to nearly 30 meters.

An extensive check of ship observations has been made, and programs were written to either track a ship as it travels, or to show all reports in a given area. Many ships were frequently called SHIP instead of using their regular call signs, and many misspellings of call signs were encountered. It is very common for a ship to report a latitude or longitude in error by 10° or 100° or in the wrong hemisphere, and these can be corrected if the ship reports almost every day.

Dropsondes were also identified and checked. Since many dropsonde observations were made in tropical cyclones, some extremely low heights were archived 500 or 1000 meters too high.

For each observation, a data indicator identifies certain problems in the sounding. For example, VIZ soundings, primarily operated by the United States, often had a certain form of data "censoring," where a relative humidity under 20 percent was reported as a dew point depression of 30° C. This program detects such observations by the presence of at least one 30° C dew point depression, no dew point depression over 30°, and no relative humidity under about 19 percent without a dew point depression of 30°. Most United States stations discontinued such censoring on 1 October 1993, but 74794 (Cape Kennedy, FL) continues this type of censoring.

### 3.2 *Prepare monthly time series for stations*

Step 2: Prepare time series of monthly values of over 200 data variables for each station, including stations with sparse data and ships, to help identify instrument-related discontinuities.

Some variables are indicators of data collection and processing, including observations at each hour of the day, surface pressure anomaly, reported and hydrostatically computed surface elevation, reported levels in each sounding, top pressure of the sounding, top pressure and lowest temperature with dew point, number of levels with low relative humidity (under 10, 20, and 30 percent) or high dew point depression (30° C or more than 30° C), average lowest relative humidity per sounding and lowest humidity per month, and occurrences of United States-style dew point censoring.

Other variables are data averages and anomalies. These include temperature, dew point, and height at 00Z, 12Z, and all hours, at 850, 700, 500, 300, and 100 mb (Low-level data includes the surface temperature and dew point and 1000-mb height). The final variables are averages and anomalies of total precipitable water and precipitable water above 700 mb.

This step also prepares time series of individual observations at each station, containing certain key variables to help identify the exact observations of instrument or other transitions.

### 3.3 ***Examine well-documented stations***

Step 3: Examine the time series at well-documented stations for discontinuities at times of reported transitions. This step develops common characteristics of each instrument type, and also helps confirm the accuracy of available metadata.

Considerable work has been done to develop global metadata, and this analysis depends on that metadata as a starting point. World Meteorological Organization (WMO) catalogs of radiosondes in use at specific times, and other sources including questionnaires sent to many countries, have been consolidated into one data base (Gaffen 1996). This metadata file can be supplemented by additional sources, including Gaffen (1993), recent radiosonde catalogs (Oakley 1998, WMO 2000), and other documentation such as Elliott et al. (2002). While these sources are incomplete and are occasionally inconsistent, much detailed metadata seems to be very accurate. However, the latest WMO catalog has been removed from the WMO web site, and it appears that efforts to maintain current metadata have nearly stopped.

As reported in Free et al. (2002), time series can be scanned automatically for change points, but slightly different methods produce substantially different change points. Automated methods do not identify the specific instruments involved, and often indicate that an instrument changed only at certain levels, or at different times at different levels. Visual examination of the time series in conjunction with available metadata is more likely to effectively identify particular instrument types.

All stations which use the same instrument should have similar characteristics. Temperatures and dew point depressions at each level should vary smoothly with location. Usually, but not always, all stations in a country have similar data processing procedures with the same instrument, but some exceptions have been found. When there is a transition, coordinated changes should occur at all levels, but differences may be undetectable in some variables and at some levels.

The most useful variable which indicates an instrument change is usually the 500-mb dew point depression. At 300 mb or higher altitudes, the dew point is often not reported, and at 700 mb or lower altitudes, there is often little discontinuity. While temperatures and heights at 100 mb show many large jumps (and discontinuities are probably larger at higher levels), many jumps do not seem to be consistent indicators of an instrument change, and some may be volcano-induced.

The available metadata lists dozens of instrument models, although some models are not distinguishable. Different models may not be distinguishable because they are really the same instrument, or the models use the same sensors but differ in other ways, or the new model has been carefully calibrated to reproduce the behavior of the old one. The next data examination probably will distinguish 40 to 45 different instrument types. Table 1 shows uniquely identified radiosondes which have been operationally used between 1973 and 2002.

If the instruments in a transition have different processing practices (such as censoring, omitting dew points beyond certain levels or at cold temperatures, significantly fewer or more levels reported) or are very different in responses at certain levels (such as Vaisala versus Russian sondes, which are quite dry and wet, respectively, in the stratosphere), then the exact observation of a transition may be identifiable. If the station uses both instrument types for a while, each instrument may be identifiable at each observation.

If differences between instruments are more subtle, such as a 1° or 2° difference in average dew point depression, then the transition time may be inferred with only a month or a few months of accuracy, and mixed use of two instrument types may be unverifiable. The most frequent way to infer the transition time in that case is to seek a discontinuity in the values of variables relative to the same month of the preceding year.

Processing procedures may help distinguish instruments but may obscure differences so it may not be possible to reliably distinguish similar instruments if high-altitude data is omitted.

### 3.4 *Infer instruments at undocumented stations*

Step 4  Examine time series at stations with little or no documentation for similar signatures of instrument types. This step does not just identify transition dates, but also infers the specific instruments involved. Data characteristics of the inferred instruments should match characteristics at well-documented stations.

Steps 3 and 4 may be repeated many times, often focusing on groups of stations, to refine inferences of instrument types and transition dates. In some cases, differences between nearby stations may help identify instrument transitions. In general, only a few different instrument models are realistic candidates for an unknown instrument type at a particular station. Candidate instruments may be identified by political alliances, colonial history, and instruments used in nearby countries.

The "penalty" for an incorrectly inferred instrument type varies, and following steps can help detect incorrect instruments. If the type is wrong but the time of use is correct, the wrong adjustment is applied and should make some variables more instead of less discontinuous. If the type is correct but the time of transition is wrong, the wrong adjustment is applied only for the period when the inferred instrument is wrong.

### 3.5 *Prepare list of instrument comparisons*

Step 5  When the identification of instrument types seems satisfactory for all or most stations, for each instrument type develop a sequence of instruments that can be compared until one of the instruments is included in the "reference."

This step first chooses the "reference instrument," since no single such instrument is operational. VIZ (since the early 1960s) and Vaisala (since the middle or late 1970s) have used modern humidity sensors. However, differences between models have been found, and most VIZ instruments average a few percent wetter than Vaisala. Here, VIZ models from 1973 through VIZ B (used until mid-1997) and Vaisala RS18 capacitive, RS80, and RS90 are included in the "reference." VIZ models used from about 1965 to 1972 were too dry in sunshine because the humidity sensor duct was accidentally heated (Teweles 1970), and VIZ B2 and Microsonde (at least since late 1999) are very dry at high levels. The Vaisala RS21 model also appears "too dry." While the true amount of moisture in the air is not known with high precision, -100° C or colder dew points frequently reported by some recent models appear unrealistically dry.

The choice of the average of instruments as a reference means that all instruments are adjusted. For a VIZ or Vaisala instrument included in the reference, the adjustment is half the difference between the two instruments (see steps 7 and 9).

The remainder of this step seeks the shortest "chain" of comparisons for each instrument type ending with one of the reference instruments, such as from "Type A" to "Type B," then to a reference instrument. It does not matter if any single station makes that exact sequence of transitions.

A comparison can be made from a station transitioning from one instrument to the other (in either order), or from nearby stations in a homogeneous environment using different instruments at the same time (examples are Berlin and East Germany, or Hong Kong and nearby China). Satisfactory paired comparisons include one to three years before and one to three years after a transition at a station, or one or more years of use of the two instruments at nearby stations. The number of observations involved in such "unintentional intercomparisons" is far greater than in the formal WMO intercomparisons.

For 1973 to 1996, no more than 3 sequential adjustments are needed for any instrument type, such as from "Type A" to "Type B" to VIZ to the average of VIZ and Vaisala. Most instrument types have a direct transition to or from VIZ or Vaisala (or another similar comparison), so most soundings have a sequence of two adjustments.

If there are no transitions to or from VIZ or Vaisala, adjustments from another type of sonde are used. For example, there are no clear-cut transitions between Japanese radiosondes and VIZ or Vaisala (except for possibly in Jakarta, Indonesia), so the most recent model is simply considered equivalent to VIZ. If this assumption is not accurate, the adjustment is biased, but all cases of the same adjustment have about the same bias (including earlier Japanese models, which are adjusted to the latest model), so trends are still corrected moderately well.

### 3.6 *Prepare station list of comparisons*

Step 6  For each pair of instruments, list all stations and time periods which can participate in the comparison. It is desirable to include as many stations as possible. If stations make the same transition at different times, it is more likely that real climate changes are not attributed to instruments.

At each station, the time period for each instrument should be an integer number of years to capture the annual cycle, and it is best to have a fairly equal amount of data on each side of the transition. An instrument transition in either direction, or a relatively brief period of use of a third instrument, is acceptable for making comparisons.

While not considered in data examinations so far, the next data examination will include comparisons involving fixed ship locations such as C7L and C7M, where alternating ships used two different instruments, changing every few weeks.

Instrument adjustments should not be obtained using only the stations that show the largest instrument-related differences, or else almost all adjustments will be too large and will overcorrect differences. However, if the instrument differences in similar environments vary significantly between stations, either a factor is omitted from the comparison (such as instrument responses in, above, or between clouds), or instrument submodels have different responses, or the instrument is incorrectly identified. So, determining differences helps check the accuracy of inferred instruments.

### 3.7 *Determine temperature differences*

Step 7: For each paired comparison, determine if there is a systematic temperature difference between the two types of instruments. In specified pressure layers (100 mb thick, above the surface and centered on 850, 700, 500, and 300 mb), differences are seen in percentiles of temperature ranges between instruments. Some differences may vary between day and night.

The surface observation is usually taken with permanent surface instruments (except for dropsondes and some field campaigns and ship observations), so there should be no discontinuity when radiosonde instruments change. Some discontinuities in the surface observation may result from changing the launch time by an hour or so to meet forecasting deadlines.

In data examinations to date, few systematic temperature differences were found in the lower and middle troposphere, indicating that operational radiation corrections have been generally effective, at least since the 1970s. This will be checked in more detail in the next data examination.

The temperature adjustment for a particular instrument type is simply the average difference between the models, for the pressure level, observed temperature, and possibly time of day. If "Type A" is 0.5° warmer than "Type B," the temperature adjustment from "Type A" to "Type B" is -0.5°. For the reference instruments, the adjustment is half the difference between instruments.

If temperature differences are not systematic between stations or levels at similar local times, they are likely to be actual climatic variations and no adjustments should be applied. Most instruments should have no temperature adjustments, at least in the lower and middle troposphere.

For each instrument type, the stored adjustments would be a three-dimensional table containing five rows (the pressure layers) and about 20 columns (temperature adjustments to apply in 5° intervals of temperature) for day and night.

### 3.8 *Apply temperature adjustments*

Step 8: Apply temperature adjustments as needed to each sounding and keep dew point depressions unchanged. In effect, this step changes dew points by the same amount as temperatures. This seems arbitrary, but is dealt with in step 9.

Adjustments are applied to each level in the report, except the surface. Stored adjustments are assumed to apply exactly only at the specified temperatures ( . . . -5°, 0°, 5°, . . .) and within 100 mb of the surface or at 850, 700, 500, or 300 mb. If the pressure is not exactly one of these values, or if the temperature is not divisible by 5°, adjustments are interpolated. Adjustments in the bottom layer (within 100 mb of the surface) are not interpolated within that interval, but are reduced by half within 10 mb of the surface. Since the day versus night differences have not been investigated in detail yet, some experimentation will need to be performed to see if adjustments should be interpolated at low sun angles.

### 3.9 *Determine dew point differences*

Step 9: Using adjusted observations from step 8 and paired instrument transitions from step 6, determine if there are systematic differences in atmospheric moisture between instruments.

Comparisons show differences in statistical distributions of dew point depressions within similar environments, which are the pressure intervals from step 7, divided here into 5° temperature intervals. For example, for instrument "Type A," the $50^{th}$ percentile of dew point depression in the 750 to 650-hPa layer, with temperatures between -2.5 and -7.5° C, may be 6° C, while the $50^{th}$ percentile for instrument "Type B" may be 8° C. In that case, "Type B" is 2° C drier than "Type A."

This comparison accounts for the temperature adjustment made in step 8. For example, suppose the thermistor and hygristor in "Type A" are radiatively heated by 1° relative to "Type B." If the hygristor is otherwise accurate, "Type A" reports a temperature 1° too warm, but the warmed hygristor reports a relative humidity that is too low, corresponding to a 1° larger dew point depression. Thermistor and hygristor errors would cancel out, so the dew point would be accurate without adjustments. Dew points between "Type A" and "Type B" would show no statistical differences.

However, step 8 lowers the temperature and dew point of "Type A" by 1°. A comparison of adjusted data would show comparable temperatures between both instruments, but the dew point of "Type A" would be 1° colder than "Type B." The adjustment in this step would raise the dew point by 1° (or lower the dew point depression by 1°), restoring the dew point to its correct value, and "Type A" and "Type B" would not be distinguishably different in either temperature or dew point.

Actually, it is unlikely that thermistor and hygristor errors would cancel each other out, and dew point differences are much larger than temperature differences. This step quantifies the differences, whether they arise from thermistor, hygristor, or processing variations.

The stored form of the adjustments is similar to the stored temperature adjustments, except that an additional dimension is added to the arrays to store separate adjustments at about 20 values of dew point depression.

For the reference instruments, adjustments are not "mirror images" (the same values with opposite signs), but still use the same comparisons. If a 6° dew point depression has the same percentile for one instrument as an 8° depression for the other, then the first instrument is 2° moister than the second, and the reference instrument would have a 7° dew point depression. For the first instrument, the adjustment to the dew point depression would be +1° when the reported dew point depression is 6°, but for the second instrument the adjustment to the dew point depression would be -1° when the reported dew point depression is 8°.

Adjustments are slightly smoothed to allow noninteger adjustments in the range where the dew point depression is reported to the nearest whole degree, and to moderate the adjustments at the extremes of the probability distributions (outside the $5^{th}$ to $95^{th}$ percentile). Also, special handling is needed for missing or censored (30°C dew point depression to indicate relative humidity under 20 percent) dew points.

This adjustment process is intermediate in sophistication between extremes of a fixed adjustment for an instrument, and attempting to model every aspect affecting the sounding (such as cloud layers, sun angle, sensor lags, balloon rise rate, and precipitation) as a deconvolution problem to reconstruct the sounding in detail.

### 3.10 *Apply dew point adjustments*

Step 10: For each observation, apply adjustments in sequence to modify the dew points to match the distribution of dew points observed for the "reference" instrument. The same sequence of adjustments is used for all observations using the same instrument type. The adjustments are not customized for each station except to the extent that the station environments differ.

In each sounding, all dew points above the surface are adjusted. The surface level is unchanged. Adjustments are interpolated between layers, temperature intervals, and dew point depression intervals. A "censored" dew point (dew point depression of 30° when the relative humidity is under 20 percent) is not changed, and this procedure does not fill in a missing dew point. The adjusted sounding looks like the original sounding, except that the dew points are changed to statistically compensate for instrument biases.

After this step, time series of the same variables from step 2 are produced using adjusted observations. If an instrument is incorrectly inferred, the wrong adjustment is applied while the instrument is incorrect, and this usually produces a transient discontinuity. The inferred instrument or time of transition is changed and all steps are repeated until all or almost all "mysterious" cases are resolved. As mentioned in step 4, candidate instrument types should not be chosen randomly. Some cases may involve use of more than one instrument type, or actual errors in operation.

Even if an instrument type is correct, since a single adjustment table is prepared for each instrument type, some stations may appear to be uncercorrected and others may appear to be overcorrected. The remaining differences are probably caused by local factors which are not accounted for in the comparisons of steps 7 and 9, such as different radiation corrections.

Systematic differences of groups of stations using the same instrument may identify a previously undocumented model. In the previous data examination, some stations reporting use of Australian Phillips Astor instruments were moist and others were dry, and some switched from a moist to a dry instrument. Developing separate adjustments for these "submodels" produced much more consistent results.

## 4. PRELIMINARY DATA ASSESSMENT

In general, earlier radiosonde types have been supposed to report conditions which average too warm and wet. Early temperature sensors were more subject to radiation errors, especially heating above the air temperature in sunlight, and newer sensors are better shielded or corrected. Older humidity sensors would slowly respond to the usual drying with height, and newer sensors respond faster and more accurately.

Actually, older instruments can have opposite errors. At night, a temperature sensor can cool below the air temperature. A humidity sensor can indicate a relative humidity that is too low if it is radiatively heated (or if the temperature and humidity sensors are both heated and the temperature error is corrected, but the reported relative humidity is not changed), and many older types of sensors record relative humidity around 70 to 90% in clouds. However, warming and drying errors of older radiosonde types dominate.

Some additional general findings from the preliminary examination of global data through mid-1996, and the current examination through mid-2002, are as follows:

(1) Some instrument types appear to be more than 15 percent too wet or too dry, compared to the "reference" instruments.

(2) Some earlier radiosonde models appear to be too dry. While United States radiosondes were too dry in the late 1960s and early 1970s (before the 1973 starting date of this study), and the cause has been well-documented (Teweles 1970), other models, possibly derived from a similar VIZ design, appear to have similar errors that persist as late as 1984. Also, the Vaisala RS-21 sonde is extremely dry in many cases (Richner and Phillips 1982), apparently by 20 percent or more in South Africa in the early 1980s. Such errors need to be investigated since some errors may be misapplied radiation corrections.

(3) The same radiosonde in different regions has many similar data characteristics. Russian radiosondes in Cuba and Vietnam are quite wet, and the Vaisala radiosonde "family" shows a similar sequence around the world. However, French sondes outside France and Australian sondes outside Australia seem much different from radiosondes in the home countries. French sondes in France show substantial drying for a few years in the middle 1980s, but French sondes in Africa show substantial moistening from about 1977 to 1982, and in French Polynesia show varying trends that may be significantly influenced by El Niño.

(4) Different instruments with the same hygristor type (such as carbon) or even the same hygristor (such as VIZ) often seem different. Russian goldbeater's skin sensors are moist, but British sondes (with goldbeater's skin sensors) in the mid-1970s were about as dry as carbon sensors.

(5) Most steplike changes in any variable seem to be related to changes in instruments or processing. Changes which primarily affect the stratosphere and upper troposphere are quite frequent and could indicate adjustments to radiation corrections or data processing formulas, or temporary volcanic changes. Instrument-related changes often appear larger and more abrupt than the large recurring natural variations caused by El Niño and La Niña.

(6) Tropospheric temperature discontinuities are quite small, but dew point discontinuities from instrument changes can exceed 5° C. In some cases, the average dew point depression is inflated by reporting under 20 percent relative humidity as a 30° C dew point depression. In other cases, similar censoring but with a different threshhold is suspected. The inflated dew point depressions exaggerate the differences from a period when there is no dew point censoring.

(7) While a station occasionally changes the radiosonde launch time by 1 hour or so to meet local forecasting deadlines, some changes in surface temperatures or dew points do not seem to be explained by changes in observing times.

(8) Almost no discontinuities have been noticed with VIZ instruments in the United States from 1973 through the VIZ B model. The VIZ B2 appears slightly drier, and the Microsonde is quite dry. The ending of dew point "censoring" at most stations on 1 October 1993 did not produce a noticeable discontinuity in unrelated variables. No discontinuities were noticed with the switch to a new hygristor about 1981. Some gradual changes in the average dew point and proportion of observations with dew point "censoring" before 1993 may indicate minor changes in formulas in dry conditions. However, small discontinuities in adjustments were noticed around 1981 and 1993, showing that the adjustment process itself may reveal some subtle instrument or processing changes that are not seen in the data itself. Also, according to Elliott et al. (2002),

Sippican started manufacturing hygristors in its Mexican plant in summer 1999. In this data, VIZ (Sippican) models became noticeably drier between July and September 1999.

(11) As an example of consistent signals, the typical sequence of Vaisala instruments has the following characteristics of five different instruments since 1973. Names of the models may not be correct, but the signals are consistent at most stations that used only Vaisala instruments.

(a) RS18 hair hygrometer: Wet with a low dew point depression.

(b) RS18 capacitive humidity sensor: Noticeably drier dew point depression and lower precipitable water. Some dew point depressions exceed 30° C. Indicators of data processing do not change (Dew points are usually reported only to -40° C before and after this transition), so the exact observation of change is not often identifiable. The transition to this sensor appeared to occur as early as mid-1974 in Brazil, 1975 in Finland, and 1976 in much of Europe and South Africa.

(c) RS21 capacitive humidity sensor: Extremely dry at many locations, especially around South Africa, where the dew point depression often exceeded 40° C. In many cases, dew points began to be reported to -60° C temperatures or 200 mb, allowing identification of the exact observation of change. Steplike drying in South Africa was about 30 percent at some stations, but only a few percent (although still with a spike in dew point depression) at some European stations. The dryness is documented in Richner and Phillips (1982). Some countries using Vaisala, such as Sweden, do not show a period of unusual dryness. While this could be a radiative problem, temperature anomalies are usually not different between day and night and even night dew points are depressed. Excessive dryness was seen in some stations as early as 1977, and at some stations for less than a year, but in South Africa the dryness lasted from the late 1970s to about 1984 or 1985.

(d) RS80 and RS90 capacitive humidity sensor: Return (generally) to moderate dryness of the previous model. In some stations, part of the recovery from excessive dryness was gradual, indicating some intermediate adjustments. Starting the late 1980s, gradual drying again occurred at some locations (Zipser and Johnson 1998), but some locations using RS80 in the Pacific seem to be extremely wet. The dryness may have reflected minor changes in the humidity sensor or its packaging. Most stations continuously using Vaisala changed to the RS80 instrument in the early to the late 1980s. According to the latest WMO catalog (WMO 2000), all stations using Vaisala use the RS80 model. However, Vaisala News reports that certain stations have switched to the RS90 model, such as in Poland in April 1999 (Finne 2000). No difference has been noticed between RS80 and RS90 sondes.

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Table 1. Tentative list of distinct radiosonde types in use between 1973 and mid-2002.

| Model | Summarized characteristics |
|---|---|
| Capacitive hygristor | |
| Vaisala RS18, RS80, RS90 | Moderately dry, all considered the same, a “reference” instrument |
| Vaisala RS21 | Quite dry, drier than RS18 or RS80 |
| Vaisala RS21 South Africa | Exceptionally dry compared to all other models |
| Carbon hygristor | |
| VIZ, VIZ A, USA VIZ B | Moderately wet, “censoring” frequent, a “reference” instrument |
| VIZ B2 | Slightly drier than VIZ models above |
| VIZ Microsonde | Almost as dry as Vaisala RS80 |
| VIZ with duct problem | Only at sta 93944 after 1972, would have low humidity in daytime |
| Space (SDS) or MSS | May be wetter than VIZ |
| AIR | Some sondes may use wet-bulb thermometer as humidity sensor |
| Swiss SRS-400 | VIZ sensor but may be drier than VIZ |
| Graw RSG | Only 4 stations, about as dry as Vaisala RS80 |
| Austria Elin | Appears to be the same as VIZ, used only at 3 stations |
| Korea VIZ Jinyang | Made to VIZ design, currently considered the same as VIZ |
| Canada Viz B | Almost as dry as Vaisala RS80 at 100 mb |
| Japan Meisei RSII-69 | Only station 89532 |
| Japan Meisei RSII-78 or Antarctica 78 | About 10% drier than Meisei RSII-56 |
| Japan Meisei RSII-85 or R-91 | RSII-85 only at station 96749, small drop in 300-mb dew point |
| Australia Philips Mark II.5 | Distinctly drier than Philips Mark II (LiCl) |
| Australia Philips Mark III | Some stations report dry relative humidity as 30° C dew point depression |
| Australia Astor RS4 | Outside Australia, wetter than RS4 LiCl, narrow dew pt depress range |
| Goldbeater’s skin hygrometer | |
| Swiss SRS-400 | Possibly one of wettest goldbeater’s skin instruments |
| United Kingdom Kew Mark IIB | Moderately dry instrument |
| Kew Mark III | Slightly wetter than Mark IIB |
| French Mesural | May need to divide into individual models but uncertain discontinuities |
| China GZZ2 through early 1975 | Dry instrument, quite a few missing surface observations |
| China Shanghai Radio | Moist |
| Russia RS049 (RZ049) | Almost all dew points reported (applies to all except MARS), quite moist |
| Russia A22 | About the same as RS049 |
| Russia RKZ1 | RKZ1, 2, and 5 may be slightly drier than RS049 and A22 |
| Russia RKZ2 | Usually no discontinuity if switching from RKZ1 |
| Russia RKZ5 | Usually no discontinuity if switching from RKZ2 or RKZ5 |
| Russia MARS | Dew point not reported if temperature under -40° C |
| Russia MRZ | Almost all dew points reported, MARS and MRZ usually drier than RKZ |
| Hair hygrometer | |
| Vaisala RS18, RS15, or earlier | Moderately wet |
| Japan Meisei RSII-56, SCM, or ES61A | Wet, last 2 reported with AMTEX’75 experiment on ships |
| East Germany Freiberg | Assumed to be similar ro Russia RKZ2 |
| Germany Graw M50, M60, or Sprenger | Wet, no discontinuities noticed when changing models |
| Lithium chloride hygristor | |
| VIZ LiCl | Not reported manufactured after early 1960s |
| Australia Astor 402 or Mark I, Philips Mark II | Quite wet, very small dew point depression |
| Australia Astor or RS4 | Used outside Australia, dry but few rel hum <30% |
| India Audiomodulated | Dry, suspected radiative heating problems |
| India Mark 3 | Not necessarily wet, based on environment |