Analyses of Inhomogeneities in Radiosonde Temperature and Humidity Time Series

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ABSTRACT

Twice daily radiosonde data from selected stations in the United States (period 1948 to 1990) and China (period 1958 to 1990) were sorted into time series. These stations have one sounding taken in darkness and the other in sunlight. The analysis shows that the 0000 and 1200 UTC time series are highly correlated. Therefore, the Easterling and Peterson technique was tested on the 0000 and 1200 time series to detect inhomogeneities and to estimate the size of the biases. Discontinuities were detected using the difference series created from the 0000 and 1200 UTC time series. To establish that the detected bias was significant, a t test was performed to confirm that the change occurs in the daytime series but not in the nighttime series.

Both U.S. and Chinese radiosonde temperature and humidity data include inhomogeneities caused by changes in radiosonde sensors and observation times. The U.S. humidity data have inhomogeneities that were caused by instrument changes and the censoring of data. The practice of reporting relative humidity as 19% when it is lower than 20% or the temperature is below −40°C is called censoring. This combination of procedural and instrument changes makes the detection of biases and adjustment of the data very difficult. In the Chinese temperatures, there are inhomogeneities related to a change in the radiation correction procedure.

Test results demonstrate that a modified Easterling and Peterson method is suitable for use in detecting and adjusting time series radiosonde data.

Accurate stations histories are very desirable. Stations histories can confirm that detected inhomogeneities are related to instrument or procedural changes. Adjustments can then be made to the data with some confidence.

1. Introduction

A worldwide Comprehensive Aerological Reference Data Set (CARDS) is being developed at the National Climatic Data Center (NCDC). The goal is to produce an upper-air dataset for use in evaluating climate models and detecting climate changes (Eskridge et al. 1995a). It is well known that inhomogeneous data cannot confidently be used in the analysis of interdecadal climate variation (Parker and Cox 1995). Many possible origins of upper-air data inhomogeneities have been identified recently by Elliott and Gaffen (1991, 1993) and Parker and Cox (1995). It is clear that VIZ radiosonde daytime relative humidity data values decreased due to a radiosonde model change during 1961–1973 period (Elliott and Gaffen 1991; Eskridge et al. 1995b; Parker and Cox 1995). However, many questions remain to be answered as we attempt to understand the real global or regional climate variations when using upper-air data. What adjustments should be made to minimize the humidity bias in the U.S. data? Are there other major biases in U.S. upper-air data? Are there biases in the data from the other countries?

In inhomogeneity research of surface data, it is common to use neighboring stations to detect and correct biases (Alexandersson 1986; Karl and Williams 1987; Easterling and Peterson 1994, 1995). This same approach was used for upper-air data by Parker and Cox (1995). Changes in upper-air observational practices, instrumentations, or observation times often take place at the same time or in a very short period throughout the entire country, sometimes even throughout the entire world (e.g., the observation times shifted from 0300 and 1500 UTC to 0000 and 1200 UTC in 1957). This means that it is not easy to identify inhomogeneities by using surrounding stations. However, changes in the observation times, practices, and instruments influence the at-site time series themselves (especially the daytime) and the effect of these changes is evident in the difference series.

Observations taken at nighttime are more reliable than those taken during daylight because of the influence of solar radiation on instruments and sensors (Crutcher and Eskridge 1994; Gaffen 1993b). Nighttime observations are a potential reference series for bias detection and adjustment. Therefore, in this paper,

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TABLE 1. Radiosonde stations and the daylight status of the 0000 and 1200 UTC soundings.

Station	CARDS number	Latitude	Longitude	Elevation	0000 UTC	1200 UTC
Kashi, CI	517 090	39.47°N	75.98°E	1288.7 m	*N*[a]	*V*
Beijing, CI	545 110	39.93°N	116.28°E	54.0 m	*D*	*N*
Guangzhou, CI	592 870	23.13°N	113.32°E	6.3 m	*D*	*N*
Fairbanks, AK	702 610	64.82°N	147.86°W	134.0 m	*V*	*V*
Anchorage, AK	702 730	61.17°N	150.01°W	45.0 m	*D*	*N*
Key West, FL	722 010	24.55°N	81.75°W	1.0 m	*V*	*V*
Amarillo, TX	723 630	35.23°N	97.47°W	362.0 m	*V*	*V*
Hilo, HI	912 850	19.72°N	155.06°W	11.0 m	*D*	*N*

[a] Here *N* represents a nighttime sounding, *D* a daytime sounding, and *V* the status related to the season.

an easily automated technique is used to examine the difference time series between the 0000 and 1200 UTC soundings for inhomogeneities. When the nighttime series are tested and found to be free of inhomogeneities, a bias adjustment can be made.

2. Data and analysis technique

Using twice daily observed upper-air data from the CARDS dataset, which has been quality controlled by the Comprehensive Hydrostatic Quality Control procedure (Collins and Gandin 1990; Eskridge et al. 1995b), monthly, seasonal, and annual means were calculated for the entire time period for several stations in both the United States and China (shown in Table 1). The period of record of radiosonde data for the United States stations is 1948 to 1990, while the period of record for the Chinese stations is 1958 to 1990. The humidity and temperature time series were examined and tested to understand the detection and adjustment of inhomogeneities in the U.S. and Chinese (PRC) upper-air data.

Since CARDS will contain approximately 50 million soundings, automated and objective methods must be developed. The technique developed by Easterling and Peterson (1995), called E–P procedure in this paper, was tested in this study. This technique was designed to detect and adjust inhomogeneities in climatological time series of surface temperature data. It relies on a reference series created from highly correlated surrounding stations (Peterson and Easterling 1994). A brief description of the E–P method is given in the appendix. Using the differences between the candidate and reference series, this technique searches for discontinuous points by employing a two-phase linear regression. Easterling and Peterson (1995) have shown, using various statistical significance tests for the discontinuities, that this method can detect multiple discontinuities and make adjustments to the time series. In this paper, the nighttime observations were used as the reference series instead of data from highly correlated surrounding stations. Moreover, the difference series was replaced with ratio series in some of the humidity data experiments. The E–P procedure was modified to use ratios instead of differences.

To judge whether the E–P adjustments for biases in a time series are acceptable, the candidate and reference series were tested using a Student's t-test. This is to confirm that the discontinuities are present in the daytime series but not in the nighttime reference series. The t test was performed using a confidence level of 95% to test the means of the two continuous periods in the candidate and reference time series to see if there is significant change.

TABLE 2a. Correlation coefficients between mean temperatures of the 0000 and 1200 UTC soundings at 100 hPa.

Period	Station	Jan	Apr	Jul	Oct	MAM	JJA	SON	DJF	Ann
1961–1990	Kashi	0.88	0.83	0.86	0.89	0.95	0.94	0.95	0.90	0.94
	Beijing	0.94	0.82	0.92	0.94	0.75	0.86	0.81	0.86	0.53
	Guangzhou	0.85	0.75	0.79	0.80	0.70	0.66	0.83	0.85	0.69
	Anchorage	0.99	0.99	0.95	0.96	0.99	0.94	0.96	0.99	0.96
	Key West	0.92	0.94	0.93	0.89	0.92	0.96	0.94	0.94	0.95
	Amarillo	0.90	0.93	0.93	0.97	0.96	0.94	0.93	0.97	0.97
1973–1990	Kashi	0.89	0.89	0.89	0.82	0.96	0.96	0.91	0.92	0.94
	Beijing	0.89	0.96	0.95	0.94	0.96	0.96	0.90	0.97	0.92
	Guangzhou	0.95	0.89	0.68	0.92	0.95	0.62	0.90	0.97	0.95
	Anchorage	0.99	0.99	0.94	0.95	0.99	0.89	0.97	0.99	0.97
	Key West	0.89	0.96	0.90	0.92	0.93	0.94	0.96	0.93	0.93
	Amarillo	0.87	0.84	0.86	0.96	0.95	0.96	0.90	0.96	0.97

TABLE 2b. Correlation coefficients between mean humidities of the 0000 and 1200 UTC soundings at 700 hPa.

Period	Station	Jan	Apr	Jul	Oct	MAM	JJA	SON	DJF	Ann
1961–1990	Kashi	0.89	0.76	0.91	0.86	0.77	0.94	0.87	0.92	0.89
	Beijing	0.81	0.83	0.82	0.54	0.80	0.84	0.53	0.81	0.81
	Guangzhou	0.92	0.88	0.84	0.94	0.81	0.77	0.94	0.77	0.77
	Anchorage	0.82	0.43	0.40	0.65	0.64	−0.16	0.63	0.83	0.42
	Key West	0.86	0.88	0.81	0.93	0.94	0.87	0.91	0.84	0.92
	Amarillo	0.84	0.84	0.62	0.86	0.86	0.69	0.78	0.81	0.70
1973–1990	Kashi	0.87	0.82	0.94	0.87	0.83	0.95	0.92	0.92	0.91
	Beijing	0.90	0.76	0.93	0.55	0.82	0.87	0.58	0.88	0.81
	Guangzhou	0.92	0.88	0.87	0.97	0.83	0.89	0.96	0.84	0.86
	Anchorage	0.75	0.77	0.72	0.73	0.86	0.52	0.74	0.89	0.80
	Key West	0.83	0.86	0.74	0.96	0.85	0.82	0.92	0.81	0.84
	Amarillo	0.89	0.84	0.87	0.87	0.89	0.89	0.86	0.86	0.87

Changing the humidity conversion algorithms can result in a time-varying inhomogeneity (Elliott and Gaffen 1993). To minimize the conversion related inhomogeneity, the following formulation developed by Alduchov and Eskridge (1995) is used in the conversion of the relative humidity to specific humidity:

$$e_w(t) = 6.1094e^{17.625t/243.04+t},$$

$$e_{wa}(t) = 1.00071e^{0.0000045p}e_w(t),$$

$$q = 0.622\frac{fe_{wa}}{p - e_{wa}},$$

where e_w is saturation vapor pressure (hPa) of pure water vapor over a plane surface for the temperature range of −40° to 50°C, e_{wa} is the saturation vapor pressure (hPa) for moist air above a plane surface of water, t is temperature (C), p is pressure (hPa), f is the relative humidity, and q is specific humidity.

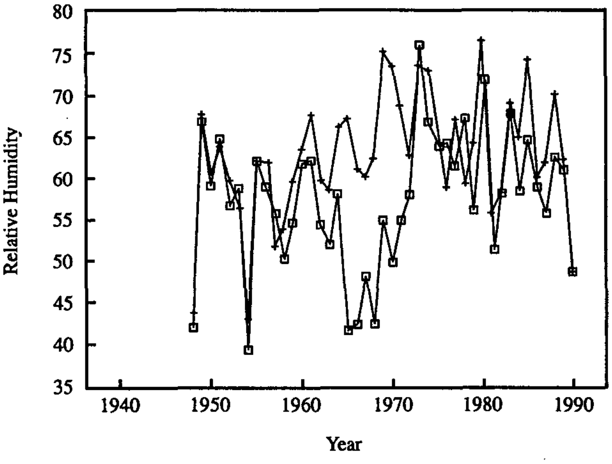

FIG. 1. Monthly mean relative humidities for April from 1948 to 1990 at Anchorage for 700 hPa for the 0000 (□) and 1200 (+) UTC soundings.

To determine whether the 0000 and/or 1200 UTC soundings are in sunlight or darkness, the solar angle α is calculated using

$$\sin(\alpha) = \sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\cos(h),$$

where ϕ is latitude and h is the solar hour angle. The solar hour is calculated using the Local Standard Time and the Julian day. The angle between the ecliptic plane and equatorial plane, ϵ, is about 23°37′. If the celestial longitude Ω is known, the solar declination δ is calculated by

$$\sin(\delta) = \sin(\epsilon)\sin(\Omega).$$

An empirical formula (Paltridge and Platt 1976) is used to calculate δ with a maximum error of 0.0006 radian (<3′),

$$\begin{aligned}\delta = {} & 0.006918 - 0.399912\cos(\theta) \\ & + 0.070257\sin(\theta) - 0.006758\cos(2\theta) \\ & + 0.000907\sin 2\theta - 0.002697\cos 3\theta \\ & + 0.001480\sin 3\theta.\end{aligned}$$

The angle θ in radians is defined in terms of Julian day, d_n, by

$$\theta = 2\pi\frac{d_n}{365}.$$

Taking into account the elevation of the radiosonde station, the time of sunrise and sunset are calculated to determine if the sounding takes place during daytime or nighttime. In Table 1, D is used for daytime, N for nighttime, and V when it depends on the season.

3. Correlation analysis

Karl and Williams (1987) indicated that it is easier to detect a discontinuity when the correlations between the candidate and reference series are high. Therefore, the correlation coefficients of the monthly, seasonal, and annual means between the 0000 and 1200 UTC

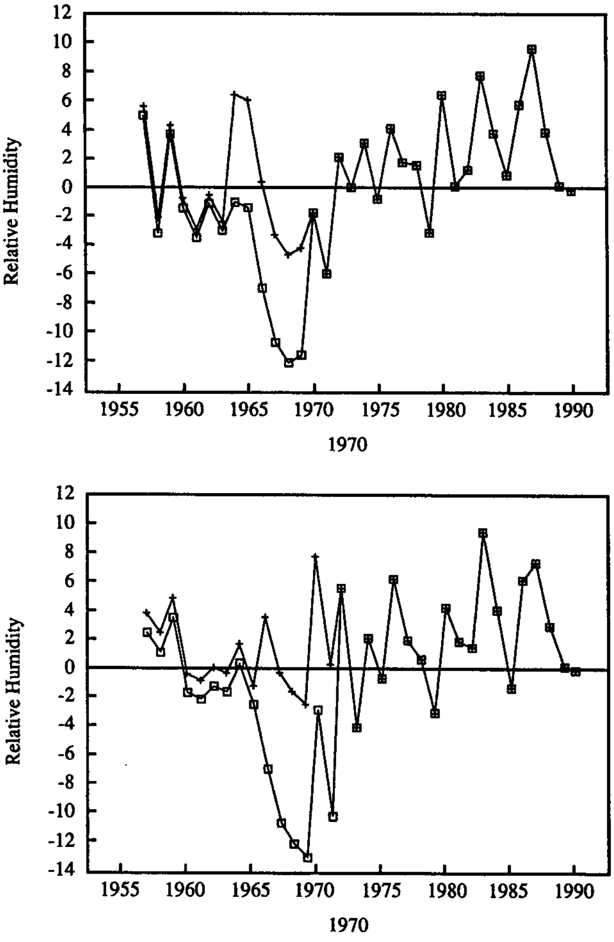

FIG. 2. (a) The 700-hPa monthly mean relative humidity at Amarillo, Texas, for July from 1957 to 1990. The night–day data, □, show the dry bias. The adjusted time series of night–day values is given by +. (b) Same as (a) except the humidities of 19% have been removed in calculating the mean.

data were calculated for temperature at 100 hPa (Table 2a) and humidity at 700 hPa (Table 2b) at several U.S. and PRC stations. Table 2 shows the correlations for the temperatures and humidities during 1961–1990 and 1973–1990 periods. Persistence has not been accounted for in calculating these correlations. The latter period contains no major changes in radiosonde instrumentation or practices. Time series of radiosonde data during this period should be relatively homogenous.

The generally high correlations in the 1973 to 1990 period (Table 2) indicate that it is reasonable to use the 0000 and 1200 UTC series for bias detection and correction. Some obviously lower correlations in the 1961 to 1990 data suggest that there are inhomogeneities in the period before 1973.

There is a high correlation between the 0000 and 1200 UTC mean temperature data in the United States at 100 hPa. Table 2a shows that the correlations are above 0.84 and most are above 0.90 in both periods. The correlations of the Chinese temperature data are higher in the 1973 to 1990 period than in the 1961 to 1990 period. These results suggest that U.S. radiosonde temperatures are more homogeneous than the PRC temperatures, and there appear to be some inhomogeneities in PRC temperatures before 1973.

In the U.S. humidity data, the correlations at Key West, Florida, are generally higher than 0.80, and there are no obvious differences between the two periods. However, at Anchorage, Alaska, the correlations in the spring and summer are much higher for the 1973–1990 period than for the 1961–1990 period. In the PRC humidity data, the correlations for the 1973–1990 period are higher than for the 1961–1990 period.

In this paper, the choice of daily data or monthly, seasonal, or annual means depends on the research goals and the seasonal variation of the bias.

4. Detecting inhomogeneities

The variation in the solar angle determines whether monthly, seasonal, or annual statistics are picked for use in the following analysis. The E–P procedure for adjusting data assumes that recent data are more accurate than older data and can be used for bias adjustments (an assumption that is not always true). DJF refers to winter, MAM to spring, JJA to summer, and SON to fall.

a. United States humidity data

Figure 1 shows the daytime and nighttime 700-hPa relative humidity series in April at Anchorage, Alaska. The year to year variations in relative humidity are large. However, the relative humidity differences between 0000 and 1200 UTC soundings are no larger than 10%, except in the period from the mid-1960s through

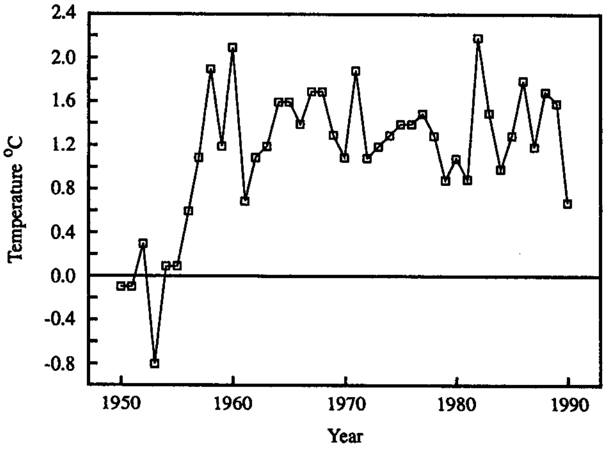

FIG. 3. The 100-hPa mean monthly temperature differences at Anchorage, Alaska: 0300–1500 UTC before July 1957, and 0000–1200 UTC thereafter.

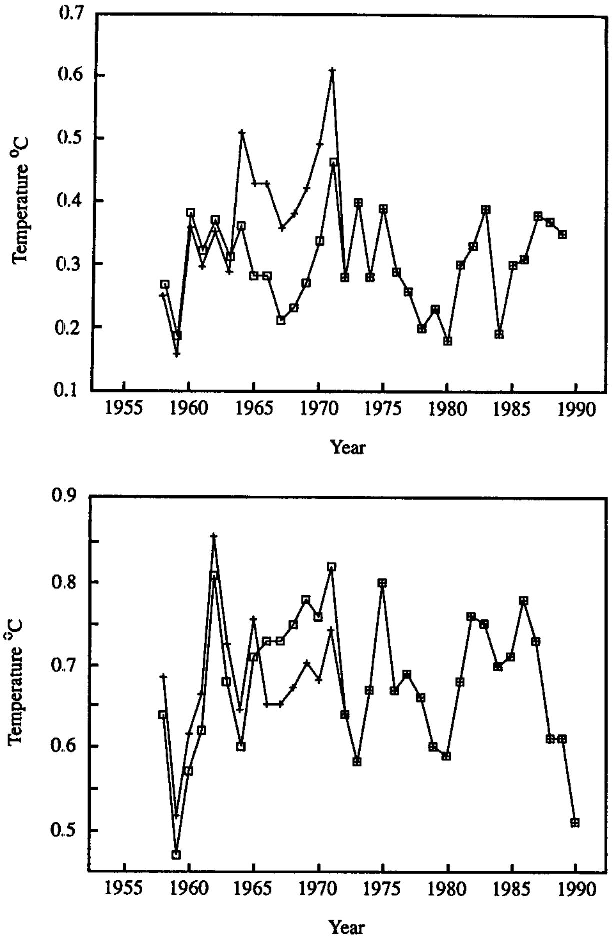

FIG. 4. (a) Annual temperatures differences for the 700-hPa level at Fairbanks, Alaska. Here + symbolizes the 0000–1200 UTC data and □ the adjusted 0000–1200 UTC data. (b) Same as (a) except for 850 hPa at Hilo, Hawaii.

early 1970s, when the daytime (0000 UTC) humidities are 15%–25% lower than the nighttime (1200 UTC) humidities. The standard deviation for the 0000 UTC April monthly relative humidity data is 8.4%, 6.5% for the 1200 UTC data, during the 1961–1990 period. The lower standard deviation at nighttime (1200 UTC) suggests the nighttime time series is more homogeneous. Prior to 1957, soundings were taken at 0300 and 1500 UTC. In this earlier period the standard deviations of the 0300 and 1500 UTC data are less than 4%. Applying the E–P procedure to the mean relative humidity data for April from 1948 to 1990, three discontinuities were found in the three years: 1958, 1965, and 1972. These breaks were found using both difference and ratio series. The station history for Anchorage, Alaska, indicates that the observation times were changed from 0300 and 1500 UTC to 0000 and 1200 UTC in June 1957, the lithium chloride hygristor was replaced by a carbon hygristor on 24 March 1965, and a new housing was introduced for the hygristor on 15 March 1972. The three discontinuities are completely consistent with the three changes in the station histories.

To apply the E–P procedure to detect humidity bias caused by instrument changes, the time series for Anchorage, Alaska, was restricted to the period after 1958. It was found that the monthly mean day–night relative humidity difference in April 1965 through 1971 was 15.7% lower than the averaged day–night differences after 1972. This implies that during the period in which the faulty housing was in use, April daytime humidity observations in Anchorage, Alaska, were biased by −15.7%. The E–P procedure also found a +6.4% bias for the humidity data collected using the lithium chloride prior to 1965. If the monthly average nighttime minus daytime relative humidity is truly zero, the monthly mean daytime observed relative humidity data were 6.4% too high in April during 1958 to 1964. Based on the ratio series, the daytime relative humidity bias values in April from 1965 through 1971 were −14.5% to −17.7% and 8% to 10% from 1958 through 1964.

Inhomogeneity detection results are not always as accurate as the results for Anchorage, Alaska. When the 700-hPa humidity data from Amarillo, Texas, were tested (0000 UTC is daytime and 1200 UTC is nighttime in July) (Fig. 2a), the E–P procedure found breaks in 1964 and 1970. However, according to the station histories, the humidity instruments were changed on 15 April 1965 and 19 January 1972. The results were not improved by using ratios instead of differences, seasonal averages instead of monthly averages, and specific humidities instead of relative humidities. A compounding factor is the "quick fix" of the VIZ radiosonde applied in 1970 and 1971. This repair reduced the heating problem with the hygristor but did not eliminate it. Station histories contain no information describing how or when the "quick fix" was applied (Eskridge et al. 1995a). Through further analysis, it was found the relative humidity data were recorded as 19% when the real values were lower than 20% after 1973. The monthly means in the reference and candidate series are both biased because of the many censored humidity values. It is clearly shown in the day–night difference series that there is an increasing trend after 1973 when 19% values are included in the calculations (Fig. 2a). The E–P inhomogeneity detection procedure strongly relies on the most recent records; this approach causes problems in the case of censored data. After removing all the humidity data below 20% and performing the average calculation again, new 0000 UTC and 1200 UTC monthly averaged relative humidity time series were produced. The detection results were greatly improved after this modification (see Fig. 2b). This raises the issue of how to calculate the "real" averaged monthly relative humidity. This issue has been investigated by Rao and Porter (1993), who have developed a method for adjusting the data.

In order to circumvent the low-humidity censoring problem in the U.S. data, the monthly median relative humidity data were tested instead of monthly averages. The results were not as good as those obtained using monthly averages. The correlation between 0000 and 1200 time series for monthly median relative humidities was found to be lower than that for the monthly averaged data. Monthly averages are better because they include all the contributions from each observation; thus they are more suitable for systematic bias detection.

b. U.S. temperature data

One obvious temperature inhomogeneity was caused by the shifting of observation times from 0300 and 1500 UTC to 0000 to 1200 UTC. A temperature break is apparent in Fig. 3, which shows the monthly averaged difference series between the primary synoptic observation times at Anchorage, Alaska. No other significant inhomogeneities in the temperature data were found at 100 hPa in this study. It is interesting that the averaged annual temperature biases were found to have a magnitude of approximately 0.15°C at 700 hPa during the mid-1960s through early 1970s at Fairbanks, Alaska (Fig. 4a), and temperature biases were also detected at 850-hPa level almost at the same period at Hilo, Hawaii (Fig. 4b). During the mid-1960s to early 1970s, the daytime minus nighttime temperatures at Fairbanks, Alaska, and Hilo, Hawaii, are higher than those in the following years. The main contributions to the annual averaged biases are from the summer months. These temperature inhomogeneities, surprisingly, are coincident with the changes in the humidity sensor and radiosonde housing. The temperature sensor is located on an arm approximately 8 in. from the housing. The new and old housings were white and about 10 by 7 by 4 in. in size. The thermal radiant properties of the housing would have to change greatly to have affected the temperature. The thermistor on the VIZ radiosonde was not changed during this period according to station histories, and we have no explanation for this apparent bias in the temperature data.

c. Chinese temperature data

Radiosonde data from Chinese stations have inhomogeneities due to the change in observation time implemented in April 1957 (Wang et al. 1987). In the following discussions, the focus is on inhomogeneities after 1957. We tried to use monthly anomaly series to

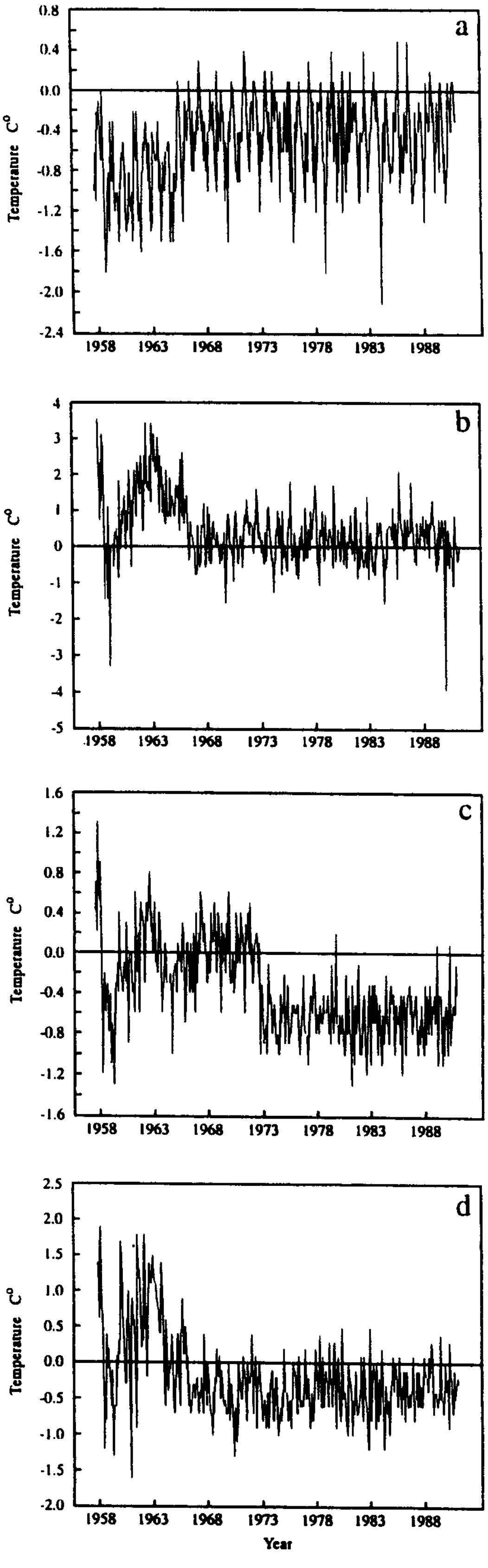

FIG. 5. (a) The 700-hPa mean monthly temperature differences, 0000–1200 UTC, at Guangzhou, China. (b) The temperature difference at 100 hPa. (c) The temperature difference at 300 hPa. (d) The temperature difference at 200 hPa.

TABLE 3. Results of the E–P procedure for annual temperatures at Guangzhou, China.

hPa	First change	Bias	Second change	Bias
100	1966	1.1°C		
200	1963	0.8°C		
300	1973	0.7°C		
500	1966	−0.6°C		
700	1966	−0.4°C		
850	1966	−0.6°C	1973	−0.2°C

reveal the temporal inhomogeneities as Gaffen (1993b) did, but it was difficult to detect inhomogeneities in PRC radiosonde temperatures using anomalies. However, inhomogeneities are clear in the 0000 and 1200 monthly averaged difference series (Fig. 5).

Since 1959, China has used solar-radiation corrections to daytime sounding temperatures above 300 hPa. For example, the northwest Chinese station Kashi has soundings in July that are in darkness (0000 UTC) and daylight (1200 UTC). The averaged temperature differences between 1200 and 0000 UTC from 1958 and 1959–1990 show the effect of the temperature corrections on the Chinese data at Kashi. At 700 hPa, the July day–night differences in 1958 and for the 1959 to 1990 period are 2.4°C. At 100 hPa, the difference in July 1958 is 2.2°C, while in the 1959 to 1990 period it is 0.9°C. This implies that a −1.3°C correction was applied to the 100-hPa daytime (1200 UTC) observed temperatures from 1959 to 1990, if the nighttime (0000 UTC) temperatures were not changed. This analysis is in agreement with the temperature correction table in the operational observation manual (China Meteorological Administration 1976). A sudden change in the temperature difference series for Guangzhou, China, at levels above 300 hPa in 1959 can be seen in the day–night difference series in Figs. 5b–d.

The average annual temperatures from 1958 through 1990 were used to test for inhomogeneities. The results from three Chinese stations located in South China, North China, and Northwest China are presented.

At the South China station, Guangzhou, and North China station, Beijing, 1200 UTC is at night and 0000 UTC is usually during daylight. Average annual temperatures were calculated for Guangzhou, where the annual variation of solar angle is small. Table 3 shows the results of testing the average annual data with the E–P procedure. Table 3 indicates that temperature inhomogeneities appear at both lower and upper levels in the Chinese data. The results from the 850-, 700-, 500-, and 100-hPa levels indicate that the discontinuity is in 1966. However, the 300- and 200-hPa data do not support the 1966 result. Although a detailed instrument history for Guangzhou is lacking, it is known that all PRC radiosonde instruments were changed from the model RZ-049 (Russian model) to the model GZZ-2 in the 1960s (Zhai 1995; Gaffen 1993a). The consistent discontinuity results at 850, 700, 500, and 100 hPa at Guangzhou suggests that the change probably occurred in 1966. Figure 5c shows that there is a step change in the temperature at 300 hPa in 1973, which is probably due to a change in the radiation-correction procedure. The 200-hPa temperatures (Fig. 5d) shows major changes in 1963 and 1966. However, the E–P procedure only identifies the break in 1963. That is due to a limitation in the detection method. The E–P procedure can only detect breaks that are at least five data points apart (Easterling and Peterson 1995). The cause of the discontinuity in Guangzhou's temperature data in 1963 is unknown.

The results of the inhomogeneities detection for Beijing are different from those for Guangzhou. At Guangzhou, there are negative biases in the lower troposphere, with positive ones in the upper troposphere and lower stratosphere. However, at Beijing, a temperature bias was found at the higher levels but not found at the lower levels. There is a discontinuity detected in 1966 in temperatures at 100 hPa with the bias of 1.2°C in the daytime series. Compared with the original 0000 UTC time series at 100 hPa, we can easily see that the E–P adjusted time series is more temporally homogeneous (Fig. 6). Figure 6 shows the inhomogeneity in the annual mean temperatures in Beijing before 1966.

Kashi is located in northwestern China, with the 0000 UTC sounding usually taken in the darkness and the 1200 UTC taken in daylight from February to November. Monthly, seasonal, and annual time series at different levels were tested separately. Detected temperature inhomogeneities depend strongly on the observation levels and seasons and therefore the solar angles. No biases were detected for the 700-hPa temperature time series, but biases were detected at 500, 300, and 100 hPa. The discontinuities found in the Kashi data were primarily in 1968, with bias magnitudes of

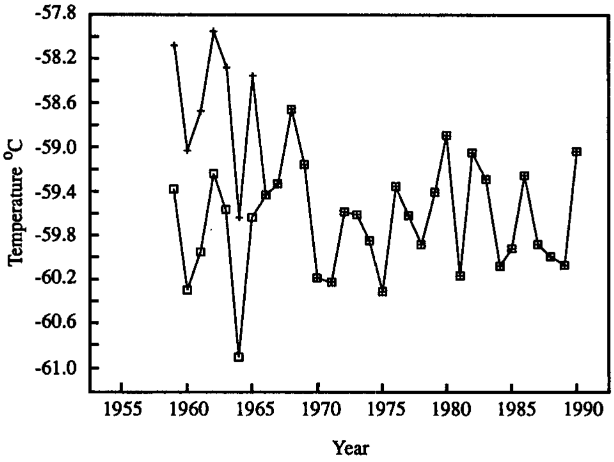

FIG. 6. Mean annual temperatures at 100 hPa for Beijing, China. Here □ symbolize the adjusted data and + the original data.

Table 4. Results of the E–P procedure for annual humidities (dewpoint depression) at Guangzhou, China.

hPa	First change	Bias	Second change	Bias
300	1966	0.9°C		
500	1966	1.0°C	1974	−0.1°C
700	1966	1.0°C		
850	1966	0.8°C		

0.4°–0.5°C at 500 hPa and 300 hPa and 0.7°C at 100 hPa in some months.

d. Chinese humidity data

Chinese humidity data were recorded as dewpoint temperature or dewpoint depression. To unify the format, Chinese humidity data recorded as a dewpoint temperature were converted to dewpoint depression.

The E–P procedure detected that there are obvious humidity inhomogeneities in the Chinese radiosonde data after 1958. Results of the E–P procedure are presented in Table 4, which shows that the daytime humidity observations at Guangzhou before 1966 are 0.8° to 1.0°C higher than in the period after 1966.

At Kashi, the E–P procedure results for humidity were found to be more consistent at the various levels than those for temperature. A strong discontinuity was found in 1968 using night–day difference time series. The annual dewpoint depression data decreased in 1968 by 1.1°C. Radiosonde models were change at Kashi in 1968 from model RZ-049 to model GZZ-2. Another break is found in 1973, with bias magnitude of about +0.5° to +0.8°C.

5. Bias adjustments

Although the E–P procedure provides the bias adjustments, they should be accepted subject to the following two restrictions.

1) The discontinuity is in the candidate time series but not in the reference time series.

2) The discontinuity is consistent with the station histories, or at least discontinuities are found at different levels, and biases in different thermodynamic variables are consistent.

The following three examples of bias adjustment are given for the change in the observation times, operational practice, and instrumentation.

a. Adjustment for the inhomogeneities caused by the change in observation time

The 100-hPa March–April–May mean temperature time series at Anchorage, Alaska, shows an example of an adjustment for a inhomogeneity resulting from the change in observation times. From 1949 to May 1957, the upper-air observation times at Anchorage were 0300 and 1500 UTC. Since June 1957, observation times have been 0000 and 1200 UTC. This change caused an inhomogeneity in the time series (Fig. 3). At Anchorage, 1200 and 1500 UTC are in the nighttime, but 0000 and 0300 UTC are in the daytime. The solar angle difference between 0300 and 0000 UTC is 4° to 5° during the March–April–May period. The E–P procedure clearly found that the discontinuity is in 1958, when the temperature time series in March–April–May was changed from 0300 and 1500 UTC to 0000 and 1200 UTC. Furthermore, according to the t-test results from both the nighttime and daytime temperature series, the discontinuity is found only in the daytime series (Table 5, case 1). The temperature difference due to the change in the daytime observational time change is 1.25°C. Both the original time series and adjusted time series can be seen in Fig. 7.

b. Adjustment for inhomogeneities caused by a change in radiation correction procedure

The E–P procedure cannot be used to adjust the bias in annual or seasonal Chinese data caused by a change in the radiation correction procedure because the observation times were changed in China in April 1957 and the radiation corrections were started in 1959. These two changes are too close to be detected using

Table 5. Results of checking for discontinuities using the Student's t-test applied to the difference of the means in temperatures and humidities.

Case	Mean period 1	Mean period 2	Candidate series t	Candidate series t_α	Reference series t	Reference series t_α	Difference series t	Difference series t_α
1	1950–1957	1958–1980	2.66	2.04	0.06	2.04	11.8	2.04
2	1958–1964	1965–1971	12.9	2.20	3.07	2.20	15.0	2.20
3	1965–1971	1972–1990	21.2	2.06	0.65	2.06	16.5	2.06

Case 1 is for the 100-hPa MAM mean temperature time series at Anchorage, Alaska. An experiment to test the adjustment of an inhomogeneity caused by the change in observation time. Case 2 and 3 are for the 850-hPa annual mean relative humidity time series at Hilo, Hawaii. An experiment to test the adjustments of inhomogeneities caused by changes in observation instruments. t is the Student's t-test statistic and t_α is the criterion for the test. If t is greater than t_α, we say the difference is significant.

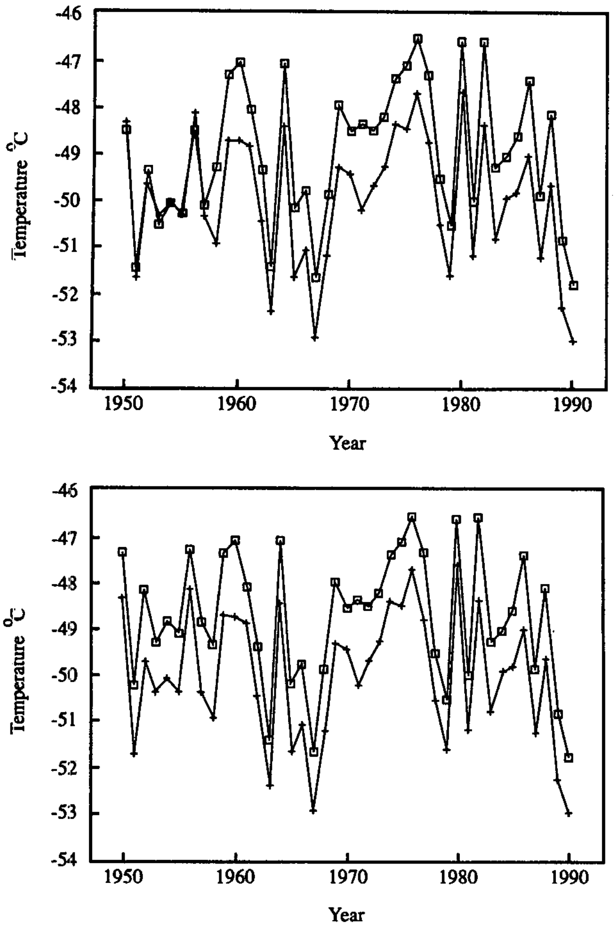

FIG. 7. (a) March, April, May seasonal mean temperatures at Anchorage, Alaska, for the 100-hPa level. The 0000 and 0300 UTC soundings are symbolized by □, and the 1200 and 1500 UTC soundings are symbolized by +. (b) Same as (a) except the 0300 UTC data (before July 1957) have been adjusted for the time change in observations.

this statistical method for annual or seasonal data. To remove the bias, the following procedure was used. The solar angles were calculated every ten days at Guangzhou, the radiation correction was applied to the uncorrected data using the correction table according to the solar angle and pressure. The adjusted time series was compared to the original series and the inhomogeneity was removed.

c. *Adjustment for inhomogeneities caused by a change in instrumentation*

The inhomogeneous relative humidity data at Hilo, Hawaii, (Elliott and Gaffen 1991) are used here as a test. To isolate the adjustments for instrument related inhomogeneities, only the time series after 1957 is tested. Since annual variation of solar angle and relative humidity at Hilo, Hawaii, are small, only the annual means were studied.

The original annual mean difference series and the adjusted annual mean difference series are shown in Fig. 8. Discontinuities were found in the 0000 UTC (daytime) series in 1965 and 1972. For the 0000 UTC data, the annual average humidities during 1965 through 1971 are 13.8% lower than those after 1971. There are also small inhomogeneities in the time series before 1965. The situation is complex. Not only was the hygristor changed in 1965 to the more accurate carbon hygristor, but the poorly designed housing was used and the humidity was decreasing. The *t* test results (Table 5, cases 2 and 3) show that the difference of the means between 1965 to 1971 and 1972 to 1990 is significant in the daytime (candidate) series but not in the nighttime (reference) series. However, in case 2, the difference of the means between 1958 to 1964 and 1965 to 1971 is significant for the daytime and nighttime series. This means the change of instrumentation in 1965 influenced not only the daytime humidity data but also the nighttime data. Therefore, only the adjustment for the daytime humidity from 1965 to 1971 is accepted. During this period the radiosondes had a housing design problem. Because of the inhomogeneity in the nighttime series before and after 1965, we do not have a reliable reference series for the data earlier than 1965. Under this circumstance, the adjustment from the E–P procedure cannot be accepted. Figure 8 shows that the adjusted difference series after 1965 is more homogeneous than the original one. The adjusted daytime and nighttime series are consistent. Meanwhile, a discontinuity still exits in the time series, with a jump in 1965 even after the adjustment using the E–P procedure.

6. Conclusions and discussion

Inhomogeneities caused by changes in observation times, solar radiation correction procedures, and instrumentation usually only occur in the daytime data. Because there is high correlation between the 0000 and 1200 UTC time series, it is possible to use the nighttime time series as a reference to detect or even adjust for daytime inhomogeneities. Inhomogeneities were corrected when a discontinuity is found in the difference series but not in the reference series and if the inhomogeneity is supported by station histories.

The Easterling and Peterson method is suitable for use with upper-air data after some modifications. This method is statistical, and it strongly depends on the data quality. Even random errors can occasional influence the detection and adjustment of biases. Therefore, it is better to remove random errors from the time series before applying this procedure.

Both the U.S. and PRC radiosonde temperature and humidity data have inhomogeneities. Common causes are changes in observation times and instrumentation.

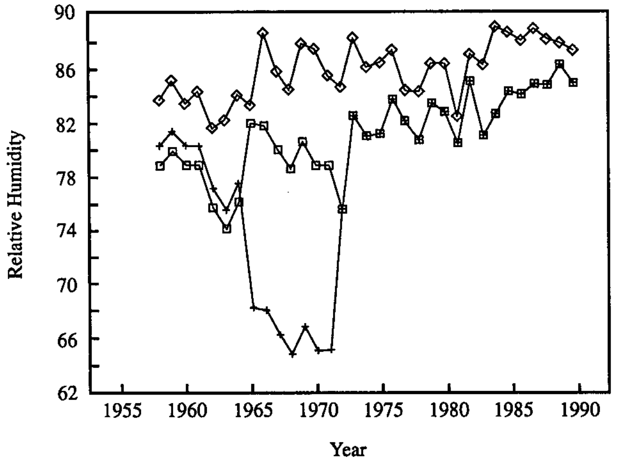

FIG. 8. Annual mean relative humidity at Hilo, Hawaii, for the 850-hPa level. Here ☐ is the adjusted 0000 UTC data, + is the 0000 UTC data, and ◇ is the 1200 UTC data.

For the U.S. humidity data, instrument-caused inhomogeneity is found not only in the 1965–1973 period, but also in the daytime series before 1965 because of the use of a different hygristor. Censoring of the low humidities cannot always be ignored. Interestingly, temperature inhomogeneities were found in the daytime series in the lower troposphere that occur at the same time as the humidity inhomogeneities in U.S. data. With the PRC data, both temperature and humidity inhomogeneities seem to be related to the change of radiosonde models in the 1960s. The annual averaged temperature and dewpoint depression biases are of the magnitude of 0.5°–1.0°C. The data prior to 1959 include another bias because a radiation correction was not performed. This kind of inhomogeneity is easy to adjust when the correction table is available. When daytime and nighttime time series are available, most of the above inhomogeneities in the daytime series can be detected and adjusted.

A method to detect and adjust the inhomogeneities when the time series at 0000 and 1200 UTC are both in the daytime needs to be developed. A physical model (Luers and Eskridge 1995) that uses solar angle and cloud condition might solve this problem.

The E–P procedure is a statistical method that is able to detect inhomogeneities in time series when station histories are not available. Furthermore, the E–P procedure also can be used to cross check the existing station histories.

APPENDIX

The following description of the Easterling and Peterson (1995) technique was extracted from their paper. It should be noted that Easterling and Peterson were working with annual surface data.

A reference series from nearby, highly correlated stations is created (Peterson and Easterling 1994). A difference series is formed from the station to be tested and the reference series. The E–P technique uses a regression approach, with the difference series as the predictand and time as the predictor. The first step is to fit a linear regression to the difference series and to calculate the residual sum of squares (RSS_1). Each year from 5 to N-5 is evaluated. A linear regression is fitted to the part of the difference series before and after the year being tested. RSS_2 is the sum of the residual sum of squares calculated from both of the two regressions. The data point with the minimum RSS_2 is flagged as a potential discontinuity. The statistic

$$U = \frac{\left[\dfrac{(RSS_1 - RSS_2)}{3}\right]}{\left[\dfrac{RSS_2}{(n-4)}\right]}$$

is tested using Student's t-test. The sections before and after a potential discontinuity are then treated in the above manner, with potential discontinuities being recorded until no more discontinuities are identified or the remaining portions of the time series are too short to test (<10 years). The statistical significance of each discontinuity is tested using multiresponse permutation procedures.

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