JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 99, NO. D2, PAGES 3667–3676, FEBRUARY 20, 1994

Temporal inhomogeneities in radiosonde temperature records

Dian J. Gaffen

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

Abstract. Historical information on changes in radiosonde instruments and observing methods is combined with time series of upper-air temperature data to estimate the effects of (1) changes in sensors, (2) changes in solar radiation corrections to the data, and (3) changes in the length of the train between the balloon and the instrument package. These changes can induce discontinuities in the temperature records from several tenths to as high as several degrees Celsius. The discontinuities can be larger than the temperature trends of a few tenths of a degree per decade, computed by previous investigators from radiosonde observations. An assessment of the 63-station network used by Angell to monitor tropospheric and stratospheric temperature suggests that about 43% of those stations' records have inhomogeneities, most notably in the stratosphere. These findings suggest that some previously computed temperature trends, especially estimates of stratospheric cooling, may be influenced by data inhomogeneities.

1. Introduction

Increases in atmospheric greenhouse gas concentrations have been predicted to cause warming of the Earth's surface and the troposphere and cooling of the stratosphere. Detecting these changes requires long-term, homogeneous, global upper-air temperature records with good vertical resolution. The obvious observing network to turn to is the global radiosonde network, which has been operating since the 1940s, with improved spatial resolution since the International Geophysical Year (1957 and 1958).

Studies of upper-air temperature trends based on radiosondes have made the tacit assumption that radiosonde temperature records form a temporally homogeneous data set. Several investigators have calculated trends in tropospheric and stratospheric temperature using data since the 1950s and found statistically significant warming of the troposphere and cooling of the stratosphere, of a few tenths of a degree Celsius per decade, as summarized in Table 1.

Because radiosonde instruments and observing practices have changed over the past half century, there is a possibility that inhomogeneities in the record may influence trend calculations, as found by *Elliott and Gaffen* [1991], who investigated inhomogeneities in the humidity data from U.S. radiosonde archives. This paper examines several sources of inhomogeneities in temperature records, using examples from around the world, and attempts to quantify their magnitude and to draw some conclusions about their implications for estimates of upper-air temperature trends.

2. Overview and Data

Most previous studies of radiosonde data homogeneity have focused on the spatial homogeneity, or compatibility, of data from contemporary radiosonde systems. Recognizing that large differences in the biases of different systems hamper analyses of temperature and height fields, stratospheric analysts have devised methods to adjust data from different radiosonde types [e.g., *Teweles and Finger*, 1960; *World Meteorological Organization* (*WMO*), 1978; *Tarbell and Tower*, 1980].

The problem of temporal homogeneity of radiosonde temperature records has not until recently received such scrutiny. The following are some conceivable causes of inhomogeneities: (1) changes in radiosonde type involving changes in temperature sensor or its exposure; (2) introduction, cessation, or modification of radiation or lag corrections applied to the data; (3) changes in the length of the train between the radiosonde and the balloon that could lead to changes in the effect of the balloon wake on the observations; (4) changes in balloon type or method of tracking the radiosonde that influence typical heights at which soundings end; (5) changes in observation time, including both the nominal and actual launch times; and (6) station relocations.

Many of these were treated by *Cox and Parker* [1992] and *Parker and Cox* [1994], who outlined a series of potential sources of inhomogeneity in upper-air pressure, temperature, humidity, and wind data, and gave some estimates of the magnitude of the effects, mainly by comparing records from neighboring stations. In sections 3, 4, and 5, examples of items 1, 2, and 3 will be given with estimates of the effect on temperature records. Section 6 presents an estimate of the extent to which *Angell*'s [1991] 63-station global network may be influenced by temporal data inhomogeneities.

The data used are of two types: historical information and climatological radiosonde data. Except where otherwise noted, the historical information is taken from a recent report summarizing the results of an international survey on historical changes in radiosonde instruments and practices and including radiosonde metadata from 50 countries [*Gaffen*, 1993].

The radiosonde temperature data are worldwide monthly mean climatological data (known as Climat Temp reports), obtained from the National Center for Atmospheric Research. Data are reported at the surface and at the 850, 700, 500, 300, 200, 150, 100, 50, and 30 hPa levels. The data period is 1950–1990, although many stations do not have

Paper number 93JD03179.

Table 1. Radiosonde-Based Temperature Trend Estimates

Reference	Region	Period	Trend, °C $(10\ \mathrm{yr})^{-1}$
Angell [1988]	Global (63 stations) 850–300 hPa layer	1958–1987	approximately +0.1
Angell [1988]	Global (63 stations) 300–100 hPa layer	1958–1987	approximately −0.2
Angell [1988]	Global (63 stations) 100–50 hPa layer	1970–1987	approximately −0.6
Oort and Liu [1993]	Global 850–300 hPa layer	1964–1988	+0.1 to +0.3
Oort and Liu [1993]	Global 300–100 hPa layer	1964–1988	−0.1 to −0.2
Oort and Liu [1993]	Global 100–50 hPa layer	1964–1988	−0.2 to −0.6
Hense et al. [1988]	Tropics 850–200 hPa layer	1965–1984	+0.4
Kahl et al. [1993]	Arctic 850 and 700 hPa	1950–1990	Winter and spring warming, summer and autumn cooling

complete records for the entire period, surface data are often missing, and data at 50 and 30 hPa are generally not available for the early part of the record. Limited data screening involved rejecting monthly data that were more than 2.5 standard deviations from the long-term monthly mean value. This eliminated generally less than a few percent of the observations from any station.

Monthly temperature anomalies were computed as the difference between the monthly mean for a given month and the long-term monthly mean for that month over the entire period of record. Because no attempt was made to correct for missing monthly data, the number of months used to calculate a given long-term mean may differ from month to month.

The general approach is to find associations between changes in instruments or observing practices and discontinuities in the radiosonde data. For prudence's sake, it is important to recognize that such associations do not prove a cause and effect relationship. However while this sort of evidence may be circumstantial, it can be convincing when (1) the discontinuity in the data is abrupt and coincident with the date of a change in the observations, (2) the discontinuity is large compared with typical interannual variations, (3) the direction of the discontinuity is consistent with known instrument characteristics or the effect of observing practices, and (4) there is no other explanation for the discontinuity.

3. Changes in Radiosonde Type

Introducing new types of radiosondes is perhaps the most obvious potential source of data inhomogeneity. In this section, examples are given of the effects of changes in sonde types, including changes from one manufacturer to another and changes in sensor type on sondes by a single manufacturer.

3.1. Changes in Manufacturer Involving Changes in Temperature Sensor Type

3.1.1. Bet Dagan, Israel. The Israel Meteorological Service has taken upper-air soundings at Bet Dagan (32.0°N, 34.8°E, about 10 km southeast of Tel Aviv) since 1962, and prior to 1962 at Be'er Yakov, less than 10 km from Bet Dagan. Until 1968, observations were made with the French radiosonde Metox, carrying a bimetal temperature sensor. In 1968, the American VIZ radiosonde, carrying a ceramic rod thermistor, was introduced.

To compare the temperature data from the two sondes, mean anomalies were computed for January 1956 to December 1967, and for January 1969 to December 1990, at all available levels from 850 to 100 hPa. At each level the mean anomaly for the earlier period was more positive than for the later period, and the difference was statistically significant at the 99% confidence level, based on the Student's t-test (with the degrees of freedom based on the number of monthly anomalies), at all but the lowest two levels. The difference increases with increasing elevation, from 0.08°C at 850 hPa, to 0.78°C at 500 hPa, to 1.52°C at 200 hPa, to 2.90°C at 100 hPa (see Figure 1).

In a study of radiosonde compatibility, Finger and McInturff [*WMO*, 1978] found that the Metox radiosonde had consistently larger values of the difference in daytime minus nighttime temperature in the stratosphere, at all solar elevation angles, than did the U.S. AN/AMT4 model radiosonde,

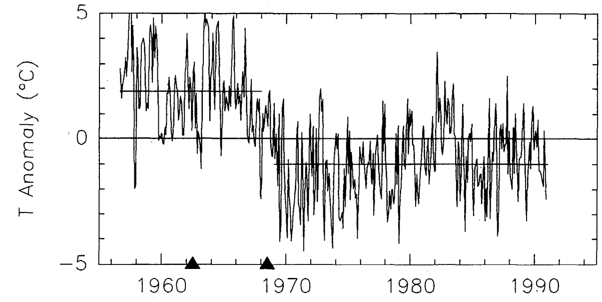

Figure 1. Time series of 100-hPa monthly temperature anomalies at Be'er Yakov and Bet Dagan, Israel. Arrows show dates of (1) station move and change in observation time from 1200 UTC only to both 0000 and 1200 UTC in 1962 and (2) change from Metox to VIZ radiosondes in 1968. Horizontal lines show the mean temperature anomaly for 1956–1967 and for 1969–1990; the difference is 2.90°C.

a VIZ product. The day-night temperature difference is generally used as a measure of the bias in daytime measurements due to solar radiation, if one assumes that the nighttime data are more accurate. At the 100 hPa level, for example, they found the VIZ sonde to have day-night differences 1° to 2°C lower than the Metox. This is in the same sense as, but smaller than, the drop in temperature observed at Bet Dagan when VIZ was introduced.

An additional inhomogeneity that may influence the Bet Dagan data is the change in 1962 from taking only 1200 UTC soundings to taking both 0000 and 1200 UTC soundings; however, the data set does not include information about what observation times were used to compute the monthly means before 1967. The daytime solar radiation error is, of course, dependent on solar elevation angle, and thus on the time of observation, especially at this station where observations are made near local noon and midnight.

3.1.2. De Bilt, The Netherlands. The Royal Netherlands Meteorological Institute has taken radio soundings at De Bilt (52.1°N, 5.2°E) since 1947, and instruments and observing practices have changed several times over the past 45 years. From 1947 until January 1, 1973, Whitely Electric Mark II radiosondes were used. At first the temperature data were uncorrected; on January 1, 1957 radiation and lag corrections for temperature data were introduced; and in January 1968 an albedo correction was added to the radiation correction. From January 1, 1973, until May 15, 1978, VIZ radiosonde models 1205 and 1221 were used. Thereafter the Finnish Väisälä radiosondes were used, the RS21 model until February 1, 1985, the RS80 model subsequently.

As shown in Figure 2, the dates of some of these changes appear to coincide with discontinuities in 50-hPa temperature anomalies. There is a sharp drop of about 1.1°C between the Whitely period and the VIZ period (1973), which could be seen at other levels as well. As at Bet Dagan, the magnitude of the change increases with height, and at De Bilt it is statistically significant only at 300 hPa and above. At 300 hPa the difference in the mean anomalies for the two periods is 0.3°C and at 30 hPa it is 1.2°C. With the introduction of the RS21 sondes (1978) there is an increase of 0.2°C in the mean 50-hPa temperature anomaly. Any effects of the modification of the radiation correction in 1968 and the change in Väisälä sonde models in 1985 are lost in the noise of the data.

3.1.3. Hong Kong. The Royal Observatory Hong Kong (22.3°N, 114.2°E) has made radio soundings since 1949, and the following chronology of radiosondes usage applies: until 1969, the British radiosonde Kew Mark IIB; from 1969 to 1974, the Finnish Väisälä model RS13; from 1975 to 1980, the Väisälä model RS18; from 1981 to 1983, the Väisälä model RS21; and since 1984, the Väisälä model RS80. With the switch from Kew to Väisälä sondes (1969), simultaneous abrupt temperature increases are recorded at all levels, and the magnitude increases with altitude. The mean anomaly differences are statistically significant at the 99% confidence level from the 500-hPa level, where the jump is 0.4°C, to the 100-hPa level, where it is 1.3°C. (Data above that level are sparse in the Kew period.) Mean 200-hPa temperature anomaly increased 1.0°C (Figure 3). (The sharp drop in temperature in 1955 will be discussed below; it may be due to solar radiation corrections.)

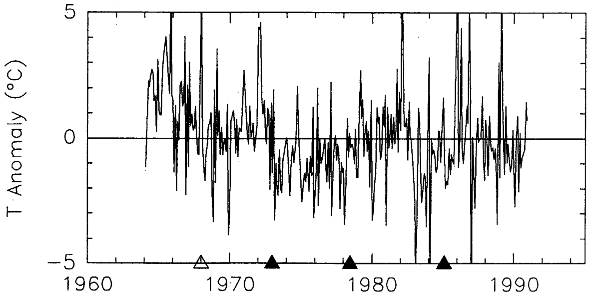

Figure 2. Time series of 50-hPa monthly temperature anomalies at De Bilt, the Netherlands. Open arrow shows date of known change in radiation corrections, while solid arrows show dates of radiosonde type changes, as noted in the text.

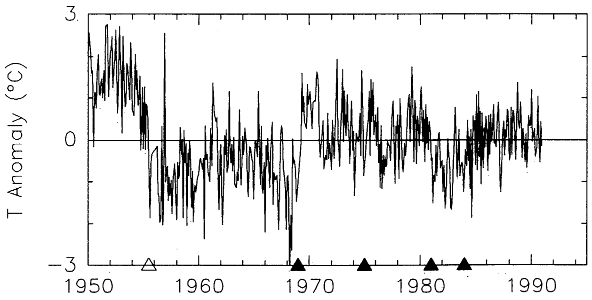

Figure 3. Time series of 200-hPa monthly temperature anomalies at Hong Kong. Open arrow shows date of change in radiation corrections, while solid arrows show dates of known radiosonde type changes, as noted in the text.

These discontinuities are consistent with the findings of *Apps* [1971], who made direct comparisons of the two radiosondes by flying them together on the same balloon in a series of tests during 1969. The Väisälä sonde gave higher temperature readings than the Kew; the difference at 200 hPa was 1°C, with larger differences at higher altitudes and smaller ones at lower altitudes. The agreement of the test results with the climatological data analysis is testament to the value of direct comparisons in assessing the likely effects of an instrument change.

Each of the Väisälä models used at Hong Kong had different temperature sensing systems, as summarized in Table 2. From Figure 3, it appears that the RS21 values (1981–1983) are substantially lower than those in the preceding and following periods. The t-test confirms that the mean anomalies of +0.17°C during the RS18 period, −0.63°C during the RS21 period, and +0.06°C during the RS80 period, are significantly different at the 99% confidence level. The ducting of the bimetal ring in the RS21 was probably designed to reduce solar radiation error, so the

Table 2. Temperature Sensors on Väisälä Radiosondes

Period	Model(s)	Temperature Sensor
1951–1955	RS11	Bimetal strip
1961–1975	RS12 to RS15	Bimetal strip (smaller than in RS11)
1976–1980	RS18	Bimetal ring
1970s to present	RS21	Bimetal ring in a duct
1981 to present	RS80	Capacitive bead

Adapted mainly from *Huovila and Tuominen* [1990].

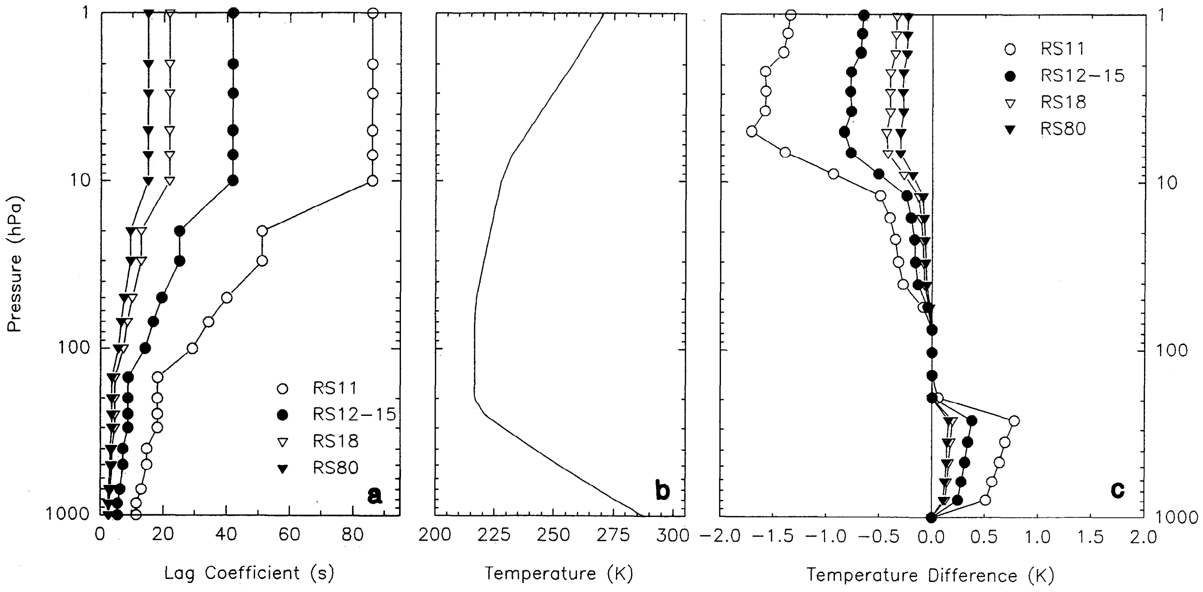

Figure 4. (a) Lag coefficients, as a function of atmospheric pressure, of temperature sensors on various models of radiosondes manufactured by Väisälä, Oy [*Huovila and Tuominen*, 1990]. (b) U.S. Standard Atmosphere temperature profile [*NOAA*, 1976]. (c) Difference between simulated temperature sounding and U.S. Standard Atmosphere sounding for each of four Väisälä radiosonde models.

lower temperatures associated with the RS21 are not surprising.

3.1.4. New Radiosondes in the United States. Since about 1960, the U.S. National Weather Service (NWS), and its predecessor organizations, have used VIZ radiosondes, carrying a white-coated ceramic rod thermistor, throughout its upper-air network. In the late 1980s, NWS introduced a new radiosonde, manufactured by Space Data Division (SDD) and carrying a ceramic flake thermistor, to some stations in the western United States. Despite tests of the sonde before its introduction in operational use, a distinct bias in the stratospheric geopotential height data between the SDD and VIZ sondes has been noted. *Baker et al.* [1991] found that the differences between the measured 100-hPa heights and those determined by the Navy's operational numerical weather prediction model are about 20 m larger for the SDD sondes than for the VIZ. If this spatial difference can be translated to a temporal difference at the stations that changed from VIZ to SDD, the result implies a spurious warming of about 0.3°C in the layer between 1000 and 100 hPa; however, it is not obvious what the vertical distribution of the change in bias might be.

3.2. Changes in Sensor Type on Radiosondes from the Same Manufacturer

Radiosondes manufactured by Väisälä, Oy, for operational use have included four different temperature sensors since the early 1950s (Table 2). Introduction of each new sensor brought an improvement in response time which was especially marked at high altitudes (Figure 4a). *Huovila and Tuominen* [1990] demonstrated an apparent drop in the nighttime surface inversion height at the Finnish stations Ilmala-Jokioinen (from 275.5 to 209.1 m) and at Sodankyla (from 334.4 to 240.7 m) associated with these sensor changes between the 1950s and 1980s. The effect on measured inversion height is large because a sharp gradient offers a challenge to the instrument. However, even in smoothly varying temperature fields, the effect of instrument response time is not negligible.

Ignoring for the sake of this analysis all other changes that were associated with these temperature sensor changes (e.g., changes in radiation correction schemes, solar radiation shields and ducts), we can estimate the effects of the changes in response time alone by simulating the ascent of these thermistors in typical atmospheric conditions, for example, the U.S. Standard Atmosphere [*National Oceanic and Atmospheric Administration (NOAA) et al.*, 1976] (Figure 4b).

The response of the temperature of the sensor T to the environmental temperature T_e is given by

$$\frac{dT}{dt} = \frac{1}{\lambda(t)} (T_e(t) - T(t)) \qquad (1)$$

where t is time and λ is the time constant of response, which is a function of t because it depends strongly on the ventilation of the sensor, which decreases rapidly with decreasing pressure [*Badgley*, 1957].

The T profile measured by each of the four Väisälä sondes ascending into the Standard Atmosphere was simulated using a finite difference approach in which the balloon was allowed to rise at the constant rate of 6.6 m s^{-1}, and T, T_e, and λ were updated at each time step. Time steps were set at the sampling rates of the sondes, 1 s for the RS18 and RS20 sondes and 6 s for the earlier sondes (Väisälä sales brochure, undated).

The differences between the simulated temperature profiles for each sonde and the Standard Atmosphere temperature profile that the sondes were supposed to sense are shown in Figure 4c. In the troposphere, where T_e decreases with height, all the sensors overestimate T_e, but the magnitude of the bias varies from about 0.6°C for the early RS11 sonde to about 0.1°C for the most recent RS80 sonde at 500 hPa, for example. The change in sensors would therefore lead to an apparent 0.5°C drop in 500 hPa temperature. In the tropopause layer, because the temperature profile changes slowly, instrument lag time does not introduce any appreciable error. In the stratosphere, sensor lag leads to an underestimate of T_e, the magnitude of which decreases with each sensor update. At 50 hPa, the change in bias between the RS11 and the RS80 sondes is about 0.04°C, and at 10 hPa it is 0.44°C, which introduces a spurious stratospheric warming. The largest change in biases occur with the earliest, most slowly responding sonde types; the effects of more recent changes are more subtle.

These predicted discontinuities are difficult to detect in data records because (1) they are not large in comparison with natural interannual variations in monthly mean temperature, (2) they are not due to isolated changes, rather, each new sonde had its own radiation correction scheme which also influences the data, and (3) few stations have used Väisälä sondes continuously since the 1950s. However, data are available for 1950–1990 from Sodankyla, Finland (67.4°N, 26.7°E), where Väisälä sondes have been used continuously, and they may be influenced by the change in sensor lags. Comparing the mean temperature anomalies for 1955–1959, when the RS11 model was used, with the mean anomalies from 1982–1990, when the RS80 model was used, shows a drop of 0.6°C at 500 hPa, significant at the 90% confidence level. This is close to the drop of 0.5°C predicted above from the change in lag coefficient, but there is no way to determine whether its cause is instrumental, as it is about one-fourth the magnitude of typical monthly temperature anomalies. Unfortunately, there are too few stratospheric data available for the RS11 period for analysis.

4. Changes in Radiation Corrections

The effect of solar radiation on radiosonde temperature measurements has been recognized for decades [*Brasefield*, 1948]. Short-wave radiation either directly from the Sun or reflected by clouds or parts of the radiosonde or balloon leads to a positive bias in the daytime temperature measurement. Adjustments for this bias have been based on the measured difference in daytime versus nighttime temperature measurement [e.g., *Teweles and Finger*, 1960], although there is some small, real, diurnal temperature fluctuation due to the solar tide [*Chapman and Lindzen*, 1970]. Corrections are often given as a function of pressure and solar elevation angle. See *Ivanov et al.* [1991] for a selection of contemporary radiation correction schemes.

4.1. Radiation Corrections in Early U.S. Data

Changes in solar radiation "corrections" (more appropriately called adjustments, since the true temperature is not known) usually accompany a change in sensor type. For example, it appears that when the United States changed, in about 1960, from radiosondes with temperature sensors mounted in ducts to exposed or "outrigger" thermistors coated with white lead carbonate, solar radiation corrections were discontinued. A series of instruction manuals for upper-air observations includes techniques for making solar radiation corrections in the early 1940s and again from about 1950 to 1964, but not in later years [*U.S. Department of Agriculture*, 1930, 1938; *U.S. Department of Commerce*, 1941, 1943, 1944, 1945, 1946, 1950, 1953, 1956, 1957, 1960, 1966].

The corrections were dependent on solar elevation angle and pressure and increased from less than 1°C at 400 hPa to more than 10°C at 10 hPa. Data since the 1950s are available for many U.S. stations, but none of those examined seemed to show discontinuities related to the change in radiation correction. This may be because the corrections for the ducted sondes were well designed, and the outrigger sonde had little radiation error, so the net effect is a more or less homogeneous record. On the other hand, observations over much of the United States are at times of relatively low solar elevation angle, so perhaps the radiation effect in the data is a small one.

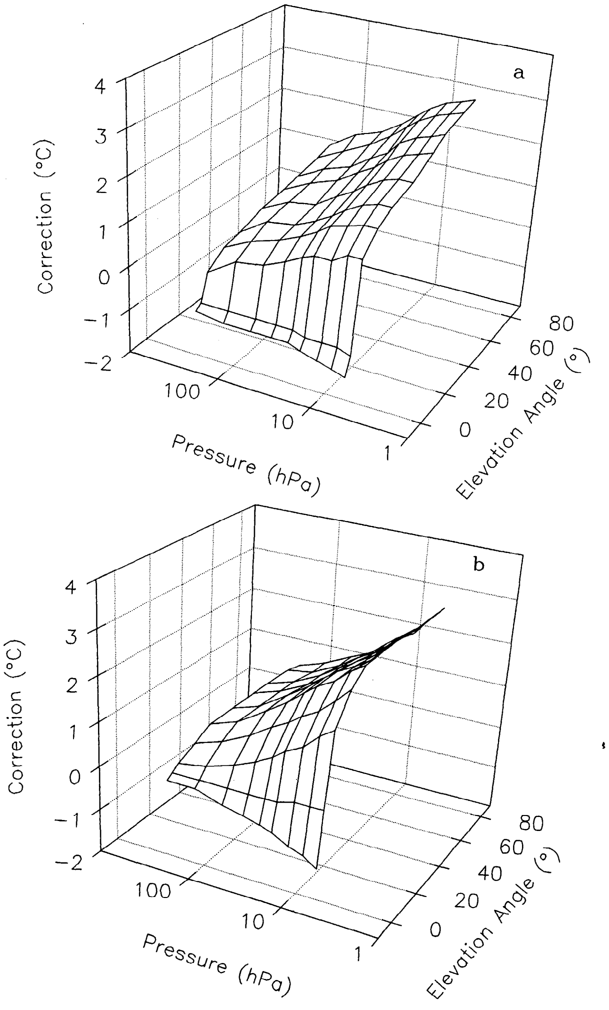

Figure 5. (a) Solar radiation corrections for the Väisälä RS80 radiosonde as a function of pressure and solar elevation angle for the early 1980s (based on Väisälä Table RSN 80B, provided by K. Goss, Väisälä, Woburn, Massachusetts). (b) Solar radiation corrections for the Väisälä RS80 radiosonde as a function of pressure and solar elevation angle for the late 1980s (based on Väisälä Table RSN 86, provided by K. Goss, Väisälä, Woburn, Massachusetts).

4.2. Radiation Corrections for Recent Väisälä Radiosondes

Sometimes radiation corrections have been changed or introduced without a change in instruments. For example, recommended solar radiation corrections for the Väisälä RS80 radiosonde changed in about 1986 (Figure 5). The corrections (which are to be subtracted from the indicated temperature) generally increase with solar elevation angle and with decreasing pressure and are adjusted according to a computed ventilation factor. The differences between the two sets of corrections are several tenths of a degree; the

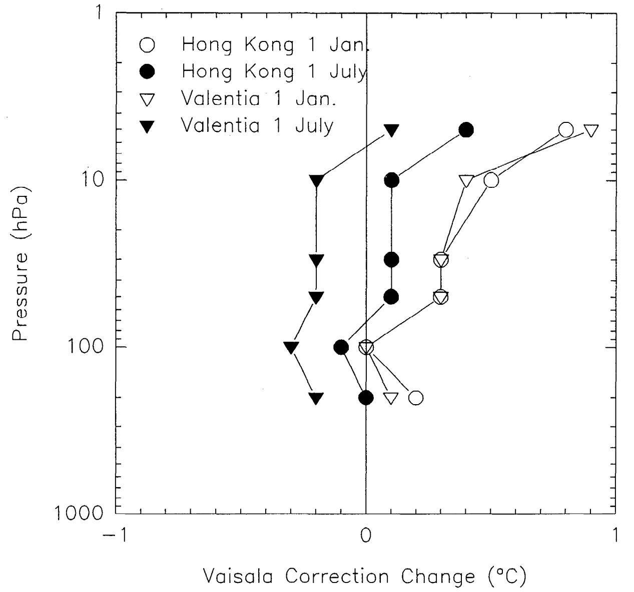

Figure 6. Estimated change in the Väisälä radiation correction that would have been applied at Valentia, Ireland, and at Hong Kong to generic January 1 and July 1 soundings, as a function of pressure. The change is the difference between the post-1986 corrections and the pre-1986 corrections for the RS80 radiosonde.

earlier corrections (Figure 5a) are smaller than the more recent ones (Figure 5b) for low solar elevations angles and larger for high angles. Thus the direction of the change will depend on all the variables that determine solar elevation angle: time of day, day of year, station latitude and longitude, and the height of the sonde.

The effect of the change in Väisälä radiation corrections on observations from a given station can be determined by calculating the solar elevation angle over the course of soundings from that station. This approach was used to quantify the effect at two stations, Hong Kong and Valentia, Ireland (51.9°N, 10.3°W), both of which used the Väisälä RS80 during the periods when the two radiation correction schemes were applicable. (It is not known whether the change was implemented at Valentia. At Hong Kong it was implemented in 1990 (K. S. Leung, Royal Observatory Hong Kong, personal communication, 1993).)

Daylight observations at Valentia are at 1200 UTC and at Hong Kong at 0000 UTC. Generic January 1 and July 1 observations were simulated using *Uddstrom*'s [1984] algorithm for computing solar elevation angle and assuming a balloon ascent rate of 6.6 m s^{-1}. Elevation angles at Hong Kong varied from 12° to 33°, as the balloon rose from the surface to 1 hPa on January 1 and from 29° to 56° on July 1. At Valentia, simulated elevation angles were from 15° to 13° on January 1 and from 60° to 58° on July 1.

With a ventilation factor of unity, the profiles of elevation angles were used to determine the recommended radiation corrections at these stations on these dates. The differences between the post-1986 and pre-1986 Väisälä correction factors are shown in Figure 6. Values are given from 200 to 5 hPa because the corrections are applicable only at those pressure levels. Except at Valentia in July, where elevation angles are high, the differences are mainly positive, meaning that a larger number is to be subtracted from the measured temperature in the post-1986 period, which implies a lowering of the reported temperature. The magnitude of the change is several tenths of a degree. Of course, the sign and magnitude of this effect will vary seasonally and from station to station.

4.3. "Scrase" Radiation Corrections for Kew Radiosondes

The effect of the change in radiation corrections for the Väisälä RS80 sonde is relatively small because it is an adjustment of an existing correction scheme. In contrast, the introduction of radiation corrections for radiosondes with severe radiation error can have a much larger effect. A good example is the *Scrase* [1956] corrections for British Kew radiosondes. In addition to radiation corrections for daytime observations at levels from 1000 to 10 hPa, Scrase recommended lag corrections between 110 and 10 hPa, but these are only of the order of 0.1°C, whereas the radiation corrections are several degrees to 21.1°C in the stratosphere.

According to *Hawson* [1956], the Scrase corrections were implemented in 1956. Valentia and Hong Kong are two stations that used the Kew Mark II sonde throughout the 1950s. As was done above for the Väisälä corrections, the effect of introducing Scrase corrections was estimated for these two stations for January 1 and July 1. Figure 7 shows that the corrections are much more dependent on pressure than on solar elevation angle and increase dramatically in the stratosphere. Introducing the corrections would indicate a spurious cooling at all levels.

The 200-hPa data at Hong Kong (Figure 3) seem to show the effect of introducing the Scrase corrections; the mean temperature anomaly after July 1955 was 1.7°C lower than before. The Hong Kong "Climat Temp" reports incorporated the Scrase correction starting in July 1955 (K. S. Leung, Royal Observatory Hong Kong, personal communication, 1993). Indeed, the signal is evident at all levels (Figure 8), and it is statistically significant at the 99% confidence level. At Valentia a similar pattern emerges

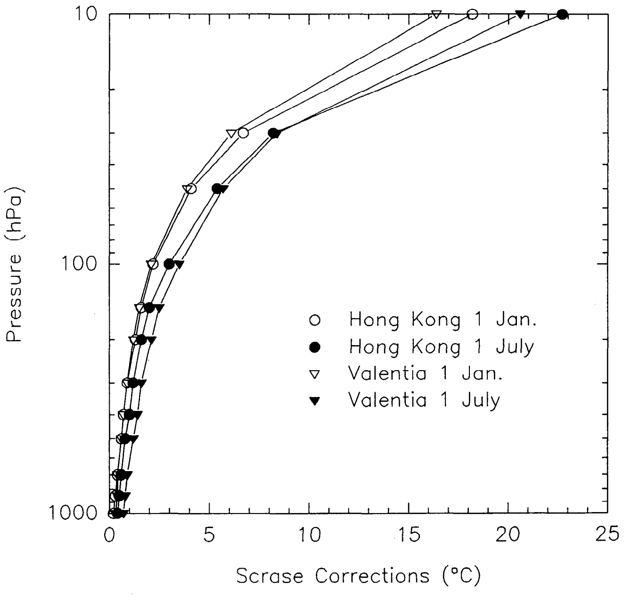

Figure 7. Estimated magnitude of the *Scrase* [1956] radiation and lag corrections that would have been applied at Valentia, Ireland, and Hong Kong to generic January 1 and July 1 soundings, as a function of pressure.

(Figure 8), suggesting that the drop may well be due to similar data treatment procedures at the two stations. Incidentally, the papers by *Hawson* [1956] and *Scrase* [1956] simply state when and how the radiation and lag corrections were introduced operationally, but they have proven of enormous use in interpreting the climate record. This is a good example of why weather services should always publish such changes in the open literature.

4.4. Soviet Radiation Corrections

In the former Soviet Union, radiation corrections were not made until 1962. Currently, official station history information is not available for each station, but it may be safe to assume that the corrections were applied throughout the network at about the same time. However, the data from the former Soviet Union do not yield a picture that is consistent with what one might expect the effect of the radiation correction to be.

The radiation corrections for the RKZ radiosonde are given by *Ivanov et al.* [1991], although whether they are the same as were used in the 1960s is not clear. The corrections increase with increasing elevation angle and with decreasing pressure, from 1000 to 10 hPa, and one would expect any signal in the data to have similar structure.

To search for this signal (a sudden drop in temperature that increases with height), mean temperature anomalies for two periods, 1958–1961 and 1963–1966, were compared for all levels between 850 and 100 hPa at all stations that had data at a given level for at least 75% of the months in each of the two periods. This criterion allowed analysis of between 27 and 18 stations, depending on the level. The mean and standard deviation of the station's anomaly temperature differences were computed. Only at the 500 and 300 hPa levels were the means different from zero by at least one standard deviation. At 500 hPa, the temperature anomaly fell by a mean of 0.64°C with a standard deviation of 0.44°C, and at 300 hPa the mean and standard deviation were 0.79° and 0.51°C, respectively. These values are quite consistent with the magnitude of the radiation corrections given by *Ivanov et al.* [1991]; however, it is surprising that similar temperature drops were not evident at other pressure levels. Perhaps this is because the records are also influenced by other changes, such as changes in instrument type.

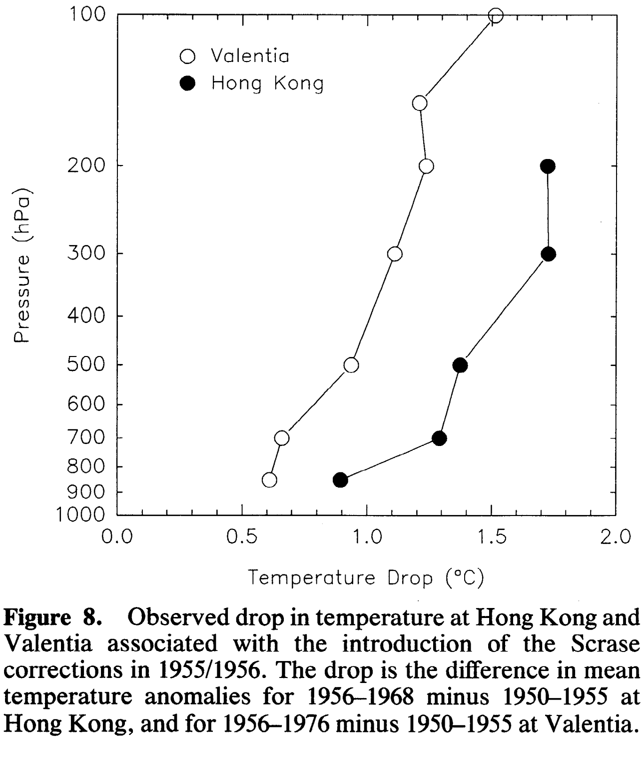

Figure 8. Observed drop in temperature at Hong Kong and Valentia associated with the introduction of the Scrase corrections in 1955/1956. The drop is the difference in mean temperature anomalies for 1956–1968 minus 1950–1955 at Hong Kong, and for 1956–1976 minus 1950–1955 at Valentia.

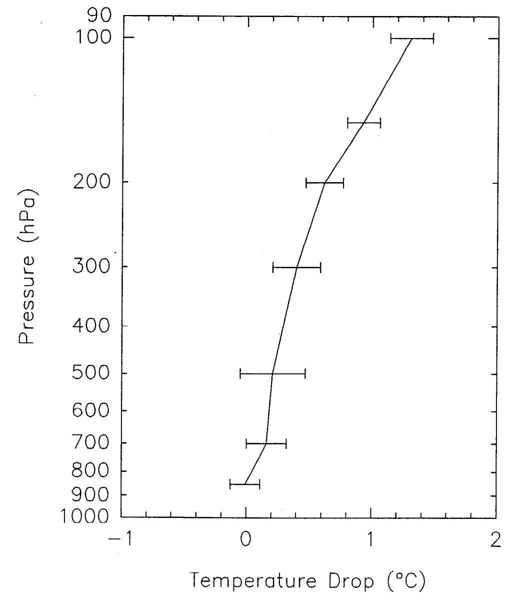

Figure 9. Average and standard deviation, over 13 stations, of the drop in temperature associated with the 1968 lengthening of radiosonde cords in Japan, as a function of pressure.

5. Changes in Wake Effects

The length of the train between the radiosonde and balloon influences the degree to which measurements are influenced by the balloon's wake. During daytime soundings, the wake tends to be warmer than ambient air because of the heating of the balloon. In July 1968 the train in Japanese radiosondes was lengthened from 7 to 15 m, which resulted in a lowering of the day-night temperature difference at 50 hPa from 2–3°C to 1°C [*Suzuki and Asahi*, 1978; *Miyagawa*, 1990]. Assuming that the change in train length did not influence the homogeneity of the nighttime data, the change implies a spurious daytime cooling of 1°–2°C. Incidentally, this change is one of several that, since 1950, have lowered the day-night stratospheric temperature difference in Japanese data. Two other important changes were the introduction of solar radiation corrections in 1956 and the change in temperature sensor in 1981, from a bimetal sensor to a white, glass-coated thermistor [*Miyagawa*, 1990].

To determine the overall effect of the lengthening of the train in Japanese radiosondes, the difference in mean temperature anomalies was computed between the periods June 1958 to June 1968 and August 1968 to August 1978, two 11-year periods in which no other changes were made [*Miyagawa*, 1990]. This was done for 13 Japanese stations that had data for at least 75% of the months in each period. The average and standard deviation of the difference are shown in Figure 9. The

Table 3. Summary of *Angell*'s [1991] Stations

Category	Number of Stations	Comments
1. Confirmed inhomogeneous	11	These include Australian and Indian stations, Singapore, Hong Kong, Wakkanai (Japan), and Antofagasta (Chile).
2. Unconfirmed inhomogeneous	16	Mainly tropical and southern hemisphere stations, including most African, some South American, and some island stations
3. Potentially inhomogeneous	16	These include most of the former Soviet, some Antarctic, and a few South American stations. They are concentrated at middle and high latitudes, where the time series are much noisier than in the tropics.
4. Confirmed homogeneous	17	All are U.S. or Canadian operated and most are in North America.
5. Unclassifiable	3	Isla de Pascua, Honiara, and Verkoyansk

Categories are explained in the text.

drop in temperature increases with altitude and is not significant until about 300 hPa. By 100 hPa it is 1.3°C.

These temperature drops were not obvious in time series plots because they are not large compared to typical month-to-month variability. To test whether the computed differences might have been the result of a temperature trend throughout the 22-year period analyzed, rather than a discontinuity in 1968, linear regression trend analyses were performed for the full 22-year period and each of the two subperiods. Results showed statistically significant negative trends for the full period at all 13 stations at the 150 and 100 hPa levels, at 12 stations at 200 hPa, 9 at 300 hPa, and 7 at 500 hPa. In contrast, no stations had statistically significant negative trends for both subperiods, except at the 150-hPa level, where two stations did. Thus the trend in the full period is not generally reflected in the two subperiods, and it is quite possible that the change in cord length represents a true data discontinuity.

6. Inhomogeneities in Angell's Network

The examples shown above are convincing, albeit anecdotal, evidence that radiosonde temperature records can be affected by inhomogeneities. It is reasonable to ask to what extent such problems influence the global network. To partially answer this question, the network used by Angell and depicted by *Angell* [1991] and *Oort and Liu* [1993] was assessed for possible inhomogeneities.

For each of the 63 stations in the network, time series plots of 500 and 100-hPa monthly temperature anomalies were made for the period 1958–1990, and these were visually inspected for sharp breaks. The stations were then subjectively categorized as follows:

Category 1: Confirmed inhomogeneous. Time series show sharp breaks coincident with a known change in instruments or observing practices.

Category 2: Unconfirmed inhomogeneous. Time series show sharp breaks, but no historical information is available.

Category 3: Potentially inhomogeneous. Historical information indicates a change in instruments or observing practices, but the effect is either negligible or smaller than the noise in the time series.

Category 4: Confirmed homogeneous. Historical information indicates no changes in instruments or observing practices, and the time series show no sharp breaks.

Category 5: Unclassifiable. The time series have too many missing data to draw any inferences about homogeneity.

In some cases, the 100-hPa data indicated an inhomogeneity, but the 500-hPa data did not. This is not surprising; as we have already seen, some changes tend to have larger effects at higher altitudes.

Table 3 is a summary of the results of this categorization. A large fraction (43%) of the stations were deemed to have inhomogeneous records (categories 1 and 2), and another 25% were suspect based on known historical changes (category 3). The former group is not uniformly distributed but is most prevalent in the tropics and the southern hemisphere, an unfortunate circumstance because the sparsity of stations there makes it difficult to find alternate, more homogeneous, records.

Of the 27 stations in categories 1 and 2, the 100-hPa time series for 18 clearly showed inhomogeneities that imply spurious cooling, three showed spurious warming, and six were unclear, often due to multiple data discontinuities, some more prominent than others, and not all in the same direction. At 500 hPa, a majority (15) of the stations were unclear. It is therefore difficult to estimate the overall consequence of the inhomogeneities, but the most striking effect is a spurious cooling of the stratosphere.

Extrapolating the results for the Angell network to the global network must be done with caution. In some regions, for example, the United States and Canada, it seems reasonable to assume that the Angell stations are quite representative of national networks covering large areas (but see section 3.1.4). However, in Europe there is no a priori reason to assume that Angell's stations have histories similar to those in other countries.

Oort and Liu [1993] compared Angell's network with the complete global network (about 800 stations) by calculating the coherence between the two for seasonal temperature anomalies in four layers for each hemisphere and for the globe for periods between 0.6 and 14 years. (See Table 3 of *Oort and Liu* [1993].) In general, the coherence increases with increasing period, suggesting that both networks reveal similar decadal patterns but somewhat different interannual patterns.

The southern hemisphere data for Angell's network are more severely affected by inhomogeneities than the northern, and the inhomogeneities are more pronounced in the stratosphere than the troposphere. For the 100- to 50-hPa layer, the coherence pattern differs markedly between the two hemispheres. The coherence is about 0.7 at each period for the northern hemisphere but varies between 0.40 at the 1.2-year period to 0.95 at the 14-year period for the southern hemisphere. Since data inhomogeneities tend to have decadal timescales and tend to dominate shorter-term fluctuations, this suggests that both networks may be similarly affected by inhomogeneities in the southern hemisphere stratosphere. The sparsity of the global network in the southern hemisphere means that Angell's and Oort and Liu's networks are more nearly alike there than in the northern hemisphere.

7. Summary

Three types of inhomogeneities in radiosonde temperature data have been assessed. Changes in instruments can lead to apparent discontinuities in temperature records of between several tenths and several degrees Celsius. Radiation corrections can produce discontinuities of the order of several degrees, whereas modifications of radiation corrections can be expected to introduce inhomogeneities of the order of 0.1°C. A seemingly minor change, the lengthening of the radiosonde train, has been shown to introduce an apparent discontinuity of about 1°C. These magnitudes are large compared with reported upper-air temperature trends, which are typically of the order of a few tenths of a degree per decade (Table 1).

These discontinuities do not always act in the same sense; either spurious warming or cooling will result, depending on the change. Some effects, for example the introduction of radiation corrections, can be expected to have a larger impact at high altitude. In general, advances in radiosonde thermometry and data treatment have addressed problems with high-altitude sensing, such as the poorer ventilation and increased radiation error, so one might expect to find more problems in the early stratospheric records than in tropospheric ones. Since the early data tend to have a high bias, we should be cautious about accepting trend calculations showing stratospheric cooling.

Not all changes in instruments or observing practices lead to discontinuities in temperature records. In the course of this study, temperature time series at stations with known changes in observing techniques were examined, and in many cases no obvious effect could be discerned. Nevertheless, knowledge of upper-air station histories is a good starting point for examining a time series for potential inhomogeneities. It is also necessary in undertaking the important but daunting task of adjusting time series to eliminate inhomogeneities.

At least 27 of 63 stations in the network used by *Angell* [1988, 1991] were found to be affected by inhomogeneities. These tend to be concentrated in the tropics and southern hemisphere. On the basis of an analysis of coherence by *Oort and Liu* [1993] between their global radiosonde network and Angell's, one might infer that the former is similarly affected, especially in the southern hemisphere stratosphere.

Radiosonde data discontinuities due to changes in instruments and observing practices tend have a timescale of the order of 10 years, although there are stations with much more frequent changes. Therefore strong climatic signals of shorter duration, for example, volcanic and El Niño-Southern Oscillation effects, might well be discernible in an inhomogeneous record. The main problem is detecting multidecadal climatic trends.

The inevitable, and unfortunate, conclusion of this study is that data from the operational radiosonde network do not provide us with a homogeneous set of observations for monitoring global temperature. To glean information about climate trends from radiosonde data, they should first be carefully examined for potential inhomogeneities. Comparison tests documenting the effects of instruments changes are useful in interpreting the record and may be helpful in efforts to adjust for inhomogeneities. However, a need for a homogeneous upper-air temperature data set would be better satisfied by an observing system designed to provide such data, rather than relying on an operational network that was not designed to provide long-term homogeneous records.

Acknowledgments. The author is grateful to Ken Goss for providing information on radiation corrections to Väisälä radiosondes. Jim Angell, Bill Elliott, and Alan Robock gave helpful comments on the manuscript. The NOAA National Climatic Data Center, Comprehensive Aerological Research Data Set Program partially supported this study.

References

Angell, J. K., Variations and trends in tropospheric and stratospheric global temperatures, 1958–87, *J. Climate*, *1*, 1296–1313, 1988.

Angell, J. K., Changes in tropospheric and stratospheric global temperatures, 1958–1988, in *Greenhouse-Gas-Induced Climate Change: A Critical Appraisal of Simulations and Observations*, edited by M. E. Schlesinger, pp. 231–247, Elsevier, New York, 1991.

Apps, R. F., Comparison between the results obtained with the new MK IIB and the Väisälä RS13 radiosondes under operational conditions in Hong Kong, *R. Obs. Tech. Note 31*, Hong Kong, 11 pp., 1971.

Badgley, F. I., Response of radiosonde thermistors, *Rev. Sci.*, *28*, 1079–1084, 1957.

Baker, N. L., R. Franke, and T. Jayachandran, An adaptive corrective procedure for radiosonde geopotential height biases, *Ninth Conference on Numerical Weather Prediction*, pp. 192–194, American Meteorological Society, Boston, Mass., 1991.

Brasefield, C. J., Measurement of air temperature in the presence of solar radiation, *J. Meteorol.*, *5*, 147–151, 1948.

Chapman, S., and R. S. Lindzen, *Atmospheric Tides*, 200 pp., Gordon and Breach, New York, 1970.

Cox, D. I., and D. E. Parker, The effects of changes in radiosonde equipment on upper-air "Climat" data, *Discuss. Pap.* (E Division), 75 pp., Hadley Centre, Meteorological Office, Bracknell, England, 1992.

Elliott, W. P., and D. J. Gaffen, On the utility of radiosonde humidity archives for climate studies, *Bull. Am. Meteorol. Soc.*, *72*, 1507–1520, 1991.

Gaffen, D. J., Historical changes in radiosonde instruments and practices (WMO/TD-541), *Instrum. and Observ. Methods Rep. 50*, 123 pp., World Meteorological Organization, Geneva, 1993.

Hawson, C. L., Meteorological Office practice for the application of radiation and lag corrections to temperatures measured by radiosonde MK IIB, *Meteorol. Mag.*, *85*, 75–78, 1956.

Hense, A., P. Krahe, and H. Flohn, Recent fluctuations of tropospheric temperature and water vapour content in the tropics, *Meteorol. Atmos. Phys.*, *38*, 215–227, 1988.

Huovila, S., and A. Tuominen, On the influence of radiosonde lag errors on upper-air climatological data in Finland 1951–1988, *Meteorol. Publ. 14*, 29 pp., Finnish Meteorological Institute, Helsinki, 1990.

Ivanov, A., A. Kats, S. Kurnosenko, J. Nash, and N. Zaitseva, WMO international radiosonde intercomparison phase III (Dzhambul, USSR, 1989) final report (WMO/TD-451), *Instrum. and Observ. Methods Rep. 40*, 135 pp., World Meteorological Organization, Geneva, 1991.

Kahl, J. D., D. J. Charlevoix, N. A. Zaitseva, R. S. Schnell, and M. C. Serreze, Absence of evidence for greenhouse warming over the Arctic Ocean in the past 40 years, *Nature*, *361*, 335–337, 1993.

Miyagawa, K., A quantitative analysis of day-night temperature differences observed by Japanese rawinsondes, *Tenki*, *2*, 38–48, 1990 (*NASA Tech. Transl. NASA-TT-21268*).

National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, United States Air Force, *U.S. Standard Atmosphere, 1976* (NOAA-S/T/76-1562), 227 pp., U.S. Government Printing Office, Washington, D. C., 1976.

Oort, A. H., and H. Liu, Upper-air temperature trends over the globe, 1958–1989, *J. Clim.*, *6*, 292–307, 1993.

Scrase, F. J., Application of radiation and lag corrections to temperatures measured with Meteorological Office radiosonde, *Meteorol. Mag.*, *1005*(85), 65–78, 1956.

Suzuki, S., and M. Asahi, Influence of solar radiation on the temperature measurement before and after the change of the length of suspension used for the Japanese radiosonde observation, *J. Meteorol. Soc. Jpn.*, *56*, 61–64, 1978.

Tarbell, T. C., and F. G. Tower, Radiation corrections used in the AFGWC stratospheric analysis models, *Rep. AFGWC/TN-80/004*, 16 pp., U.S. Air Force, Air Weather Service (MAC), Air Force Global Weather Central, Offutt AFB, 1980.

Teweles, S., and F. G. Finger, Reduction of diurnal variation in the reported temperatures and heights of stratospheric constant pressure surfaces, *J. Meteorol.*, *17*, 177–194, 1960.

Uddstrom, M. J., Solar radiation corrections for New Zealand and Australian radiosondes, *N. Z. Meteorol. Serv. Sci. Rep. 6*, 43 pp., New Zealand Meteorological Service, Wellington, 1984.

U.S. Department of Agriculture, Weather Bureau, Instructions for making aerological observations, (W.B. No. 1022), 94 pp., Circular P, Aerological Division, U.S. Government Printing Office, Washington, D. C., 1930.

U.S. Department of Agriculture, Weather Bureau, Instructions for making aerological observations by means of airplanes and sounding balloons, 85 pp., Circular P, Revised: Aerological Division, U.S. Government Printing Office, Washington, D. C., 1938.

U.S. Department of Commerce, Weather Bureau, Instructions for modulated audio frequency radiosonde observations, Circular P, 3rd ed., *Publ. 12-3912*, unnumbered pages, U.S. Government Printing Office, Washington, D. C., 1941. (Reprinted 1942).

U.S. Department of Commerce, Weather Bureau, Instructions for modulated audio frequency radiosonde observations, 98 pp., Circular P, 4th ed., U.S. Government Printing Office, Washington, D. C., 1943.

U.S. Department of Commerce, Weather Bureau, Radiosonde observation computation tables and diagrams, unnumbered pages, U.S. Government Printing Office, Washington, D. C., 1944.

U.S. Department of Commerce, Weather Bureau, Instructions for modulated audio frequency radiosonde observations (WBAN RAOB Manual), Circular P, 5th ed., 87 pp., U.S. Government Printing Office, Washington, D. C., (plus Supplement S-1 Radiosonde Observation Tables and Diagrams (WBAN), 51 pp., plus Addendum, 20 pp.), 1945.

U.S. Department of Commerce, Weather Bureau, Radiosonde observation computation tables and diagrams, Station Operations Division, unnumbered pages, U.S. Government Printing Office, Washington, D. C., 1946.

U.S. Department of Commerce, Weather Bureau, Radiosonde observation computation tables and diagrams, 73 pp., U.S. Government Printing Office, Washington, D. C. (plus Supplementary Tables A1 to A24), 1950.

U.S. Department of Commerce, Weather Bureau, Radiosonde observation computation tables and diagrams, 73 pp., U.S. Government Printing Office, Washington, D. C. (plus tables A3 and A4 plus Change No. 2, approximately 60 pp.), 1953.

U.S. Department of Commerce, Weather Bureau, Radiosonde observation computation tables and diagrams, 119 pp., U.S. Government Printing Office, Washington, D. C., 1956.

U.S. Department of Commerce, Weather Bureau, Manual of radiosonde observations (WBAN), Circular P, 7th ed., 184 pp., Washington, D. C. (includes revisions dated 1958, 1960, 1961, 1964, 1967, 1968), 1957.

U.S. Department of Commerce, Weather Bureau, Radiosonde observation computation tables and diagrams, 123 pp., U.S. Government Printing Office, Washington, D. C., 1960.

U.S. Department of Commerce, U.S. Weather Bureau, U.S. Department of the Air Force, and U.S. Department of the Navy, Radiosonde observation computation tables, 67 pp., U.S. Government Printing Office, Washington, D. C., 1966.

World Meteorological Organization, The compatibility of upper-air data: Part I, Research on compatibility of data from radiosondes, rocketsondes and satellites, by F. G. Finger and R. M. McInturff; Part II, The compatibility and performance of radiosonde measurements of geopotential height in the lower stratosphere for 1975–76, by E. A. Spackman, *WMO 512*, *Tech. Note 163*, 103 pp., 1978.

D. J. Gaffen, Air Resources Laboratory, NOAA Environmental Research Laboratories, 1315 East-West Highway, SSMCIII Room 3151, Silver Spring, MD 20910.

(Received June 8, 1993; revised November 8, 1993;
accepted November 8, 1993.)