Evaluation of the Effect of the Luers–Eskridge Radiation Adjustments on Radiosonde Temperature Homogeneity

IMKE DURRE, THOMAS C. PETERSON, AND RUSSELL S. VOSE

National Climatic Data Center, Asheville, North Carolina

(Manuscript received 9 July 2001, in final form 4 December 2001)

ABSTRACT

The effect of the Luers–Eskridge adjustments on the homogeneity of archived radiosonde temperature observations is evaluated. Using unadjusted and adjusted radiosonde data from the Comprehensive Aerological Reference Dataset (CARDS) as well as microwave sounding unit (MSU) version-d monthly temperature anomalies, the discontinuities in differences between radiosonde and MSU temperature anomalies across times of documented changes in radiosonde are computed for the lower to midtroposphere, mid- to upper troposphere, and lower stratosphere. For this purpose, a discontinuity is defined as a statistically significant difference between means of radiosonde–MSU differences for the 30-month periods immediately prior to and following a documented change in radiosonde type. The magnitude and number of discontinuities based on unadjusted and adjusted radiosonde data are then compared. Since the Luers–Eskridge adjustments have been designed to remove radiation and lag errors from radiosonde temperature measurements, the homogeneity of the data should improve whenever these types of errors dominate.

It is found that even though stratospheric radiosonde temperatures appear to be somewhat more homogeneous after the Luers–Eskridge adjustments have been applied, transition-related discontinuities in the troposphere are frequently amplified by the adjustments. Significant discontinuities remain in the adjusted data in all three atmospheric layers. Based on the findings of this study, it appears that the Luers–Eskridge adjustments do not render upper-air temperature records sufficiently homogeneous for climate change analyses. Given that the method was designed to adjust only for radiation and lag errors in radiosonde temperature measurements, its relative ineffectiveness at producing homogeneous time series is likely to be caused by 1) an inaccurate calculation of the radiation or lag errors and/or 2) the presence of other errors in the data that contribute significantly to observed discontinuities in the time series.

1. Introduction

One of the most pressing issues in climate change research today is the observed disparity between surface and tropospheric temperature trends. While near-surface temperatures are estimated to have warmed by 0.25°–0.4°C in the global mean since 1979, tropospheric temperatures as measured by satellites exhibit a change of 0° to +0.2°C over the same period [National Research Council (NRC) 2000, hereafter NRC 2000]. Radiosonde measurements of upper-air temperatures may assist in reconciling the records of surface and satellite-observed upper-air temperatures by providing both an independent check of the satellite observations and an extension of the upper-air temperature record back to at least the early 1960s.

Analyses of observed long-term climate change require data that are free of inhomogeneities such as those caused by changes in instrumentation, observing practices, and station location (Peterson et al. 1998). While considerable efforts have been made to identify and remove artificial biases from surface and satellite observations (Peterson et al. 1998; Christy et al. 2000), less progress has been made on improving the homogeneity of radiosonde data. Although several techniques for identifying and accounting for biases in radiosonde temperature data have been developed, the number and magnitude of adjustments made by these techniques vary considerably (Free et al. 2002). Therefore, any adjustment methodology must be carefully evaluated before the adjusted data are used for the calculation of upper-air temperature trends.

This paper presents an evaluation of the Luers–Eskridge method, a physically based approach to the problem of adjusting radiosonde temperatures for two common measurement errors: the so-called radiation and lag errors. Developed by Luers and Eskridge (1995, 1998) as part of the National Climatic Data Center's (NCDC's) Comprehensive Aerological Reference Dataset (CARDS) project, this method involves the application of numerical models that simulate the heat balance of various temperature sensors to the archived soundings; adjustments are made by replacing the reported tem-

Corresponding author address: Imke Durre, National Climatic Data Center, 151 Patton Avenue, Asheville, NC 28801.
E-mail: imke.durre@noaa.gov

perature at every level of every sounding with the corresponding temperature predicted by the appropriate model. In this study, the effect of the Luers–Eskridge adjustments on the homogeneity of the data is assessed by comparing time series of unadjusted and adjusted radiosonde temperature anomalies to temperature anomalies derived from the microwave sounding unit (MSU). The comparison focuses on the magnitudes of discontinuities in radiosonde–MSU temperature anomaly differences around times of transitions between radiosondes.

The remainder of this article is organized as follows. Sections 2 and 3 provide some background on homogeneity issues affecting radiosonde temperatures and a brief review of the Luers–Eskridge method. A description of the data and explanation of the comparison methodology employed here follow in sections 4 and 5. The results of the radiosonde–MSU comparisons are presented in section 6. The paper concludes with a discussion of the results in section 7 and a summary in section 8.

2. Homogeneity issues affecting radiosonde temperatures

Over the last several decades, vertical profiles of atmospheric temperature have been measured by balloon-borne radiosondes at least once daily (usually at 0000 and 1200 UTC) at locations around the world. During its 1- or 2-h ascent from the surface into the stratosphere, a radiosonde radio transmits its measurements to ground receiving stations where they are processed and sent to weather service offices and data centers for operational use. Primarily as a result of technological advances and financial considerations, radiosonde models, temperature sensors, ground equipment, observing practices, and data processing procedures have changed frequently over the period of record, introducing both random and systematic errors into the data (Schwartz and Doswell 1991; Gaffen 1994; Eskridge et al. 1995; Parker and Cox 1995).

One of the best-understood systematic errors that affects radiosonde temperature measurements is the so-called radiation error, which arises when the shortwave absorptivity and longwave emissivity of the instrument are different from those of the surrounding air (Brasefield 1948; Scrase 1954; Teweles and Finger 1960; Gaffen 1994; Luers and Eskridge 1995, 1998). Both theory and observations suggest that this error manifests itself in a systematic, diurnally varying bias in temperature measurements whose magnitude and sign vary with altitude, solar elevation angle, and the radiative properties of instruments. A commonly used method for quantifying the radiation error has been the comparison of diurnal temperature ranges measured by different instruments. Based on such comparisons as well as other empirical and theoretical analyses, the magnitude of the radiation error is estimated to increase with altitude, reaching a value of up to several degrees in the stratosphere.

Various instrument-specific procedures have been developed for adjusting radiosonde-measured temperatures for the radiation error on an operational basis (e.g., Scrase 1956; Teweles and Finger 1960). Such adjustments are generally applied during the initial data processing at ground receiving stations, using so-called radiation correction tables supplied by the radiosonde manufacturers. The accuracy of the operational radiation adjustments, however, remains uncertain. One reason for this uncertainty is the possibility that attempts to estimate the radiation error may be complicated by the effects of additional factors such as the shading of the radiosonde by the balloon, the pendulation of the radiosonde, the radiative effects of clouds and humidity, and the conduction and convection of heat to the temperature sensor (Teweles and Finger 1960; Luers and Eskridge 1995, 1998). Furthermore, the observed diurnal temperature range, from which the magnitudes of the adjustments are generally derived, can be explained in part by small, natural diurnal temperature fluctuations due to the solar tide. Similarly, the day–night temperature difference alone does not give an indication of the individual nighttime and daytime errors (Teweles and Finger 1960; Gaffen 1994). In addition, updates to the adjustment procedures have occasionally been developed, and the date of implementation of a given procedure at a particular station is not always known accurately (Gaffen 1994). Thus, despite the application of radiation adjustments on an operational basis, archived radiosonde data may contain discontinuities at times of changes in radiosondes and changes in ‘‘correction’’ tables.

Another source of error is the response time of the instrument to the temperature of the surrounding air (Brasefield 1948; Scrase 1954; Gaffen 1994; Luers and Eskridge 1995). This ‘‘lag error’’ results in an overestimation of the temperature in the troposphere as well as an underestimation inside inversion layers, most notably the stratospheric and nighttime near-surface inversions. Since newer instruments tend to exhibit a faster response time than older instruments, this bias may also contribute to inhomogeneities in the data. The magnitude of the lag error depends on the ventilation of the sensor, which decreases with height, and is generally smaller than the interannual variability of temperature (Gaffen 1994).

The effects of other types of biases are less well understood but nevertheless can significantly compromise the homogeneity of the data (Schwartz and Doswell 1991; Gaffen 1994; Parker and Cox 1995; Parker et al. 1997; Gaffen et al. 2000). Other sources of bias include changes or errors in observation time, the type of balloon used, the electronics and calibration of the temperature sensor, as well as the manual and automatic procedures used for data processing and transmission. Even changes in the length of the tether connecting the radiosonde to the balloon can cause an inhomogeneity by changing the ventilation of the radiosonde.

3. The Luers–Eskridge method for adjusting radiosonde temperatures

In an effort to remove radiation and lag errors from radiosonde temperature data, James Luers and Robert Eskridge designed ''temperature correction models'' for many of the major radiosondes used since 1960. Each model estimates the atmospheric temperature from the sensor-measured temperature by simulating the heat transfer processes that significantly affect the sensor (Luers and Eskridge 1995, 1998). In calculating the sensor's heat balance, the model takes into account the absorption of solar radiation as well as the absorption and emission of longwave radiation by the sensor, the conduction of heat between the sensor and its attachments, the convective heat transfer between the sensor and the surrounding air, and the lag in the sensor's response to its environment. Models for ducted sondes (i.e., radiosondes whose temperature sensor is housed inside one or two radiation shields) also include equations for heat transfer processes involving the outer and inner walls of the duct(s) as well as the ''ventilation air'' that passes across the sensor.

Several of the models for modern, unducted radiosondes have been compared using data from World Meteorological Organization (WMO) International Intercomparison Experiments (Nash and Schmidlin 1987) in which different types of radiosondes were flown on the same balloon. Based on these comparisons, the widely used VIZ and Vaisala RS-80 radiosondes may be the most accurate since, despite differing sources of error, output temperature profiles of the two models are in good agreement with each other (Luers and Eskridge 1995). As additional evidence for the accuracy of the adjustments, Luers and Eskridge (1995) provide examples in which the application of the radiation adjustments to the measurements of three differently colored VIZ thermistors mounted on the National Aeronautics and Space Administration (NASA) three-thermistor radiosonde yields temperature profiles that are very similar to each other. In each of the models for older, ducted radiosondes, the ventilation velocity through the duct is fixed at a value that ensures that, at a sample station, no discontinuity in the time history of 1200 minus 0000 UTC temperature differences remains when a new, unducted radiosonde is introduced.

As input, the models require the dimensions, geometry, and thermal properties of the sensor, observed vertical profiles of temperature and humidity, the launch time and rise rate of the radiosonde, latitude and longitude, ground albedo, the amounts and vertical distributions of clouds and aerosols, and information on which, if any, of the manufacturer-prescribed radiation adjustments were applied operationally. The sources for this information include the radiosonde manufacturers, data and station history information from the CARDS archive, as well as written documents and personal communication on the national observing practices of different countries. Since detailed observations of cloudiness are frequently not available, the amount and altitude of cloud cover are calculated based on changes in the vertical gradients of temperature and humidity measurements during the radiosonde ascent (Chernykh and Eskridge 1996).

In applying the adjustment to a particular station, the first and last dates of use of each radiosonde and operational radiation adjustments are determined from station history information and plots of stratospheric 1200 minus 0000 UTC temperature differences smoothed with a Kolmogorov–Zurbenko (KZ) filter (Zurbenko et al. 1996). The 1200–0000 UTC temperature differences are used based on the premise that an abrupt increase or decrease in the day–night temperature difference at stratospheric levels is indicative of a change in the magnitude of the radiation error associated with the introduction of a new radiosonde. In cases in which the type of radiosonde or operational radiation adjustments used are not known accurately, the number of possible radiosonde types is narrowed down based on the location of the station, period of record in question, and manufacturing dates of radiosondes. From the resulting limited list of models, that temperature adjustment model is chosen that is most effective at removing discontinuities in the 1200–0000 UTC temperature difference time series. When the actual launch time and rise rate cannot be determined from the data and metadata, as is usually the case at U.S. stations before the 1980s and at stations outside the United States, they are estimated based on stated national practices or average values computed from portions of the station's record for which sufficient information is available.

If any radiation adjustments have been made operationally, estimates of these adjustments are removed before the new adjustments are calculated. Next, the data for each portion of the record during which the same radiosonde was used are processed by the applicable Luers–Eskridge temperature adjustment model, replacing the reported sensor-measured temperature with the model-predicted temperature at each level of each sounding. Finally, the geopotential heights are recalculated to ensure that the temperatures and heights of each sounding are consistent with hydrostatic balance. The effectiveness of the adjustments is evaluated by examining the time series of KZ-filtered 1200–0000 UTC temperature differences at the highest usable pressure level for discontinuities.

Among the various methods for adjusting radiosonde temperature data that have been developed (Free et al. 2002), the Luers–Eskridge method is unique in that it relies neither on statistical techniques nor on satellite measurements for determining the magnitudes of the adjustments. This characteristic appears to be advantageous when producing a dataset of upper-air temperatures suitable for a wide range of climate studies since the adjustments are not affected by long-term trends in the data and are independent of the satellite record. On the other hand, the Luers–Eskridge method was designed to calculate only radiation and lag errors and, therefore, is unable to remove other types of errors (Luers and Eskridge 1998). Furthermore, the effects of additional inhomogeneities in the data as well as the method's requirement for information that is generally not archived may limit the method's ability to accurately compute radiation and lag error adjustments.

4. Data

The data used for the radiosonde–MSU comparisons presented in this article include MSU version-d monthly temperature anomalies for the period 1979–99 as well as unadjusted and adjusted soundings and station history information from the CARDS data archive.

a. Radiosonde data

The CARDS database (Eskridge et al. 1995) consists of historical records of mostly twice-daily (0000 and 1200 UTC) soundings from more than 2500 stations. The data have been quality controlled for gross errors by complex quality control procedures developed as part of the CARDS project (Alduchov and Eskridge 1996). These data are referred to as unadjusted radiosonde data in this paper. At the time of this analysis, the Luers–Eskridge adjustments had been applied to quality-controlled data from 83 stations, most of which are either active U.S. National Weather Service stations or part of the core subset chosen by Wallis (1998). The period of record and completeness of the data vary considerably from station to station. For the purpose of this study, only data from 1979 onward are considered since the MSU measurements are not available until 1979.

b. MSU data

Deep-layer MSU version-d temperature anomalies for the lower to midtroposphere (T2LT), mid- to upper troposphere (T2, MSU channel 2), and stratosphere (T4, MSU channel 4) are available on a global 2.5° × 2.5° grid (Christy et al. 2000, available online at nsstc.uah.edu/data/msu). Currently, the MSU record used in this study consists of measurements taken by microwave sounding units flown on nine different National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites [*Television Infrared Observational Satellite* (*TIROS-N*) and *NOAA-6*, *-7*, *-8*, *-9*, *-10*, *-11*, *-12*, and *-14*]. The unprocessed MSU observations are affected by a gradual loss in altitude of each satellite, a gradual change in local time of satellite observations, variations in sensor gain (i.e., the ratio of the perceived signal to the actual signal), and intersatellite biases. In an effort to remove these errors, Christy et al. (2000) have applied a number of adjustment procedures to the data.

5. Comparison methodology

The homogeneity of unadjusted and adjusted radiosonde temperature data is assessed by comparing time series of radiosonde temperature anomalies to temperature anomalies derived for the same location from the MSU. To facilitate the comparison between the twice-daily radiosonde measurements available at individual levels and the vertically averaged monthly MSU temperature anomalies, vertical averages of the radiosonde measurements are calculated for the three atmospheric layers covered by MSU, defined above. This computation, as well as the production of monthly anomaly time series from the twice-daily observations, is accomplished using a software application known as the Climatological Averaging of Temperature Soundings (CATS), which was developed by William Norris and John Christy at the University of Alabama at Huntsville. The change in the mean radiosonde–MSU difference across the time of a transition between radiosondes is then used as a measure of the discontinuity introduced by the instrument change.

a. Simulation of MSU temperatures with radiosonde data

In order to generate ''simulated-MSU'' time series of monthly anomalies for the lower to midtroposphere, mid- to upper troposphere, and lower stratosphere from radiosonde observations, the CATS program first uses linear interpolation in time and pressure to fill in temporal and vertical gaps in the temperature measurements. Next, it computes vertical averages of the temperatures of each sounding using a static MSU weighting function for each of the three atmospheric layers. The use of a static weighting function does not take into account the varying effects of humidity that Spencer and Christy (1992a,b) have demonstrated to be negligible. The CATS program then calculates anomalies relative to the annual cycle and finally computes monthly means from the daily anomalies. Details on CATS can be found in the CATS documentation and source code available online at nsstc.uah.edu/data/outgoing/norris/cats.

The CATS interface permits the user to choose values for the minimum number of ''valid'' (observed + interpolated) temperatures required for a monthly mean (min_obs), the maximum number of consecutive missing observations that may be interpolated (max_span), and the minimum height a sounding must reach in order to be considered (sounding_top, in mb). The parameter sounding_top was set to 300 mb for computing simulated-MSU temperature anomalies for layer 2LT, to 50 mb for channel 2, and to 30 mb for channel 4. These values correspond to approximately the 99th, 95th, and

87th percentiles of the respective MSU weighting functions. The peaks of the atmospheric portions of these weighting functions are located around 637.5, 337.5, and 57.5 mb, respectively. For the other two parameters, the values min_obs = 20 and max_span = 10 were chosen in an effort to create sufficiently complete time series of relatively robust monthly means for comparison with the MSU data. In most cases, the reference period of 1979–98 is used as a basis for calculating anomalies. When data are not available for the entire 20-yr period, only the 7-yr period around the date of a documented radiosonde change are used. Sensitivity experiments indicate that varying the values of any of these parameters does not significantly impact the results of this study.

b. Selection of radiosonde transitions

A radiosonde transition was included in the analysis if 1) the transition occurred at least 3 yr after the beginning of the satellite record in January 1979 and at least 3 yr before the end of the station's record, 2) no other radiosonde change occurred within 3.5 yr of this transition, and 3) lower-tropospheric simulated-MSU temperature anomalies for both 0000 and 1200 UTC could be obtained for at least 70% of the months during months 7–36 before the transition and months 7–36 after the transition. These criteria yield a total of 36 suitable transitions that are listed in the appendix. While sufficient data are available for all of these transitions in the lower to midtroposphere, the number of samples is limited to 19 in the mid- to upper troposphere and 11 in the lower stratosphere. The smaller number of suitable transitions at higher levels in the atmosphere is due to the increase in the frequency of gaps with altitude in the radiosonde data. When the date of a change in radiosonde is known only to the nearest year, it is arbitarily assigned to June of that year. The 6-month window that is left before and after the time of radiosonde transition insures that such uncertainties in the date of radiosonde change do not impact the analysis.

c. Analysis of radiosonde–MSU differences

For a particular station and atmospheric layer, the appropriate time series of MSU temperature anomalies at the grid point nearest the station is subtracted from the corresponding time series of radiosonde-simulated MSU temperature anomalies to form a radiosonde–MSU difference (RMD) series. The magnitude of the transition-related RMD ''jump'' is then calculated by subtracting the 30-month mean RMD for months 7–36 before the transition from the mean RMD for months 7–36 after the transition. This computation is performed separately for unadjusted and adjusted radiosonde data and for the lower to midtroposphere, the mid- to upper troposphere, and the lower stratosphere using only those months in a time series for which MSU temperature anomalies as well as anomalies of unadjusted and adjusted 0000 and 1200 UTC radiosonde temperatures are available. The statistical significance of each jump is determined using a *t* test in conjunction with Leith's (1973) formula for calculating the number of degrees of freedom.

Although Christy et al. (2000) have attempted to remove systematic biases from the MSU data, small errors due to these sources are likely to remain in the data and other, as yet undiscovered, errors may be present (Hurrell et al. 2000; NRC 2000; Stendel et al. 2000). In particular, any lingering intersatellite biases could introduce abrupt discontinuities into the MSU time series and thereby adversely impact the effort to assess the homogeneity of radiosonde data based on radiosonde–MSU differences. However, as will be shown in the following section, examination of RMD time series does not reveal any striking discontinuities at times of satellite changes. Furthermore, the effect of any inhomogeneities in the MSU data on the results of this study should be reduced significantly when the results are averaged relative to the dates of radiosonde transitions, which occur at various times throughout the period of record examined (see the appendix). Although such averaging would not eliminate the effects of any potential global-scale long-term drift in the MSU, inspection of the time series of radiosonde–MSU differences indicates that such a trend, if it exists, is likely to be considerably smaller in magnitude than the discontinuities introduced by changes in radiosondes. Thus, if radiation and lag errors are the largest sources of error in radiosonde temperature measurements, and the Luers–Eskridge adjustments are effective at removing these errors, then the magnitudes of the radiosonde transition-related RMD jumps should be systematically smaller when adjusted radiosonde temperatures are used than when unadjusted data are used. In addition, there should be few statistically significant discontinuities in the radiosonde–MSU differences based on adjusted radiosonde measurements at times of radiosonde transitions.

6. Results of the radiosonde–MSU comparisons

Figure 1 shows radiosonde–MSU differences based on unadjusted and adjusted radiosonde temperatures averaged over all stations where a change from a VIZ to a Vaisala RS-80 radiosonde has taken place. Because the VIZ and RS-80 are two of the most commonly used radiosondes, transitions between them account for a majority of the transitions analyzed (17 in the lower to midtroposphere, 13 in the mid- to upper troposphere, and 9 in the lower stratosphere). For each of the three atmospheric layers, values are plotted on a time axis extending from 36 months before to 36 months after a change in radiosonde. Thus, a dot at time zero, for example, represents the average RMD during the month of a documented change in instrumentation.

In the lower stratosphere, the RMDs based on unadjusted radiosonde data (Fig. 1a, top) are characterized

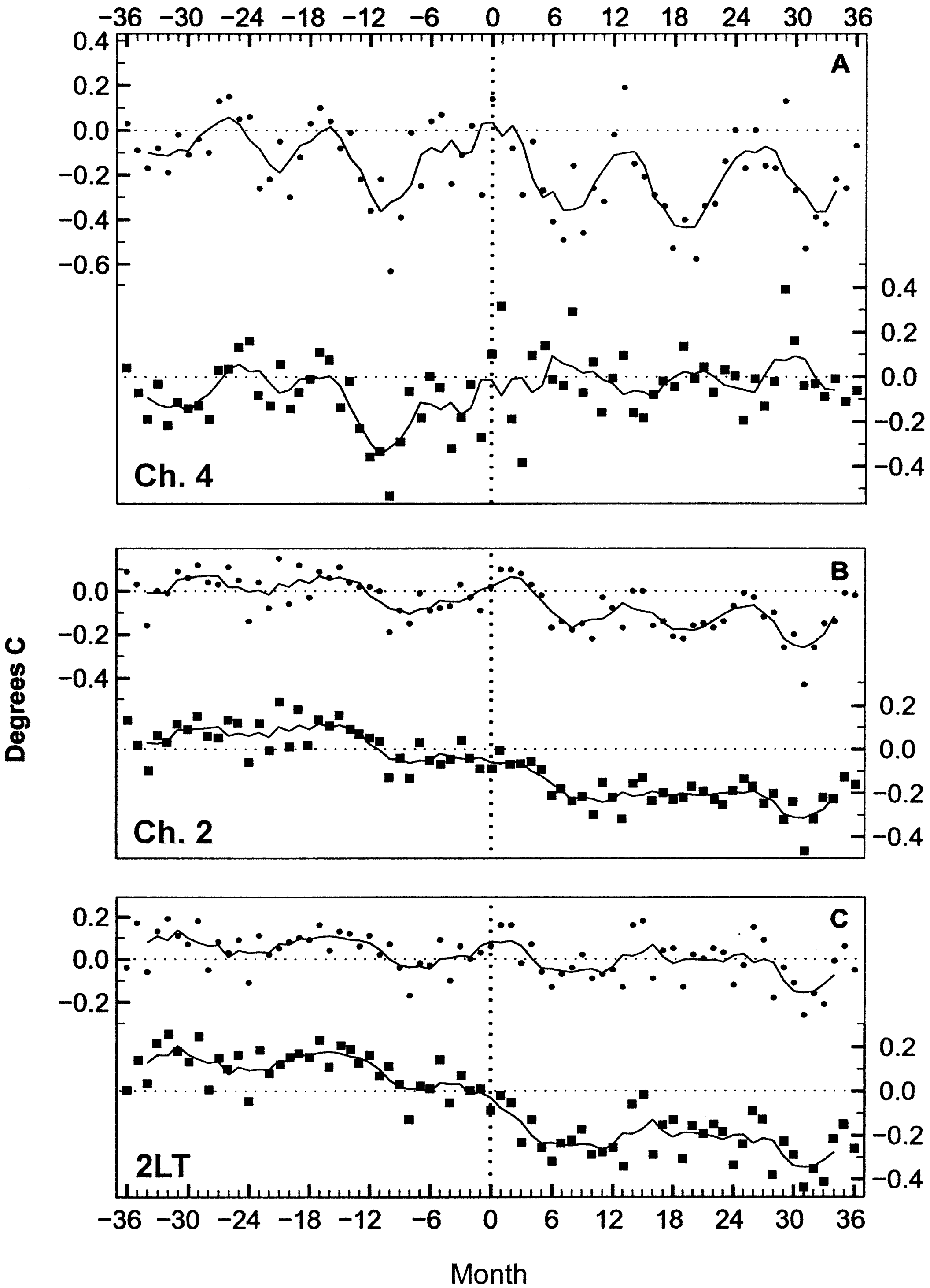

FIG. 1. Radiosonde–MSU temperature anomaly differences (in °C) relative to the date of transition from a VIZ to a Vaisala RS-80 radiosonde for (top) unadjusted and (bottom) adjusted radiosonde data in (a) the lower stratosphere (MSU channel 4; 9 transitions); (b) the mid- to upper troposphere (channel 2; 13 transitions); and (c) the lower to midtroposphere (layer 2LT; 17 transitions). Time along the horizontal axis is expressed in months relative to the date of radiosonde change. Each time series is shown as individual monthly values (dots and squares) and smoothed with a 5-month running mean (solid lines).

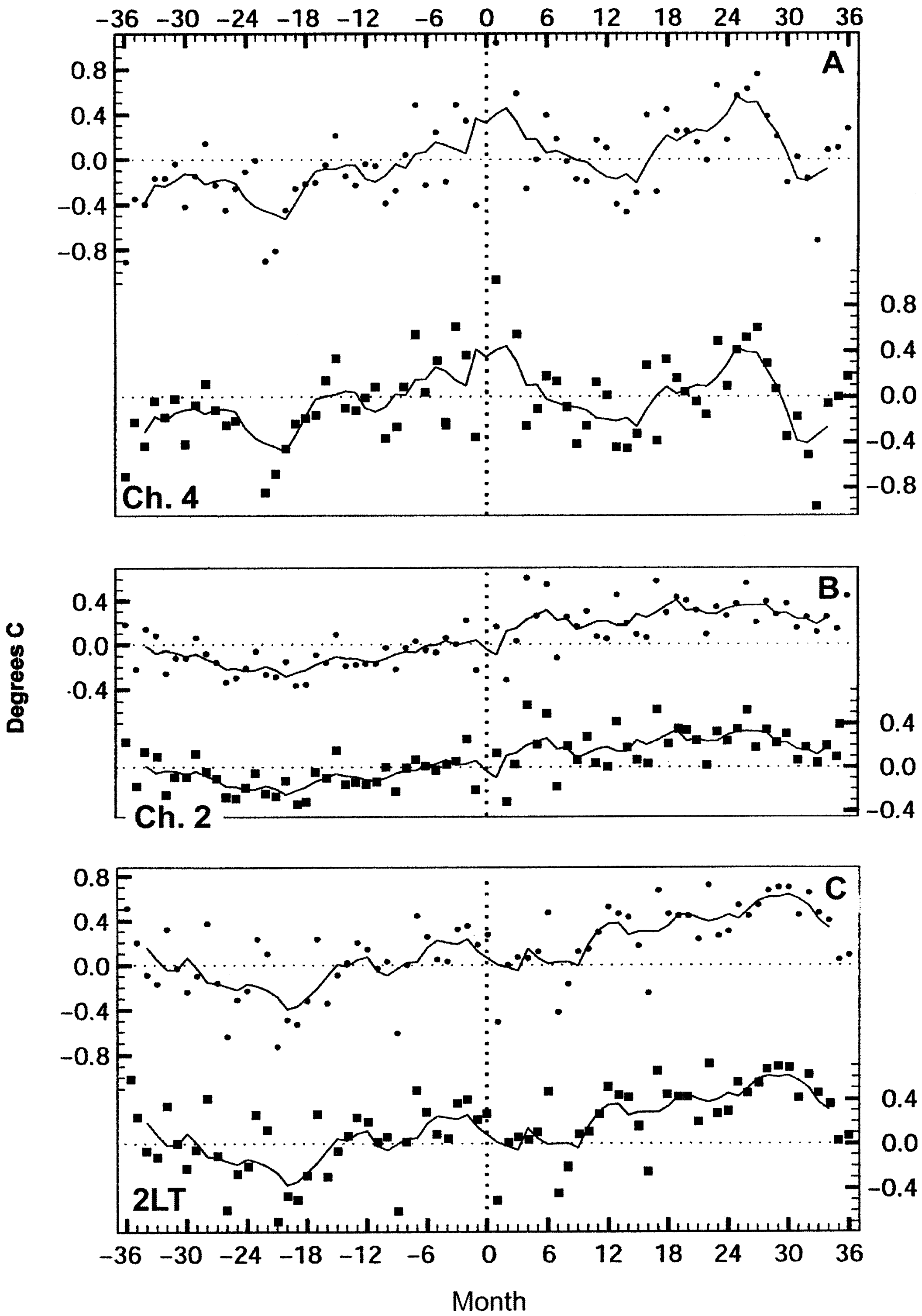

FIG. 2. Same as Fig. 1, but for transitions between the RKZ-5 and Mars radiosondes. The curves are based on (a) one transition in the lower stratosphere (b) three transitions in the mid- to upper troposphere, and (c) five transitions in the lower to midtroposphere.

by large fluctuations that increase in amplitude and become more periodic after the change from VIZ to Vaisala RS-80. In addition, values appear to be slightly more negative after the transition. Examination of the radiosonde and MSU time series (not shown) reveals that the transition-related changes in the character of the RMD curve stem primarily from variations in the radiosonde temperature anomalies. The effect of the Luers–Eskridge adjustments is to remove much of the posttransition variability, but leave the pretransition variability unchanged (Fig. 1a, bottom). As a result, the RMD curve based on adjusted radiosonde data is smoother but also appears to exhibit a decrease in variability and a slight tendency toward less negative values across the time of transition.

For the mid- to upper troposphere, the mean RMD based on unadjusted data becomes slightly more negative around the time of a change in radiosonde (Fig. 1b, top), indicating a cooling of the radiosonde temperatures relative to the MSU temperatures. Such a change is not apparent in the corresponding curve for the lower to midtroposphere (Fig. 1c, top). However, after the application of the Luers–Eskridge adjustments, mean RMD values in both tropospheric layers are clearly more negative during the Vaisala RS-80 period (to the right of month 0) than during the VIZ period. Thus, it appears that for VIZ-to-Vaisala RS-80 transitions, the mean transition-related change in tropospheric radiosonde–MSU temperature differences is amplified, rather than reduced, by the Luers–Eskridge adjustments.

Another set of transitions analyzed in this study involves the RKZ-5 and Mars radiosondes used at many stations in the area of the former Soviet Union. Although these two radiosondes carry identical thermistors, the radiative properties of the mounts to which the thermistors are attached differ (Luers and Eskridge 1998; Gaffen et al. 2000). The bright antiradiation coating of the mount of the Mars radiosonde absorbs less shortwave and longwave radiation than the darker mount of the RKZ-5. As a result, the Mars thermistor is less sensitive to solar and infrared radiation than the RKZ-5 thermistor (Luers and Eskridge 1998).

Curves analogous to those presented in Fig. 1 are shown for transitions between the RKZ-5 and Mars radiosondes in Fig. 2. The plot for the lower stratosphere (Fig. 2a) is based on only one transition (at Kiev, Ukraine), whereas the plots for the mid- to upper troposphere (Fig. 2b) and lower to midtroposphere (Fig. 2c) are based on three and five transitions, respectively. Figure 2 suggests that the transition from RKZ-5 to Mars is associated with a warming of radiosonde temperature anomalies relative to the MSU in all three atmospheric layers. While the adjustments appear to somewhat reduce the amplitude of this warming in the lower stratosphere (Fig. 2a) and mid- to upper troposphere (Fig. 2b), they do not seem to have a significant impact in the lower to midtroposphere (Fig. 2c).

More quantitative measures of the effects of the Luers–Eskridge adjustments are provided in Table 1 for various groups of radiosonde transitions (see Table A1 for individual transitions). The numbers suggest that the adjustments frequently reduce the magnitude of the transition-related change in radiosonde–MSU differences in the lower stratosphere. Nevertheless, due to an increase in the magnitude of the RMD jump at some stations and/or a decrease in the variability of RMDs by the adjustments, the RMD jumps based on adjusted radiosonde data are statistically significant at the 99% level in 10 out of the 11 cases analyzed for this layer.

In both tropospheric layers, the adjustments significantly amplify the magnitudes of RMD discontinuities associated with transitions between VIZ and Vaisala RS-80 radiosondes, as expected from Fig. 1. For transitions between RKZ-5 and Mars, some reduction in the RMD jump is seen in the mid- to upper troposphere, yet significant jumps remain at two of the three transitions. In all other cases, the overall effect of the adjustments on the homogeneity of radiosonde–MSU differences in the troposphere is negligible. The net result in the average over all available transitions is that both the magnitude of the RMD jumps and the number of significant jumps in the troposphere are slightly larger for adjusted radiosonde data than for unadjusted data.

In order to investigate whether the transition-related discontinuities in radiosonde–MSU differences are attributable to inhomogeneities in the MSU data at times of changes between satellites, time series of RMDs averaged over seven U.S. stations are plotted for the period 1979–99 in Fig. 3. Besides featuring reliable metadata

TABLE 1. Statistics on changes in RMDs at times of radiosonde transitions. The number of transitions (NT) is analyzed. Jump is the magnitude of the average change in 30-month-mean RMD (in °C) from months 7–36 before to months 7–36 after a transition. Nsig is the number of jumps that are significant at the 99% confidence level. Jump and Nsig are shown for RMDs based on unadjusted (Una) and adjusted (Adj) radiosonde data. Ninc is the number of jumps whose magnitude increases as a result of the Luers–Eskridge adjustments; Ndec is the number whose magnitude decreases.

Transition	NT	Jump Una/Adj	Nsig Una/Adj	Ndec	Ninc
Lower stratosphere (channel 4)					
VIZ to Vaisala RS-80	9	0.30/0.21	5/8	5	4
RKZ-5 to Mars	1	0.74/0.63	1/1	1	0
Others	1	0.01/0.10	0/1	0	1
All	11	0.31/0.24	6/10	6	5
Mid- to upper troposphere (channel 2)					
VIZ to Vaisala RS-80	13	0.21/0.31	11/13	3	10
RKZ-5 to Mars	3	0.46/0.36	3/2	3	0
Others	3	0.32/0.36	1/3	1	2
All	19	0.27/0.32	15/18	7	12
Lower to Midtroposphere (layer 2LT)					
VIZ to Vaisala RS-80	17	0.24/0.37	14/15	4	13
RKZ-5 to Mars	5	0.46/0.42	5/5	4	1
Others	14	0.33/0.32	9/9	6	8
All	36	0.30/0.36	28/29	14	22

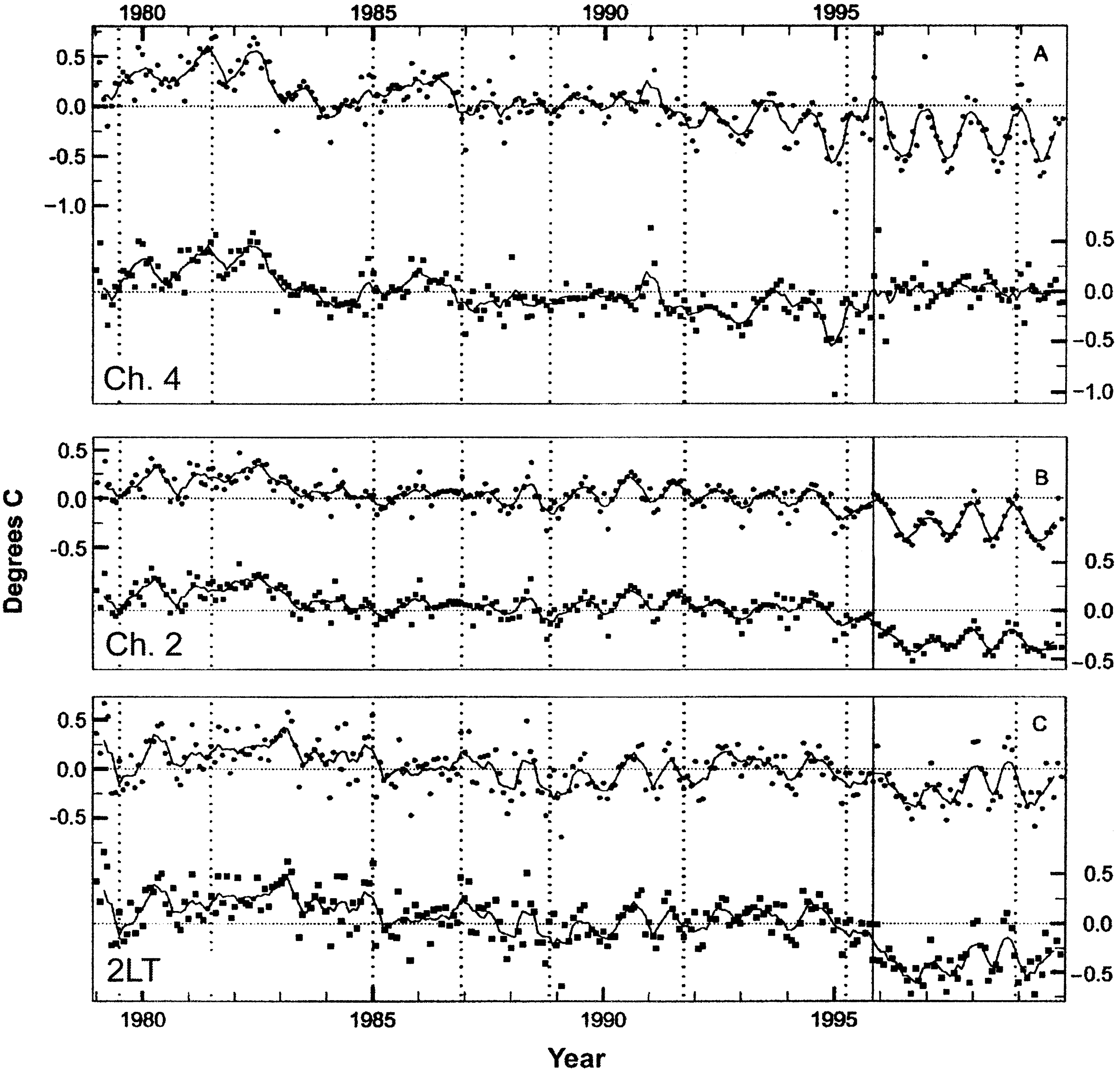

FIG. 3. Time series of radiosonde–MSU temperature anomaly differences averaged over seven stations in the United States for the period 1979–99 in (a) the lower stratosphere, (b) the mid- to upper troposphere, and (c) the lower to midtroposphere. In each panel, the top curve is based on unadjusted radiosonde data, and the bottom curve is based on adjusted radiosonde measurements. Dots and squares indicate individual monthly values, and solid lines represent time series smoothed with a 5-month running mean. Dotted vertical lines indicate the dates of changes in satellite, and the solid vertical line indicates the approximate time of transition from a VIZ to a Vaisala RS-80 radiosonde. The stations include Kotzebue (WMO number 70133), King Salmon (70326), Kodiak (70350), Sterling/Washington (72403), Denver (72469), International Falls (72747), and Lihue (91165). These stations were the only U.S. stations that had been adjusted, that had both 1200 and 0000 UTC data back to 1979 and that had Nov 1995 transitions from VIZ to Vaisala RS-80 as their only change in instrumentation during the 1979–99 period.

and relatively complete records of radiosonde measurements in both the troposphere and stratosphere, each of these stations underwent a switch from a VIZ to a Vaisala RS-80 radiosonde in November 1995, as indicated by the solid vertical line in Fig. 3. Since the correlation coefficient between radiosonde and MSU temperature anomalies (not shown) is greater than 0.85 in all three atmospheric layers at these stations and greater than 0.9 in all but two of these cases, the radiosonde measurements appear to capture much of the same variability that is captured by the MSU.

The time series of both unadjusted and adjusted RMDs in Fig. 3 are rather smooth across times of satellite changes (indicated by the dotted vertical lines). However, particularly the time series based on adjusted radiosonde data in the troposphere (Figs. 3b and 3c, bottom) exhibit a distinct drop when the radiosonde changes. Considering this finding, it appears that discontinuities in radiosonde–MSU differences at times of radiosonde transitions can be attributed primarily to changes in the radiosonde observations rather than inhomogeneities in the MSU data.

One distinct feature of Fig. 3, as well as Fig. 1, is the seasonal cycle in the radiosonde minus MSU difference. Both the radiosonde and MSU data used in all figures already had the seasonal cycle removed by turning them into anomalies relative to their long-term monthly mean values before the MSU was subtracted from the radiosonde temperature. The seasonal cycle in the RMD, therefore, is an indication that the differences between one radiosonde type and another vary depending on the time of year. In the Fig. 3 example, the Vaisala RS-80 is much cooler than the VIZ during the summer while only slightly cooler during the winter. Given that the solar elevation angle is larger during the summer, the difference in the seasonal cycles of the two radiosondes is consistent with the fact that radiation adjustments are applied operationally to the RS-80 measurements, but not to measurements taken by the VIZ. Thus, a seasonally varying adjustment profile is required for homogenizing the VIZ and Vaisala records. The Luers–Eskridge radiation models produce such a profile. Nevertheless, a seasonal cycle, albeit reduced in amplitude, remains in the RMD time series based on adjusted radiosonde data.

7. Discussion

The comparison of unadjusted and adjusted radiosonde temperature anomalies to anomalies derived from the MSU indicates that significant inhomogeneities remain in the radiosonde temperature data after the Luers–Eskridge adjustments have been applied. The results appear to be somewhat more favorable for the lower stratosphere than for the troposphere, with a smaller average magnitude of the RMD jump and reduced variability in RMDs in the adjusted data. This may be expected considering the rather large radiation errors in this layer and the fact that Luers and Eskridge evaluate their results by looking for jumps in the day–night temperature difference at the highest available level. It should be noted, however, that even in the stratosphere, increases in the RMD jump as a result of the adjustments are reported at nearly half of the stations analyzed.

Judging from the variety of dates of radiosonde transitions as well as the relative homogeneity of radiosonde–MSU differences during periods without changes in radiosondes, significant RMD jumps at times of radiosonde transitions appear to be related primarily to the change in radiosonde rather than to the introduction of a new satellite. The continuous increase in radiosonde–MSU differences in Fig. 2, however, raises the question as to whether a long-term drift in the MSU is contributing to the results for the transition from RKZ-5 to Mars radiosondes. A drift in the MSU data, if it exists, is likely to be global in nature (Stendel et al. 2000). Therefore, if the MSU data are responsible for the trend seen in Fig. 2, one would expect this trend to be common to many, if not all, time series of radiosonde–MSU differences used in this study. Neither the RMD time series for the individual stations that contribute to Fig. 2 (not shown) nor the average time series for selected U.S. stations in Fig. 3 reveal such a common trend. Thus, any remaining long-term trend in the MSU is likely to be considerably smaller than the changes in radiosonde–MSU differences associated with transitions between radiosondes. The trendlike appearance of the curves in Fig. 2 could be the result of inaccurate station history information. If, for example, the actual date of a change in radiosonde differs from the reported date at one or more stations, then the averaging of time series for these stations relative to the reported date could produce a trend rather than a more abrupt discontinuity that is generally expected in conjunction with the introduction of a new radiosonde. Similarly, a gradual phasing in of the Mars radiosonde in favor of the RKZ-5 around the reported date of change could result in such a trend.

The fact that a considerable number of large discontinuities remain in the adjusted tropospheric data suggests that inhomogeneities unrelated to radiation and lag errors are present in the radiosonde time series. Possible causes for these inhomogeneities include any changes in the practices of observing, processing, and reporting radiosonde measurements (Gaffen 1994; Parker et al. 1997). Not only can these inhomogeneities not be removed by the Luers–Eskridge adjustments (Luers and Eskridge 1998), but they may also complicate the computation of appropriate radiation and lag error adjustments.

The effectiveness of the adjustments in improving the homogeneity of radiosonde temperature data may also be compromised by inaccurate metadata. Imprecise information on the dates of introduction of new radiosondes and operationally applied radiation correction tables can result in the application of an inappropriate radiation model over a period of days to years. Additional uncertainties in the adjustments are introduced by the estimation of parameters such as cloudiness and balloon rise rate. The skill of predicting the type and distribution of clouds from changes in vertical gradients of humidity and temperature may be sensitive to inaccuracies of humidity measurements at low temperatures and tends to decrease when thin cloud layers or cloud amounts of less than 20% are involved (Chernykh and Eskridge 1996). The balloon rise rate, a parameter that can rarely be inferred from an archived sounding, is used to derive the altitude of the radiosonde as a function of time and, therefore, influences the calculation of both the lag error and the time of exposure of the sensor to sunlight. Significant differences between the balloon speeds estimated by Luers and Eskridge and the actual rise rates, which vary based on local practices, flow patterns, and the type of balloon used, could lead to significant errors in the calculated temperature adjustments, particularly when the radiosonde is launched near the time of sunrise or sunset (Scrase 1954; Teweles and Finger 1960; Luers and Eskridge 1995, 1998). Sensitivity analyses conducted by Luers and Eskridge (1995, 1998) indicate that the sensitivity of their adjustments to variations in cloud cover and rise rate depends on the radiation model used. Thus, uncertainties due to the estimation of cloudiness and rise rate may contribute to inhomogeneities remaining in adjusted radiosonde temperature data.

8. Summary and conclusions

In this paper, the performance of the Luers–Eskridge adjustments to radiosonde temperature observations has been evaluated by comparing the homogeneity of radiosonde minus MSU temperature anomaly differences based on unadjusted and adjusted radiosonde data. The results of this comparison suggest that significant inhomogeneities remain in the radiosonde data after the Luers–Eskridge adjustments have been applied, thus limiting the value of the adjusted data in climate change studies. Although discontinuities at times of satellite changes as well as a long-term trend may remain in the MSU time series, the effects of any such problems on the time series of radiosonde–MSU differences appear to be small compared to the effects of transitions between radiosondes.

The inability of the Luers–Eskridge adjustments to produce homogeneous radiosonde temperature time series is likely to be the result of 1) an incorrect calculation of the radiation and/or lag errors, either due to inaccuracies in the models themselves or due to the frequent lack of reliable metadata, and/or 2) the presence of other errors in the data that contribute significantly to the discontinuities in the time series. Various other groups of scientists have been developing adjustment methodologies that show promise for significantly improving the homogeneity of archived radiosonde temperature data. Rigorous evaluations of the various procedures as well as comparative analyses such as those presented by Free et al. (2002) will help to establish whether one or more of these methods produce time series suitable for climate change studies.

Acknowledgments. This work was performed while Imke Durre held a National Research Council Associateship Award at the National Climatic Data Center. The work was supported by the National Climatic Data Center, NOAA's Climate and Global Change Climate Change Data and Detection Program, and the Office of Biological and Environmental Research of the U.S. Department of Energy. The authors acknowledge the anonymous reviewers whose comments greatly improved this manuscript.

APPENDIX

Station-by-Station Results

To supplement the results presented in the main body of the text, Table A1 lists transition-related changes in radiosonde–MSU temperature anomaly differences for each individual transition analyzed. As described in section 5, the transition-related RMD change is expressed as the absolute magnitude of the difference between the 30-month RMD means for months 7–36 before the transition and months 7–36 after the transition. The 6-month window that is left before and after the time of transition allows for uncertainties in the reported date of radiosonde change. The sign of the RMD change is rarely affected by the Luers–Eskridge adjustments and therefore information on this is omitted.

TABLE A1. Radiosonde transition and transition-related changes in radiosonde–MSU differences (in °C). Results are given for radiosonde–MSU differences based on unadjusted (Una) and adjusted (Adj) radiosonde data in the lower stratosphere (channel 4), mid- to upper troposphere (channel 2), and lower to midtroposphere (layer 2LT). Changes significant at the 99% confidence level are printed in boldface type. Blank cells indicate that the amount of data for the corresponding transition and atmospheric layer is insufficient. Station ID is the WMO station number. Lat and Long are the latitude (°N) and longitude (°E) of the station, rounded to the nearest degree. Month/Yr is the date (month/year) of radiosonde change. See text for further explanation.

Station ID	Station name	Lat	Lon	Month/Yr	Channel/layer 4 Una/Adj	Channel/layer 2 Una/Adj	Channel/layer 2LT Una/Adj
				VIZ to Vaisala RS-80			
04018	Keflavik	64	−23	1990			**0.12**/**0.42**
70133	Kotzebue	67	−163	Nov 1995	0.13/**0.23**	0.07/**0.19**	0.06/**0.30**
70326	King Salmon	59	−157	Nov 1995	0.17/**0.39**	**0.23**/**0.32**	**0.37**/**0.61**
70350	Kodiak	58	−152	Nov 1995	**0.33**/**0.58**	**0.11**/**0.18**	**0.29**/**0.53**
71600	Sable Island	44	−60	Dec 1994	0.01/**0.09**	0.05/**0.17**	**0.24**/0.04
71816	Goose Bay	53	−60	Jan 1994		**0.07**/**0.18**	**0.31**/0.01
71925	Cambridge Bay	69	−105	Jul 1994	**0.33**/0.04	**0.14**/**0.12**	**0.16**/**0.11**
71926	Baker Lake	64	−96	May 1995		**0.34**/**0.53**	**0.37**/**0.58**
71934	Ft. Smith	60	−112	Feb 1994		**0.09**/**0.36**	0.13/**0.42**
72403	Sterling/Washington	39	−77	Nov 1995	**0.25**/**0.16**	**0.20**/**0.34**	0.09/**0.23**
72469	Denver	40	−105	Nov 1995	**0.17**/**0.13**	**0.33**/**0.44**	**0.37**/**0.57**
72747	Intern. Falls	49	−93	Nov 1995	0.16/**0.06**	**0.18**/**0.38**	**0.18**/**0.50**
91165	Lihue	22	−159	Nov 1995	**1.14**/**0.25**	**0.46**/**0.42**	**0.20**/**0.43**
91334	Truk	7	152	Dec 1995			**0.30**/**0.55**
91408	Koror	7	134	Dec 1995			**0.18**/**0.43**
91765	Fatuna Island	−14	−171	Dec 1995			**0.24**/**0.46**
93844	Invercargill	−46	168	Apr 1989		**0.48**/**0.34**	**0.43**/**0.18**
				RKZ-5 to Mars			
21432	O. Kotel'nyy	76	138	Oct 1986		**0.47**/**0.40**	**0.71**/**0.64**
21982	O. Vrangelya	71	−179	Sep 1986		**0.31**/**0.13**	**0.32**/**0.19**
23418	Pechora	65	57	Nov 1984			**0.26**/**0.22**
24944	Olekminsk	60	120	Aug 1986			**0.80**/**0.84**
33345	Kiev	50	30	Apr 1984	**0.74**/**0.63**	**0.16**/0.56	**0.21**/**0.18**
				Vaisala RS-21 to Vaisala RS-80			
04339	Soresbysund	70	−22	Oct 1985			**0.31**/**0.27**
04360	Angmagssalik	66	−38	Nov 1983			0.10/0.10
16245	Pratica di Mare	42	12	Oct 1986			**0.25**/**0.42**
				Vaisala RS-18 to Vaisala RS-80			
02465	Stockholm	59	18	1989			0.06/0.07
04220	Egedesminde	69	−53	Feb 1985			**0.53**/**0.50**
				A22 to MRZ			
24266	Verkhoyansk	68	133	Nov 1990			**0.50**/**0.32**
				Diamond-Hinman to VIZ			
93844	Invercargill	−46	168	1982			**0.26**/**0.27**
				Mars to MRZ			
33345	Keiv	50	30	Jan 1988	0.01/**0.10**	**0.91**/**0.89**	**0.94**/**0.96**
				Philips-MK-I to Vaisala RS-80			
94672	Adelaide	−35	139	1989		0.03/**0.08**	**0.18**/0.06
				RKZ-2 to Mars			
20674	O. Dikson	74	80	May 1986			0.00/0.01
				U.S.W.B.-Electronic to VIZ			
71845	Pickle Lake	51	−90	1982		0.01/**0.10**	0.13/0.14
				VIZ to Mesural			
78397	Kingston	18	−77	1982			**0.47**/**0.47**
				VIZ to MSS			
91366	Kwajalein Atol	9	168	1993			0.04/**0.04**
				VIZ to Vaisala RS-21			
16245	Pratica di Mare	42	12	1982			**0.81**/**0.79**

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