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

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## *Abstract*

Data from global reanalyses are routinely used as initial and lateral boundary conditions for regional numerical weather prediction modeling. Reanalyses have also been used for longer term assessments of tropospheric temperature trends. 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 in order to assess the quantitative agreement between the two types of data. In our analyses, we found that the average radiosonde trends generally fell in between the average reanalysis trend values and indicate that reanalyses are indeed appropriate to use for climate trend analysis.

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.

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## 1. Introduction

Reanalyses provide an effective dataset for inserting atmospheric variables into regional numerical weather prediction models as initial conditions and as lateral boundary conditions (e.g., see Castro et al. 2005). The reanalyses use a global numerical model framework to assimilate observational data into a model which has constraints from the conservation principles of physics. There is also interest in anthropogenic climate change (IPCC 2001; NRC 2005) in which tropospheric temperature trends over decades is one of the atmospheric metrics of interest. Radiosonde data are one type of information that is assimilated into the reanalyses.

Our paper focuses on the degree of quantitative agreement between radiosonde data and reanalysis values for the same area and time. We use the multi-year trends in the tropospheric temperature trends as the diagnostic to compare the degree of agreement between the radiosonde and reanalyses temperatures.

Numerous studies have investigated temperature trends in the troposphere. Satellites have been used for monitoring tropospheric and surface temperature trends over the past few decades. One satellite series in particular that has been heavily used for temperature trend analyses is the Microwave Sounding Unit (MSU) satellite series (e.g., Spencer and Christy 1990; Christy and Spencer 1995; Christy et al. 2000; Christy et al. 2003; Mears et al. 2003; Vinnikov and Grody 2003; Fu and Johanson 2005). There have also been similar investigations using radiosonde data sources (Angell 1988; Oort and Liu 1993; Parker et al. 1997; Angell 2000; Gaffen et al. 2000) and model reanalysis data (Pielke 1998; Chase et al. 2000; Pielke et al. 2001; Santer et al. 2003a; 2003b).

Questions have been raised in the climate community regarding the utility of reanalyses for monitoring tropospheric temperature trends (Santer et al. 2003a; 2003b; Bengtsson et al. 2004; CCSP 2006), which brings into question the accuracy of the reanalyses in their use as initial and lateral boundary conditions. However, despite continued caution in the climate community about the use of reanalyses in climate trend analyses, 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 datasets. The value of using winds has been quantified in Pielke et al. (2001). Radiosonde wind and temperature fields do provide a real world constraint on the reanalyses, while the reanalyses provide physical constraints on the data. Therefore, reanalyses are appropriate to use to evaluate long term temperature trends.

Radiosondes are one of the other remaining sources, besides satellite and reanalysis data, for observational data in the free troposphere. Radiosonde data provide 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, or CARDS (Eskridge et al. 1995) and the Integrated Global Radiosonde Archive (IGRA)

Comparison studies on tropospheric temperature 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 is only one study that we are aware of that have compared tropospheric temperature trends between reanalysis and radiosonde datasets (Agudelo and Curry 2004).

A primary reason for the necessity of further comparisons of reanalysis and radiosonde temperature trends 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 (Kalnay et al. 1996; Simmons and Gibson 2000). The availability of winds provides another measure of the temperature field, particularly at mid- and high-latitudes, since the thermal wind relationship is closely followed (Pielke et al. 2001).

Indeed, in light of a possible day-night bias in the radiosonde measurements (Sherwood et al. 2005), the use of winds would reduce any such bias, although some tidal effects remain in the mid-upper troposphere wind measurements (Bluestein and Banacos 2002). The European Centre for Medium-Range Weather Forecasting (ECMWF) 40-year (ERA-40) reanalysis also assimilates surface information and both the ERA-40 and the National Centers for Environmental Prediction (NCEP) reanalyses ingest satellite soundings (which, although frequently updated by the radiosondes, are still another set of vertical profile information; i.e., go online to www.climatesci.org/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)(Kalnay et al. 1996; Simmons et al. 2000). Consequently, while we should expect a strong correlation between the reanalyses and the radiosondes, there is no assurance that they have identical profiles.

The work presented here complements initial studies on reanalysis/radiosonde trend comparisons as completed by Agudelo and Curry (2004). This paper investigates *differences* in tropospheric temperature trends for 1979-2001 between CARDS radiosonde sites and collocated ERA-40 and NCEP reanalysis datasets. Agudelo and Curry (2004) investigated differences between these same radiosonde and reanalysis datasets for annually-averaged temperatures for the tropospheric layer 850-300 mb. Our paper analyzes upper-tropospheric (200 mb) trend differences, along with trend differences at 300 mb, 500 mb, 700 mb, and, for lower-elevation stations, 850 and 1000 mb. Our paper also extends the work by Agudelo and Curry (2004) to investigate seasonal variations in these trend differences. No attempt is made here to interpret the magnitudes of the trends themselves.

The time period of 1979-2001 was selected because previous studies have indicated that a temperature increase should become most evident during this time (e.g., Chase et al. 2000). More importantly, this is the 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 was not available after 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 datasets (e.g. MSU, radiosonde) that have been used to assess long-term trends.

## 2. Data and Methods

### *a. Data sources*

Tropospheric temperature 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.

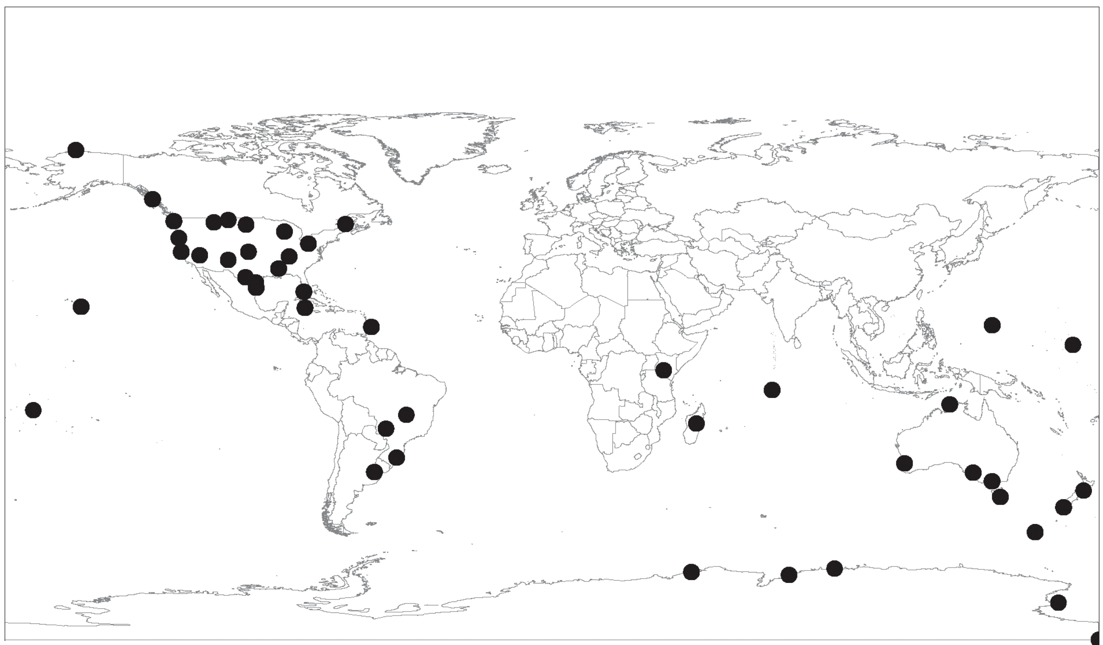

Fig. 1. Map of sites used in the comparisons of the CARDS and reanalysis datasets.

The subset of the CARDS radiosonde dataset used in this study was obtained from Dr. John Christy at the Earth System Science Center (ESSC) in Huntsville, Alabama. This CARDS subset includes the most reliable radiosonde sites for the southern hemisphere plus the VIZ radiosonde sites in the northern hemisphere (see Christy and Norris 2004). The radiosonde sites not included in this subset, including many sites from Europe, Africa, and much of Asia, had some artificial discontinuities due to instrumentation changes during the period 1979-2001, and thus were not included in this study.

Data from the NCEP reanalysis dataset (Kalnay et al. 1996) were provided for the years 1979-2001 in twice-daily format (00Z and 12Z) by the National Center for Atmospheric Research in Boulder, Colorado. We computed monthly averages from these twice-daily data. Identical procedures were performed on the ERA-40 dataset (Simmons and Gibson 2000), which was also in twice-daily form and was obtained directly from the ECMWF Hadley Centre data server. Both reanalysis datasets are available at grid intervals of 2.5°.

*b. Analysis*

The Climatological Averaging of Temperature Soundings (CATS) program, designed and maintained by ESSC (Norris 2002), was used to retrieve twice-daily temperature data from the CARDS radiosonde dataset (hereafter referred to as CARDS) and then computes monthly averages for the years 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 CARDS with the corresponding NCEP and ERA-40 data, monthly-averaged reanalysis data were extracted for the years 1979-2001 from the nearest gridpoint to each station in CARDS (Fig. 1). Next, raw time series of the monthly averages of temperature were constructed for each site and temporal temperature trends were computed with the SAS-ETS® program on each time series for the CARDS, NCEP, and ERA-40 datasets from 1979-2001, using a linear model

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

where $\beta$ represents the trend to be estimated and $\varepsilon$ 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 by employing the Z test statistic (Devore 1995).

## 3. Tropospheric Temperature Trend Comparisons

To begin the tropospheric trend analysis for each site, all monthly-averaged trends were averaged together to obtain an annually-averaged trend estimate at each pressure level of interest (Fig. 2). 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 trends estimates among the reanalyses and radiosonde datasets. Despite exceptions at 700 and 1000 mb, the average ERA-40 temperature trends show the most relative warming/least relative cooling[1] of the three datasets. The average NCEP temperature trends, on the other hand, often show the least relative warming, except at 700 mb. The significance of the differences between the reanalyses and CARDS averaged temperature trends is generally greatest in the upper levels (200 and 300 mb) of the troposphere (Table 1). At these upper levels, the values of the CARDS average temperature trends are in between those of the ERA-40 (relatively warmer) and NCEP (relatively cooler) average temperature trends. At middle levels, such as 500 and 700 mb, the differences between the reanalyses and CARDS trends is generally not statistically significant, with some exceptions. At 1000 mb, the CARDS trends are warmer than both reanalysis datasets, significantly so in relation to the NCEP trends.

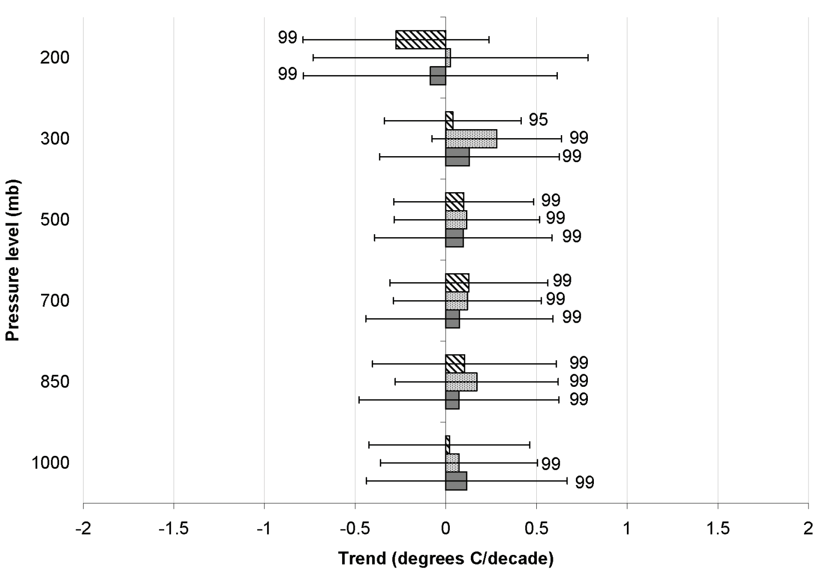


**Fig. 2.** Annually-averaged temperature trends (error bars indicate standard deviations) at selected pressure levels, for the sites shown in Fig. 1. Numbers beside error bars indicate the exceedance significance level met by the averaged trend. Results are shown for straight averages over all local 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.

[1] *Note that warming and cooling, in the context of this paper refer to temperature increase and decrease, respectively.*

| 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 |

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.

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. 3a), the same general patterns are observed as in the annually-averaged case (Fig. 2, Table 1). For example, among all three datasets, the averaged ERA-40 trends generally show the most warming, while the averaged NCEP trends show the least warming. The CARDS average trend shows less warming 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 temperature trends of the CARDS and reanalysis datasets occurs for the difference between the ERA-40 and CARDS temperature trends at 300 mb. The differences between the NCEP and CARDS temperature trends are not statistically significant.

The differences between the ERA-40 and CARDS average temperature trends for the months of April-June (AMJ, Table 1) show that ERA-40 trends are significantly warmer than CARDS at both 200 and 300 mb, but significantly cooler than CARDS at 1000 mb. NCEP shows significantly less warming than CARDS at 200, 300, and 1000 mb. The CARDS average temperature 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. 3b). The differences between the datasets are generally not statistically significant at the middle levels (Table 1).

The months of July through September (JAS, Fig. 3c) continue many of the same patterns that were evident during AMJ. The average temperature trends for ERA-40 are significantly warmer than CARDS in the upper troposphere, at 700 mb, and at 850 mb (Table 1). The NCEP temperature trends in the upper troposphere show significantly less warming compared to the corresponding CARDS trends. In the middle levels, NCEP average temperature trends are warmer than the CARDS trends. At 850 mb, this pattern begins to change and at 1000 mb, NCEP again shows less warming than CARDS.

For the months of October-December (OND), the ERA-40 average temperature trends are warmer than the CARDS average temperature trends at all pressure levels (Fig. 3d) but are significantly warmer at only 300 and 850 mb (Table 1). On the other hand, the NCEP and CARDS average temperature trends have no significant differences at any pressure level.

The seasonal progression of these comparisons (Fig. 3, 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 relatively smaller warming of the reanalyses average trends compared to the CARDS average trends at 1000 mb, which was 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 investigate, for the troposphere, *differences* in temperature trends between CARDS and reanalysis datasets. This work augments previous comparisons of these datasets (Agudelo and Curry 2004) by examining these differences on a seasonal basis.

It should be reiterated that 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 the warmest among the three datasets considered here, while the NCEP data show relatively less warming than the other two datasets. As a result, the CARDS average temperature trend values generally fall in between those of the NCEP and ERA-40 reanalyses. This would then indicate that for tropospheric temperature trends, available reanalysis datasets do agree satisfactorily with the CARDS data and reanalyses are in fact appropriate for evaluating long-term regional trends in tropospheric temperature. The agreement between observations and

Fig. 3a.

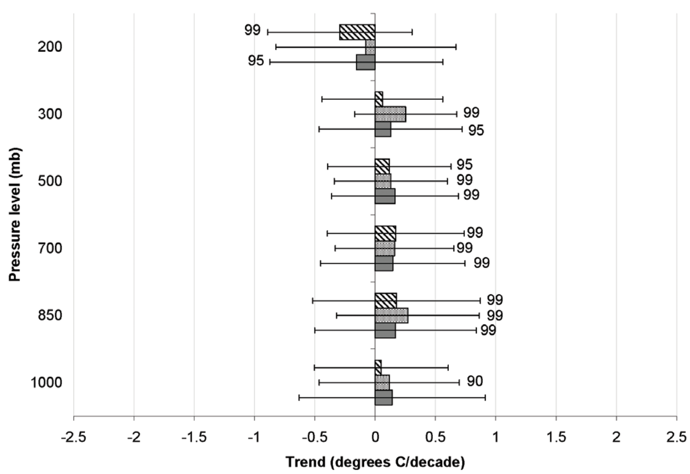


Fig. 3c.

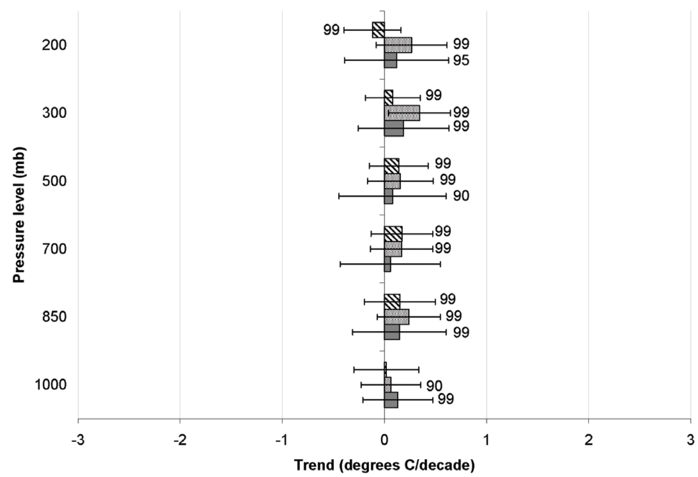


Fig. 3b.

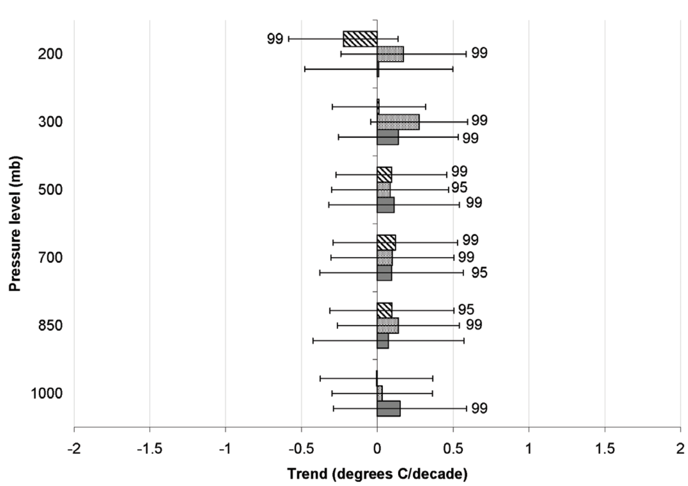


Fig. 3d.

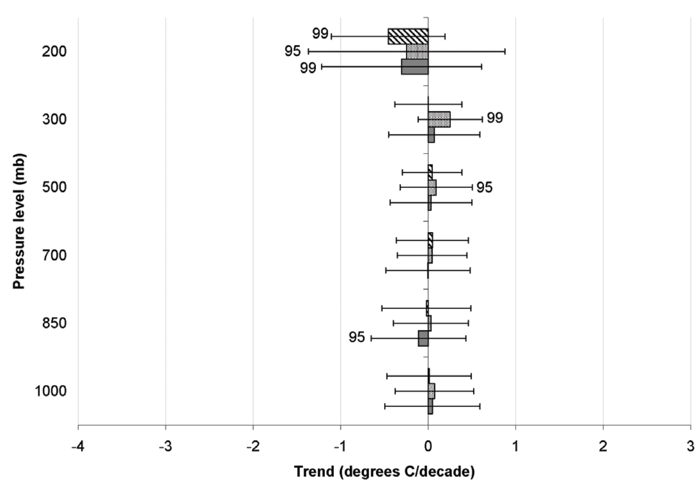


Fig. 3. As in Fig. 2, but for seasonally-averaged temperature trends (error bars indicate ±1 standard deviations) at selected pressure levels, for (a) JFM, (b) AMJ, (c) JAS, and (d) OND.

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 present.

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 we conducted our study, IGRA was not yet available, hence the use of CARDS data. Further work on this topic is recommended and would benefit from using the IGRA dataset.

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## Acknowledgments

This work was supported under the NSF fellowship program entitled “Graduate Teaching Fellows in K-12 Education (GK-12)” (GKA01-0177), the NSF GLOBE project (GEO-0222578), and the F/DOE/The University of Alabama in Huntsville’s “Utilization of Satellite Data for Climate Change Analysis” (DE-FG02-04ER 63841 through the University of Alabama at Huntsville). John R. Christy and William B. Norris provided much-needed support on the CARDS dataset used in this study. Dallas Staley and Odie Bliss performed outstanding support for editorial oversight of the paper.

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