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1973–1996 Trends in depth-averaged tropospheric temperature

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Abstract. The analysis of thickness derived from the National Center for Environmental Prediction (NCEP) reanalysis indicates that there has been no statistically significant warming trend in layer-averaged global tropospheric temperatures during the period 1979–1996. While this result is at variance with data based on surface information, NCEP trends and interannual variations are closely related to tropospheric mean-layer temperatures obtained from the satellite-based microwave sounding unit (MSU) lower-tropospheric data set. When a longer period, 1973–1996, is used for the NCEP analysis, a warming trend within a 95% confidence interval is derived. However, it is nearly half the magnitude of the surface-derived trends. Strong correlations of the yearly global surface temperature anomalies and those calculated for several layers in the NCEP data indicate coincident interannual temperature variations throughout the depth of the troposphere. The disagreement of both our analysis and satellite-derived estimates with surface data could be due to a land surface measurement bias, a result of land use changes such as deforestation and agricultural expansion whose effects are not yet accounted for in the global temperature records, and/or a decoupling between surface and lower-tropospheric temperature over the last several years.

1. Introduction

There has been considerable interest in global climate in response to the possible influence on climate due to anthropogenically-caused increases in carbon dioxide, methane, and other radiatively active gases [*Intergovernmental Panel on Climate Change (IPCC)*, 1990, 1992, 1996]. One component of these global change studies is the search for evidence of changing climate, which has been hypothesized on the basis of results obtained from general circulation model (GCM) simulations. Temperature trends have been examined using surface, radiosonde, and satellite data, sometimes with contradictory results.

Surface temperatures have been interpolated globally and it has been concluded that a warming trend is occurring [*Jones*, 1995]. Selected radiosonde data have also found warming trends within the troposphere; however, this evidence is more ambiguous. *Angell* [1988], for example, presented data for the 1000–100 mbar layer from 63 radiosonde sites that were extrapolated globally. The inclusion in his analysis of levels up to 100 mbar, however, means that stratospheric data were included for at least the higher latitudes. *Angell* [1994] evaluated more recent data as well as other layers. *Reitenbakh et al.* [1997] present a radiosonde network analysis of 850–300 mbar and 100–50 mbar temperature anomalies for the period 1991 to April 1996. *Oort and Liu* [1993] used over 800 radiosonde sites to obtain monthly mean values on a 2.5° latitude by 5° longitude global grid. Their procedure used temperatures at standard pressure levels (850, 700, 500 mbar, etc.) to obtain estimates of mean layer temperature, rather than deriving mean layer temperatures from the vertical distance between pressure levels. Both *Angell* [1994] and *Oort and Liu* [1993] concluded there was a warming trend at both the surface and in the troposphere according to the data they used.

Satellite measures of tropospheric temperatures [*Christy*, 1995; *Spencer and Christy*, 1994], however, show no clear evidence of a statistically significant trend since 1979. *Hansen et al.* [1995], *Hurrell and Trenberth* [1996], and *Christy et al.* [1998] discussed the relation between satellite and surface temperature data, pointing out the physical differences and therefore possible reasons for the divergence in trends in the two data sets.

In this paper we use the National Center for Environmental Prediction (NCEP) reanalysis and satellite-based microwave sounding unit (MSU) data to evaluate tropospheric layer-averaged temperature (thickness) trends for selected layers. (*Christy et al.* [1998] discuss the MSU products. In this paper we use their lower-tropospheric analysis referred to as MSU 2R [*Christy et al.*, 1995] and will refer to this as "the MSU" data.) The MSU data are available over the time period 1979–1995; the NCEP reanalysis data are available from 1973 to 1994 [*Shea et al.*, 1994], with recent additions for 1995–1996. Thickness data have been used by other investigators and have been a valuable assessment tool in the evaluation of trends. *Wallace et al.* [1996], for example, showed that hemispheric-mean surface air temperature anomalies based on land station data were related to 1000–500 mbar thickness using monthly mean data for the period November 1946 to April 1993.

2. Procedure

2.1. Data Sets

We analyzed layer thickness and depth-averaged temperatures derived from the NCEP reanalysis [*Kalnay et al.*, 1996]. Trends and anomalies in these records were compared with MSU-derived tropospheric temperature data [*Christy*, 1995; *Christy et al.*, 1995] and surface temperature data.

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Global surface data are taken from a blended annual anomaly data set obtained from the Goddard Institute for Space Studies (GISS) website which combines surface temperature (see *Hansen and Lebedeff* [1987] for a discussion of these data) with sea surface temperature (SST) data (*Smith et al.* [1996] before 1982, an updated version of the *Reynolds and Smith* [1994] data set thereafter). This data set is subsequently referred to as the GISS data. GISS surface temperature anomalies are provided with respect to the 1951–1980 base period.

In one case where SST data are examined by itself, the data are taken only from *Smith et al.* [1996] (data are not available for 1996). The base climatology for the SST anomalies is 1950–1979.

We analyzed the NCEP data for two periods (1973–1996 and 1979–1996). The NCEP reanalysis used a consistent processing technique for all years. However, TIROS Operational Vertical Sounder (TOVS) data were not added until November 1979. The data set before then indicates relatively large cool anomalies, which is why we analyzed the data in two time slices. Analyses by *Basist and Chelliah* [1997] and *Hurrell and Trenberth* [1998] discuss other issues with respect to this data set, including an apparent step change in mid-1991. For a complete description of the NCEP data, see *Kalnay et al.* [1996].

For comparison, we used the MSU 2R data which measure the lower-tropospheric temperature with a maximum vertical weighting around 700 mbar for 1979–1995 [*Christy et al.*, 1995, 1998]. Possible discrepancies within the MSU data set have been discussed by *Hurrell and Trenberth* [1996, 1997, 1998] and *Christy et al.* [1998]. The primary concern is associated with the intersatellite calibration, although possible emissivity bias and noise are also addressed, particularly over areas of high terrain.

2.2. Calculation of NCEP Thickness and MSU Temperature Anomalies

We evaluated several atmospheric layers from the NCEP data set for possible trends in the monthly and annual thickness anomalies. The NCEP set has data every 6 hours: using these data, we determined the anomalies for each 2.5° zonal band. For global and hemispheric averages, each latitude band was areally weighted. Trends in the anomalies and corresponding confidence levels were produced using linear regression analysis. The same spatial and temporal averaging procedures were also applied to the MSU data to obtain the satellite-retrieved lower tropospheric temperature anomalies.

The height difference (depth) between two pressure surfaces is referred to as the "thickness" Δz of the corresponding layer. Thickness is related to the mean temperature of the layer $\bar{T}$ by

$$\Delta z = \frac{R}{g} \ln \frac{P_1}{P_2} \bar{T}, \tag{1}$$

where R is the gas constant of dry air, g is the gravitational acceleration, and P_1 and P_2 are the two pressure surfaces. The NCEP reanalysis utilizes temperature $\bar{T}$ rather than virtual temperature to compute pressure height surfaces. Henceforth, in this paper, we will interpret Δz to be with respect to $\bar{T}$. If moisture effects were included, and if there was an increase in layer-averaged water vapor over the period of record, our estimate of $\bar{T}$ would be too warm. A change in Δz over some time period $\delta(\Delta z)$ is related to a change in mean layer temperature $\delta\bar{T}$ by

$$\delta(\Delta z) = \frac{R}{g} \ln \frac{P_1}{P_2} \delta\bar{T}. \tag{2}$$

We used the annual and daily thickness anomalies to back out temperature perturbations corresponding to the thickness changes.

For the 1000–500 mbar layer Δz, a 1°C change in $\bar{T}$ corresponds to about a 20 m thickness change. For the 1000–700 mbar and 1000–850 mbar Δz values, a 1°C change yields ~10.5 m and 5 m changes, respectively. As an example of the application of this technique, *Michaels et al.* [1990] used thickness to investigate 1000–500 mbar mean annual temperatures over the continental United States, southern Canada, and adjacent oceans.

The precision of calculating a mean layer temperature from height data from an individual sounding is discussed by *Elliott et al.* [1994]. They report root-mean-square (rms) errors of 0.31°C for the 1000–850 mbar layer (for random errors) and 0.21°C if the errors in heights were correlated (i.e., of the same sign). The other layers used in our study were not presented by *Elliott et al.* [1994] but should have about the same accuracy. Averaging many layers should reduce the error if the errors are random between soundings. In assessing the internal and external differences of the NCEP reanalysis, *Kalnay et al.* [1996] indicated rms errors of 0.32°C (1.6°C) and 0.64°C (1.28°C) for the 1000–200 mbar layer of the northern (southern) hemisphere, respectively. They also point out that upper air mass and temperature fields are well defined by the observations and are further improved by processing techniques employed in the reanalysis than would be obtained from observations alone.

3. Results

3.1. Thickness-Derived Temperature Time Series

Figures 1a–1e show yearly global temperature anomalies for the NCEP 1000–850, 1000–700, 1000–500, 1000–300, and 1000–200 mbar layers, respectively. The MSU lower tropospheric temperature anomalies are also plotted in Figures 1a–1c. Although absolute magnitudes of the anomalies are not large, there are significant year-to-year changes in all records. The two records are highly correlated in the years for which both data sources are available (Figure 4b).

The NCEP anomalies have the largest magnitude of variability when the thickness layer includes the tropopause (Figure 1e). The strong cooling in 1991 in both the NCEP and the MSU records corresponds to the Mount Pinatubo eruptions.

3.2. Thickness-Derived Temperature Trends

Tables 1a–1c show the results of the linear regression analysis for the globe and for the northern and southern hemispheres, respectively. Globally, all layers show a statistically nonsignificant cooling over the period starting in 1979. Comparable trends from the MSU data for the same periods are also negative or near zero and statistically not significant (Tables 1a–1c). The cooling tendency in the NCEP record probably arises from a cold bias after 1991, as discussed by *Basist and Chelliah* [1997], which they suggest is due to changes in satellite retrievals, a reduction of data from the former Soviet Union, from Mount Pinatubo, and/or drift in the NOAA-11 sensor.

In contrast, when the NCEP reanalysis data, analyzed over the period 1973–1996, are used, there is a significant global warming trend for all levels at the 0.95 confidence level (Table 1a). The southern hemisphere shows a nearly constant warming signal at all layers below 200 mbar of ~0.08°C decade^{-1}

(Table 1c). The strongest warming trend of 0.1°C decade^{-1} is found in the northern hemisphere 1000–200 mbar layer (Table 1b). This overall trend arises primarily from cold anomalies in the mid-1970s and which apparently were eliminated with the introduction of satellite (TOVS) soundings in 1979. Therefore it appears that the pre-1979 nonsatellite sounding atmospheric profiles have a cold bias relative to the later profiles which utilized satellite soundings (Figure 1). This suggests that this spurious jump in the reanalysis climate statistics may be caused by the incorporation of these data. Alternatively, the change in the late 1970s may reflect changes in atmospheric circulation. *Hurrell* [1996] associated warming in surface temperature in the northern hemisphere since the mid-1970s with changes in

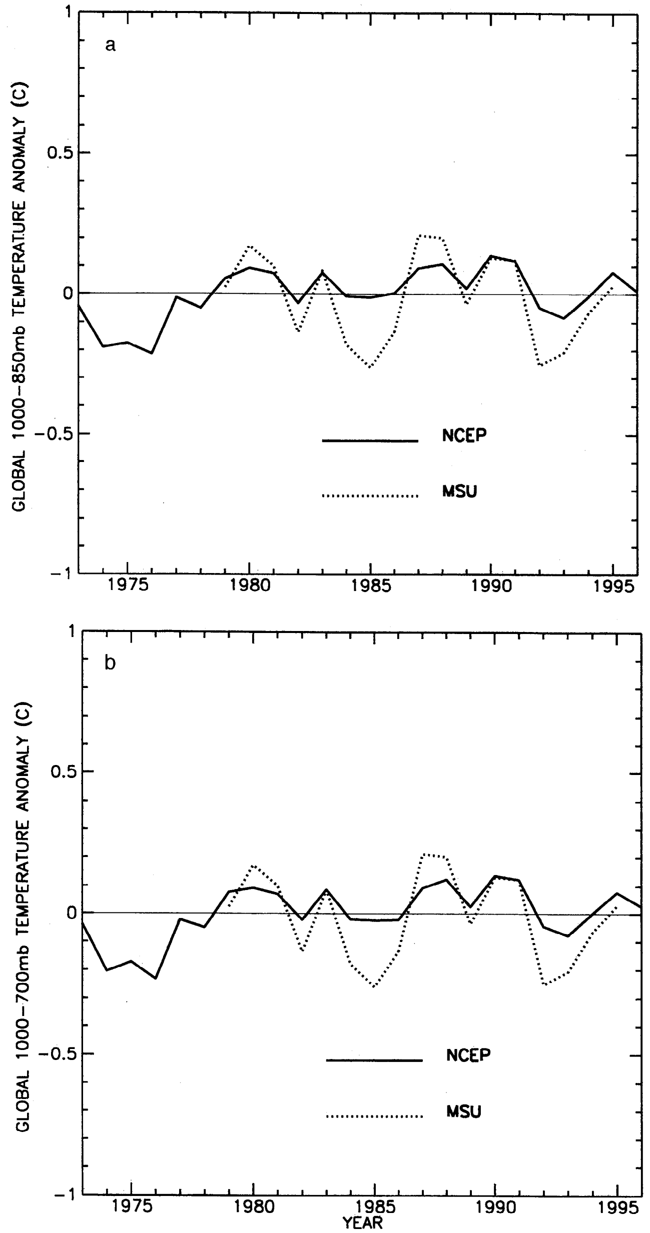

Figure 1. National Center for Environmental Prediction (NCEP) (1973–1996) global layer temperature anomaly (°C) time series for (a) 1000–850, (b) 1000–700, (c) 1000–500, (d) 1000–300, and (e) 1000–200 mbar. Also plotted are microwave sounding unit (MSU) lower-tropospheric temperature anomalies (1979–1995) for the lower-tropospheric layers, where it is defined.

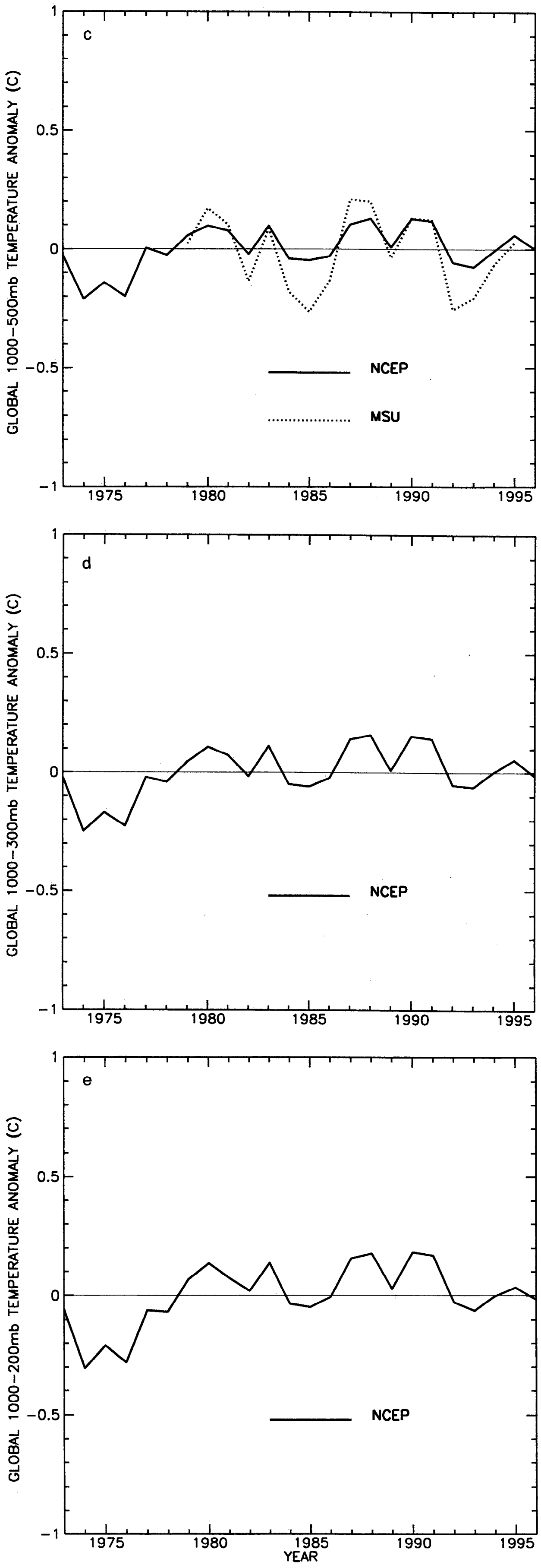

Figure 1. (continued)

Table 1a. Global Trends in Tropospheric Temperatures From NCEP

Layer, mbar	NCEP Reanalysis 1973–1996 Trend °C/yr	NCEP Reanalysis 1979–1996 Trend °C/yr
1000–850	0.0064[a]	−0.0021
1000–700	0.0069[a]	−0.0019
1000–500	0.0054[a]	−0.0025
1000–300	0.0068[a]	−0.0022
1000–200	0.0089[a]	−0.0038
MSU[b]	N/A	−0.0054

[a] Indicates the trend meets the 95% confidence interval.

[b] The MSU trends are for 1979–1995 and are presented here for comparison.

the Southern Oscillation, the North Atlantic Oscillation, and circulation over the North Pacific.

In addition to the yearly calculated trends, we examined monthly trends for 1973–1996 and 1979–1996 in the NCEP reanalysis data. The monthly trends for the 1000–200 mbar layer for each hemisphere and the globe for those two periods are shown in Figures 2a and 2b. There is a seasonal dependence in the trends that is relatively large in the northern hemisphere compared to the southern hemisphere during both time periods. During 1973–1996 the trends are positive throughout the year, while for 1979–1996, only the summer in the northern hemisphere has a warming trend. The magnitude of the trends peak in summer in the respective hemispheres. The larger magnitude of northern hemisphere anomalies is likely due to the larger areal extent of the land surface in the northern hemisphere. Seasonal dependence in global trend tends to be dominated by the northern hemisphere signal as a result of its larger magnitude.

3.3. Comparison With Surface Temperature Trends

Figure 3a presents the GISS surface temperature changes for the period 1973–1996, which was discussed in section 2.1 of our paper. Also shown for 1973–1996 are the layer mean temperature changes from the NCEP reanalysis for the 1000–850 mbar layer. The GISS data have a trend of 0.0148°C per year, while the NCEP trend is 0.0064°C per year.

The larger surface temperature trend relative to the 1000–850 mbar NCEP thickness data is consistent with the conclusions of *Hurrell and Trenberth* [1996] which suggested that a tropospheric to surface disparity arose because surface temperature variability is dominated by processes controlling surface fluxes and heat storage, while tropospheric depth-averaged temperatures (specifically in their case, MSU

Table 1b. As in Table 1a Except for Northern Hemisphere

Layer, mbar	NCEP Reanalysis 1973–1996 Trend °C/yr	NCEP Reanalysis 1979–1996 Trend °C/yr
1000–850	0.0045	−0.0056
1000–700	0.0056[a]	−0.0042
1000–500	0.0039[a]	−0.0040
1000–300	0.0059[a]	−0.0029
1000–200	0.0101[a]	−0.0037
MSU[b]	N/A	0.0003

Table 1c. As in Table 1a Except for Southern Hemisphere

Layer, mbar	NCEP Reanalysis 1973–1996 Trend °C/yr	NCEP Reanalysis 1979–1996 Trend °C/yr
1000–850	0.0084[a]	0.0013
1000–700	0.0082[a]	0.0005
1000–500	0.0070[a]	−0.0010
1000–300	0.0077[a]	−0.0016
1000–200	0.0077[a]	−0.0038
MSU[b]	N/A	−0.0057

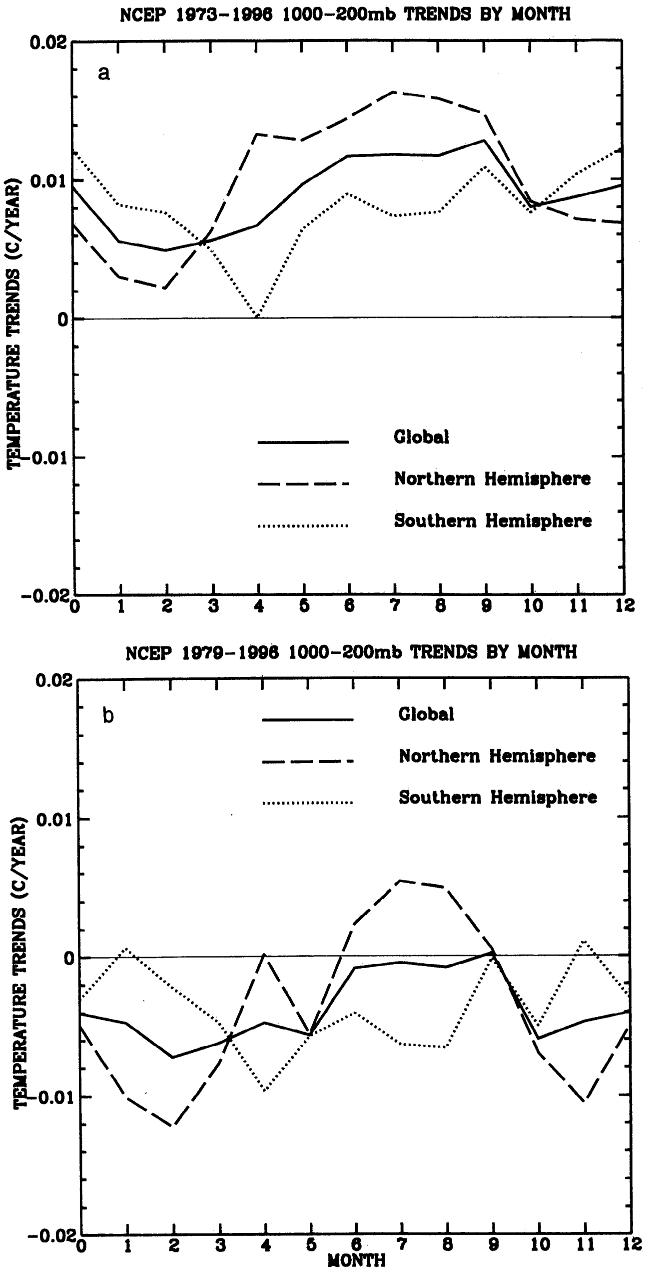

Figure 2. Global and northern and southern hemispheres monthly 1000–200 mbar layer temperature trends (°C yr^{-1}) calculated from the NCEP reanalysis for (a) 1973–1996, and (b) 1979–1996. Months are plotted along the x axis (0 = December, 1 = January, . . . , 12 = December).

temperatures) are primarily forced by advection. They inferred that the surface record is dominated by warming over land because of differences between land and ocean heat capacities. They also attributed the disparity to changes in circulation patterns, at least over the northern hemisphere, which enhanced land surface warming relative to sea surface temperatures and which further contributed to the global positive trend at the surface versus in the tropospheric (MSU) record [*Hurrell and Trenberth*, 1997; *Hurrell*, 1996; *Wallace et al.*, 1996].

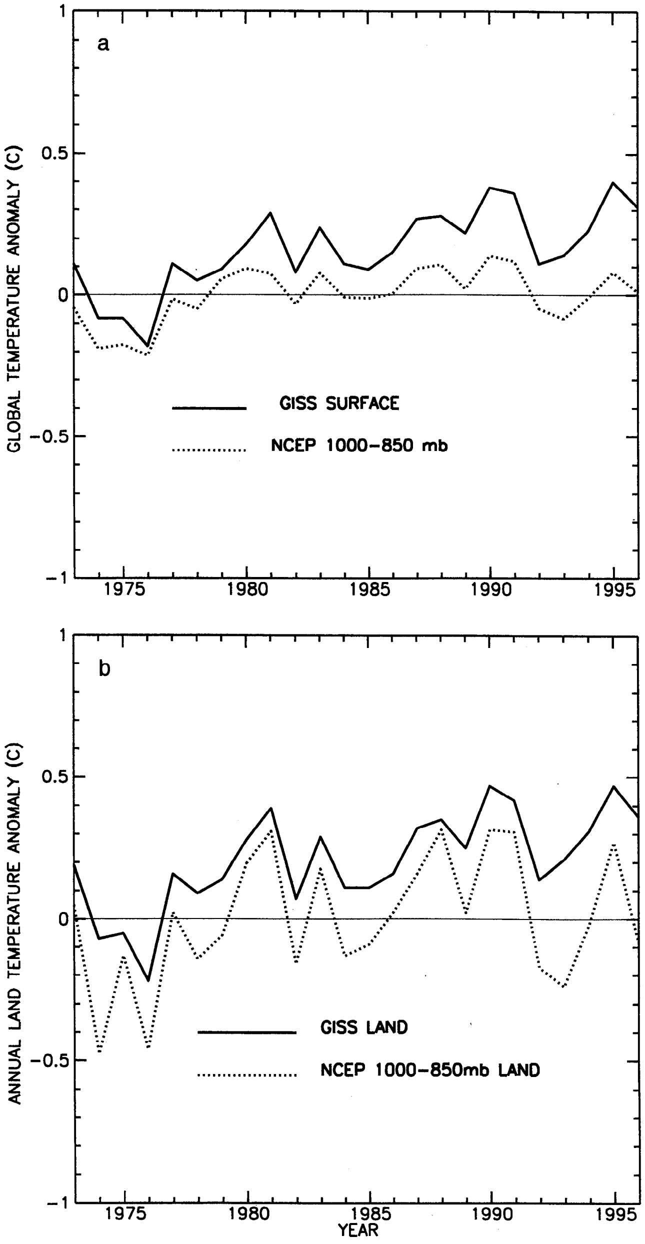

Figure 3. (a) Global surface and NCEP 1000–850 mbar layer-mean temperature for the period 1973–1996. The global surface temperatures were obtained as discussed in section 2.1 of this paper; (b) land surface temperature anomalies and NCEP 1000–850 mbar layer temperature anomalies over land for 1973–1996; and (c) surface temperature anomalies for northern and southern hemisphere land and ocean areas (SST data through 1995 only). Note that although the base from which the anomalies are computed are obtained differently for the two data sets, this does not affect the trend analysis.

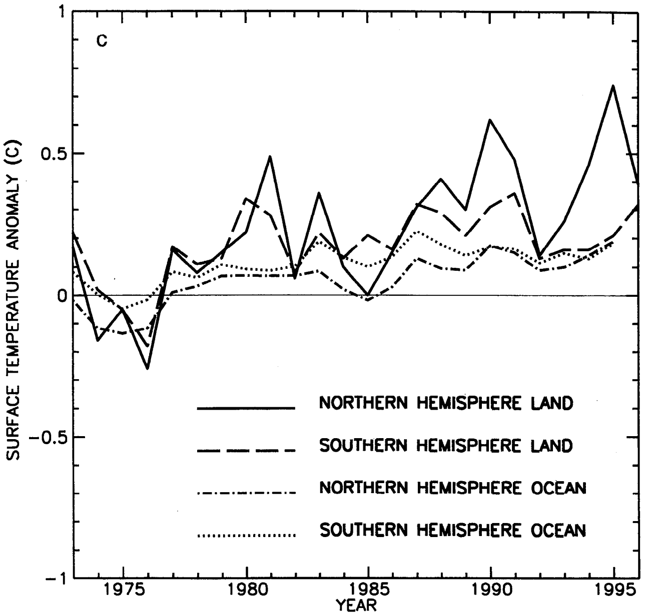

Figure 3. (continued)

The land-only yearly anomalies of the GISS and NCEP 1000–850 mbar data are shown in Figures 3b and 3c. The global and northern and southern hemisphere NCEP land-only trends are 0.016°, 0.023°, and 0.009° year^{-1}, respectively, for the period 1973–1996. Notice that large positive anomalies are readily apparent in the northern hemisphere surface record in the last 10 years of the record (Figure 3c). These trends are statistically significant ($p < 0.05$) and are nearly 1.5–4 times larger than the shallow layer (1000–850 mbar) tropospheric trends calculated from the NCEP record over the same period for the globe (Table 1a). The surface trend is larger for the northern hemisphere land than for the southern hemisphere land, while the NCEP 1000–850 mbar trend is smaller due to the cool anomaly in the early 1990s (Figure 3a). The GISS and 1000–850 mbar NCEP data are displayed in Figure 3b. The primary difference between the records is in the trend, although the interannual variations in time match quite well.

Figure 3c illustrates that since the late 1970s, the trend in the global surface temperature record is dominated by the northern hemisphere land data, with only a weak upward trend in northern hemisphere ocean and little trend in the southern hemisphere.

3.4. Correlations

Given the similarities in trends calculated from the different data sets, correlation coefficients were calculated for the various levels for global and hemispheric yearly anomalies. Where it was appropriate, the period 1973–1996 was used (NCEP and GISS), while a shorter period (1979–1995) was used in comparing with MSU data.

Figure 4a shows the high correlations of the NCEP and MSU data sets with the surface temperature record for the various levels indicated. Figure 4b displays the temporal correlations of the MSU data set with the NCEP data set. Both sets of data have large correlations with the NCEP analysis.

4. Conclusions

From the NCEP data, there is no evidence of significant trends in large-scale lower-tropospheric-averaged tempera-

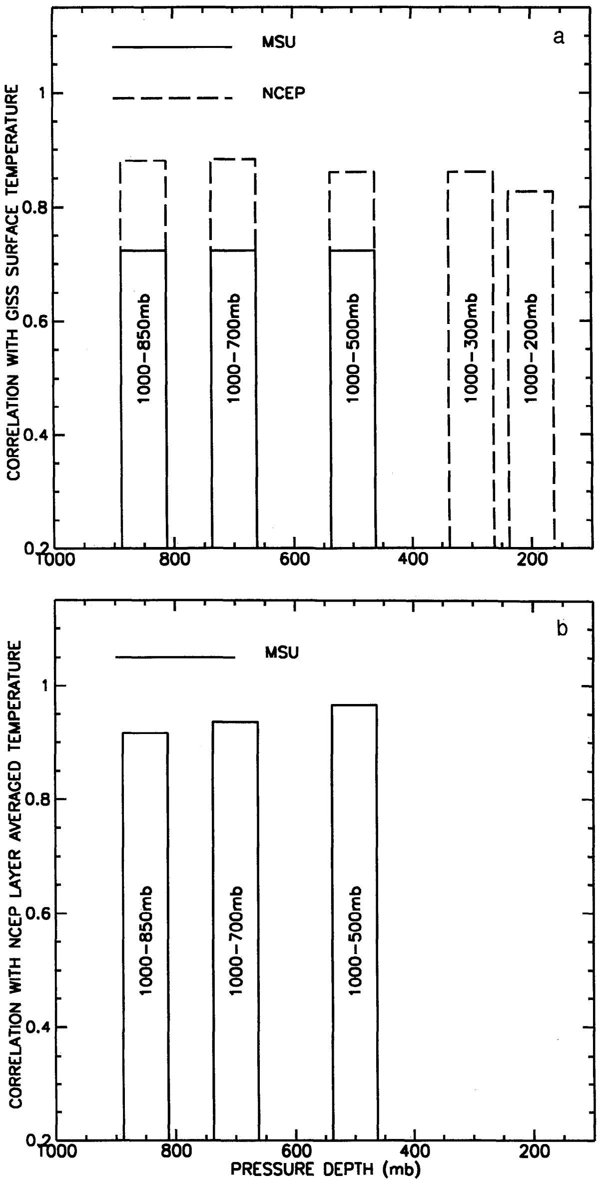

Figure 4. (a) Pearson's correlation coefficients for NCEP and MSU between 1000 mbar and the indicated level with the surface record. (b) Pearson's correlation coefficients between NCEP and lower-troposphere MSU data between 1000 mbar and the level indicated; MSU comparison with the two deeper layers have been omitted. (The MSU data correspond to only one averaged lower-tropospheric layer; see *Christy et al.* [1998, Figure 1] for the weighting function.)

tures since 1979; the slight cooling relative to the MSU data evident after 1991 is probably due to the cold bias discussed by *Basist and Chelliah* [1997]. This result is consistent with the satellite-derived MSU lower-tropospheric temperature record trends [*Christy*, 1995], the analysis of European Center for Medium-Range Weather Forecasts (ECMWF) temperature trends [*Wiin-Nielsen*, 1997], and the *Michaels et al.* [1990] analysis of reconstructed North American thicknesses since 1900. Our NCEP results differ from the study of *Weber* [1995] who found evidence of some warming in the 1000–300 mbar layer over the northern hemisphere over the same period. In contrast, the 1979–1995 NCEP and MSU trends are cool relative to the warming trend observed in the surface temperature data; this difference is greatest over the northern hemisphere.

The differences between the various data records and the NCEP data set, including the role of an NCEP cold bias since 1991 [*Basist and Chelliah*, 1997], however, remains to be clarified. *Hurrell and Trenberth* [1996] and *Christy et al.* [1998] debate this issue in the literature.

With respect to future analyses of thickness, improved estimation of pressure surface heights could be obtained directly if accurate global positioning (i.e., GPS) is used on radiosonde instruments. This would provide a direct measure of layer-mean virtual temperature (i.e., by including the moisture effect on the density of air in the layer). If the radiosonde measurements and/or other observational platforms could be used to extract the moisture contribution to the virtual temperature, it would provide a more precise measure of the layer-integrated mean temperature.

5. Discussion

One suggested explanation for the disagreement between tropospheric analyses and surface analyses such as *Jones* [1995] is that the surface record (1) is biased by the land record and (2) has been subjected to the effects of land use change. In the first case, a similar suggestion was proposed by *Christy* [1995] who stated that "the disproportionate representation of extratropical continents with their high-temperature variance, may bias any long-term 'global' surface trend towards a maximum possible value than would be calculated had all regions (including those with much lower responsiveness) been monitored." This bias in the surface record, which arises from oversampling of northern hemisphere land areas, is also supported by analyses of *Karl et al.* [1994] and *Hurrell and Trenberth* [1992]. *Hurrell and Trenberth* [1996] also suggested that satellite and surface-derived global temperature records differ because of (1) differential heating responses of the land, oceans, and troposphere, (2) recent circulation changes that have further enhanced this pattern, and (3) because of different land versus ocean sampling aspects of these two records. Independently, *Wallace et al.* [1996] found that much of the trends in northern hemisphere winter 1000–500 mbar thickness can be explained by a stronger cold ocean and warm land pattern present in the late 1970s through early 1990s.

Gallo et al. [1996] also show that the warming in the surface temperature record is predominantly associated with increases in the minimum temperatures over land. Because such an increase would be confined to a shallow nocturnal boundary layer, its effect would not be seen in either the NCEP or the MSU data. Since this effect occurs over land, it also suggests that landscape changes that have occurred over time could have contributed to changes in minimum temperature.

Specific evidence that the land temperature record has been influenced by changing landcover over time is demonstrated in modeling experiments by *Chase et al.* [1996] and *Bonan et al.* [1992] on the global scale, by *Copeland et al.* [1996] for the conterminous United States, and from observations on a regional scale [*Nasrallah and Balling*, 1995; *O'Brien*, 1995; *Lewis*, 1998; *Majorowicz and Skinner*, 1997]. These studies indicate that land use modifications can significantly influence surface temperatures both regionally and through climatic teleconnections. While attempts have been made to remove an urban bias from the global temperature record [i.e., *Karl et al.*, 1988; *Epperson et al.*, 1995; *Johnson et al.*, 1994], the much larger area that has undergone change due to deforestation, agriculture, grazing, etc., has not yet been accounted for in the land surface temperature record.

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