

Analysis of spatial distribution in tropospheric temperature trends

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[1] Regional patterns in tropospheric and sea surface temperature (SST) trends are examined for the period 1979–2001 using MSU, NCEP-NCAR, ECMWF reanalyses, NOAA OI SST, and the CARDS radiosonde data set. Trends are estimated using a nonparametric approach. Substantial regional variability in temperature trends is seen in all data sets, with the magnitude of the variability (including substantial regions with cooling trends) far exceeding the average warming trend. The global analyses from MSU and reanalyses are used to identify sampling problems in using radiosonde network to infer global trends. Analysis of tropospheric temperature trends concurrent with trends in SST shows regions where the signs disagree for both surface cooling and warming. Interpretation of these differing trends using the reanalyses suggest that the models used for the reanalyses are simulating the necessary dynamics/thermodynamics that could lead to a tropospheric cooling in contrast to a surface warming (and vice versa). *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 1635 Global Change: Oceans (4203); 1640 Global Change: Remote sensing. **Citation:** Agudelo, P. A., and J. A. Curry (2004), Analysis of spatial distribution in tropospheric temperature trends, *Geophys. Res. Lett.*, 31, L22207, doi:10.1029/2004GL020818.

1. Introduction

[2] Documenting trends in atmospheric temperature is a key to understanding climate change and evaluating model simulations of this change [e.g., Houghton *et al.*, 2001]. Considerable efforts have been made to determine atmospheric temperature trends from radiosonde observations and also from satellites. Different analyses have produced diverse results, including apparent inconsistencies of tropospheric temperature trends with trends in surface temperature.

[3] Since the original analysis of atmospheric temperature trends by Angell [1988], numerous analyses have focused on obtaining homogeneous data sets, free of gradual and sudden artificial changes resulting from observation procedures [e.g., Lanzante *et al.*, 2003a; Christy *et al.*, 2003]. Another source of uncertainty is the different statistical methods used to estimate trends [e.g., Santer *et al.*, 2000]. A general conclusion has been that the estimation of global average trends from radiosonde data is robust in sign against uncertainties due to different data sets and statistical methods used. In particular, Lanzante *et al.* [2003b] conclude that artificial discontinuities in radiosonde data are not large enough to alter the average global atmospheric tendencies. An implicit assumption in most analyses is that

trends determined using the global radiosonde network (predominantly over Northern Hemisphere land locations) is sufficient to infer global atmospheric temperature trends.

[4] Satellites can provide global analyses of atmospheric temperature trends. Data from the Microwave Sounding Unit (MSU), available since 1979, have been used in several temperature trend analyses [Christy *et al.*, 2003; Mears *et al.*, 2003]. Challenges to determining trends from satellite include calibration drift, temporal drift, and intercalibration among different satellites. These uncertainties, notably the manner in which NOAA-9 is calibrated, have resulted in different analyses of atmospheric temperature trends from the MSU data.

[5] While most studies have focused on the analysis of average global or hemispheric trends in atmospheric temperature, the goal of this paper is to analyze the spatial distribution of recent trends in tropospheric and sea surface temperatures. To address this issue, we use diverse data sets and examine the most prominent regional features. No attempt here is made to establish definitive magnitudes in the trends; rather we focus on the regional variations in the trends and their consistency among the data sets. We argue that the use of average global trends can be misleading both in documenting and understanding the temperature trends, since the observed trends are not spatially homogeneous, with both warming and cooling trends apparent. Further, because of regional variability in the trends, inference of global trend from the radiosonde network can be misleading owing to sampling issues.

2. Data and Methodology

[6] Data sets used in this analysis include both satellite-based, and numerical weather prediction reanalysis products for the period 1979–2001. Additional global analyses are obtained from surface and radiosonde measurements. These data sets are described briefly:

[7] • Version 5.1 of the University of Alabama in Huntsville (UAH) MSU retrieval data set [Christy *et al.*, 2003] for 2.5-degree monthly temperatures of the low-middle troposphere (TLT).

[8] • NOAA Optimum Interpolation (OI) Sea Surface Temperature (SST) [Reynolds and Smith, 1994]. This data set consists in one-degree monthly fields from 12/1981 to present.

[9] • Global sea-Ice and SST (GISST Version 2.3b) that updates GISST 2.2 described by Rayner *et al.* [1996]. GISST provides one-degree monthly SST for 1871 to February 2003. HadCRUT2 is a combined land and marine temperature anomalies on a 5-degree grid [Rayner *et al.*, 2003].

[10] • Tropospheric temperatures from two reanalyses, National Center for Environmental Prediction - National

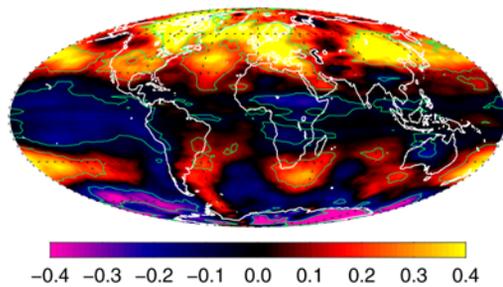


Figure 1. Spatial distribution of B ($^{\circ}\text{C}/\text{Decade}$) for MSU TLT. The green line represents the 95% statistical significance for randomness rejection based on Z . B is estimated for the period 1979–2001.

Center for Atmospheric Research (NCEP-NCAR) described in Kalnay *et al.* [1996] and European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-40 [Simmons and Gibson, 2000].

[11] • Global temperature anomalies based on 87 homogenized radiosonde stations part of the Comprehensive Aerological Reference Data Set (CARDS) [Lanzante *et al.*, 2003a; Siedel *et al.*, 2004]. The spatial distribution of 155 CARDS stations part of GUAN is also used.

[12] Reanalyses are included here as additional sources of information on regional variability in atmospheric temperature trends. While the utility of the reanalyses have not been entirely established for determining the magnitude of the temperature trends, the regional variability of the trends is considered here to supplement the MSU analysis. Trend precision issues have been addressed by Bengtsson *et al.* [2004] and Christy and Norris [2004].

[13] To compute temperature trends, monthly anomalies were generated as deviations from the mean monthly values over the data period for each data set. MSU and HadCRUT2 data are available as monthly anomalies. Global, regional and collocated trends were determined by calculating the monthly mean temperature anomalies of the region before estimating the trend.

[14] Testing for trends was conducted using the nonparametric Mann–Kendall test, and the Seasonal Kendall test, described by Hirsch *et al.* [1982]. An advantage of this test is that no assumption of a specific distribution of the anomalies is necessary. These rank-based procedures are suitable to detect monotonic trends, not necessarily linear, during some interval of time. Trends are quantified as a slope using the seasonal Kendall slope estimator B [Hirsch *et al.*, 1982], which is robust against extreme values. To

address concerns about the statistical method used to determine trends we compared B with the slope estimated by linear regression using least squares and a least absolute deviation, and found that the results were not sensitive to the statistical method used.

3. Results

[15] Figure 1 shows the spatial distribution of temperature trends in $^{\circ}\text{C}/\text{Decade}$ estimated using B for the UAH MSU TLT data. The area within the green line corresponds to a region where randomness is rejected at 95% significance level. Significance is estimated using the seasonal Kendall statistic (Z). Negative values of Z indicate the existence of negative (cooling) trends and positive Z represent positive (warming) trends.

[16] The UAH MSU data show that generalized warming of the lower-middle troposphere is not present. In fact, some regions show very consistent cooling trends, primarily over the ocean. Among these regions, the equatorial Pacific Ocean, equatorial Africa and the southern extra-tropical ocean show a statistically significant cooling trend. Other equatorial regions over South America, Atlantic Ocean and most part of Indian Ocean reveal essentially no temperature tendency. Areas with predominant warming trends are especially evident in the Northern Hemisphere above 30°N . Northeast Canada, Greenland, Europe and Northeast Asia present particularly large warming above $0.4^{\circ}\text{C}/\text{Decade}$. An oceanic belt around 35°S from 75°E to 100°W also has a positive trend.

[17] Figure 2 shows the regional variability in trends for the reanalyses in layer 850–300 mb. Distribution of temperature trends is comparable among both reanalyses and the MSU TLT data set. However, while the tropical cooling is present in both reanalysis, the structure in the extratropical Southern hemisphere is different, with ECMWF trends showing warming south of 50°S . Both reanalyses show Northern hemisphere warming, with the ECMWF distribution closer in magnitude to the MSU TLT. Since NCEP-NCAR trends are tied directly to radiosondes through a weekly retrieval update and ERA-40 trends are influenced by both satellite radiances and radiosondes, the reanalyses are essentially independent of each other, and from the UAH MSU for long-term trends.

[18] While comparison of the different satellite analyses and NWP reanalyses generally support the UAH MSU TLT analysis in terms of regional variations, some researchers regard the surface radiosonde network as the “gold standard” for atmospheric temperature data and trends. Here we examine the impact of sampling deficiencies in estimates of

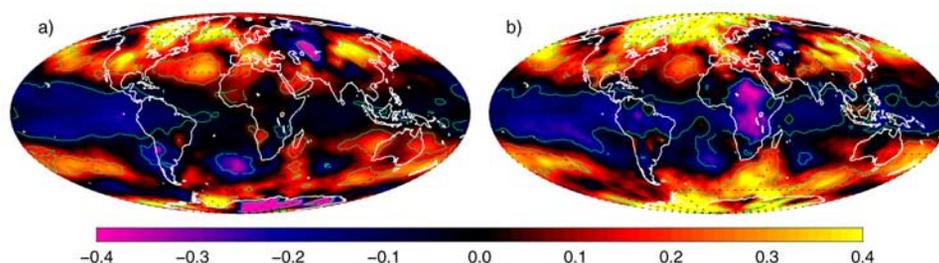


Figure 2. Same as Figure 1 for a) NCEP-NCAR and b) ECMWF (ERA-40) reanalyses in the 850–300 mb layer.

Table 1. Seasonal Kendall Slope Estimator B for Global Monthly Temperature Anomalies in the Lower Troposphere and the Collocated “Global” Anomalies 1979–2001

Data Set	87 Locations	155 Locations	Global
MSU TLT (Christy)	0.121 ^a	0.089 ^a	0.053 ^a
NCEP-NCAR (850–300)	0.049 ^a	0.035 ^a	0.043 ^a
ECMWF (850–300)	0.097 ^a	0.070 ^a	0.119
Lanzante (850–300) ^b	0.044 ^a	-	-

^aValues are significantly different from zero at the 95% confidence level.
^b1979–1997.

the global tropospheric temperature trend using radiosonde data. To address this issue, in Table 1 we collocated the MSU analysis and reanalysis grid with each of 87/155 CARDS stations. We then calculated a “global” temperature trend for the satellite and reanalysis data sets. We further compare these trends using the CARDS locations with the true global trends derived from the satellite and reanalyses. A global estimate using 87 homogenized CARDS stations from 1979–1997 is also included.

[19] In Table 1, the column “87 locations” reflects the fundamental differences among the data sets in terms of the various methods used to determine lower tropospheric temperatures. The four different trend analyses differ by a factor of 3 (about 0.08 °C/decade), with the reanalyses values intermediate to the MSU (warmest) and radiosonde (coolest). The absolute difference between those values would change if trends were estimated using latitude bands as suggested by *Angell* [1988]. Since the band selection is not standard, we calculated global collocated trends for MSU considering *Angell* [1998] and *Lanzante et al.* [2003a], obtaining 0.081 and 0.105 °C/decade respectively. While different selection of latitude bands results in different trends values, the difference between radiosonde and MSU estimates is still significant. If the “global” radiosonde trend (0.044) is compared with the true global MSU trend (0.053), this apparent agreement in the radiosonde and MSU global trends masks substantial differences in the two data sets when MSU is actually co-located with the radiosondes. Comparison of the columns “87 locations” and “155 locations” indicates a consistent 25–30% uncertainty in the trend associated with sampling of the existing radiosonde stations to infer a “global” trend. Of particular interest is the range among MSU, NCEP-NCAR, and ECMWF of the difference in trends between “87 locations” and global, ranging from a decrease of 71% for MSU, to little change for NCEP-NCAR, to an increase of 18% for ECMWF. The dominant component of the differences

between “87 locations” and global estimates is the lack of values over the ocean in the sounding data set.

[20] To further explore the differences in the trend analyses over the oceans, we examine variations SST. Several authors have pointed out not only that there is low correlation of anomalies between the surface and the tropospheric temperature in tropical oceanic regions but also that global tropical SST and atmospheric temperatures have shown different trends [e.g., *Hurrell and Trenberth*, 1996; *Christy et al.*, 2001]. Here we compare the main features observed in the SST and tropospheric temperature trends. In order to estimate SST trends for the same period as the tropospheric trends (1979–2001), we combined NOAA OI-SST with GISST in the same manner as both Reanalysis projects, using GISST from 1979 to 1981 and NOAA OI-SST onwards. Since this merge could generate artificial trends, we compared the trends without the 3-GISST years and the differences are not significant. Surface temperature trends are also estimated using HadCRUT2.

[21] Figure 3 shows the global distribution of B (°C/Decade) for the combined SST. As in the case of tropospheric temperatures, it is apparent from Figure 3 that there is no generalized warming trend in the SST. Similar results were obtained using HadCRUT2. The regional variability of the SST trends shows qualitatively many of the same features shown in the MSU atmospheric trends. Here we compare quantitatively the trends in SST with the trends in atmospheric temperature trends for specific regions.

[22] For the tropical oceans, *Christy et al.* [2001] found a negative tendency for the tropospheric temperatures (MSU TLT) and a positive one for the SST’s. Table 2 compares the trends in SST and the lower troposphere for the global tropics (between 10°N and 10°S) and for the tropical eastern versus western Pacific Ocean and Indian Ocean. Although for the whole tropics the estimated SST trends are positive, there is a zonal gradient in the SST trends (Figure 3). This is manifested by an overall surface cooling in the eastern tropical Pacific and warming in the western tropical Pacific and Indian Ocean. The atmospheric cooling trend is consistent with the cooling trend in SST over the Eastern Pacific, but opposite in sign over the Western Pacific Ocean and Indian Ocean. We note that the atmospheric temperature trends over the Western Pacific Ocean and Indian Ocean from MSU and NCEP-NCAR are substantially smaller than the cooling trend in ECMWF, and are not statistically different from zero.

[23] Table 3 compares the SST and the tropospheric trends for five different regions in the global ocean. In the tropical eastern Pacific, a cooling tendency is seen for both the surface and the atmospheric temperatures. A high correlation

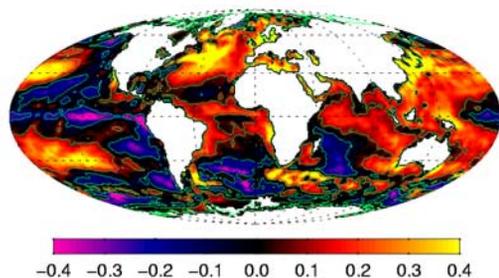


Figure 3. Same as Figure 1 for extended NOAA OI-SST using GISST.

Table 2. Seasonal Kendall Slope Estimator B for the Tropics (10°S–10°N, 0–360) and Two Non-Overlapping Tropical Regions (Tropics 1: 10°S–10°N, 170–280 and Tropics 2: 10°S–10°N, 290–160) From 1979 to 2001

Data Set	Tropics	Tropics 1	Tropics 2
MSU TLT (Christy)	-0.068 ^a	-0.118 ^a	-0.047
NCEP-NCAR (850–300)	-0.080 ^a	-0.145 ^a	-0.033
ECMWF (850–300)	-0.155 ^a	-0.166 ^a	-0.137 ^a
SST	0.037 ^a	-0.114 ^a	0.134 ^a
HadCRUT	0.100 ^a	-0.045	0.185 ^a

^aValues are significantly different than zero at the 95% confidence level.

Table 3. Seasonal Kendall Slope Estimator B for the Period 1979–2001 for Region A: 15°S–15°N, 200–270; Region B: 10°S–10°N, 50–110; Region C: 45°N–60°N, 190–220; Region D: 65°S–35°S, 320–10; and Region E: 30°N–°50°N, 300–340

Data Set	A	B	C	D	E
MSU TLT (Christy)	−0.144 ^a	−0.047	0.046	−0.073	0.272 ^a
NCEP-NCAR (850–300)	−0.173 ^a	−0.031	0.030	−0.038	0.185 ^a
ECMWF (850–300)	−0.183 ^a	−0.091 ^a	0.052	0.159 ^a	0.174 ^a
SST	−0.078 ^a	0.126 ^a	−0.115 ^a	−0.111 ^a	0.371 ^a
HadCRUT2	−0.034	0.157 ^a	−0.045	−0.218 ^a	0.398 ^a

^aValues are significantly different from zero at the 95% confidence level.

of the surface and atmospheric temperature anomalies in this region was noted by Hurrell and Trenberth [1996]. Over the equatorial Indian Ocean (Region B) trends in SST are positive, differing in sign from the negative tropospheric temperature trends. A region including the Gulf of Alaska (Region C) shows the atmosphere with slightly positive trends and a strong cooling trend over the ocean. Region D, in the Southern Ocean, shows cooling in the SST, MSU and NCEP-NCAR, while ECMWF shows strong warming. This non-conclusive evidence could be related to the fact that quality of SST records in the Southern Ocean is questionable. Over the north Atlantic (Region E) both atmospheric and oceanic trends are significantly positive.

[24] Such troposphere-ocean surface differences might be explained if thermal trends are considered together with regional dynamical/thermodynamical features and possible trends in the circulation, particularly in the Indian Ocean and the western tropical Pacific. The fact that NCEP-NCAR and ERA-40 reanalyses, that use the same SST data sets used in Figure 3, are able to capture differing trends between the ocean and the atmosphere implies that models used for reanalysis are simulating the necessary dynamics/thermodynamics that could lead to a tropospheric cooling in contrast to a surface warming.

4. Conclusions

[25] This paper has focused on regional variability in tropospheric temperature trends during the period 1979–2001. The UAH MSU analysis and the NCAR/NCEP and ECMWF reanalyses show qualitatively similar regional distributions in tropospheric temperature trends, although the magnitudes differ among the data sets. All three analyses show substantial regional variability in temperature trends, with the magnitude of the variability (including substantial regions with cooling trends) far exceeding the average global warming trend. Given this large variability, inferences using the global average value can be misleading for a variety of applications.

[26] Collocation of the MSU and reanalysis data sets with the location of the CARDS radiosonde data set showed a factor of 3 (about 0.08 °C/decade) variability in the different estimates of tropospheric temperature trends. From the regional variability shown by the MSU and reanalyses, we infer that the subsampled 87 locations results in an overestimate by 25–30% of the temperature trend relative to the complete data set with 155 locations. This inference is still valid if latitudinal banding is used. While the latitudinal weighting might account for the problems due to the non-homogeneous latitudinal distribution of the stations over land, it does not resolve the lack of observations over the

ocean, ignoring the ocean/land zonal gradients in temperature trends. A fortuitous (and potentially misleading) agreement between the “global” estimate using the homogenized radiosonde data set (87 locations) with the global MSU value masks a factor of 3 difference in the collocated temperature trends.

[27] Recent observations of SST and tropospheric temperature showing opposite trends are clarified regionally, including documentation of a strong gradient in SST trends in the tropical Pacific Ocean, with surface cooling in the east and warming in the west. Analysis of the reanalysis products lends credibility to the differences in signs of trends between the sea surface and tropospheric temperature trends whereby it appears that models used for reanalysis are simulating the necessary dynamics/thermodynamics that could lead to a tropospheric cooling in the presence of a surface warming (and vice versa).

[28] While improved estimates of magnitudes of global atmospheric warming trends awaits improved analysis of the satellite data sets, we have demonstrated that the regional variability of the trends observed by satellite is qualitatively consistent with the reanalyses. While the utility of the reanalysis products has not been established for documenting global tropospheric temperature trends, this study has demonstrated their utility in documenting and clarify regional variability in temperature trends. Such regional analysis is necessary to understand the differences among different data sets, which is important for improved estimates of global trends as well as regional trends, the latter which may eventually be more useful for applications and policy making.

[29] **Acknowledgments.** NCEP Reanalysis data and NOAA Optimum Interpolation (OI) SST V2 data provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA (www.cdc.noaa.gov). UAH MSU data set was obtained from www.ghcc.msfc.nasa.gov, ECMWF ERA-40 data from the ECMWF data server at data.ecmwf.int/data/, and HadCRUT2 data from www.cru.uea.ac.uk/cru/data/temperature/. Thanks to C. Hoyos, D. Seidel, W. Rossow, and J. Bates for informative discussions.

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