Long-Term Free-Atmosphere Temperature Trends in China Derived from Homogenized In Situ Radiosonde Temperature Series

YANJUN GUO
National Climate Center, and Laboratory for Climate Studies, China Meteorological Administration, and Institute of Atmospheric Physics, and Graduate School of the Chinese Academy of Sciences, Chinese Academy of Sciences, Beijing, China

YIHUI DING
National Climate Center, and Laboratory for Climate Studies, China Meteorological Administration, Beijing, China

(Manuscript received 14 February 2008, in final form 10 July 2008)

ABSTRACT

In this paper, radiosonde temperature time series (RTT) from 1958 to 2005 collected by the 116-station Chinese radiosonde network are examined. Quality control and homogenization are used to obtain a reliable RTT. The homogenization results revealed significant discontinuities in the RTT. Analysis suggested that 70% data availability is the minimum data requirement (MDR) for these RTTs. A new dataset is built by meeting this MDR, which reduced the number of potential stations from 116 to 92. Analysis on this dataset reveals that warming trends in the troposphere and cooling trends in the stratosphere were weakened by reducing the stations. Averaged RTT trends for China were generally consistent with those of global scale, but with some discrepancies. During 1958–2005, averaged temperatures in China tended to decrease in the lower stratosphere and upper troposphere, in contrast to warming trends in the mid- and lower troposphere. The trends varied with two different subperiods. For 1958–78, cooling trends in the entire atmosphere were similar to trends at the global scale. For 1979–2005, warming occurred in the lower troposphere, with the amplitude of the warming tending to weaken with increases in altitude and shifting to a cooling trend above 400 hPa. Seasonal trend structures suggest that warming in the lower troposphere is attributable to temperature increases in December–February (DJF); cooling in the upper troposphere and stratosphere was found mainly in June–August (JJA). Unlike with results of a larger spatial scale, a robust cooling layer was found around 300 hPa.

1. Introduction

Many studies have examined climate change detection and attribution, focusing on the vertical structure of atmospheric temperature changes (Santer et al. 1996; Solomon et al. 2007) and demonstrating the importance of changes in upper-air temperatures as an indicator of human influences on climate (Santer et al. 1996; Tett et al. 1996; Thorne et al. 2002; International Ad Hoc Detection and Attribution Group 2005). Long-term tropospheric warming and stratospheric cooling are among the most confidently detected changes associated with an enhanced atmospheric greenhouse effect, which likely explains the prominent use of upper-air temperature change data. However, such key findings have been deduced only at the global scale or for the tropics at the regional scale. Given the complexity of the climatic system, it is clearly necessary to investigate changes in the free-atmosphere temperature at the regional scale using data from geographically denser upper-air observation networks. The recent establishment of surface and upper-air climate datasets can aid in such climate change investigations at the regional, hemispherical, and global scales.

Recent climatological analyses have shown increases in surface air temperature in China for the past 97 yr with a warming rate of 0.08 K decade $^{-1}$, a rate that exceeds the global and Northern Hemispheric averages reported by the Intergovernmental Panel on Climate Change’s (IPCC) Third Assessment Report (Tang and Ren 2005; Wang and Gaffen 2001). China has a dense radiosonde network that was launched in the 1950s; the
network includes 116 radiosonde stations and mandatory pressure levels specified by the World Meteorological Organization (WMO 1996). However, previous research of the free-atmosphere climatology only used data from several of the stations (Zhai and Eskridge 1996). Elucidating trends in free-atmosphere temperature over China based on valid radiosonde data should provide insight into important aspects of the global climate system and is our aim.

Most long-term climate records likely contain variations caused by nonclimatic factors such as changes in instrumentation, measurement practices, and station surroundings and locations. Such nonclimatic factors might create inhomogeneities, with the magnitude of the effects varying by location, altitude, and time. Upper-air radiosonde data may also contain serious discontinuities, including both random errors and time-varying biases resulting from changes in instrumentation, operation, and processing procedures. For temperature, the biases can be large, ranging from several tenths to as much as several degrees Celsius in individual radiosonde records (Gaffen 1994). Inhomogeneity in the radiosonde temperature time series (RTTs) of Chinese stations has been reported and preliminarily assessed (Wang and Wang 1987; Zhai and Eskridge 1996). However, the homogenization of RTTs over China was a necessary prerequisite for our study. In section 2, we explain the data and methods used. In section 3, we present the detection of break points for individual RTTs and trends at seven levels for various time scales. In section 4, we discuss the nationwide mean trends for different levels and correlations to global climatic signals, as well as the trend sensitivity to data quality. In section 5, we summarize our findings.

2. Data and methodology

a. Data

Radiosonde observations, provided by the Chinese National Metrological Information Center/China Meteorological Administration (NMIC/CMA), form the basis for this analysis. We discuss the findings for seven mandatory pressure levels: 850, 700, 500, 400, 300, 200, and 100 hPa. Twice-daily observations at 0000 and 1200 UTC were used for quality control (QC); data that were filtered out by the QC process were treated as missing. Seasonal anomalies were computed with reference to 1971–2000. The 0000 and 0012 UTC series were combined into a merged RTT for the final homogenization procedure; sets of merged series were considered missing if either the 0000 or 1200 UTC series was missing.

The 116 Chinese radiosonde network stations were distributed throughout China (Fig. 1). We examined the data availability for each station in the 850–100-hPa layer and included as many valid stations as possible. The minimum data requirement (MDR) for a station was based on the maximum percentage of missing data among multiple levels (Gaffen et al. 2000). For 1958–2005 at all seven levels within the layer, by reducing the MDR percentage from 99% to 70%, the network size increased from 17 to 92 stations that met the MDR, but further relaxing of the percentage gained only a few additional stations (Fig. 2). Thus, based on an MDR of 70%, we selected a new network (Fig. 1, open circles). The analysis yielded a nominal RTT network of 92 stations for 1958–2005.

Many previous studies have separately analyzed trends in free-atmosphere temperatures for the presatellite era and the satellite era, which began in approximately 1979. We compared station numbers meeting different MDRs during 1958–78 and 1979–2005 in Fig. 2 as well. In the satellite era, 97% of the candidate stations satisfied the critical MDR of 70%, and 84 stations met the MDR of 100%. In the presatellite era, the number of stations were more sensitive versus MDR, it changed to 97 to 76 stations versus MDR 30% to 70% respectively. The results imply that the availability of Chinese radiosonde network RTTs during 1958–2005 is mainly determined by missing data in the presatellite era.

Station history information (metadata) was obtained from NMIC/CMA and included information on changes in instrumentation and correction methods. Although the accuracy and completeness of the histories are not perfect, these metadata can be used to estimate the dates on which we might expect changes in the error characteristics of the temperature time series. The significance of metadata events was examined by comparing them to the breakpoint detection results (section 3a).

b. Methodology

1) QUALITY CONTROL

For QC, we used the hydrostatic method, as first described by Collins and Gandin (1990). The basic form of the hydrostatic residual (S) for a layer between the two mandatory levels l1 and l2, each containing a height and temperature, is give as (Collins 2001)

\[ S_{l1,l2} = Z_{l2} - Z_{l1} - A_{l1,l2} - B_{l1,l2}(T_{l1} + T_{l2}) \]

where \( T \) is the virtual temperature in degrees Celsius and \( Z \) is the geopotential height. The coefficients \( A \) and \( B \) are given by
where \( T_0 = 273.15 \text{ K} \), \( R \) is the gas constant for dry air, and \( g \) is the acceleration of gravity. For \( S \), Zhai (1997) deduced a critical value for temperature time series.

2) METHODS OF DETECTING BREAKPOINTS AND ADJUSTMENT

The two-phase regression (TPR) method, a technique initially described by Solow (1987), was used to detect breakpoints. Easterling and Peterson (1995) developed a variation of the TPR in which the regression lines

\[
A_{11,12} = \frac{RT_0}{g} \ln \left( \frac{p_{11}}{p_{12}} \right) \quad \text{and} \quad B_{11,12} = \frac{R}{2g} \ln \left( \frac{p_{11}}{p_{12}} \right),
\]

FIG. 1. Map of the Chinese radiosonde network used. Open circles indicate stations with MDR > 70%; filled symbols indicate stations with MDR of 30%–70%.

were not constrained to meet, and a linear regression was fitted to the part of the difference series before the point being tested and another part after the year being tested:

\[
T(i) = T_{\text{CAN}} - T_{\text{REF}} \text{ and } T(i) = \mu + \alpha i, \quad (3)
\]

where \(T_{\text{CAN}}\) and \(T_{\text{REF}}\) represent the candidate and reference series, respectively. The residual sum of squares from a single regression through the entire time series was also calculated with a critical value, \(U(i)\), as

\[
U(i) = \frac{(\text{RSS}_1 - \text{RSS}_2)/3}{\text{RSS}_2/(n - 4)}, \quad (4)
\]

for which \(\text{RSS}_1\) is the residual sum of squares for \(i = 1, \ldots, c\), and \(\text{RSS}_2\) is the residual sum for \(i = c + 1, \ldots, n\). The significance of the two-phase fit was tested with a likelihood ratio statistic using the two residual sums of the squares and with the difference in the means of the difference series before and after the discontinuity as evaluated by a Student’s \(t\) test and the multiresponse permutation procedure (MRPP; Mielke 1991). If the breakpoint was significant at the 95% level (probability: \(P = 0.05\)), it was considered to be a true discontinuity. If the discontinuity was significant, the time series was subdivided into two at that year and a breakpoint was identified.

A homogenized array was created by

\[
T^1(i) = \begin{cases} 
\mu_1 + \alpha_1 i & 1 \leq i \leq c \\
\mu_2 + \alpha_2 i & c < i \leq n,
\end{cases} \quad (5)
\]

with \(\alpha_1\) and \(\alpha_2\) calculated by

\[
\alpha_1 = \frac{\sum_{i=1}^{c} (i - \bar{i})(T_1 - \bar{T})}{\sum_{i=1}^{c} (i - \bar{i})^2}, \quad \mu_1 = (T - \alpha_1 \bar{i})
\]

and

\[
\alpha_2 = \frac{\sum_{i=c+1}^{n} (i - \bar{i})(T_1 - \bar{T})}{\sum_{i=c+1}^{n} (i - \bar{i})^2}, \quad \mu_2 = (T - \alpha_2 \bar{i}). \quad (6)
\]

The adjustment that was applied to all data points prior to the discontinuity was the difference in the means of the two windows of the difference series. This test was repeated for all years of the time series up until the discontinuity became insignificant; then, adjusted time series are gained. The performances of identification were conducted level by level, at seven levels of candidate stations. Several works have proven that the TPR method is suitable for the Chinese radiosonde network (Zhai and Eskridge 1996; Guo et al. 2007)

3) Reference series

Ideally, a reference series should consist of high quality data having a climate variation that resembles that at the candidate site. Peterson and Easterling (1994) suggested the use of successive differences instead of the actual data to calculate the correlation coefficients used in the TPR method. This will reduce the risk of poor estimations of the correlations between the candidate site and a reference site if one or both of these sites has inhomogeneities within the common time period used to calculate the correlation coefficients. Reanalysis data for the free-atmosphere temperature include both temperature and wind data and use model equations to produce atmospheric fields that are consistent with model dynamics. The availability of wind data provides another measure of the temperature field. Indeed, the use of winds can reduce any dataset bias in the RTT caused by radiative heating (Pielke 1999). We used background forecasts based on the reanalysis product as a reference time series; the reanalysis datasets were from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) for the period 1958–2005 (Kistler et al. 2001). The NCEP–NCAR reanalysis data are provided in a monthly averaged format and are available at grid intervals of 2.5°. Data corresponding to the station locations in China (Fig. 1) were extracted from the global reanalysis archive as a representative sample of the Global Climate Observing System (GCOS) upper-air network (Daan 2002). A global homogenization effort with a similar approach using 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) ReAnalysis background data was made by Haimberger (2007). It is demonstrated that inhomogeneities in the RTT due to changes in instrumentation can be automatically detected and adjusted.

3. Results and analysis

a. Detected breakpoints and adjustment

Using the method described in section 2, we conducted breakpoint identification and homogenization for all selected candidate RTTs. We examined the seasonal anomalies at stations 58362 (Fig. 3) and 52533 (Fig. 4) for the original and adjusted merged time series and adjustments at selected levels from 1958 to 2005. The metadata events in China mainly occurred in the mid-1960s and 2000s. However, the detected breakpoints were uniformly distributed over the study period, implying that not all metadata events were significant causes of breakpoints. At station 58362, six metadata events were related to instrument changes (in 1960,
1962, 1963, 1964, 1976, and 2003) and three metadata events were related to correction method changes. At station 52533, the role of metadata events could not be confirmed. Even if the procedure identified breakpoints individually by mandatory levels, the vertical coherence of the detected breakpoints was still discernable at station 58362 in 1964, 1976, 1991, and 2003. Among these coherently detected points, just one (1991) was not assigned to metadata events. Furthermore, three metadata events during 1962–64 were treated as one, because the procedure treats all breakpoints within 2 yr to be the same (Peterson and Easterling 1994).

The difference in the distribution of the detected breakpoints between stations 58362 (Fig. 3) and 52533 (Fig. 4) reflects the variation in the homogenization by station. However, a common temporal feature of homogenization is a higher stratospheric temperature, but with a decreased tropospheric temperature, in the initial period. Clearly, homogenization eliminated the warming trend in the troposphere, but enhanced the cooling in the stratosphere. There were evident differences between the original and adjusted time series, especially in the stratosphere, implying that the adjustment commonly increases with altitude.

In Fig. 5, we compared the adjustment of the breakpoints with metadata breakpoints and that of the breakpoints without metadata at station 58362. There is no clear difference in the adjustments between the two types of breakpoints. All of the adjustments roughly increase versus pressure. Lanzante et al. (2003) also documented the vertical profiles of the absolute adjustment values, showing that except for at near-surface levels, the adjustment magnitude generally increases upward from the lower troposphere. The finding from this work is consistent with expectations because lower air density at higher elevations enhances the instrument bias due to solar radiation and other possible factors.

b. Trends at different levels

We calculated trends by a least squares linear fitting method derived from homogenized in situ time series at 100, 200, 300 500, 700, and 850 hPa for 1958–2005 (Fig. 6); the significance of the trend is examined for 95%
of a t test. For the region of China, 100 hPa is located within the stratosphere (Frederick and Douglass 1983). The spatially averaged temperature trend at 100 hPa was $-0.11 \text{ K decade}^{-1}$ during 1958–2005 over China. Both warming and cooling occurred alternately at 100 hPa; however, the significance of the warming was lower. The alternation of positive and negative trends at 100 hPa illustrates the spatial heterogeneity of the stratospheric temperature trend in China, as evidenced by the almost equal but opposite trends of 0.80 and $-0.82 \text{ K decade}^{-1}$ at subtropical stations 56964 and 58362, respectively. For our target region, 200 hPa is recognized as the tropopause level (Frederick and Douglass 1983). Interestingly, the negative trend was more widely found at that level than at 100 hPa. The spatial variability in the trend was relatively gentle compared to that at 100 hPa, and the range of the trend variation was also smaller.

The trend in the spatial distributions differed greatly at 300 and 500 hPa. At 300 hPa, the negative trend was rather robust. A positive trend distribution was found in southern and northwestern China, but cooling was rather significant in northern China, and the trends for 78 (85%) of the stations were negative. At 500 hPa, 39 (42%) of the stations had positive trends; the magnitudes of the positive trends were small, at $< 0.4 \text{ K decade}^{-1}$. The largest positive trend occurred over the Tibetan Plateau.

Consistent with the conclusion of warming in the lower troposphere at a global scale, a positive trend dominated at 700 and 850 hPa. At 700 hPa, 57 stations (67%) in the network had warming trends at a maximum
The most pronounced warming was at 850 hPa, for which 61 stations (80%) showed warming and 28 stations (27%) warmed by more than 0.25 K decade$^{-1}$. At the surface (Fig. 7), the warming trend was more significant; a negative trend was deduced at just three of the stations, with an averaged trend of 0.24 K decade$^{-1}$.

Figure 6 clearly reveals the spatial variability in the trend during 1958–2005. It is interesting that similar trends (positive or negative) are clustered in the figure, which implies that the distribution of the trend may be related to some feature of the atmospheric circulation. It is generally known that China’s nationwide atmospheric circulation has been concluded to be extremely complex, as it is coupled with the tangled topography, which leads to heterogeneous atmospheric dynamics and results in different trends in the upper-air temperature. It is rather difficult to compare this spatial variability to previous published work, because most of the prior results for the upper-air temperature trend were of 0.52 K decade$^{-1}$. The most pronounced warming was at 850 hPa, for which 61 stations (80%) showed warming and 28 stations (27%) warmed by more than 0.25 K decade$^{-1}$. At the surface (Fig. 7), the warming trend was more significant; a negative trend was deduced at just three of the stations, with an averaged trend of 0.24 K decade$^{-1}$.

Figure 6 clearly reveals the spatial variability in the trend during 1958–2005. It is interesting that similar trends (positive or negative) are clustered in the figure, which implies that the distribution of the trend may be related to some feature of the atmospheric circulation. It is generally known that China’s nationwide atmospheric circulation has been concluded to be extremely complex, as it is coupled with the tangled topography, which leads to heterogeneous atmospheric dynamics and results in different trends in the upper-air temperature. It is rather difficult to compare this spatial variability to previous published work, because most of the prior results for the upper-air temperature trend were
made at large spatial scales, such as hemispheric and even global. Lanzante et al. (2003) reported a significant difference between the latitudinal and longitudinal zone trends.

c. Nationwide averaged time series

We averaged the time series of the annual anomalies for various layers over the selected 92 stations in China (Fig. 8). The lower stratosphere is represented by 100 hPa; the upper, middle, and lower troposphere are represented by averages from 200 to 300, 400 to 500, and 700 to 850 hPa, respectively. Nationwide, the lower stratosphere and upper troposphere showed cooling during 1958–2005 with trends of $-0.10$ and $-0.17$ K decade$^{-1}$, respectively. The midtroposphere had a slight downward trend of $-0.06$ K decade$^{-1}$. Only the lower troposphere exhibited a warming trend, of $0.11$ K decade$^{-1}$, and only the lower troposphere showed a cooling trend between the presatellite and satellite eras. The overall results indicate cooling of the lower stratosphere and warming of the troposphere. These results are qualitatively consistent with previous results at the global scale found by Santer et al. (1996), Parker et al. (1997), and Lanzante et al. (2003).

d. Comparison of trends in the presatellite and satellite eras

In Fig. 9, we compare the profiles of the median trends from the original (ORI), reanalysis (RAN), and adjusted (ADJ) time series at the 92 stations for the periods 1958–2005, the presatellite era (1958–78), and the satellite era (1979–2005). The vertical structure of the ADJ trends clearly shows stratospheric cooling in China dating back to 1958. Lower-stratospheric cooling was more intensive in the two most recent decades, being roughly twice as great as that before 1980; this is consistent with the general features observed at the global scale (Lanzante et al. 2003). The different vertical patterns in 1958–78, 1979–2005, and 1958–2005 indicate that tropospheric warming in China has been significant only in recent decades, rather than over the whole period. During the satellite era, troposphere temperatures tended to warm, with more significant positive trends in levels closer to the land surface. In the presatellite period, tropospheric temperatures tended to decrease. Researchers have reached different conclusions regarding the tropospheric trend during 1958–78. Parker et al. (1997), Angell (2000), and Sterin (2000) proposed that global cooling had occurred in the 850–300-hPa layer during 1958–78 at $-0.03$ to $-0.08$ K decade$^{-1}$. However, Santer et al. (2000) suggested that there was a weak warming of the same layer during the same period. Our results show a cooling trend for the entire atmosphere over China during 1958–78, ranging from $-0.15$ to $-0.41$ K decade$^{-1}$. At the global scale, most of the lower-stratospheric cooling in the past four decades has generally been thought to have occurred since the mid-1980s, in association with stratospheric ozone loss (Gaffen et al. 2000). Our analysis implies that climate change characterized by warming in the lower troposphere and cooling in the upper atmosphere has occurred since the 1980s in China. Early data may contain some uncertainties associated with artificially abrupt cooling signals, as suggested by Gaffen (1994).

The error bars of the ADJ time series, note the standard deviation of the trend from all stations, imply significant spatial variability in the trend; such heterogeneity can be seen from Fig. 6 as well. Vertical variation of the error range indicates the differences in heterogeneity among the levels: they were smaller at 500 and 400 hPa. The standard deviations in the presatellite era were clearly larger than those in satellite era, implying larger heterogeneity in the trend in the earlier period.

Unlike radiosonde series, reanalysis time series incorporate physics to provide consistent spatial and temporal fields; reanalysis time series can offer additional insight and have become common reference time series for homogenized radiosonde data (e.g., see Pielke and Chase 2004). However, caution should be exercised when using reanalysis data to examine climate trends (Bengtsson et al. 2004), given the doubts regarding the reliability of reanalysis data for long-term temperature
investigations. In our homogenization procedure, the NCEP–NCAR reanalysis product is applied as a reference (Fig. 9; RAN). During the satellite era, the average radiosonde trends generally matched the RAN trends well, with the maximum difference between the ADJ and RAN profiles being just 0.08 K decade\(^{-1}\) at 500 hPa. Even in the presatellite era, the ADJ and RAN trend profiles had similar patterns as a function of pressure. Nevertheless, for the extended period from 1958 to 2005, the trends of ADJ and RAN varied differently versus altitude and also showed abnormal enhanced cooling around 300 hPa, this finding identifies a special regional climatic signal in the study region. The result at the global scale generally demonstrated that most of the robust cooling was occurring in the stratosphere and gradually weakened at the lower troposphere (Solomon et al. 2007).

d. Seasonal structure of the trends

The seasonality of the trends may have some relevance to the detection and attribution of climate change.
in conjunction with the strong seasonality of the ozone depletion in the stratosphere, as well as with the tropospheric response to increases in greenhouse gases (Stott and Tett 1998). We investigated the seasonally varying structure of the trend by comparing vertical profiles at seven levels among the four seasons from 1958 to 2005 (Fig. 10). The analysis of the seasonal series suggests that there were both common features and significant differences. In particular, the tropospheric temperature increase observed annually for the last four decades did not have the same importance in all seasons: it was evident in autumn and winter, but not in March–May (MAM) and June–August (JJA). The profiles clearly illustrate significant warming of the middle and lower troposphere in December–February (DJF). Another striking feature of the seasonal structure of the trend profiles was the significant cooling of the stratosphere and upper troposphere in JJA. During MAM, a cooling trend was robust at 300 hPa, which is representative of the upper troposphere. In sections 3b and 3c, we addressed the contrasting changes in the upper-air temperature over China, that is, the cooling trend in the stratosphere and the warming of the lower troposphere. The seasonal structure of the trends indicates that these contrasting trends were not in phase: that is, stratospheric cooling was predominant in JJA, but tropospheric warming mainly occurred in DJF.

No previous reports have provided definitive conclusions about the seasonality of stratospheric cooling; thus, it is impossible to compare our results to the findings for other regions or at the global scale. However, for the seasonality of the tropospheric warming, our findings are somewhat inconsistent with the results for the meridional region and the global scale. Brunetti
et al. (2006) reported that tropospheric warming over Italy for the last two decades occurred in MAM and JJA. Lanzante et al. (2003) described significant September–November (SON) warming in the upper troposphere over the Northern Hemisphere and tropics, as well as enhanced MAM cooling in the Southern Hemisphere. Davey et al. (2008) deduced the seasonal structure at the global scale, demonstrating a cooling trend at 200 hPa for all seasons and a warming trend from 300 to 850 hPa for 1979–2004. Obvious tropospheric warming in DJF and stratospheric cooling in JJA have not yet been reported.

4. Discussion

a. Impacts of homogenization to RTTs

Standard deviation is a basic measure of the variability of time series and provides a context within which to examine the more climate-relevant measures of temperature variability. Table 1 compares the standard deviations of ORI, ADJ, and RAN for 1958–2005, 1958–78, and 1979–2005. The average, maximum, and minimum were accounted for at all stations used in this work. Standard deviations of these three datasets show similar vertical patterns for all period: in the lower stratosphere (100 hPa) the standard deviation typically exceeds 1.0 K, which is larger than that in the troposphere (850–300 hPa). The standard deviations at the 300–100-hPa layer are around 1.0 K. The temporal variability of the datasets is comparable for the given layers, with their similar standard deviations, even if for different periods. The variabilities of the ORI and ADJ are slightly larger compared with RAN, which is likely due to the fact that the RAN is a grid dataset while the others are in situ. The impacts of different spatial sampling schemes are discussed in the next section.

The difference between the ADJ and ORI profiles in Fig. 9 can serve as a measure of the sensitivity of the trend to the breakpoint removal or the influence of homogenization on the deduced trend. During the presatellite era (1958–78), homogenization weakened the cooling trend compared to that of the ORI series in the upper and middle troposphere, creating differences of 0.13, 0.18, 0.17, and 0.07 K decade$^{-1}$ at 500, 400, 300, and 200 hPa, respectively. Over the satellite era (1979–2005), the cooling trend compared to the ORI trend was enhanced at 0.16 and 0.06 K decade$^{-1}$ at 200 and 100 hPa, whereas the warming trend at 400 and 500 hPa was weakened at 0.14 and 0.09 K decade$^{-1}$, respectively. For 1958–2005, breakpoint removal only affected the trend at 100 hPa, leading to a weakening of the cooling trend by 0.12 K decade$^{-1}$; at other levels, the ADJ and ORI profile trends matched well. The adjustments did not significantly alter the relative warming in the troposphere, but reduced the cooling trend. The differences in the vertical structures of the trends during different periods illustrate that these trends are sensitive to homogenization in the upper troposphere, but the effects of homogenization vary by period. The adjustment for the upper troposphere was large during both 1958–78 and 1979–2005, but it was negative in the former period and positive in the latter. These opposite influences before and after 1979 may be offset when calculating the average for 1958–2005. Homogenization only altered the trend in the stratosphere for this longer period.

b. Sensitivity of trend to data quality

Free and Seidel (2005) demonstrated that the method of spatial sampling is a key factor that can alter the mean trend of a radiosonde dataset. Gaffen et al. (2000) found that the missing data rate and station selection may also affect our interpretation of the temperature vertical profiles. However, to date, there is no set standard for determining the sampling procedure for upper-air datasets. In addition, there is no common critical MDR for evaluating RTTs and computing the mean trend over a region. As described in section 2a, the Chinese radiosonde network has 116 stations. Of these, 92 met the critical value of MDR = 70% for the

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>850</td>
<td>0.94</td>
<td>1.13</td>
<td>0.94</td>
</tr>
<tr>
<td>700</td>
<td>0.97</td>
<td>0.91</td>
<td>0.97</td>
</tr>
<tr>
<td>500</td>
<td>0.97</td>
<td>0.95</td>
<td>0.97</td>
</tr>
<tr>
<td>300</td>
<td>0.97</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>200</td>
<td>0.98</td>
<td>0.96</td>
<td>0.98</td>
</tr>
<tr>
<td>100</td>
<td>0.96</td>
<td>0.85</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Table 1. Standard deviations (K) of ORI, ADJ, and RAN for 1958–2005, 1958–78, and 1979–2005. The average, max, and min were accounted for at all stations used in this work.
trend analysis (Table 2). To illustrate the effects of the data source choice, we compared the mean trend profiles for various MDRs over the satellite era (1979–2005) and the full study period (Fig. 11).

For the satellite era, the trends corresponding to various MDRs for this period were generally very similar. This finding can be elucidated by results illuminated in Figs. 2 and 9. First, the spatial variability of the trend for the satellite era is definitely small. Second, the missing rate of the RTTs was not substantial, with evidence of 112 stations that satisfied the 70% MDR; therefore, the averaged trend was little changed with different MDRs corresponding to a stable station number. However, for the full study period of 1958–2005, there were significant differences in the trends associated with various MDRs. Changing the MDR from 99% to 70% changed the number of stations from 17 to 92; correspondingly, the trend averaged from the 17 stations differed from that based on the 92 stations by 0.05, −0.01, −0.03, −0.08, −0.02, 0.09, and −0.01 K decade$^{-1}$ at 850, 700, 500, 400, 300, 200, and 100 hPa, respectively. Furthermore, for the extreme MDR of 99% (17 stations) and the total network (116 stations), the differences in the averaged trends were 0.02, −0.04, −0.05, −0.10, −0.06, 0.10, and 0.07 K decade$^{-1}$ at 850, 700, 500, 400, 300, 200, and 100 hPa, respectively. Increasing the number of stations enhances the deduced warming trend, but weakens the cooling trend below 300 hPa (Fig. 11). In contrast, meeting higher MDRs (i.e., decreasing the number of valid stations) eventually weakens the cooling trend at the top of the troposphere and lower stratosphere (200 and 100 hPa).

Therefore, we conclude that both the warming trend in the troposphere and the cooling trend in the stratosphere will weaken for our data source if the number of stations used is decreased to enhance the data quality. Previous investigations of upper-air temperature trends have been based on different datasets, including different station networks, periods of records, and statistical approaches. Because no standard upper-air dataset exists at present, the differences among the study methods and datasets may hinder our understanding of upper-atmospheric changes. Free and Seidel (2005) compared the trends deduced from various radiosonde temperature datasets such as the Global Climate Observing System (GCOS) Upper-Air Network (GUAN) data, the Hadley Centre’s global radiosonde gridded temperature anomalies product (HadRT), and the Hadley Centre’s radiosonde temperature product (HadAT) and found that increasing the number of stations did not lead to any reliable improvement in the network results.

The statistical method used can also alter the resulting mean regional trend. We computed the final mean

<table>
<thead>
<tr>
<th>Period</th>
<th>99%</th>
<th>90%</th>
<th>80%</th>
<th>70%</th>
<th>60%</th>
<th>50%</th>
<th>40%</th>
<th>30%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1958–2005</td>
<td>17</td>
<td>68</td>
<td>79</td>
<td>92</td>
<td>103</td>
<td>111</td>
<td>115</td>
<td>116</td>
</tr>
<tr>
<td>1958–78</td>
<td>19</td>
<td>47</td>
<td>69</td>
<td>76</td>
<td>78</td>
<td>84</td>
<td>89</td>
<td>97</td>
</tr>
<tr>
<td>1979–2005</td>
<td>84</td>
<td>105</td>
<td>109</td>
<td>112</td>
<td>114</td>
<td>116</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 11. Comparison of the mean vertical trend profiles with different minimum data requirements for the periods 1958–2005 and 1979–2005.
trend using the subgrid mean method and compared the results to those using the arithmetical mean method. The differences in the trends between using the two statistical methods were 0.001, 0.026, 0.011, 0.012, 0.083, and 0.024 at 850, 700, 500, 400, 300, 200, and 100 hPa, respectively. The larger differences were found at 200 and 100 hPa, but these are not significant, nor is the difference shown in Fig. 11. Furthermore, scaling in situ data for a regional representation is still a challenge, especially for upper-atmospheric changes (Free and Seidel 2005).

5. Conclusions

To extract a regional climate signal from historical radiosonde measurements, we examined long-term trends in upper-air temperatures based on in situ data from the Chinese radiosonde network. The homogenization conducted for data from 116 stations indicated significant discontinuities in the RTTs. The necessity of homogenization is evidenced by its effects on the averaged trends for various time scales. For the period of 1958–78, the removal of breakpoints weakened the cooling trend compared to the original trend in the upper and middle troposphere (200–500 hPa). Over the satellite era (1979–2005), the stratospheric cooling of the original trend was enhanced after homogenization, and the warming trends at 400 and 500 hPa were weakened. The metadata, which record changes in the instrumentation and correction method, can partially explain the identified breakpoints. The large adjustment indicates the importance of the metadata in homogenization.

The quality of the RTTs has been evaluated by MDR, an important factor that can affect the averaged trends for China. Averaged RTT trends in China varied significantly when the MDR was 70%. Therefore, we set the MDR for the temperature time series at 70%. Meeting the MDR of 70%, we built a new dataset by reducing the number of candidate stations from 116 to 92. The analysis of the averaged trend profiles versus MDRs revealed that both the warming trend in the troposphere and the cooling trend in the stratosphere weakened as the number of stations used decreased.

Analysis of the new dataset reveals that the lower stratosphere and lower troposphere showed opposite trends in air temperature during 1958–2005 over China, with predominant cooling from 100 to 300 hPa and warming in the lower troposphere. Decadal variability analysis revealed that these opposing trends between the tropospheric and stratospheric temperatures have only occurred significantly since the 1980s in China. The

<table>
<thead>
<tr>
<th>Level/layer (hPa)</th>
<th>Trend (K 10a⁻¹)</th>
<th>Region</th>
<th>Period</th>
<th>Dataset (reference)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>-0.10</td>
<td>China</td>
<td>1958–2005</td>
<td>This work</td>
</tr>
<tr>
<td>100–50</td>
<td>-0.32</td>
<td>NH-EX</td>
<td>1960–2004</td>
<td>RATPAC-B (Free and Seidel 2005)</td>
</tr>
<tr>
<td></td>
<td>-0.40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.45</td>
<td>G</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300–100</td>
<td>-0.16</td>
<td>China</td>
<td>1958–2005</td>
<td>This work</td>
</tr>
<tr>
<td></td>
<td>-0.06</td>
<td>NH-EX</td>
<td>1960–2004</td>
<td>RATPAC-B (Free and Seidel 2005)</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>NH</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.02</td>
<td>G</td>
<td></td>
<td></td>
</tr>
<tr>
<td>850–300</td>
<td>0.04</td>
<td>China</td>
<td>1958–2005</td>
<td>This work</td>
</tr>
<tr>
<td></td>
<td>0.17</td>
<td>NH-EX</td>
<td>1960–2004</td>
<td>RATPAC-B (Free and Seidel 2005)</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>NH</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>G</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>-0.74</td>
<td>China</td>
<td>1979–2005</td>
<td>This work</td>
</tr>
<tr>
<td>100–50</td>
<td>-0.63</td>
<td>NH-EX</td>
<td>1979–2004</td>
<td>RATPAC-B (Free and Seidel 2005)</td>
</tr>
<tr>
<td></td>
<td>-0.71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.75</td>
<td>G</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100–50</td>
<td>-0.66</td>
<td>G</td>
<td>1979–2004</td>
<td>RAOBCORE (Haimberger 2007)</td>
</tr>
<tr>
<td>300–100</td>
<td>-0.42</td>
<td>China</td>
<td>1979–2005</td>
<td>This work</td>
</tr>
<tr>
<td></td>
<td>-0.09</td>
<td>NH-EX</td>
<td>1979–2004</td>
<td>RATPAC-B (Free and Seidel 2005)</td>
</tr>
<tr>
<td></td>
<td>-0.07</td>
<td>NH</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.14</td>
<td>G</td>
<td></td>
<td></td>
</tr>
<tr>
<td>850–300</td>
<td>0.12</td>
<td>China</td>
<td>1979–2005</td>
<td>This work</td>
</tr>
<tr>
<td>850–300</td>
<td>0.24</td>
<td>NH-EX</td>
<td>1979–2004</td>
<td>RATPAC (Free and Seidel 2005)</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>NH</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.11</td>
<td>G</td>
<td></td>
<td></td>
</tr>
<tr>
<td>850–300</td>
<td>0.11</td>
<td>G</td>
<td>1979–2004</td>
<td>RAOBCORE (Haimberger 2007)</td>
</tr>
</tbody>
</table>
seasonal structure of the trend illustrates the dominant warming in the mid- and lower troposphere in DJF and cooling in the stratosphere and upper troposphere in JJA.

To clarify the regional features of the upper-air temperature changes in China, the averaged trends for 1958–2005 and 1979–2005 were compared with that at larger scale in Table 3. We select recent published results for comparability between the periods of study. Our quoted results were deduced from the global-scale dataset of the Radiosonde Atmospheric Temperature Products for Assessing Climate (RATPAC-B) and Radiosonde Observation Correction Using Reanalyses (RAOBCORE; Haimberger 2007), both of which were homogenized. For longer time scales (1958–2005 and 1960–2004), the cooling trend at 100 hPa averaged over China was smaller than that at 100–50 hPa at a larger spatial scale; this is anticipated to be caused by our study which cannot reach the layer higher than 100 hPa due to data quality problem. The cooling trend in the 300–100-hPa layer was rather robust in China; the warming trend for the entire troposphere was clearly weak compared to that at larger scales. For the satellite era, the trend in the lower stratosphere and troposphere in China is consistent with that at larger scales, but it is inconsistent in the 300–100-hPa layer. In fact, larger cooling was deduced from the original dataset around 300 hPa too (Fig. 9), and our homogenization altered slightly the averaged trend. Figure 9 also clarified that robust cooling had occurred during 1958–78. Figure 6 revealed this robust cooling at around 300 hPa was predominant in northern China. Thus for this regional climatic signal, the cooling around 300 hPa is reasonable from the observational evidence, which may improve our understanding on regional climatic changes.

Acknowledgments. We thank the Chinese National Meteorological Information Centre/China Meteorological Administration ((NMIC/CMA) for providing the radiosonde temperature data for China. Thanks to Prof. Huang Bingxun for helpful comments and Dr. Liqingxiang for providing homogenized surface temperature time series. We are particularly grateful to Prof. T. C. Peterson for providing the Fortran code used in the two-phase regression method. This work was supported by the Climate Change Special Fund of the China Meteorological Administration (CCSF2007-7) and the National Natural Science Fund of China (40775045).

REFERENCES


