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GLOBAL PRECIPITABLE WATER VARIATIONS SINCE 1973 BASED ON PRELIMINARY RADIOSONDE INSTRUMENT ADJUSTMENTS

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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.

Another paper in this meeting (Schroeder 2003) 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, and differences from the reference instrument. Since no operational reference instrument exists, the reference instrument used in this study is the average of certain VIZ (now Sippican) and Vaisala models widely used in the 1980s and 1990s. If a different instrument type (or types) had been chosen as the reference, the overall trends should be very similar, although the absolute average values would differ, if that chosen instrument turned out to be warmer or colder, or wetter or drier, than the VIZ and Vaisala average.

The steps involved in determining global trends of one or more atmospheric variables (such as total precipitable water), starting with raw data archived in Data Set 353.4 at the National Center for Atmospheric Research (NCAR), are as follows. The steps were not followed strictly in sequence, and some steps may be repeated, partially or completely, to incorporate new information. Steps (1) to (10) are described in more detail in Schroeder (2003), and the other steps are described here.

(1) Preprocess the data files to eliminate bad data or observations (such as fragmentary soundings) and to correct certain erroneous data (such as erroneous elevations, some mislabeled stations, some temperature sign errors, and some miscoded heights).

(2) Prepare time series of monthly values (counts, averages, and some extremes) of over 200 data variables for each station, including stations with sparse data and ships. Also prepare time series of individual observations containing certain key variables to help identify the exact observations of instrument or other transitions.

(3) Starting at well-documented stations, examine the time series for discontinuities in the data variables at the times of reported transitions. This helps develop common characteristics of each instrument type, and also helps confirm the accuracy of the available metadata.

(4) Examine time series at stations with little or no documentation for similar signatures of instrument types. 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.

(5) When the identification of instrument types seems satisfactory for all or most stations, develop a sequence of pairs of instruments that can be compared until one of the instruments is included in the "reference." For example, instrument type A might be compared with type B, which then can be compared with type C, which finally can be compared with one of the reference instruments. A "comparison" can be one of two types: A transition from one instrument to the other at a station, or simultaneous use of the two instrument types at nearby stations. It is not necessary for all of the comparisons to be made at any single station, since it is assumed that the same instrument has the same characteristics at all stations where it is used.

(6) For each pair of instruments to compare, list all stations and time periods which can participate in the comparison. 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. It is desirable to have as many stations as possible included in the comparison, and especially to compare the instruments averaged together as the "reference." It is best to have about the same

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number of radiosonde observations on each side of the comparison.

(7) For each paired comparison, first determine if there is a systematic temperature difference between the two types of instruments. Within specified pressure layers (100 mb thick), differences would be seen by different percentiles of various temperature ranges between the instruments. In some cases, the temperature differences vary between day and night. If the temperature differences do not appear systematic, they may be random and not due to instrument errors. In each comparison where the temperature differences appear to be instrument-caused, prepare adjustment factors that statistically modify the temperature distributions for instrument "type A" to match the distribution for instrument "type B." For VIZ and Vaisala instrument models included in the "reference," prepare VIZ to Vaisala and Vaisala to VIZ differences. The correction of VIZ or Vaisala to the average is half of the difference between models.

(8) Apply the temperature corrections as needed to each observation and keep the dew point depressions unchanged. Temperature adjustments are applied sequentially, such as from type A to type B, then to Vaisala, then to the "reference." In effect, this step changes temperatures and dew points by the same amount.

(9) Using the adjusted observations from step 8 and each list of paired instrument transitions from step 6, determine if there are systematic differences in atmospheric moisture between instruments. The moisture comparisons are more complex than the temperature comparisons, since the percentile distributions are computed for each 5° C interval in each pressure interval. Prepare adjustment factors that statistically modify the dew points for instrument "type A" to match the distribution for instrument "type B."

(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. This produces a data base which still contains all usable observations, but each observation is adjusted to compensate for instrument biases.

(11) The remaining steps compute global averages which are used to derive trends. For each day, place all available observations (or computations of the desired variable, such as total precipitable water) on a grid. Here, 00Z observations are weighted half as much as observations at other times and are attributed both to the day that is ending and the day that is starting.

(12) From the daily grids for each month, develop monthly grids containing averages of all observations in each grid box. Only grid boxes with usable observations on at least 10 percent of the days are used for statistics.

(13) The best way to fill in the grid, since many large areas have no observations, is to express averages in terms of anomalies and then develop grids of anomalies. Develop grids of climatological averages of the desired variable for each month of the year in each grid box with observations on at least 10 percent of the days.

(14) Fill in the climatological grids by searching around each empty box, weighting nearby boxes with sufficient observations inversely according to distance. In the weighting process, adjust precipitable water from other boxes to the elevation of this grid box, and reduce the weighting of grid boxes with a large difference in elevation from this grid box. Also, compute a climatological annual average grid as the average of the 12 monthly climatological grids, and compute global monthly and annual average climatology values by area-weighting the grid by the cosine of the latitude.

(15) Express the monthly average grids from step 12 in terms of anomalies from the climatological averages. An annual anomaly grid for any year is simply the average of the 12 monthly anomaly grids.

(16) Fill in monthly and annual anomaly grids using the same procedure as in step 13. Compute area-weighted global anomalies as in step 14. To get actual values of precipitable water if desired, add back the climatological values. Area-weighted averages also can be computed for regions (such as a given latitude-longitude box) or latitude bands.

Since evaluation of data through 2002 is not complete, this paper describes results from an earlier evaluation of data from 1973 to mid-1996. While identification of instrument types and transitions improves with each reexamination of the data, future changes are unlikely to have a large effect on the global trends found in that study.

2. DETERMINING GLOBAL PRECIPITABLE WATER AVERAGES

This section discusses steps 11 through 16 in more detail than in the summary above. The first 10 steps produce adjusted radiosonde observations. An adjusted observation differs from an unadjusted observation only by having different dew points (and possibly temperatures) at the same pressure levels as in the original observation.

Precipitable water (PW) is obtained from a single sounding by summing up the specific humidity (times 1 / *g*) in 1-hPa layers from the surface to 1 hPa. Saturation vapor pressures, from which other moisture variables are obtained, are computed from the Wexler formula (Buck 1981, eq. 5a, and eq. f_{w5} in Table 3).

If dew point "censoring" is detected, a dew point depression is substituted which corresponds to a relative humidity about 17 percent, or gradually lower as the temperature exceeds 12° C. (Dew point "censoring," primarily used with VIZ instruments until 1993, reports a relative humidity under 20 percent as a 30° dew point depression. Such censoring is assumed to occur in a sounding if there is at least one 30° dew point depression and none greater than 30°, and no levels with lower relative humidity than about 20 percent except for the 30° dew point depressions.)

Between reported levels, relative humidity is assumed to vary linearly. If the dew point is not reported at the surface, the relative humidity is set to 70 percent, minus 1 percent for each degree warmer than 10° C. Above the top reported dew point, relative humidity is assumed to stay constant, but above the tropopause level, the relative humidity is reduced 1 percent per millibar, but not to below 20 percent. From 300 to 1 mb, the specific humidity is not allowed to exceed certain values. These adjustments allow the computation of a plausible PW value even if soundings end at differing pressures, but will not restore lost information content. Observations with insufficient humidity data near the surface are rejected.

After computing PW values for each usable observation, steps 11 to 16 are performed to develop statistics of global averages and trends. The steps are discussed in more detail as follows:

Step 11: For each day, place all available precipitable water values on a grid. In this study, the grid boxes are 2.5° latitude and longitude, starting with a box centered at 0° N, 0° E. The 00Z observations (actually, 21Z through 02Z) are weighted half as much as observations at other times and are attributed both to the day that is ending and the day that is starting. Each day has two grids stored. One grid contains a number from 0 to 9 in each box, where each 00Z (21Z to 02Z) observation is weighted 1 unit and observations at other hours (03Z to 20Z) are weighted 2 units, and the other grid contains the weighted average of all observations in the grid box. It is rare to have more than 4 observations in a day in a grid box.

Step 12: From the daily grids for each month, develop monthly grids containing averages of all observations in each grid box. Only grid boxes with usable observations on at least 10 percent of the days are used for statistics.

Step 13: Develop grids containing climatological averages for each month of the year. Set up two grids for each month of the year. One of the two grids contains the total number of points (usually twice the number of soundings) for each month, and the other grid contains the weighted average. Only grid boxes with usable observations on at least 10 percent of the days are used for statistics.

Step 14: Fill in the monthly climatological grids by scanning in a diamond-shaped area around each empty box. Weight observations inversely according to distance, with the weight decreasing faster in the meridional direction. In the weighting process, adjust precipitable water from other boxes to the elevation of this grid box. Further reduce the weighting of grid boxes with a large difference in elevation from this grid box. While the weighting process and factors are empirical, this gives quite realistic patterns, including identification of the South Pacific Convergence Zone (SPCZ) and computation of realistic global averages that are close to other published averages. Also, compute a climatological annual average grid as the average of the 12 monthly climatological grids, and compute global monthly and annual average climatology values by area-weighting the grid by the cosine of the latitude.

Step 15: Express the monthly average grids from step 12 in terms of anomalies from the climatological averages. An annual anomaly grid for any year is simply the average of the 12 monthly anomaly grids.

Step 16: Fill in monthly and annual anomaly grids using the same procedure as in step 13. The reason for filling in grids of anomalies instead of absolute values is that a conservative averaging process tends to fill in large data voids with values near the average of the surrounding (but distant) stations. With anomaly grids, the average is likely to be near zero, implying near-normal conditions. With grids of actual values, the average of surrounding stations is likely to include unrepresentative climate regimes. Distortions are most noticed if a station operated only in part of the data period. For example, observations are only occasionally made at Christmas Island, in a narrow equatorial dry area, while surrounding stations are in the very moist Inter-Tropical Convergence Zone (ITCZ). When no observations are available at Christmas Island, a grid-filling procedure projects the ITCZ

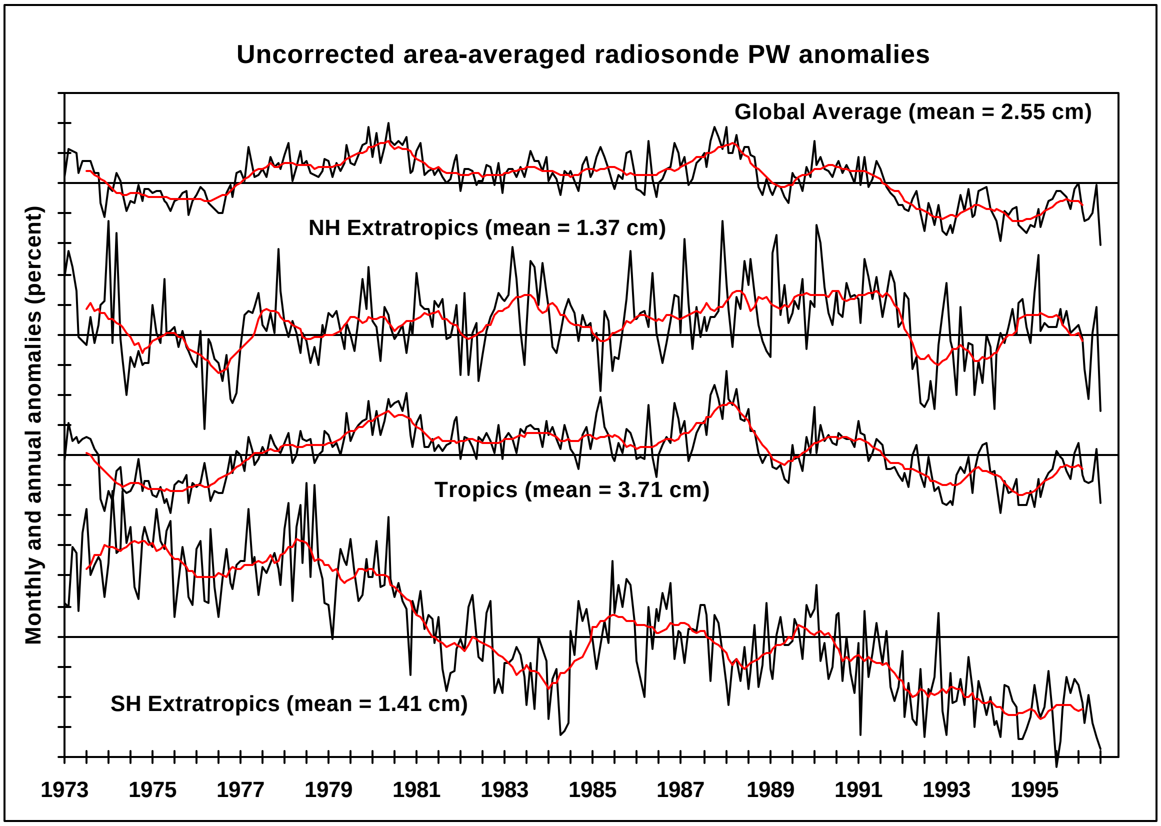

Figure 1. Uncorrected area-averaged radiosonde precipitable water anomalies, based on a preliminary examination of global radiosonde data from January 1973 to early July 1996. The tick marks at the bottom represent January and July of each year. The straight lines in each category represent zero anomalies, and the tick marks at the left are separated by 2 percent. The smoothed lines in each category are 12-month running averages.

averages or anomalies to that location. Projecting anomalies into that area is reasonable (When that part of the ITCZ is moist, Christmas Island is usually moist relative to its average), but projecting averages is unreasonable, since Christmas Island is almost never as wet as the ITCZ.

In step 16, compute area-weighted global anomalies as in step 14. To get actual values of precipitable water if desired, add back the climatological values. Area-weighted averages also can be computed for regions (such as a given latitude-longitude box) or latitude bands.

3. PROBLEMS WITH UNCORRECTED TRENDS

In the Introduction, it was stated that radiosonde instrument changes make upper air trends derived from radiosonde data highly questionable. While global averages and trends from surface data have similar difficulties (in addition to spurious warming from urban growth), major global data bases appear to have corrected these errors satisfactorily and still show about 0.3° C warming since the late 1970s (Peterson et al. 1998, Jones et al. 1994).

Reported trends above the surface are more variable and more disputed. Microwave Sounding Unit temperatures from NOAA polar orbiting satellites starting 1979 show tropospheric cooling except for brief warming in the 1997-98 El Niño, and substantial cooling in the lower stratosphere (Waple et al. 2002). Parker et al. (1997) state that, for the lower stratosphere, "this gradual relative global cooling is likely to be the outcome of many asynchronous, instrument-related, sudden coolings at individual stations."

The amount of water vapor in the air is expected to grow in step with global warming as

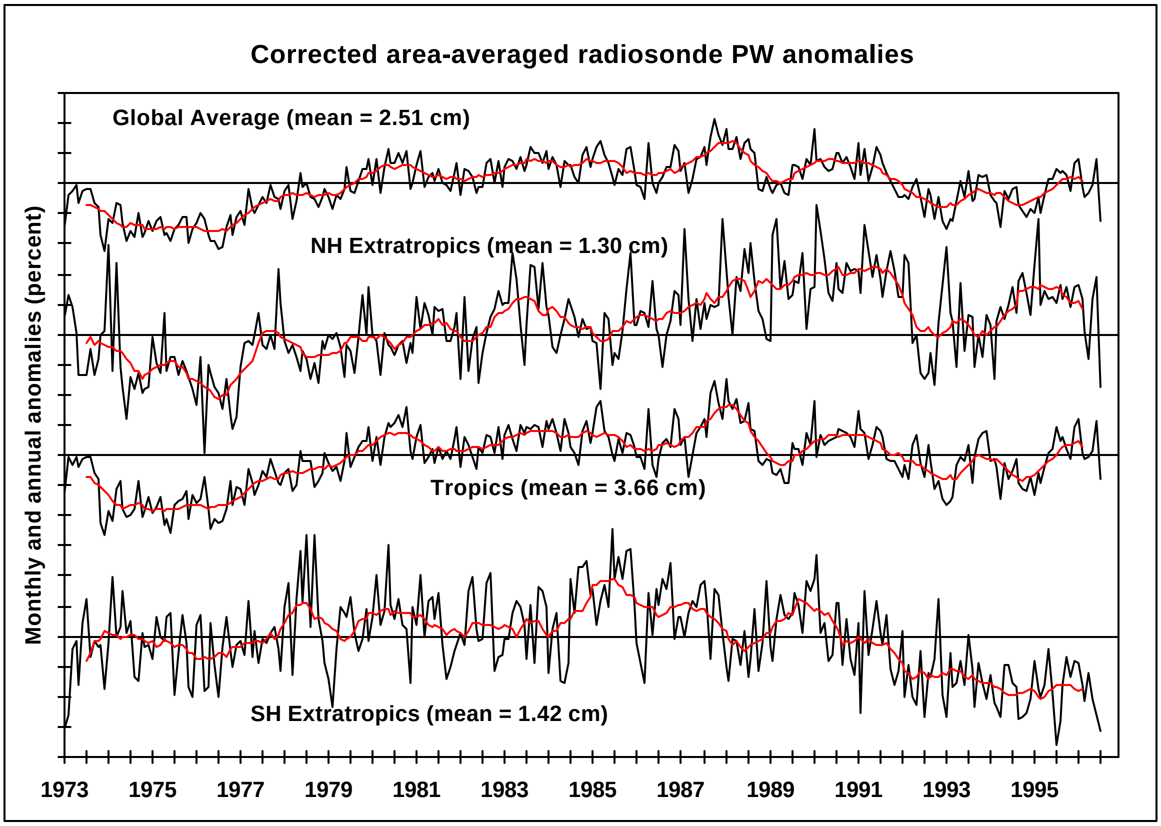

Figure 2. Corrected area-averaged radiosonde precipitable water anomalies, based on a preliminary examination of global radiosonde data from January 1973 to early July 1996. The tick marks at the bottom represent January and July of each year. The straight lines in each category represent zero anomalies, and the tick marks at the left are separated by 2 percent. The smoothed lines in each category are 12-month running averages.

long as the relative humidity stays approximately unchanged, but an analysis of total precipitable water in the tropics from 1979 to 1995 (based on TIROS Operational Vertical Sounder data from the NOAA satellites, but calibrated by radiosondes) shows about 3% steplike drying starting in the late 1980s (Schroeder and McGuirk 1998a). This drying has been attributed to gradual introduction of more responsive radiosondes (Ross and Gaffen 1998).

As mentioned in the Introduction, this study describes an effort to identify specific radiosonde instrument changes and make preliminary adjustments to compensate for the instrument-caused discontinuities so unbiased water vapor trends can be determined. Schroeder (2003) describes the methods for identifying instruments and adjusting to a common standard. This paper describes some preliminary findings of a preliminary examination of global radiosonde data from 1973 to mid-1996. Examination of the data through 2002 is not completed, but is not likely to result in large changes to the trends from 1973 to 1996.

When the steps from Part 2 above were applied to uncorrected radiosonde observations, monthly and average grids of global average precipitable water anomalies were obtained. A 2.5° global grid was used, containing 73 rows from 90° S to 90° N and 144 unique columns from 180° W to 177.5° E.

In preparing daily grids, each precipitable water value was adjusted to the average elevation of its grid box using a 2.5-km scale height. For example, if a station was 100 m below the average elevation in a grid box, its precipitable water was reduced by about 4 percent (specifically, multiplied by *exp* [-100/2500]). All soundings on each day in each grid box were averaged to obtain a daily value, but a sounding near 00Z was weighted half

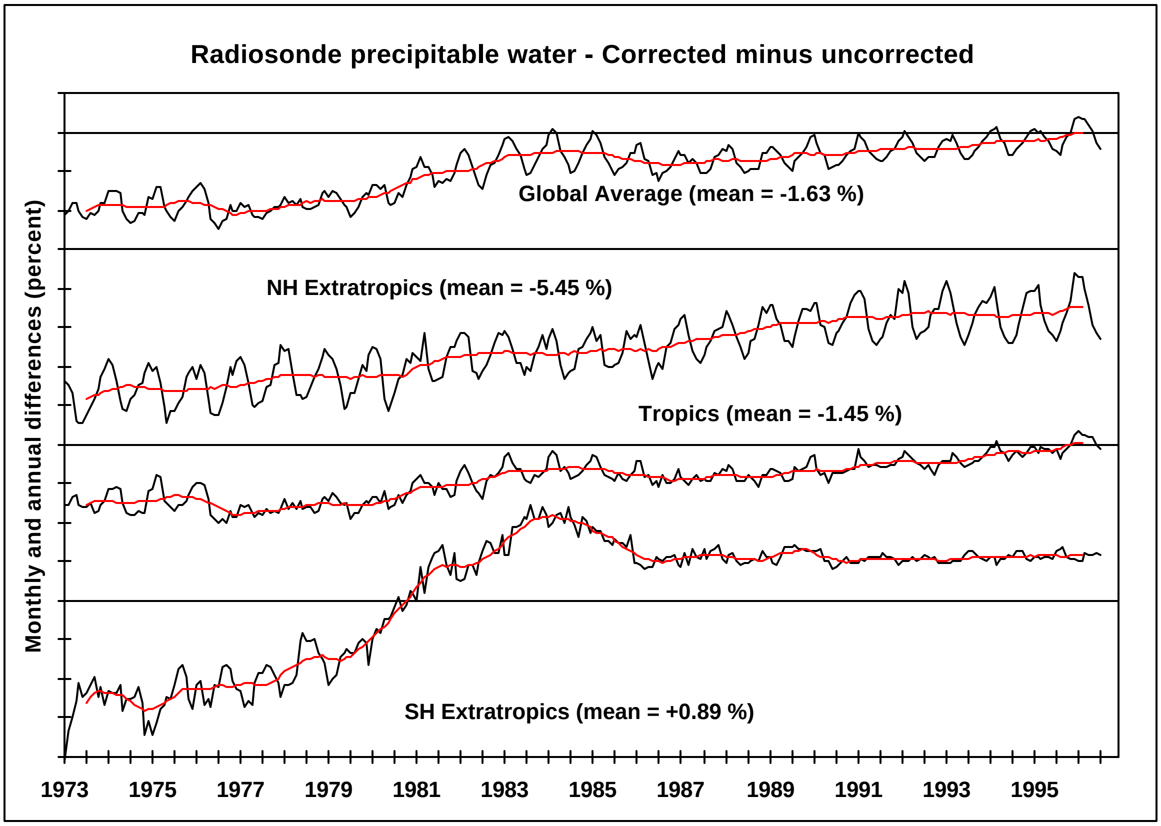

Figure 3. Corrected minus uncorrected area-averaged radiosonde precipitable water values (in percent of the corrected mean), based on a preliminary examination of global radiosonde data from January 1973 to early July 1996. The tick marks at the bottom represent January and July of each year. The straight lines in each category represent zero anomalies, and the tick marks at the left are separated by 2 percent. The smoothed lines in each category are 12-month running averages.

to that day and half to the preceding day.

Monthly climatological grids averaged all nonempty days in that month in all years. Even those grids were mostly empty, so the grids were filled to determine global averages. The precise method of filling grids (step 14 above) is not extremely important in determining trends, but it is important in determining absolute averages. After obtaining filled climatology grids, area-weighted global and regional averages were computed. The annual climatology was the average of the monthly grids. With uncorrected data, the long-term climatological average amount of precipitable water is 2.55 cm. The "tropical half" of the world (30° N to 30° S) contains about 73 percent of the global precipitable water.

To produce time series from the monthly grids, the grids were not filled until the climatology was developed. Each grid box with soundings in each monthly grid was expressed as an anomaly from the climatological mean, and the grids of anomalies were filled, as described in steps 15 and 16 above.

As shown in Figure 1, uncorrected trends show possible weak global moistening in the late 1970s (depending on whether the 1973 moist period was temporary) followed by drying starting in late 1988. Trends are similar in the tropics since the global average is dominated by the tropics. The Northern Hemisphere extratropics moistened from the late 1970s to the early 1990s, but the Southern Hemisphere extratropics dried over 10 percent since the late 1970s.

The same procedure was followed to develop monthly grid averages using the adjusted soundings. As shown in Figure 2, the corrections caused the global and tropical moistening trend of the late 1970s to be increased, but the drying starting in 1991 (or late 1988 in the tropics) was not

Table 1. Uncorrected and corrected area-averaged precipitable water differences between periods (percent). Uncorrected differences are shown in *italics*, and corrected differences are shown in **bold**.

	1978-87 minus 1973-76	1989-95 minus 1978-87	1989-95 minus 1973-76
Northern Hemisphere	*+1.3%*	*- .0%*	*+1.2%*
Extratropics (30° to 90° N)	**+2.9%**	**+2.0%**	**+4.9%**
Tropics (30° S to 30° N)	*+2.8%*	*- 2.0%*	*+ .7%*
	+3.8%	**- .9%**	**+2.8%**
Southern Hemisphere	*- 3.9%*	*- 3.8%*	*- 7.5%*
Extratropics (90° to 30° S)	**+2.2%**	**- 2.8%**	**- .7%**
Global average	*+1.6%*	*- 2.0%*	*- .4%*
	+3.4%	**- .8%**	**+2.6%**

eliminated by applying the corrections. Over the entire 1973 to 1996 period, there was a slight moistening trend. With the corrections, the Northern Hemisphere extratropics moistened substantially although the period since 1991 was drier than the late 1980s. The Southern Hemisphere extratropics dried noticeably since 1985.

Figure 3 shows the average percentage magnitude of the preliminary corrections. The corrections were negative at the beginning (almost all stations used "moist" instruments) and reached zero only in 1996 (on a grid basis, "moist" and "dry" instruments were about equally in use). Since the average correction in the 1970s was about -4%, an uncorrected global trend would underestimate moistening (or overestimate drying) by about 4 percent from 1973 to 1996. The corrections in the northern hemisphere extratropics were still about -3% in 1996, reflecting the large number of "moist" instruments still in use in Russia, China, and India. Preliminary examination of recent data in these countries showed only a few stations that appear to have switched to modern-type instruments by 2002. The substantial moistening corrections in the southern hemisphere extratropics in the early 1980s reflected large numbers of stations using excessively dry Vaisala RS21 instruments, especially around South Africa. Of course, anomalies in each country were projected into a large area of ocean, so any southern hemisphere extratropics trends may be questionable regardless of the quality of the corrections.

Table 1 shows the differences between three periods that define decadal-scale climatic regimes. Climate shifts about 1977 and 1988 have been documented in many studies (Ebbesmeyer et al. 1991, Ting et al. 1996), and these periods are distinct, especially in the tropics. Schroeder and McGuirk (1998a) reported about 3 percent drying in the tropics using satellite data from 1979-87 to 1989-95, and this study finds about 2 percent drying in the uncorrected radiosonde data (with a starting date of 1978). The drying is reduced, compared to the drying in satellite retrievals, because there is no radiosonde data in certain areas of strong satellite-reported drying such as the southeastern Pacific. The drying found in the satellite data is still probably real, relative to adjustments to the available sounding stations surrounding these data-void areas, because the satellite algorithm was stable worldwide in comparison with over 1 million collocated soundings.

After applying corrections, the tropical drying in the later period is still about 0.9 percent, while tropical warming implied about 1 percent moistening, based on steady relative humidity with the tropical temperature changes reported in Figure 5 of Waple et al. (2002).

Future corrections are unlikely to change these results substantially, since the preliminary corrections have been based on the most "obvious" stations and may be somewhat too large. Erroneously identified instruments in the preliminary analysis are probably about equally wet and dry.

The corrections have not eliminated the tropical drying (and account for only a little over a third of the difference between the expected and uncorrected results). Part of the reason for the small impact of the corrections is that determining differences between periods produces more stable results than attributing changes to a linear trend, if the total period of record is short and the true time trend is not monotonic. However, it is likely that the drying was localized (concentrated in the tropics) and transient (though it persisted for nearly a decade). In the context of a longer time period back to 1973, tropical and global moistening is substantial, and it is possible that updated data which includes the 1997-98 El Niño will show resumed moistening in all regions.

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