Effect of Exclusion of Anomalous Tropical Stations on Temperature Trends from a 63-Station Radiosonde Network, and Comparison with Other Analyses

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ABSTRACT

A 63-station radiosonde network has been used for many years to estimate temperature variations and trends at the surface and in the 850–300-, 300–100-, and 100–50-mb layers of climate zones, both hemispheres, and the globe, but with little regard for the quality of individual station data. In this paper, nine tropical radiosonde stations in this network are identified as anomalous based on unrepresentatively large standard-error-of-regression values for 300–100-mb trends for the period 1958–2000. In the Tropics the exclusion of the 9 anomalous stations from the 63-station network for 1958–2000 results in a warming of the 300–100-mb layer rather than a cooling, a doubling of the warming of the 850–300-mb layer to a value of 0.13 K decade^{-1}, and a greater warming at 850–300-mb than at the surface. The global changes in trend are smaller, but include a change to the same warming of the surface and the 850–300-mb layer during 1958–2000. The effect of the station exclusions is much less for 1979–2000, suggesting that most of the data problems are before this time. Temperature trends based on the 63-station network are compared with the Microwave Sounding Unit (MSU) and other radiosonde trends, and agreement is better after the exclusion of the anomalous stations. There is consensus that in the Tropics the troposphere has warmed slightly more than the surface during 1958–2000, but that there has been a warming of the surface relative to the troposphere during 1979–2000. Globally, the warming of the surface and the troposphere are essentially the same during 1958–2000, but during 1979–2000 the surface warms more than the troposphere. During the latter period the radiosondes indicate considerably more low-stratospheric cooling in the Tropics than does the MSU.

1. Introduction

A 63-station radiosonde network (see Fig. 1) has been used for nearly three decades to estimate temperature variations and trends at the surface and in the 850–300- (troposphere), 300–100- (tropopause), and 100–50-mb (low stratosphere) layers, where the layer-mean (virtual) temperatures have been determined from the difference in height of bounding mandatory pressure surfaces and application of the hydrostatic equation (e.g., Angell and Korshover 1983). Until now, temperature trends for climatic zones have, with one exception, been obtained by averaging the annual anomalies of temperature for all stations within the zone, and then applying linear least squares regression to these averages to obtain a trend for the climate zone (e.g., Angell 1999). The resulting trends have then been promulgated without consideration of the quality of the individual station trends within the zones. The one exception was Angell (2000), where temperature trends were estimated for individual stations for the periods 1959–98 and 1979–98 in order to compare trends for the Microwave Sounding Unit (MSU) period of observation and a period twice as long. However, no estimate was made of the impact on tropical, hemispheric, or global trends of the anomalous stations.

Santer et al. (1999) have dealt in general with the uncertainties in observationally based estimates of temperature change in the free atmosphere, and Gaffen (1994), Gaffen et al. (2000b), and Lanzante et al. (2003) have shown, in particular, that changes in radiosonde instruments and operational procedures have contaminated the trends at many of the stations in the 63-station network. In order to estimate the impact of this contamination on the tropical, hemispheric, and global trends obtained from the 63-station network, least squares linear regression has been applied to the annual temperature anomalies at each station and, based on an objective criterion, the contaminated or anomalous station was identified. In this paper the 9 anomalous stations so identified are excluded from the 63-station network, resulting in an ‘‘after-exclusion’’ (54 station) network whose temperature trends are compared with other radiosonde trends and MSU trends.

2. Procedures

Anomalous radiosonde temperature trends generally become more apparent with an increase in record length

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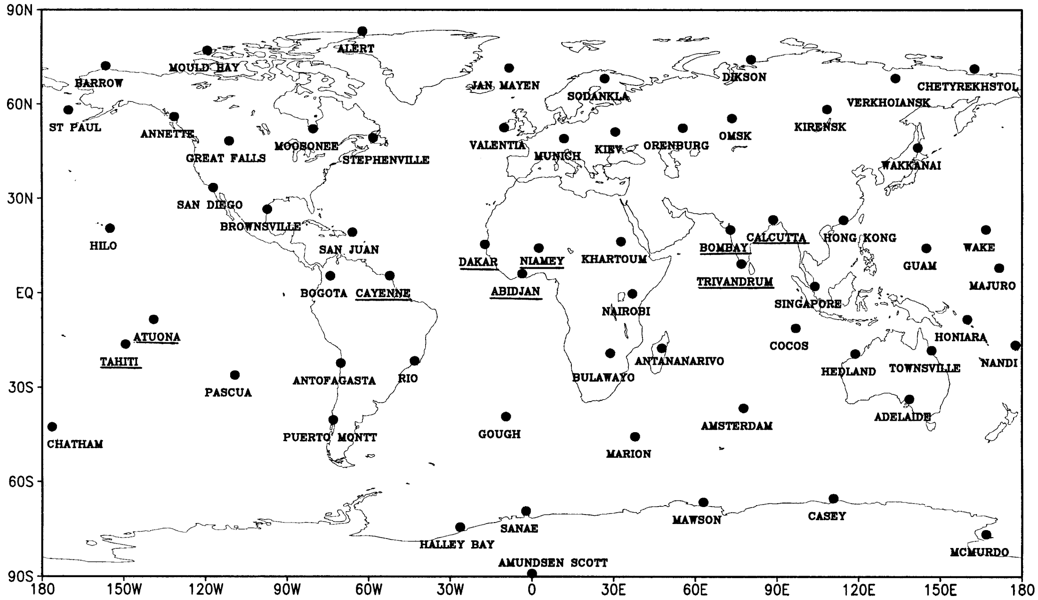

FIG. 1. The 63-station radiosonde network. The nine underlined tropical stations are those found to be anomalous.

and an increase in height (Gaffen 1994). However, because 9 of the stations in the 63-station network do not have sufficient data for representative estimates of the 100–50-mb trend, the 300–100-mb data for the 43-yr period 1958–2000 best define the anomalous stations for the whole network. Figure 2 presents the 300–100-mb temperature trends (K decade^{-1}) for all 63 radiosonde stations in the network, the confidence intervals (horizontal bars) extending two standard errors of regression (Brooks and Carruthers 1953, p. 226) on both sides of the station trends. The extratropical trends are quite consistent, with all the stations in the north and south polar zones showing significant cooling (significance assumed if the horizontal bars do not intersect the zero axis), 11 of the 12 stations in the north temperate zone showing cooling (6 significant), and 5 of the 6 stations in the south temperate zone showing cooling (4 significant). In the Tropics (30°S–30°N), however, the trends are diverse, with several of the cooling trends differing widely from the majority of trends that show little warming or cooling. At least in the 63-station network, problems with hemispheric and global trends would appear to reflect mainly problems with the tropical radiosonde-station trends.

Figure 2 shows that the radiosonde stations with anomalously large cooling trends in the Tropics also tend to be the stations with anomalously large confidence intervals. Thus, anomalous stations could be defined by either the magnitude of the cooling trend or the size of the confidence interval. I have opted for the latter because it indicates the extent to which annual temperatures deviate from the line of regression, and thus is a measure of the consistency or homogeneity of the radiosonde-derived yearly data. Accordingly, anomalous stations have been defined here as those tropical stations in Fig. 2 whose two standard error of regression values exceed 0.2 K decade^{-1}, a choice based on the finding of a gap in the statistical distribution of two standard errors of regression at this round number. Designated at the right in Fig. 2, and indicated by "×" in the plot, are the nine stations thus defined as anomalous. They are the 3 Indian stations in the 63-station network, as well as the 6 French or ex-French-colonial stations in this network.

3. Effect of the exclusion of anomalous stations on the 1958–2000 and 1979–2000 trends

Figure 3 presents the variation with height of the average of the radiosonde-station temperature trends in the Tropics, both hemispheres, and the globe for the period 1958–2000, based on the full 63-station network (left), this network after the exclusion of the 9 anomalous tropical stations denoted by × in Fig. 2 (middle), and the change in trend from the former to the latter (right). The horizontal bars at the left and center extend two standard errors of the mean (two standard deviations divided by the square root of the number of stations) on both sides of the average trends as determined from individual station trends. If these bars do not intersect at the zero axis, the average trends are assumed significant at only the 90% level because of interstation correlations (Jones et al. 1997; Angell 2000). Owing to the greater variability of station trends in the full 63-station network than in this network after the exclusion of anomalous stations, the confidence intervals (horizontal bars) tend to be smaller in the latter than in the former, particularly in the Tropics. It is emphasized that the size

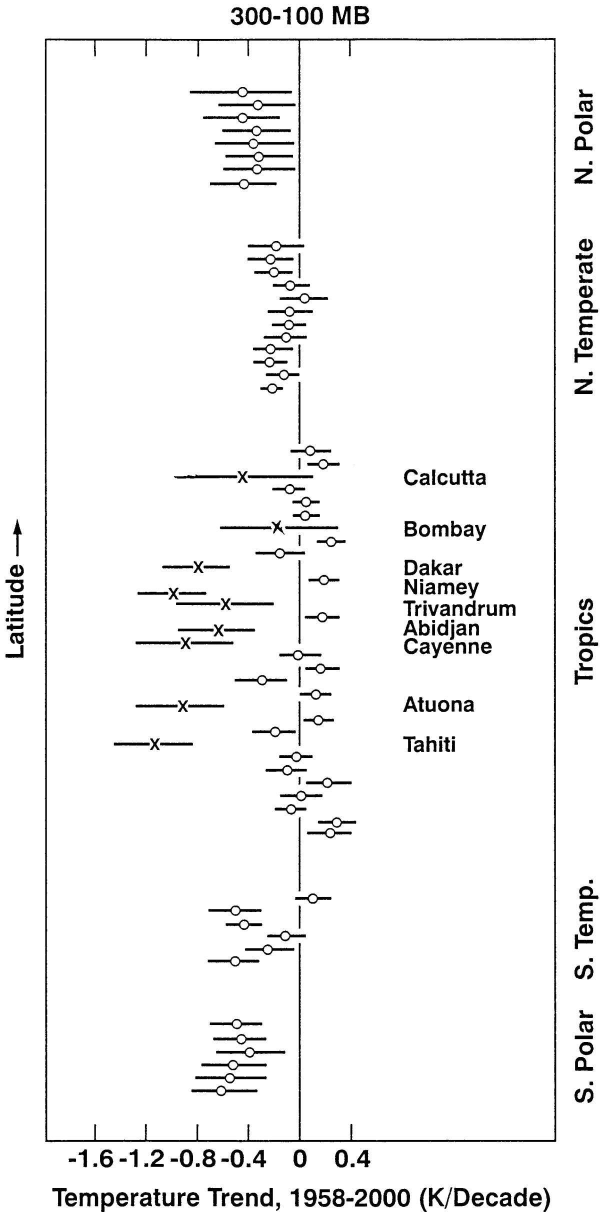

FIG. 2. The 300–100-mb temperature trends (K decade^{-1}) at the 63 radiosonde stations ordered by latitude, with climate-zone boundaries at 30° and 60°, based on least squares linear regression for 1958–2000. Horizontal bars extend two standard errors of regression on both sides of the station values of trend, and the nine tropical stations whose values thereof exceed 0.2 K decade^{-1} are considered to be anomalous, denoted by ×, and designated at right.

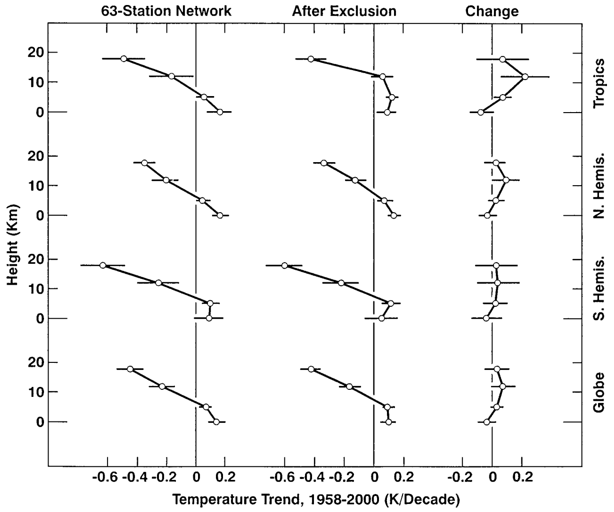

FIG. 3. Variation with height of the average of radiosonde-station temperature trends in the Tropics, both hemispheres, and the globe for 1958–2000, based on (left) the full 63-station network, (middle) the 54-station network that results from exclusion of the 9 anomalous tropical stations designated in Figs. 1 and 2, and (right) the change in trend from the former to the latter. Northern Hemisphere and Southern Hemisphere include those tropical stations north and south of the equator, respectively. Average trends are plotted at the surface and at heights of 5, 12, and 18 km, the approximate midpoints of the 850–300-, 300–100-, and 100–50-mb layers. Horizontal bars extend two standard errors of the mean on both sides of average trends as determined from individual station trends, and two std devs on both sides of the changes in the average trends as estimated from twice the square root of the sum of the 63-station and after-exclusion variances in the station trend divided by the respective number of stations.

of the horizontal bar (confidence interval) in Fig. 3 is a measure of the variability in individual station trend, and thus is completely different from the horizontal bar in Fig. 2 that reflects the variance of annual deviations about the line of regression.

Based on the 31 tropical stations in the full 63-station network there is an 0.16 K decade^{-1} cooling of the 300–100-mb layer during 1958–2000 (curve at top left in Fig. 3), whereas after the exclusion of the 9 anomalous tropical stations there is a warming of 0.06 K decade^{-1}. As shown at the top right, this is quite a significant change in trend as estimated from twice the square root of the sum of the 63-station and the after-exclusion variances in station trend divided by respective number of stations (Hoel 1947, p. 71). In addition, exclusion of the anomalous stations results in a barely significant increase in the warming of the tropical 850–300-mb layer from 0.06 to 0.13 K decade^{-1}. The anomalous cooling trends in the tropical 300–100-mb layer (see Fig. 2) are often, but not always, accompanied by unrepresentatively large cooling trends in the 850–300-mb layer as well, so that the full 63-station network underestimates the 850–300-mb warming in the Tropics during 1958–2000. Indeed, Fig. 3 shows that in the Tropics there is a reversal, from the surface warming 0.10 K decade^{-1} more than the 850–300-mb layer in the full 63-station network to the 850–300-mb layer warming of 0.04 K decade^{-1} more than the surface in the 54-station network.

Globally, the most noticeable feature is the change from the surface warming 0.07 K decade^{-1} more than the 850–300-mb layer in the full 63-station network to the same warming (0.10 K decade^{-1}) in the 54-station network. Otherwise, the changes in the global trend are

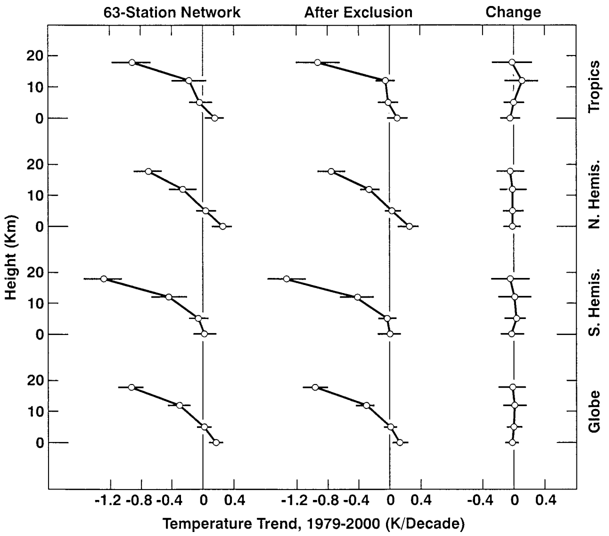

FIG. 4. As in Fig. 3, except for the 1979–2000 period and with a twofold difference in the abscissa scale.

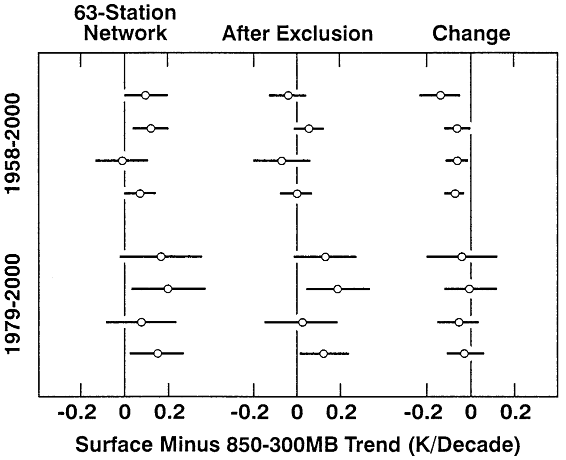

FIG. 5. Difference in the surface and the 850–300-mb temperature trend (K decade^{-1}) in the Tropics (TR), Northern Hemisphere (NH), Southern Hemisphere (SH), and the globe (GL) for (top) 1958–2000 and (bottom) 1979–2000 based on (left) the full 63-station network, (middle) the 54-station network, and (right) the change in trend difference from the former to the latter. Horizontal bars extend two standard errors of the mean on both sides of the average difference in the surface and the 850–300-mb trend, and two std devs on both sides of the change in the trend difference (see Fig. 3 caption).

small. Thus, the station exclusions result in the global 100–50-mb trend changing only from -0.45 to -0.42 K decade^{-1}, the 300–100-mb trend from -0.23 to -0.16 K decade^{-1}, the 850–300-mb trend from 0.07 to 0.10 K decade^{-1}, and the surface trend from 0.14 to 0.10 K decade^{-1}, none of these changes are significant. Note that if the global trends were estimated from an area-weighted average rather than a station average, owing to the greater number of stations in the Northern Hemisphere (38) than the Southern Hemisphere (25), and the warming of the 850–300-mb layer relative to the surface in the Southern Hemisphere, the global 850–300-mb warming would have been slightly greater than the global surface warming during 1958–2000.

Figure 4 presents the variation with height of the average of the radiosonde-station temperature trends in the Tropics, both hemispheres, and the globe for the period 1979–2000, based on the full 63-station network (left), the 54-station network (middle), and the change in trend from the former to the latter (right). Exclusion of the anomalous stations has had very little impact on the temperature trends for this period, the only appreciable change being the 0.11 K decade^{-1} smaller cooling of the tropical 300–100-mb layer. The much smaller impact of station exclusions on the 1979–2000 trend than the 1958–2000 trend suggests that most of the data problems at these nine stations occurred before 1979.

Figure 5 shows the effect of the exclusion of the nine anomalous tropical stations on the difference in the surface and the 850–300-mb temperature trend during 1958–2000 (top) and 1979–2000 (bottom). For 1958–2000, the confidence intervals at the upper right do not intersect the zero axis, so that the decrease in the difference between the surface and the 850–300-mb trend resulting from the exclusion of anomalous stations can be considered significant at the 90% level in the Tropics, both hemispheres, and the globe. After exclusion only the Northern Hemisphere continues to show warming of the surface relative to the 850–300-mb layer during 1958–2000, though none of these differences in trend is significant in the Tropics, both hemispheres, or the globe. On the other hand, for the period 1979–2000, both before and after the station exclusions the warming of the surface relative to the 850–300-mb layer is significant in the Northern Hemisphere and the globe.

4. Comparison of 1958–2000 and 1979–2000 trends in the 54-station network

Because of their greater representativeness, the subsequent discussion will consider only the temperature trends resulting from the exclusion of the 9 anomalous tropical stations from the 63-station radiosonde network. Figure 6 presents the tropical, hemispheric, and global trends for 1958–2000 and 1979–2000, and the change from the former to latter, on the same diagram and with the same abscissa scale. The most striking feature is the much greater cooling of the low-stratospheric 100–50-mb layer during 1979–2000 than 1958–2000, by at least a highly significant 0.4 K decade^{-1}. The tendency for a greater cooling of the 300–100-mb layer, or a change from warming to cooling of this layer, is also significant in the Tropics, both hemispheres, and the globe. The change from warming of the 850–300-mb layer during 1958–2000 to less warming or even cooling during 1979–2000 is significant except in the Northern Hemisphere, although at the surface there has been a greater warming during 1979–2000 than 1958–2000 except in the Southern Hemisphere. There is evidence that the

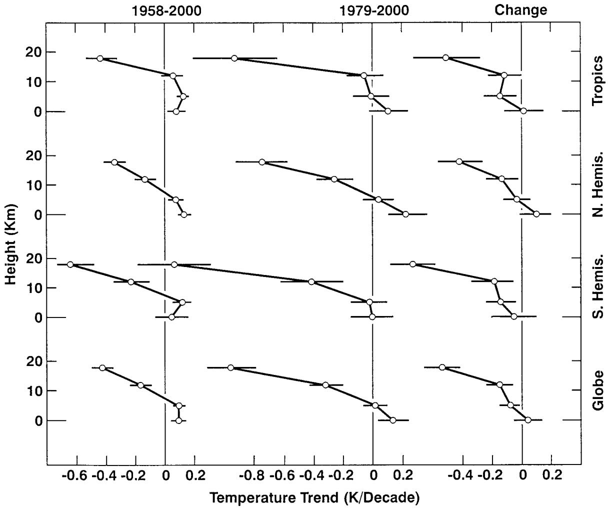

FIG. 6. Temperature trends for (left) 1958–2000, (middle) 1979–2000, and (right) the change from the former to the latter, based on the 54-station network. Horizontal bars extend two standard errors of the mean on both sides of the average trends and their change with time.

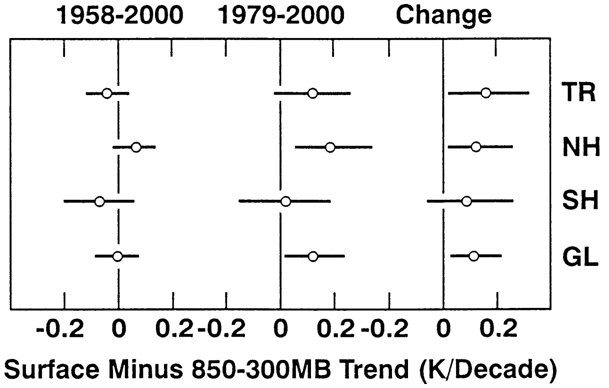

FIG. 7. The difference in the surface and the 850–300-mb temperature trend in the Tropics, both hemispheres, and the globe for (left) 1958–2000, (middle) 1979–2000, and (right) the change in trend difference from the former to the latter, based on the 54-station network. Horizontal bars extend two standard errors of the mean on both sides of average differences in the surface and the 850–300-mb trend and their change with time.

lapse rate is increasing, both near the surface and in a layer extending from the surface into the low stratosphere.

Figure 7 presents the difference in the surface and the 850–300-mb trend in Fig. 6 and its significance, as well as the change from 1958–2000 to 1979–2000 in this difference and its significance. During 1979–2000 there is a significant tendency for greater warming of the surface than the 850–300-mb layer in the Northern Hemisphere and the globe. Furthermore, except in the Southern Hemisphere, the warming of the surface relative to the 850–300-mb layer is significantly greater during 1979–2000 than 1958–2000. The evidence for an increase in low-level lapse rate is impressive.

5. Comparison with other radiosonde and MSU trends

Santer et al. (2000b) showed in their Fig. 7 that the global low-stratospheric cooling trends obtained from the full 63-station network were about a factor of 2 greater than the trends obtained by others, including from reanalyses, for 1979–93. Figure 8 compares the trends obtained from the 54-station network (trends with confidence intervals, and connected by solid lines) with other radiosonde and MSU trends for a slightly longer period. Based on a painstaking analysis of temperature data from 87 globally distributed radiosonde stations, the solid triangles show the tropical, hemispheric, and global temperature trends for 1959–97 and 1979–97 obtained by Lanzante et al. (2003) through the use of several procedures, some subjective, for identifying discontinuities in the individual radiosonde temperature records and adjusting for them. The agreement between the two datasets is generally good, the triangles falling within the 54-station confidence intervals except in the 100–50-mb layer of the Southern Hemisphere for both periods, and the 300–100-mb layer of the Southern Hemisphere and globe for the longer period (Lanzante et al. finding less cooling in all cases). This would be expected due to the distribution of stations in the 54-station network, in which both south temperate and south polar zones are represented by 6 stations (see Fig. 2). This gives too much weight to the south polar zone with its large stratospheric cooling associated with the Antarctic ozone hole. Note that for the 1958–2000 period there is usually worse agreement between the trends of Lanzante et al. and those for the full 63-station network (small circles in Fig. 8), than between Lanzante et al. and the 54-station network, particularly in the case of the 300–100-mb layer. This is evidence that exclusion of the anomalous stations indeed results in more representative estimates of the temperature trend.

Table 2.3 of the IPCC report ‘‘Climate Change 2001,’’ (Folland et al. 2001) provides, for 1958–2000 and 1979–2000, tropical and global temperature trends at the surface (Jones et al. 2001; Hansen et al. 1999) denoted, respectively, by J and H in Fig. 8; and in the lower troposphere and lower stratosphere (Parker et al. 1997; Christy et al. 2000) denoted, respectively, by P and M in Fig. 8. Note the very different estimates of the trend in the 100–50-mb (low stratosphere) layer of the Tropics during 1979–2000, ranging from a cooling of only about 0.3 K decade^{-1} based on satellite MSU data (M) to about 0.9 K decade^{-1} based on both Lanzante et al. and the 54-station network [the radiosonde results of Parker et al. (P) are about halfway between these]. Because Parker et al. adjusted some inhomogeneous stations' data using MSU, it is not surprising that their results are intermediate between MSU and other radiosonde analyses.

Caution is needed with regard to these apparent dif-

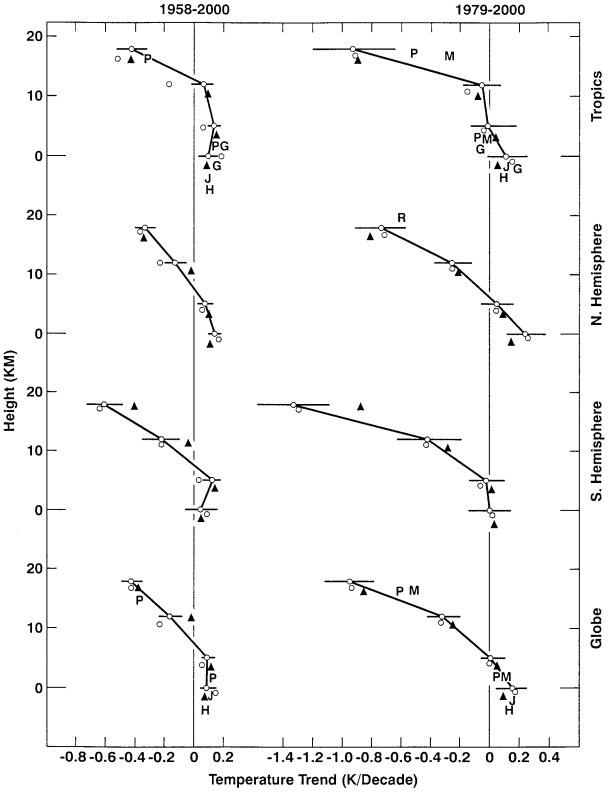

FIG. 8. Comparison of temperature trends estimated from the 54-station radiosonde network (trends with confidence intervals as in Fig. 6, and connected by solid lines, but with a doubled ordinate scale), with the radiosonde trends of Lanzante et al. (2003; solid triangles), Parker et al. (1997; P), and Gaffen et al. (2000a; G), as well as with MSU trends of Christy et al. (2000; M), the radiosonde-satellite-analysis trends of Ramaswamy et al. (2001; R), and surface temperature trends of Jones et al. (2001; J) and Hansen et al. (1999; H). Record lengths are 1959–97 and 1979–97 for Lanzante et al., 1960–97 and 1979–97 for G, and 1979–94 for R. The small circles indicate the trends for the full 63-station radiosonde network.

ferences because of the dissimilarities in the datasets. Thus, Table 2.3 of the IPCC report defines the Tropics as 20°S–20°N or 23.5°S–23.5°N, whereas in the present paper it is 30°S–30°N. More importantly, the vertical layers being compared vary from dataset to dataset, some based on the MSU vertical weighting function or an approximation thereto, whereas the present study considers the 100–50-mb layer. The MSU stratospheric weighting function still has considerable weight near 100 mb, which, in the Tropics, is near the tropopause where there is a rapid transition from stratospheric cooling to tropospheric warming. This could help explain the lesser cooling indicated by MSU than the radiosonde at the upper right in Fig. 8. Finally, the spatial sampling is quite different among the datasets, with the findings from this paper and Lanzante et al. based on global radiosonde networks of 54 and 87 stations, respectively, the findings of Parker et al. based on interpolations and extrapolations from a considerably denser radiosonde network, and the MSU findings based essentially on global data. In this regard it is of interest that the estimate of the Northern Hemisphere low-stratospheric temperature trend obtained by Ramaswamy et al. (2001) based on a mix of radiosonde data, MSU satellite data, and map analyses, for 1979–94, and denoted by R in Fig. 8, is in good agreement with the radiosonde estimates of both Lanzante et al. and the 54-station network.

There has been much discussion in recent years concerning the greater warming of the surface than the troposphere indicated by MSU satellite data and radiosonde data in comparison with surface temperature data (Hurrell et al. 2000; National Research Council 2000), with the paper of Santer et al. (2000a) showing that a model forced by a combination of anthropogenic factors and volcanic aerosols yields the surface–troposphere trend differences closest to those observed. Figure 8 shows that there is generally good agreement in the estimates of the surface and the 850–300-mb (troposphere) trend obtained from the 54-station network, the radiosonde data of Lanzante et al. and Gaffen et al. (2000a), the latter denoted by G in Fig. 8, and from Table 2.3 of the IPCC report. All datasets agree that there has been a slight warming of the tropical 850–300-mb layer relative to the surface during about the last 40 years (upper-left diagram of Fig. 8) and, with the exception of Lanzante et al., a substantial warming of the tropical surface relative to the 850–300-mb layer during about the last 20 years.

To clarify the relation between the surface and the 850–300-mb (troposphere) trend, Fig. 9 presents the differences in these trends (K decade^{-1}) for 1958–2000 (top), 1979–2000 (middle), and the change in this trend difference between these two periods (bottom). There is agreement that the tropical troposphere warmed relative to the surface during 1958–2000, but globally Lanzante et al. continue to show warming of the troposphere relative to the surface whereas the 54-station network and Parker–Jones (P–J) show the same warming of the troposphere and surface. For the period 1979–2000 there is a huge disparity in estimates of the difference in the tropical and 850–300-mb (troposphere) trend, Lanzante et al. indicating essentially the same warming of the surface and the 850–300-mb layer, but Gaffen et al. (G) indicating a warming of the surface relative to the 850–300-mb layer of 0.24 K decade^{-1}, the latter in better agreement with other estimates including that of Brown et al. (2000) as denoted by B. Globally, the agreement is better, the warming of the surface relative to the 850–300-mb layer varying from 0.04 to 0.14 K decade^{-1} for 1979–2000 for the various estimates. The bottom values of Fig. 9 show that the amount by which the surface temperature trend exceeds the 850–300-mb (tropospheric) trend is always greater during 1979–2000 than 1958–2000. Thus, there is consensus for an increase in low-level lapse rate with time.

6. Summary and conclusions

The following are the significant (at the 90% level) effects on the 1958–2000 trend resulting from the ex-

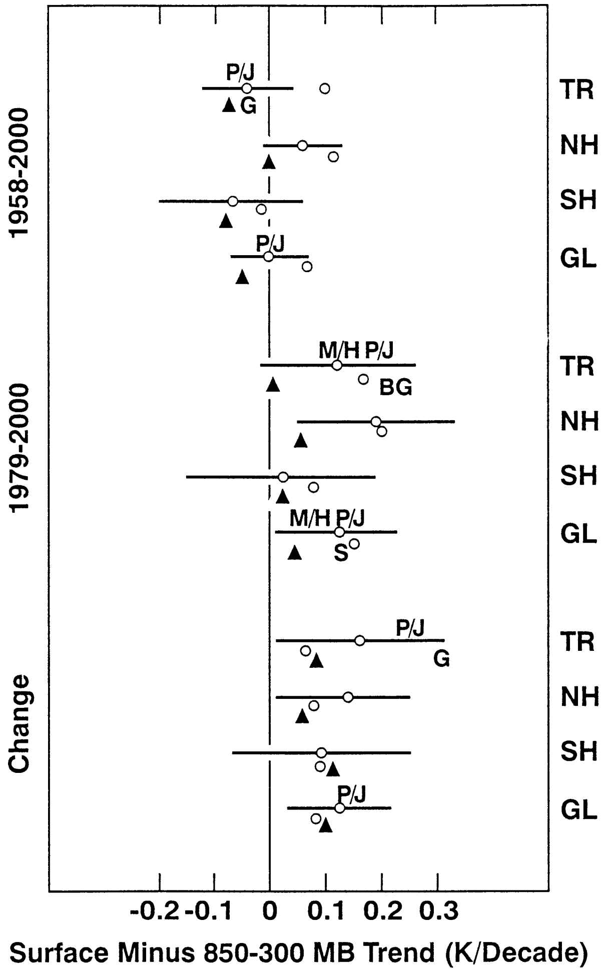

FIG. 9. Comparison of the difference of the surface and the 850–300-mb (or low troposphere) temperature trends estimated from the 54-station radiosonde network (trend differences with confidence intervals as in Fig. 7), with the radiosonde trend differences of Lanzante et al. (solid triangles), G, S, and B, as well as with the difference of low-troposphere radiosonde trend of and surface trend of Jones et al. (P/J), and low-troposphere MSU trend of M and surface trend of Hansen et al. (M/H). At the bottom is the change from 1958–2000 to 1979–2000 in the difference of the surface and the 850–300-mb trend. Record lengths are as in Fig. 7, except 1979–98 for Santer et al. The small circles indicate the trend differences for the full 63-station network.

clusion of 9 anomalous tropical stations from a 63-station global radiosonde network:

1) In the tropical 300–100-mb layer there is a change from a cooling, to a warming of 0.06 K decade^{-1}.
2) In the tropical 850–300-mb layer there is a change from a small warming, to a warming twice as great (0.13 K decade^{-1}).
3) In the Tropics there is a change from the surface warming more than the 850–300-mb layer, to the 850–300-mb layer warming more than the surface by 0.04 K decade^{-1}.
4) For the globe as a whole there is a change from the surface warming more than the 850–300-mb layer, to the same warming of the surface and the 850–300-mb layer (0.10 K decade^{-1}).

In addition, the exclusions result in the warming of the surface relative to the 850–300-mb layer becoming significantly greater in 1979–2000 than 1958–2000 in the Tropics, the Northern Hemisphere, and the globe. However, both before and after the exclusions there is a significantly greater surface than 850–300-mb warming in the Northern Hemisphere and the globe during 1979–2000.

Comparison with MSU and other radiosonde analyses shows that, after the exclusions

1) All datasets agree that in the Tropics the troposphere warmed more than the surface during 1958–2000, but during 1979–2000 the surface warmed more than the troposphere except in the dataset of Lanzante et al.
2) The datasets also agree that the global warming of the surface and the troposphere were basically the same during 1958–2000, but that during 1979–2000 the global surface warmed more than the troposphere. The latter is significant based on the 54-station network.
3) The 54-station network shows too much cooling of the Southern Hemisphere low stratosphere, to be expected due to overweighting (because of station distribution) of the large stratospheric cooling in the south polar zone associated with development of the Antarctic ozone hole.
4) Radiosonde trends in general, and the 54-station trends in particular, show much more cooling of the tropical low stratosphere during 1979–2000 than does MSU. This is believed to be partly due to the difference in the vertical extent of the layers being examined; in the Tropics the MSU stratospheric layer extends into the troposphere.

In conclusion, while the exclusion of 9 anomalous tropical stations from a 63-station global radiosonde network results in significant changes in tropical trends for the 1958–2000 period, the changes in global trends for this period are relatively small. For the 1979–2000 period the exclusions have little impact on either the tropical or global trend, indicating that most of the data inhomogeneities at these stations occurred before 1979. The problem of the 63-station network showing more low-stratospheric cooling than other analyses is not completely resolved by the exclusion of the 9 anomalous tropical stations.

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