ANNUAL AND SEASONAL TROPOSPHERIC TEMPERATURE TREND COMPARISONS OF RADIOSONDE AND REANALYSIS DATA AT REGIONAL SCALES

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Abstract

With the current widespread interest in anthropogenic climate change, many studies have investigated tropospheric temperature trends. These studies have used data from various satellite, reanalysis, and radiosonde sources. Of those studies that have been conducted comparing temperature trends between datasets, few have focused on the differences between radiosonde and reanalysis trends. Since radiosonde data are input for reanalyses, the two datasets could be expected to agree well with each other, but this is not guaranteed since the reanalyses utilize other information such as winds. These comparisons are needed in light of existing uncertainty over the use of current reanalyses in climate trend research. Our study compares linear tropospheric temperature trend estimates for radiosonde and reanalysis data, both annually and seasonally, at land-based sites in the Americas and Australasia/Oceania from 1979-2001. The average radiosonde trends generally fell in between the average reanalysis trend values and indicate that reanalyses are indeed useful for climate trend analysis. We do clearly document the value of using current reanalyses for regional long-term tropospheric trend assessments. The most significant differences between the radiosonde and reanalysis datasets occurred during the Northern Hemisphere growing season (April – September), and at upper levels of the troposphere (200 and 300 mb). The semiannual variations in the significance of the reanalysis-radiosonde average temperature trend differences may be indicative of regional variations in these differences. Additional reanalysis-radiosonde comparisons using newer radiosonde datasets that have more global coverage are recommended to further investigate such regional patterns and better understand global properties of these trend differences.

1. Introduction

There is currently much interest in inadvertent anthropogenic climate change (IPCC 2001; NRC 2005). This paper investigates the differences tropospheric temperature (T) trends for 1979-2001 between radiosonde observations and collocated NCEP and ERA-40 reanalysis datasets. Questions have been raised as to whether reanalysis are useful for tropospheric temperature trends over this time period (Santer et al. 2003a, b; CCSP 2005).

There have been various studies investigating T trends in the troposphere. Satellites have been used for monitoring tropospheric and surface T trends over the past few decades. One satellite series in particular that has been heavily used for T trend analyses is the Microwave Sounding Unit (MSU) satellite series (e.g. Spencer and Christy 1990; Christy and Spencer 1995; Christy et al., 2000, 2003; Mears et al. 2003; Fu and Johanson 2005).

There have also been such investigations using model reanalysis data (Pielke 1998; Chase et al. 2000; Pielke et al. 2001b Santer et al. 2003a,b) and radiosonde data sources (Angell 1988; Oort and Liu 1993; Parker et al. 1997; Angell 2000; Gaffen et al. 2000b). Radiosonde data is one of the other remaining sources, besides satellite and reanalysis data, for observational data in the free troposphere. Radiosonde data provides more detailed vertical resolution and a longer record than satellite data currently does (Free et al. 2002).

Caution must be exercised in using radiosonde data, however. These data are known to suffer from numerous inhomogeneities (Lanzante et al. 2003a). Some of these inhomogeneities are caused by changes in instrumentation and observational practices (Gaffen 1994). Others can be attributed to various environmental factors such as solar heating (Luers and Eskridge 1998; Sherwood et al. 2005). Fortunately, many of these problems are being addressed with newer radiosonde datasets that are now available. These datasets include the Comprehensive Aerological Reference Data Set (CARDS – Eskridge et al. 1995) and the Integrated Global Radiosonde Archive (IGRA).

Comparison studies on tropospheric T trends have been done between satellite and reanalysis data (Pielke 1998; Chase et al. 2000; Chelliah and Ropelewski 2000; Sturaro 2003; Agudelo and Curry 2004; Bengtsson et al. 2004) and satellite and radiosonde data (Christy et al. 2000; Hurrell et al. 2000, Lanzante et al. 2003b, Agudelo and Curry 2004). As of yet, however, there are few available studies that have compared tropospheric T trends between reanalysis and radiosonde datasets (e.g., Agudelo and Curry 2004). This paper complements the initial studies on reanalysis/radiosonde trend comparisons such as those done by Agudelo and Curry (2004).

Another motivation for why further comparisons of reanalysis and radiosonde T trends are needed is that the degree of constraint of reanalyses by the temperatures that are measured by radiosondes has not been thoroughly evaluated. While reanalyses ingest temperatures, they also insert winds, and use the model equations to produce atmospheric fields which are consistent with the model dynamics. The availability of winds provides another measure of the T field, particularly at mid- and high-latitudes, since the thermal wind relationship is closely followed (Pielke 1988).

Indeed, in light of the issue of a possible day-night bias in the radiosonde measurements (Sherwood et al. 2005), the use of winds provides a data set to reduce any such bias. The ERA-40 reanalysis also assimilates surface information and both reanalyses ingest satellite soundings (which although frequently updated by the radiosondes are still another set of vertical profile information; i.e. see http://blue.atmos.colostate.edu/publications/pdf/R-

278b.pdf). Moreover, the radiosondes measure along a column in the vertical while the reanalyses represent a grid volume average (with a horizontal footprint of 2.5 degrees latitude by 2.5 degrees longitude grid interval). Thus while we should expect a strong correlation between the reanalyses and the radiosondes, there is no assurance that they have identical profiles.

Our paper examines the degree of agreement between trend estimates generated from a subset of the CARDS radiosonde dataset and the NCEP and the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-40 reanalyses. We perform this evaluation by examining interannual variability and trends for 1979-2001. The time period was selected because previous studies have indicated that warming should become most evident during this time (e.g., Chase et al. 2000). This is a time period where global observations through the full depth of the atmosphere have been the most reliable (Bengtsson et al. 1999). Also, the ERA-40 dataset stops at 2001 and satellite data were not incorporated into the ERA-40 dataset until the late 1970s. While there are issues with the temporal homogenization of the reanalyses, this is true of each of the tropospheric data sets (e.g. MSU, radiosonde) that have been used to assess long term trends.

Despite continued caution in the climate community about the use of reanalyses in climate trend analyses (Bengtsson et al. 2004), it must be noted that the reanalyses offer additional insight, not only because they incorporate physics to provide consistent spatial and temporal fields (e.g., see Pielke and Chase 2004), but also because they use the wind field as another constraint on the temperatures which is not present in the other data sets. The value of using winds has been quantified in Pielke et al. (2001). Since the radiosonde wind and T fields do provide a real world constraint on the reanalyses, and the reanalyses provide physical constraints on the data, this resource is appropriate to use to evaluate long term T trends.

2. Data and Methods

Tropospheric T trends were compared for radiosonde and reanalyses datasets at selected sites (Fig. 1). The sites being considered here are all land-based, so this study does not consider open-ocean areas. We stress that most of the sites considered in this study are located either in North and South America or in the general region of southeast Asia and Australia. Results will, therefore, be weighted more towards these regions and should by no means be considered to be representative of the entire globe. The tropospheric levels of interest in this study are 1000, 850, 700, 500, 300, and 200 mb.

The radiosonde data were obtained from the Comprehensive Aerological Reference Data Set (CARDS – Eskridge et al. 1995). The subset of the CARDS dataset used in this study was obtained from Dr. John Christy at the Earth System Science Center (ESSC) in Huntsville, Alabama, USA. This subset of CARDS data includes the most reliable radiosonde sites for the southern hemisphere plus the VIZ radiosonde sites in the northern hemisphere (as in Christy and Norris 2004).

The two reanalysis datasets used in this study are the National Centers for Environmental Prediction (NCEP) Reanalysis product (Kalnay et al. 1996) and the European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year reanalysis product (ERA-40 – Simmons and Gibson 2000). The NCEP reanalysis data was provided in monthly-averaged format by the National Center for Atmospheric Research in Boulder, Colorado, USA. The

ERA-40 dataset was obtained directly from the ECMWF Hadley Centre's dataserver. Both reanalysis datasets are available at grid intervals of 2.5°.

The Climatological Averaging of Temperature Soundings (CATS) program, designed and maintained by ESSC (Norris 2002), was used to retrieve daily T data from the CARDS radiosonde dataset and then use these data to compute monthly averages for the period of 1979-2001. These data were obtained for each of the mandatory pressure levels but only the pressure levels at 1000, 850, 700, 500, 300, and 200 mb were analyzed.

To compare the radiosonde data, hereafter referred to as CARDS, with the corresponding NCEP and ERA-40 data, monthly-averaged reanalysis data were extracted for 1979-2001 from the nearest gridpoint to each station in CARDS (Fig. 1). As has been previously discussed, CARDS data are for points while each corresponding reanalysis value is an average value for a 2.5° grid cell. It is rarely the case that the coordinates of a CARDS site and the center coordinates of its corresponding reanalysis grid cell will coincide. Next, raw time series of the monthly averages of T were inspected for each site.

Temporal T trends were then computed with the SAS-ETS® program on each time series for the CARDS, NCEP, and ERA-40 datasets over the period of 1979-2001, using a linear model

$$y = \beta x + \varepsilon , \qquad (1)$$

where β represents the trend to be estimated and ε represents the error. Autocorrelation effects up to lag-4 were accounted for, to remove effects from interannual variations having cycles up to 4 years in duration. The autoregressive error model used here is the Yule-Walker (YW) method (Gallant and Goebel 1976). Trends were estimated only for those time series having at least 15 data points (years) available. Finally, we investigated the differences between the CARDS and reanalyses trend estimates.

3. Tropospheric Temperature Trend Comparisons

a. Time series

The raw time series of T for the CARDS, ERA-40, and NCEP datasets do not indicate any obvious trends in T over time. The overall time series at each site are generally neutral for T. The primary variations are caused by the annual T cycles, with greater cycle amplitudes observed for higher-latitude sites.

The T time series of the CARDS and reanalysis datasets usually agree well with each other. In a relatively small number of cases, however, the values of the CARDS and reanalysis datasets are displaced from each other by some value (Fig. 2). There is no consistent pattern in these displacements between dataset values. For some of these sites, it is either the ERA-40 or the NCEP reanalysis that is displaced from the other datasets (e.g., 912170 - Guam/Taguac). Also, a few sites show that the CARDS T values are displaced from the reanalysis values (e.g., 637410 - Nairobi/Dagoretti, 723650 - Albuquerque). This latter problem was only observed in the lowest layers of the troposphere (1000 mb) and may be at least partially caused by reanalysis data being extrapolated below ground.

b. *Annual, seasonal comparisons*

To begin the tropospheric trend analysis for each site, all observed trends for each month are averaged together to obtain an annually-averaged trend estimate at each pressure level of interest (Fig. 3). These are straight averages, where each station (or respective grid box for the reanalysis datasets) is weighed equally in the average computation. The intent here is to look at relative differences between the trend estimates among the reanalyses and radiosonde datasets. Despite exceptions at 700 mb and 1000 mb, the average ERA-40 T trends show the most warming/least cooling of the three datasets. The average NCEP T trends, on the other hand, often show the most cooling, except at 700 mb. The significance of the differences between the reanalyses and CARDS averaged T trends is generally greatest in the upper levels of the troposphere (Table 1). At these upper levels (200 and 300 mb), the values of the CARDS average T trends are in between those of the ERA-40 (relatively warmer) and NCEP (relatively cooler) average T trends. At middle levels, such as 500 and 700 mb, the differences between the reanalyses and CARDS trends is generally insignificant, with some exceptions. At 1000 mb, the CARDS trends are warmer than both reanalysis datasets, significantly so in relation to the NCEP trends.

Next, we averaged together all observed trends over 3-month periods to look at seasonal variations in these reanalysis-CARDS trend differences. For the months of January-March (JFM, Fig. 4a), the same general patterns are observed as in the annually-averaged case (Fig. 3, Table 1). For example, the averaged ERA-40 trends are generally the warmest while the averaged NCEP trends are generally the coolest. The CARDS average trend is cooler than both reanalyses average trends at 1000 mb. The most significant differences between the datasets generally occur at the upper levels (Table 1). The significances of the reanalysis-CARDS trend differences are reduced greatly compared to the annual case, however. The only significant difference between the average T trends of the CARDS and reanalysis datasets occurs for the difference between the ERA-40 and CARDS T trends at 300 mb. The differences between the NCEP and CARDS T trends are generally insignificant.

The differences between the ERA-40 and CARDS average T trends for the months of April-June (AMJ, Table 1) show that when all trend estimates are considered, ERA-40 trends are significantly warmer than CARDS at both 200 mb and 300 mb, but significantly cooler than CARDS at the 1000-mb level. NCEP shows significantly less warming than CARDS at 200, 300, and 1000 mb. The CARDS average T trends at the upper levels of the troposphere (200 and 300 mb) are again intermediate in value between the ERA-40 (warmer) and NCEP (cooler) reanalyses (Fig. 4b). The differences between the datasets are largely insignificant at the middle levels (Table 1).

The months of July through September (JAS, Fig. 4c) continue many of the same general patterns that were evident during AMJ. Considering all individual trends, the average T trends for ERA-40 are significantly warmer than CARDS in the upper troposphere, at 700 mb, and at 850 mb (Table 1). The NCEP T trends in the upper troposphere show significantly less warming or even cooling compared to the corresponding CARDS trends. In the middle levels, NCEP average T trends are warmer than the CARDS trends. At 850 mb, this pattern begins to change and at 1000 mb, NCEP shows significantly *less* warming than the CARDS data.

For the months of October-December (OND), the ERA-40 average T trends are warmer than the CARDS average T trends at all pressure levels (Fig. 4d) but are significantly warmer at only 300 mb and 850 mb (Table 1). On the other hand, the NCEP and CARDS average T trends have no significant differences at any pressure level.

The seasonal progression of these comparisons (Fig. 4, Table 1) indicates that the most significant differences between the CARDS and reanalyses trends generally occur during the months of April-September. Less significant differences generally occur during the rest of the year. The relative coolness of the reanalyses average trends compared to the CARDS average trends at 1000 mb, noted previously, is also the most significant during the months of April-September and becomes less significant at other times of the year. The upper levels of the troposphere consistently have the most significant reanalysis-CARDS trend differences (ERA-40 warmer, NCEP cooler) in all seasons.

4. Discussion and Conclusions

The goal of our study was to perform, for the troposphere, a comparison of trends in T between CARDS and reanalysis datasets. This work augments previous comparisons of these datasets (e.g., Agudelo and Curry 2004) by examining these comparisons on a seasonal basis.

The study period chosen here (1979-2001) was dictated primarily by the available datasets. The CARDS data were only available after 1979. Also, satellite data were beginning to be more extensively incorporated into reanalysis data in the late 1970s. It would be preferable, of course, to conduct these trend analyses over a much longer time period, to help reduce the error in the estimated trends.

Annually and seasonally, the ERA-40 reanalysis average trends tend to be relatively warmest among the three datasets considered here, while the NCEP data have the relatively coolest trends. As a result, the CARDS average T trend values generally fall in between those of the NCEP and ERA-40 reanalyses. This would then indicate that for tropospheric T trends, the CARDS data do agree satisfactorily with available reanalysis datasets and reanalyses are in fact appropriate for evaluating long-term regional trends in T. The agreement between observations and the reanalyses for locations where the information is coincident provides support that the reanalysis permits realistic assessments of regional trends for locations where radiosonde observations are not present, but satellite derived vertical soundings are.

The level of significance of the differences between the averaged trends of CARDS and reanalyses seems to follow a semiannual pattern, with the more significant differences occurring roughly during the Northern Hemisphere growing season (i.e., April-September). This may be indicating a notable semiannual spatial variation in reanalysis versus radiosonde datasets between the Northern and Southern Hemispheres, which could be looked into more fully by using additional sites around the globe.

One dataset that would provide this additional radiosonde site coverage around the globe is the IGRA dataset, introduced earlier. At the time our study discussed here was conducted, IGRA was not yet available, hence the use of CARDS data. Further work on this topic is recommended and would benefit from the utilization of the IGRA dataset.

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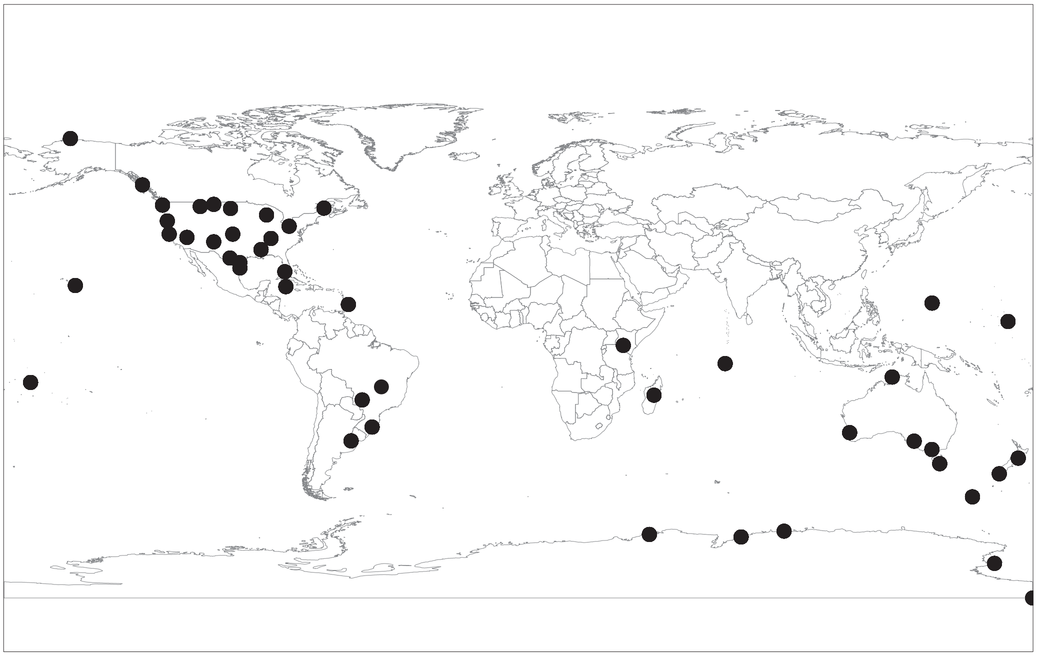
FIGURE CAPTIONS

FIG. 1. Map of sites used in the comparisons of the CARDS and reanalysis datasets.

FIG. 2. 1979-2001 temperature time series at 1000 mb, for Corpus Christi, Texas, USA (722510), Nairobi/Dagoretti, Kenya (637410), Albuquerque, New Mexico, USA (723650), and Guam/Taguac (912170). ERA40 time series are shown in grey, NCEP time series are shown in thick black, and radiosonde time series are shown in thin black.

FIG. 3. Annually-averaged T trends (error bars indicate standard deviations) at selected pressure levels, for the sites shown in Fig. 1. Numbers beside error bars indicate the exceedance significance level met by the averaged trend. Results are shown for straight averages over all local trends. NCEP trends are shown by the striped bars, ERA-40 trends are shown by the light stippled bars, and the CARDS trends are shown by the dark grey bars.

FIG. 4. As in Fig. 3, but for seasonally-averaged T trends (error bars indicate standard deviations) at selected pressure levels, for JFM (a), AMJ (b), JAS (c), and OND (d).



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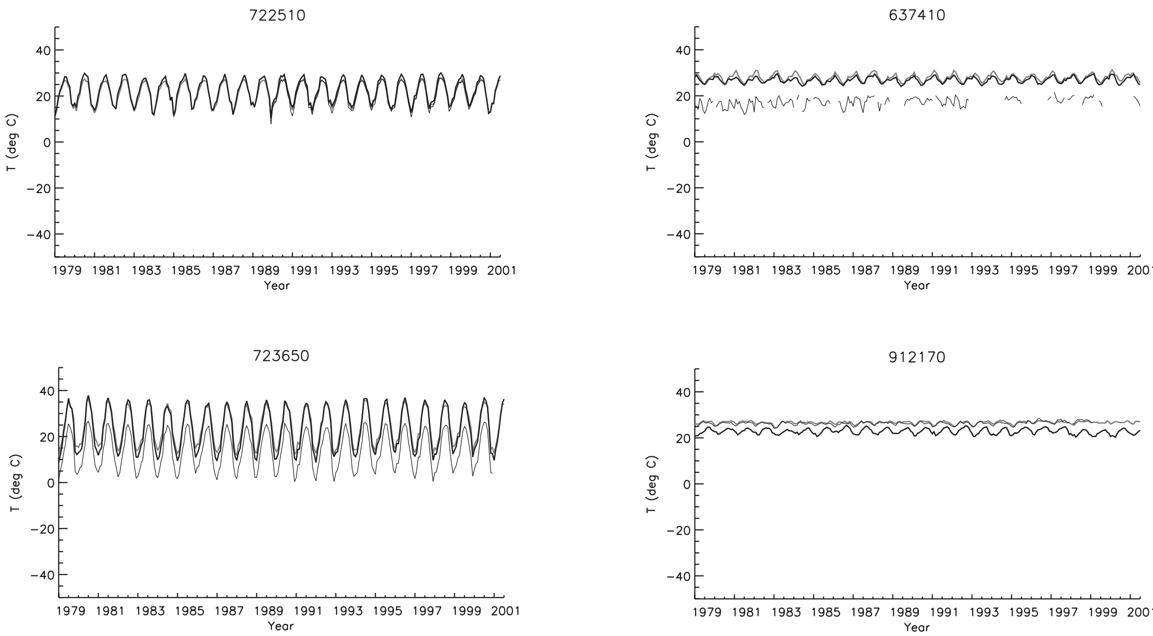


FIG. 2. 1979-2001 temperature time series at 1000 mb, for Corpus Christi, Texas, USA (722510), Nairobi/Dagoretti, Kenya (637410), Albuquerque, New Mexico, USA (723650), and Guam/Taguac (912170). ERA40 time series are shown in grey, NCEP time series are shown in thick black, and radiosonde time series are shown in thin black.

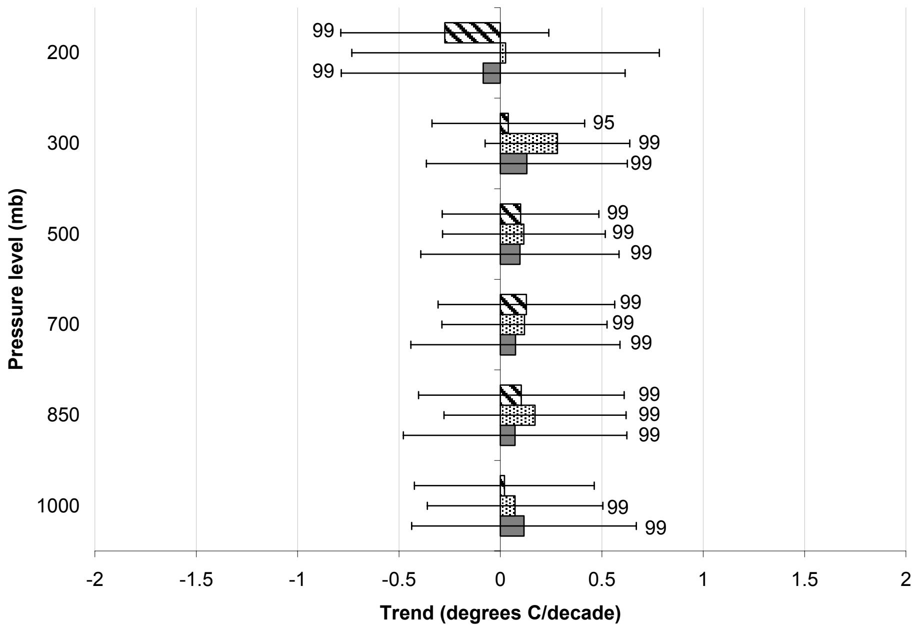
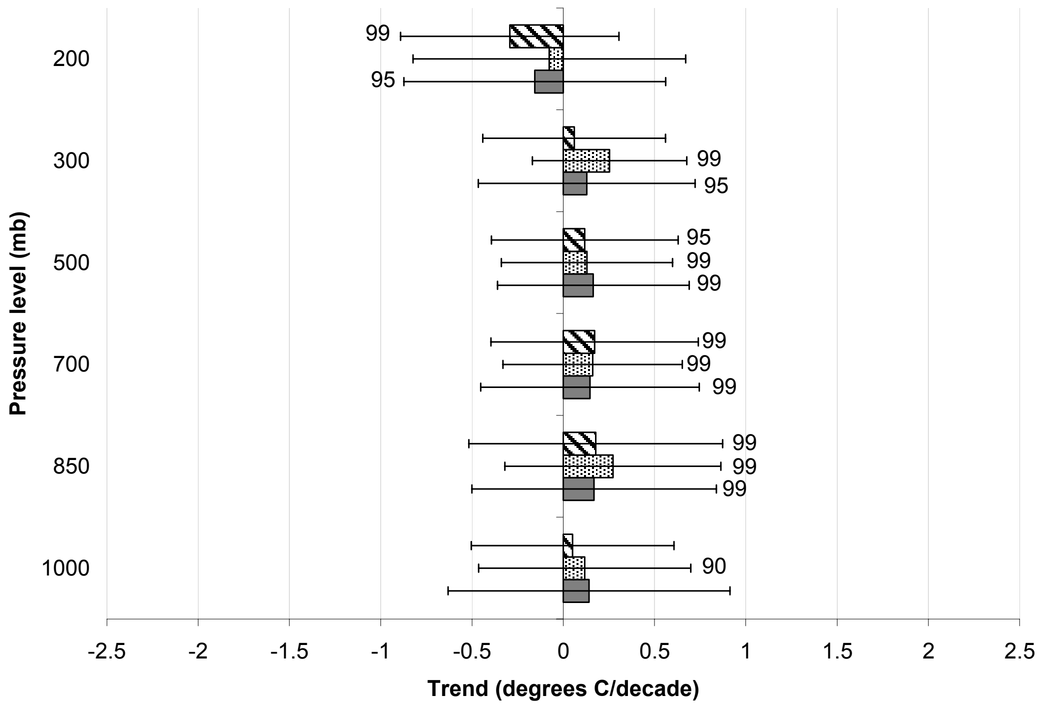
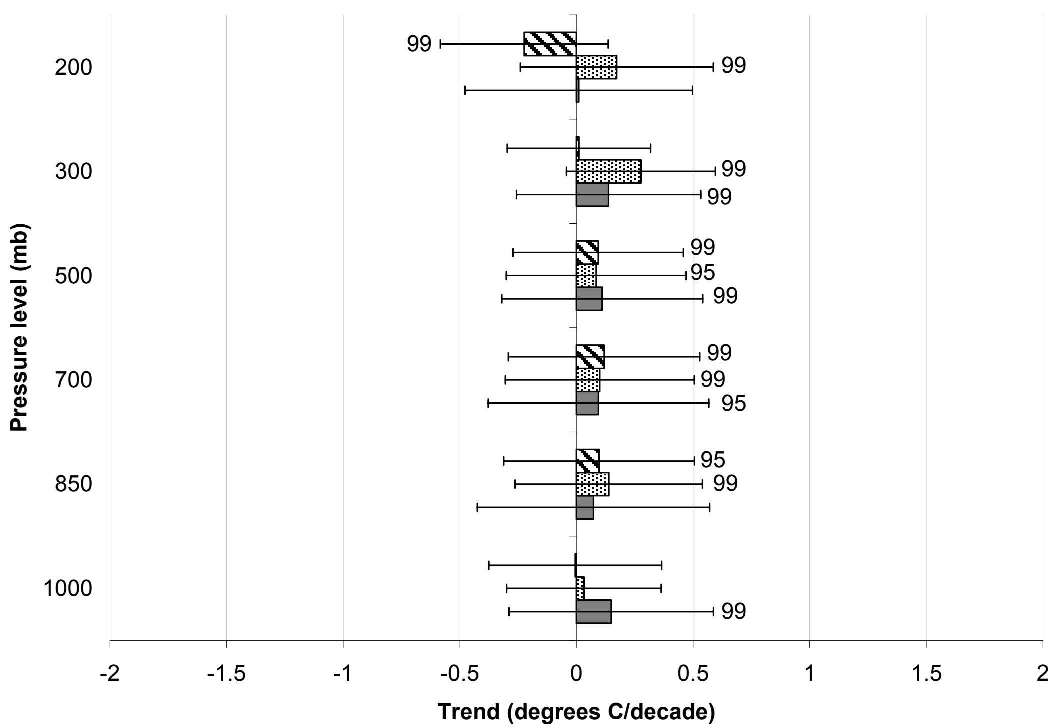


FIG. 3. Annually-averaged T trends (error bars indicate standard deviations) at selected pressure levels, for the sites shown in Fig. 1. Emphases are placed on *differences* between trend estimates. Numbers beside error bars indicate the exceedance significance level met by the averaged trend. Results are shown for straight averages over all local trends. NCEP trends are shown by the striped bars, ERA-40 trends are shown by the light stippled bars, and the CARDS trends are shown by the dark grey bars.

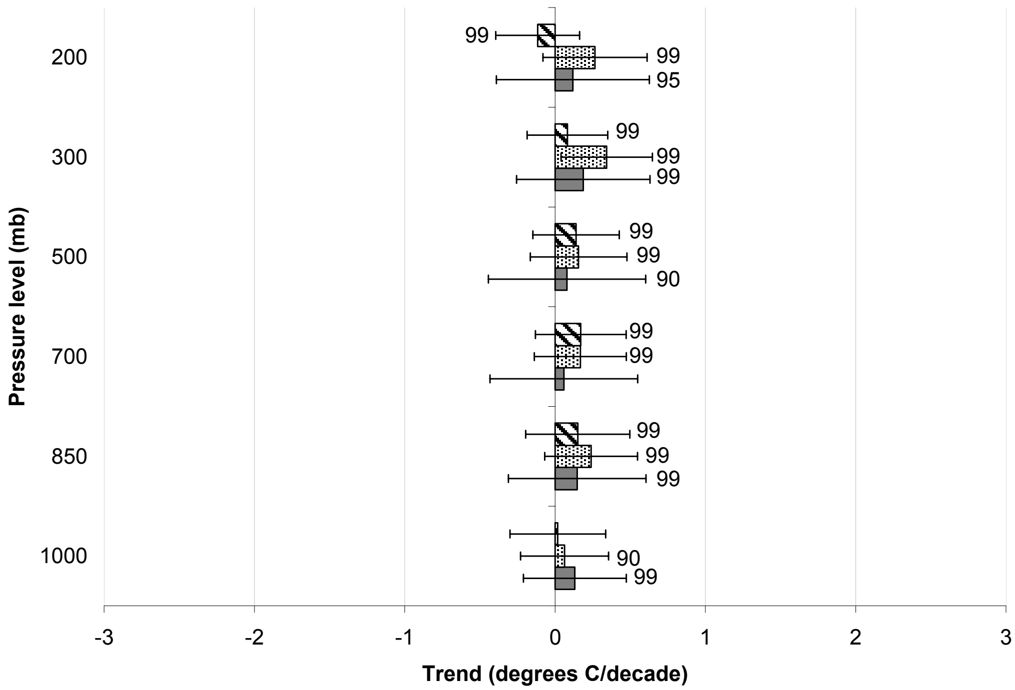
a)


99
200
95
300
99
95
95
500
99
99
99
700
99
99
99
850
99
99
90
1000
Pressure level (mb)
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
Trend (degrees C/decade)

b)


99
200
99
300
99
99
99
500
95
99
99
700
99
95
95
850
99
1000
99
Pressure level (mb)
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Trend (degrees C/decade)

c)



d)

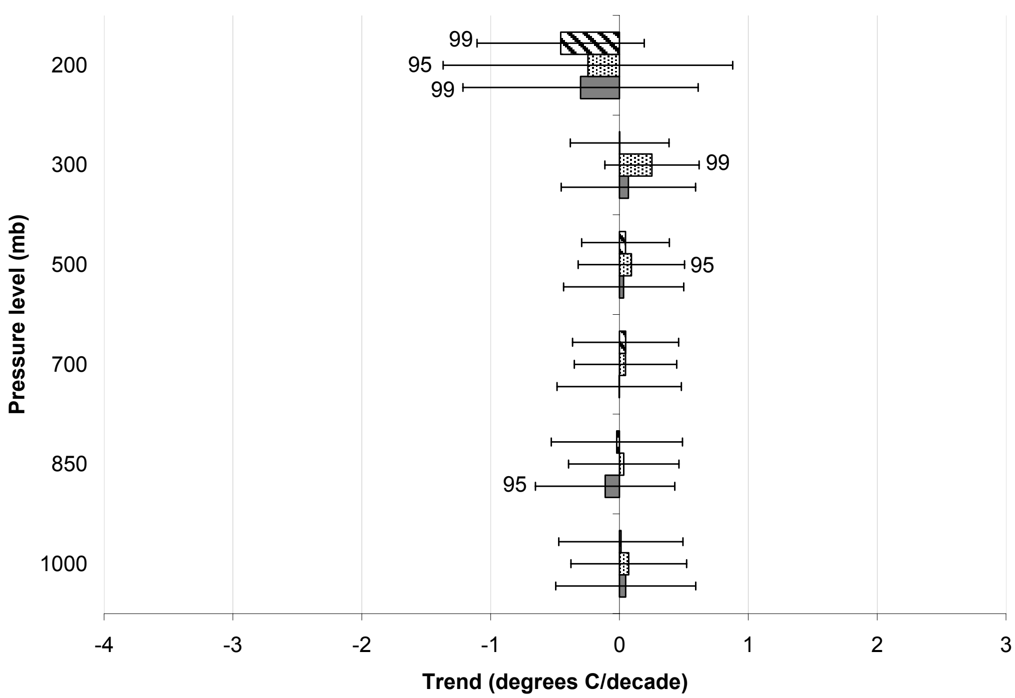


FIG. 4. As in Fig. 3, but for seasonally-averaged T trends (error bars indicate standard deviations) at selected pressure levels, for JFM (a), AMJ (b), JAS (c), and OND (d). Emphases are placed on *differences* between trend estimates.

TABLE 1. Z test statistic values of differences between averaged 1979-2001 temperature trends of CARDS and ERA-40 datasets (ERA-40 – CARDS) and the CARDS and NCEP datasets (NCEP – CARDS), annually and seasonally. Straight averages are done for all stations (grid boxes). The significance of a given difference is > 90% if |Z| > 1.65, > 95% if |Z| > 1.96, and > 99% if |Z| > 2.58.

Pressure level (mb)	Annual	JFM	AMJ	JAS	OND
ERA-40 – CARDS					
200	2.36	0.84	2.76	2.63	0.44
300	5.44	1.90	2.98	3.19	3.18
500	0.66	-0.55	-0.49	1.37	1.07
700	1.49	0.21	0.08	2.06	0.87
850	2.99	1.25	1.10	1.80	2.25
1000	-1.08	-0.22	-1.80	-1.27	0.30
NCEP – CARDS					
200	-4.78	-1.60	-4.12	-4.38	-1.52
300	-3.26	-0.97	-2.74	-2.21	-1.16
500	0.09	-0.69	-0.33	1.10	0.28
700	1.72	0.34	0.41	2.11	0.87
850	0.87	0.10	0.40	0.07	1.29
1000	-2.34	-0.83	-2.22	-1.99	-0.44