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A COMPARISON OF REGIONAL TRENDS IN 1979–1997 DEPTH-AVERAGED TROPOSPHERIC TEMPERATURES

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ABSTRACT

This study examines regional temperature trends during the period 1979–1997 from the Microwave Sounding Unit (MSU) 2r satellite measurements and compares them with the same trends in depth-averaged tropospheric temperatures derived from the National Center for Environmental Prediction (NCEP) reanalysis, in an attempt to determine whether regional trends exist which are larger than known inhomogeneities in the data. Large, statistically significant regional trends were found in both the NCEP and the MSU data that are of both signs and have larger magnitude than documented biases in the data. The datasets have overall agreement on the location and strength of these significant regional trends at mid and high latitudes but agreement decreases in the tropics.

A global annual average of the significant regional trends with larger amplitudes than reported data biases and areally weighted over the globe yields −0.02°C over the 19-year period of the record in the MSU 2r Version C dataset, and −0.05°C/19 years in the NCEP data in the 1000–500 mb layer. Increasing the bias threshold by as much as five times still results in an average cooling in both datasets.

Subjecting the surface temperature record to the same regional analysis yields a regionally significant trend of 0.17°C/19 years, approximately halving the trend obtained when all regions, regardless of significance, are considered. In addition, many regions with significant warming trends in the surface network occur in areas with limited observations over oceans and are not confirmed by the other datasets. Discrepancies between significant regional trends in the surface record and the upper-air observations are not systematic. In no case are regionally significant, tropical, warming trends at the surface magnified at higher levels in the MSU and NCEP tropospheric data. In the case of the NCEP reanalysis, both warming and cooling trends on average become larger, more significant, and cover larger areas in shallower tropospheric layers.

These results suggest that the disparity between global trends in satellite/rawinsonde/reanalysis datasets and those of the surface record are not simply the result of large-scale changes in the vertical structure of the atmosphere or to large-scale biases in the satellite observations, but instead are linked to processes which are regional in nature.

KEY WORDS: temperature trends; regional climate; tropospheric temperature

1. INTRODUCTION

Significant controversy exists over the accuracy of all long-term global temperature datasets. The surface network as a whole is hampered by inadequate spatial sampling and missing data, as well as by discontinuities which affect each station differently including changes in sensor type, sensor interpretation, positioning, microclimate, local land use change and the possibility that a particular station is unrepresentative of the broad region around it (e.g. Karl and Jones, 1989; Balling, 1991). These effects have not been fully quantified (Jones, 1995; Karl *et al.*, 1995). The rawinsonde network shares many of the uncertainties

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of the surface network, with documented problems owing to inadequate spatial sampling as well as to spurious trends because of systematic equipment changes (e.g. Jenne and McKee, 1985; World Meteorological Organization, 1986; Gaffen *et al.*, 1991; Gaffen, 1994; Parker *et al.*, 1997).

The two primary datasets used in this study—the Microwave Sounding Unit (MSU) 2r Version C satellite data (Spencer and Christy, 1990) and the National Center for Environmental Prediction (NCEP) reanalysis (Kalnay *et al.*, 1996)—are attractive to those concerned with regional climate changes because of their relatively consistent global coverage and the relative uniformity of methodology and sensors, which facilitates documentation of biases. However, spurious trends have been identified in both the MSU data and the NCEP reanalysis (Stendel *et al.*, 1998; Hurrell and Trenberth, 1998; Santer *et al.*, 1999) to the extent that some (e.g. Conference Summary, 1998; Hurrell and Trenberth, 1998) have argued that both datasets are unsuitable for trend analysis.

This paper examines the regional trends in depth-averaged tropospheric temperatures as represented in the NCEP reanalysis data and in the MSU data for the period 1979–1997. This period is interesting not only because of the availability of relatively independent data sources, but also because it has been suggested by some observational and modelling studies that the hypothesized lower tropospheric warming owing to increasing greenhouse gas concentrations should become most evident at about this time (e.g. Yu-Hong and Shao-Wu, 1992; Bengtsson, 1997). Despite the fact that the surface network observations must be used cautiously at regional scales, because inhomogeneities can be statistically compensated for only over large areas (Jones, 1995), the MSU and NCEP data are also compared with the surface data, in order to assess regional consistency. An attempt is made to circumvent the issue of spurious trends by focusing solely on regional temperature trends that are of statistical significance and have magnitudes larger than documented biases. These are regions that are most likely to be experiencing real climatic shifts, particularly when they are mirrored in several datasets. Regional trends are also a more relevant quantity, from a human standpoint, than zonal or global averages, both of which smooth out spatial structure. Regional trends are, therefore, essential to monitor for trend and bias detection, for comparisons with climate model simulations and for use by the impact assessment community (Beniston, 1998).

2. DOCUMENTED BIASES

The MSU satellite data have received significant scrutiny for discontinuities and biases because globally-averaged linear trends in these data contradict those of the surface observing network (e.g. Hurrell and Trenberth, 1997; Jones *et al.*, 1997; Stendel *et al.*, 1998; Santer *et al.*, 1999). Discontinuities in 1981 and 1991 resulting from changes in satellite (Hurrell and Trenberth, 1997) have apparently been adjusted for in the MSU data used here (Version C; Christy *et al.*, 1998; Stendel *et al.*, 1998). Additional biases owing to orbital decay (up to 0.30°C/19 years; Prabhakara *et al.*, 1998; Wentz and Schabel, 1999) and instrument heating have not, as yet, been compensated for, but preliminary estimates of their combined impact on the MSU data is slightly less than 0.1°C/19 years in the global average (Christy *et al.*, 1998; Stendel *et al.*, 1998). These errors in trend estimates have been discussed in terms of global averages and any possible latitudinal or regional biases resulting from these adjustments are undocumented. Potential errors in MSU retrievals caused by systematic regional changes in atmospheric hydrometeor content have also been identified (Prabhakara *et al.*, 1996), although strong trends in these quantities have not, as yet, been shown over this time period nor is there consensus on the magnitude of the error (Spencer *et al.*, 1996). All regional trends significant at the 90% level in a two-tailed t-test in the MSU data exceeded ± 0.1°C/19 years and can thus be considered reliable, in the sense that they exceed an average documented bias and are statistically different from zero.

NCEP reanalysis biases are more difficult to quantify than in the MSU because of the use of various data sources in different regions and for various portions of the record. Nevertheless, several biases in the reanalysis data have been documented during the period since 1979. These include biases carried over from inclusion of rawinsonde and satellite data, which may introduce regional errors in this dataset. Santer *et al.* (1999) documented a 0.15°C/19 years global trend difference between similar radiosonde datasets, attributable mostly to differences in areal coverage. Regional biases in the radiosonde data are potentially much larger but these are poorly documented (Gaffen, 1994; Parker *et al.*, 1997). In addition, the satellite data assimilated into the reanalysis are uncorrected for documented biases resulting from change of sensor, which are of the order of 0.1°C/19 years (Hurrell and Trenberth, 1997). Additional biases owing to changes in satellite retrieval algorithms have also been identified (Basist and Chelliah, 1997). Although having greater potential for spurious regional trends than the MSU data, the threshold of 0.1°C/19 years is again used to determine a base level trend in the NCEP reanalysis.

However, because regional biases are not well quantified for either dataset and are potentially much larger than 0.1°C/19 years, the sensitivity of the results are also compared when the minimum trend threshold considered is increased by up to a factor of five. This is larger than any documented bias in either dataset, although regional disparities between various datasets affecting this study may be of this magnitude or larger (e.g. Hansen *et al.*, 1995 found a trend difference of 0.8°C/19 years between radiosonde data and MSU 2r during 1979–1993 for a portion of North America). Spatial consistency is then examined between the two datasets and with the surface observational network, as a step towards both identifying local biases and confirming real trends.

3. MSU 2r REGIONAL TRENDS

Figure 1 shows the 1979–1997 trends from the MSU channel 2r. All regions where trends fail to meet the following criteria are ignored: (i) statistical significance at the 90% level in a two-tailed *t*-test, and (ii) the magnitude of the trend is larger than documented systematic biases (see discussion in Section 2).

In the annual average (Figure 1(a)), several regions show strong trends of both warming and cooling in the MSU data. Regions of significant warming include central east Asia, the western coast of the US, the central North Atlantic, the northern North Atlantic, Western Europe and one region in the Southern Hemisphere ocean. Regions of significant cooling include tropical Africa, southern Asia, eastern Canada, the northwest coast of Australia and adjacent ocean as well as several other regions in the Southern Hemisphere oceans. An area-weighted average over the significant regions only (Table I, first column of values) gives a trend of −0.16°C/19 years. When significant trends are weighted over the entire area of the globe (Table I, second column of values), the average significant trend is −0.02°C/19 years. Because MSU trends in regions of high terrain, such as Antarctica, are suspect (Christy *et al.*, 1998; Stendel *et al.*, 1998), averages which exclude regions south of 60°S are also provided (Table II). In the annual average, the trend for the globe north of 60°S is −0.14°C/19 years averaged only over regions with significant trends and −0.02°C/19 years when the significant trends are weighted over the entire area north of 60°S. Tables I and II also provide the global average of all trends, both significant and insignificant, for comparison (third column of values).

In the December–February (DJF) averages, significant trends of both signs are also evident (Figure 1(b)). Note that for 1979, only January and February are included in the DJF average. Warming occurs in Western Europe, east central Asia, the North Pacific, the central North Atlantic, the eastern US and off the southern coast of Africa. Cooling occurs in eastern Canada, tropical and southern Africa, southeast Asia and the maritime continent, the equatorial Pacific, Australia, the southern tip of south America and off the eastern coast of South America. Cooling is indicated over much of Antarctica although, again, measurements in this region are suspect. The average of these trends for the DJF season over regions of significance is −0.39°C/19 years (Table I) and is −0.23°C/19 years (Table II) when regions south of 60°S are excluded.

In the June–August (JJA) averages (Figure 1(c)), significant trends of both sign are again apparent. Small regions of warming occur in western Alaska, off the west coast of the continental US, the central North Atlantic, the central South Pacific and two regions off the coast of Antarctica centred at approximately 90°E and 150°W. Most of Antartica shows warming in this season. Regions of cooling include the northern North Atlantic, northwestern Asia, southern and southeastern Asia, tropical Africa, and four centres in the Southern Hemisphere oceans. JJA season averages over areas of significance are 0.16°C/19 years (Table I) and −0.55°C/19 years (Table II) when regions south of 60°S are excluded.

4. NCEP REGIONAL TRENDS

Figure 2 shows the corresponding NCEP 1000–500 mb depth-averaged temperature trends derived from height data at the two levels, as described in Pielke *et al.* (1998a,b). This layer includes most of the atmosphere sampled by the MSU 2r sensor, which has a retrieval weighting function peaking near 740 mb (Christy, 1995). For annual trends (Figure 2(a)), a warming occurs in central east Asia, the western coast of the US, the central North Atlantic, Western Europe and in a centre in south central Africa. Cooling regions include northern and southern Africa and adjacent ocean, west central Asia, the central North Pacific, the maritime continent and ocean south of India, northern South America, the ocean off the

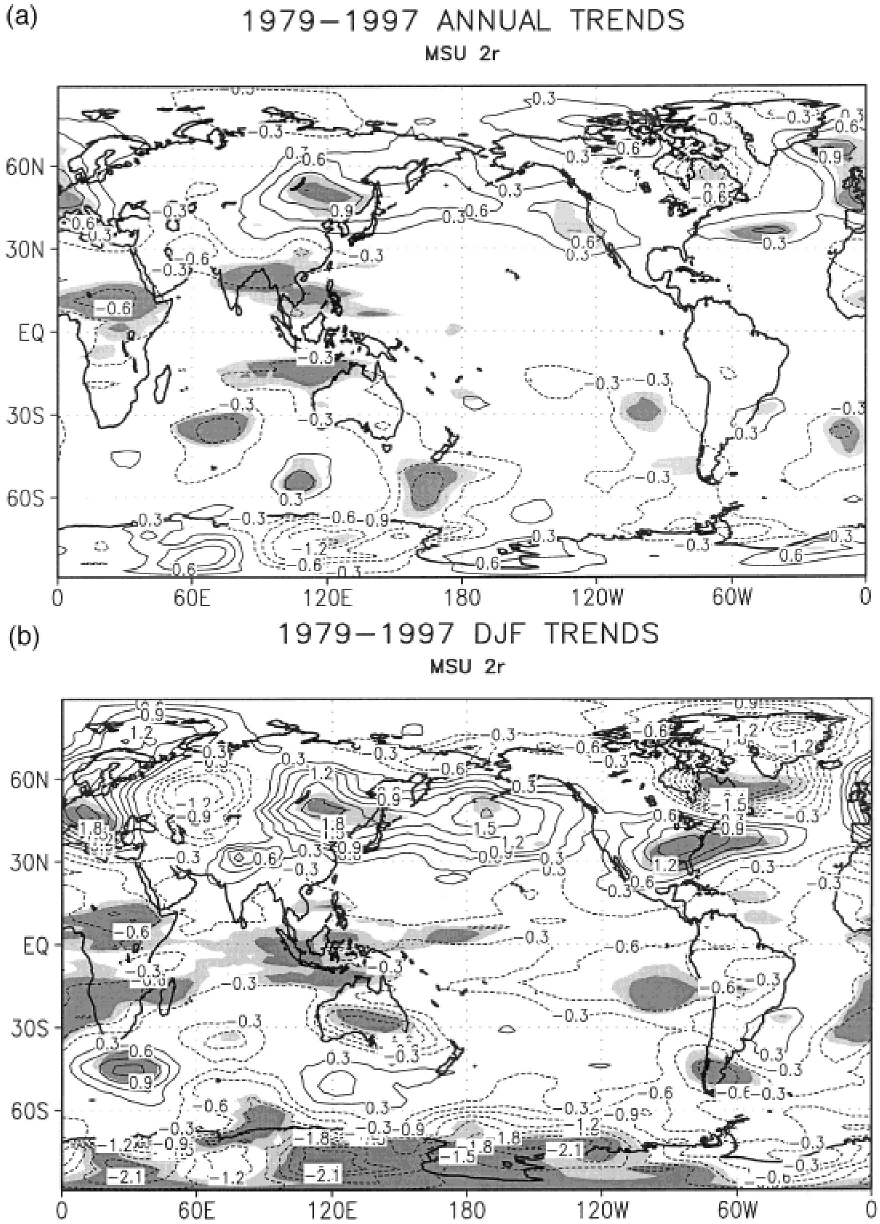


Figure 1. 1979–1997 trends in °C/19 years for (a) annual MSU, (b) DJF MSU and (c) JJA MSU. Contours are by 0.3 for values from 0 to ±3.0 and by 1.0 thereafter. Light and dark shaded regions are significant at the 90% and the 95% levels, respectively

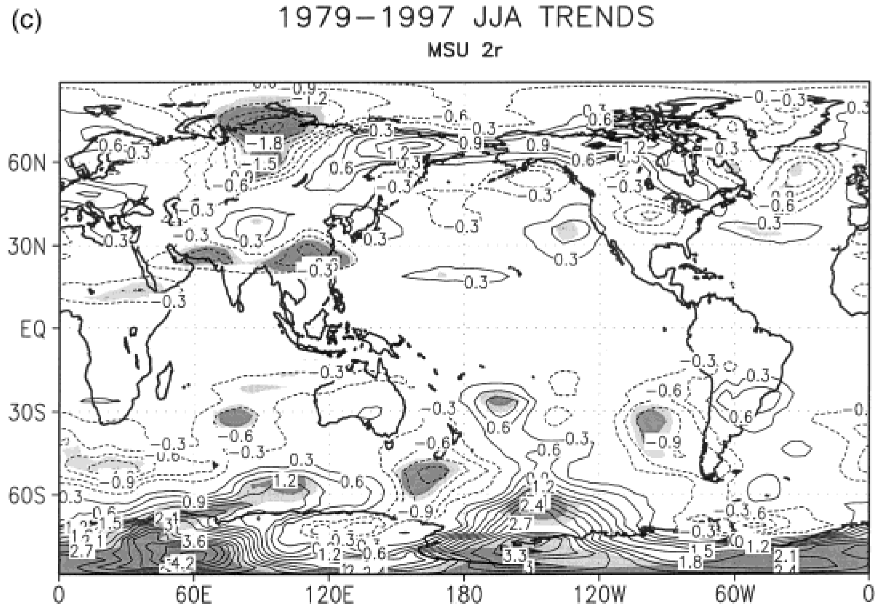


Figure 1 (*Continued*)

southwest coast South America, and at two centres southeast and southwest of Australia, respectively. Eastern Antarctica shows cooling, although reanalysis data in this region are mostly the result of satellite retrievals. The averages of these trends across regions of significance are − 0.32°C/19 years (Table I) and − 0.24°C/19 years (Table II) for regions north of 60°S. Significant trends weighted over the area of the globe are − 0.05°C/19 years and − 0.04°C/19 years for the area north of 60°S.

For the DJF season (Figure 2(b)), warming occurs in Central and Western Europe, east central Asia, the Arabian sea, the southeastern US into the North Atlantic and off the southern tip of Africa. Cooling occurs in west central Asia, northern and southern Africa and adjacent ocean areas, eastern Canada, Australia, and southern South America. Antarctica shows cooling. The area averages of these trends over regions of significance are − 0.50°C/19 years (Table I) and − 0.16°C/19 years (Table II) when regions south of 60°S are exclude.

The JJA season (Figure 2(c)) also shows trends of both sign in the NCEP data, with warming centres in southwestern Asia, southern Africa, Alaska and the central North Atlantic. Areas of warming also occur off the coast of Antarctica in three different areas. Cooling is centred on northwestern Asia, south

Table I. MSU and NCEP 1979–1997 globally-averaged trends in °C/19 years

	Significant trends	Global average significant trends	Global average trends
MSU 2r			
Annual	−0.16	−0.02	−0.08
DJF	−0.39	−0.07	−0.17
JJA	0.16	0.01	0.00
NCEP 1000–500 mb			
Annual	−0.32	−0.05	−0.11
DJF	−0.50	−0.07	−0.19
JJA	0.08	0.01	0.00

Columns report: significant trends averaged over areas of significance; significant trends weighted over area of globe where zero trends were assumed if the regional trends were statistically insignificant; and global average trends where no level of minimum bias or significance is assumed.

Table II. As in Table I but averaged from 60°S to 90°N

	Significant trends	Global average significant trends	Global average trends
MSU 2r			
Annual	−0.14	−0.02	−0.08
DJF	−0.23	−0.04	−0.11
JJA	−0.55	−0.03	−0.07
NCEP 1000–500 mb			
Annual	−0.24	−0.04	−0.10
DJF	−0.16	−0.02	−0.13
JJA	−0.39	−0.04	−0.08

central Asia, the Arabian Sea, the maritime continent, Amazonia and three centres in the Southern Hemisphere oceans. The average trends across regions of significance are 0.08°C/19 years (Table I) and −0.39°C/19 years (Table II) when regions south of 60°S are excluded.

5. REGIONAL COMPARISON BETWEEN MSU AND NCEP TRENDS

It is clear from the previous two sections that lower tropospheric warming is not dominant in either areal extent or magnitude among the most reliable trends in both datasets discussed. In both the DJF and in the annual means, averaging over regions of significant trends in the last 19 years, the areally weighted trend is cooling. In JJA, there is a warming of lesser magnitude than in DJF cooling, although this warming mostly occurs in Antarctica (e.g. Figure 1(c)) while cooling dominates regions to the north of 60°S. Next, the coherence of the two datasets with respect to the regional trends is examined.

While these datasets are not exactly comparable in terms of vertical weighting, the purpose of this paper is not a strict intercomparison but rather to highlight the similarities and differences between the regional trends found in MSU data and those found using the depth-averaging technique, based on height data discussed by Pielke *et al.* (1998a,b) for the NCEP data. It is known that the MSU data and NCEP reanalysis data are well correlated temporally (e.g. Hurrell and Trenberth, 1998; Santer *et al.*, 1999); the spatial consistency of trends in these data since 1979 will now be examined.

First, all trends, both significant and insignificant, are compared in both datasets. Spatial correlations between the MSU and the NCEP 1000–500 mb annual, the DJF and the JJA trends are given in Table IV, and an overlay of the two datasets is presented in Plate 1. Plate 1 shows high qualitative correspondence between trends in the two datasets at mid and high latitudes (particularly over land) in both the Northern and the Southern Hemispheres, which is reflected, for the most part, in the strong correlation coefficients for these latitude belts in Table III. This adds confidence to these higher latitude regional trends. The spatial correspondence between the two datasets decreases markedly for tropical regions, particularly for 0–30°S in the annual average. Correlations between the two datasets are generally highest in the Northern Hemisphere and in DJF. Correlations in the annual average can be quite a bit smaller than both the DJF and the JJA correlations, indicating weaker correlation in the spring and autumn seasons for those latitude belts. While both datasets show overall tropical cooling, the weak correlation makes annual, JJA and DJF regional trends in low latitude regions suspect until other, independent confirmation occurs.

Next, the paper focuses on regions of significant trends in the annual, the DJF and the JJA averages. These regions are often offset slightly in space and, in some cases, have different areal extent in the two datasets. However, there exists substantial qualitative agreement on the position and the strength of significant annual trends (Figures 1(a) and 2(a)) in the mid latitudes of both hemispheres. Agreement again decreases significantly in the tropics, although both datasets show a general annual cooling among significant trends in this region. Significant warming trends over east central Asia, the western coast of the

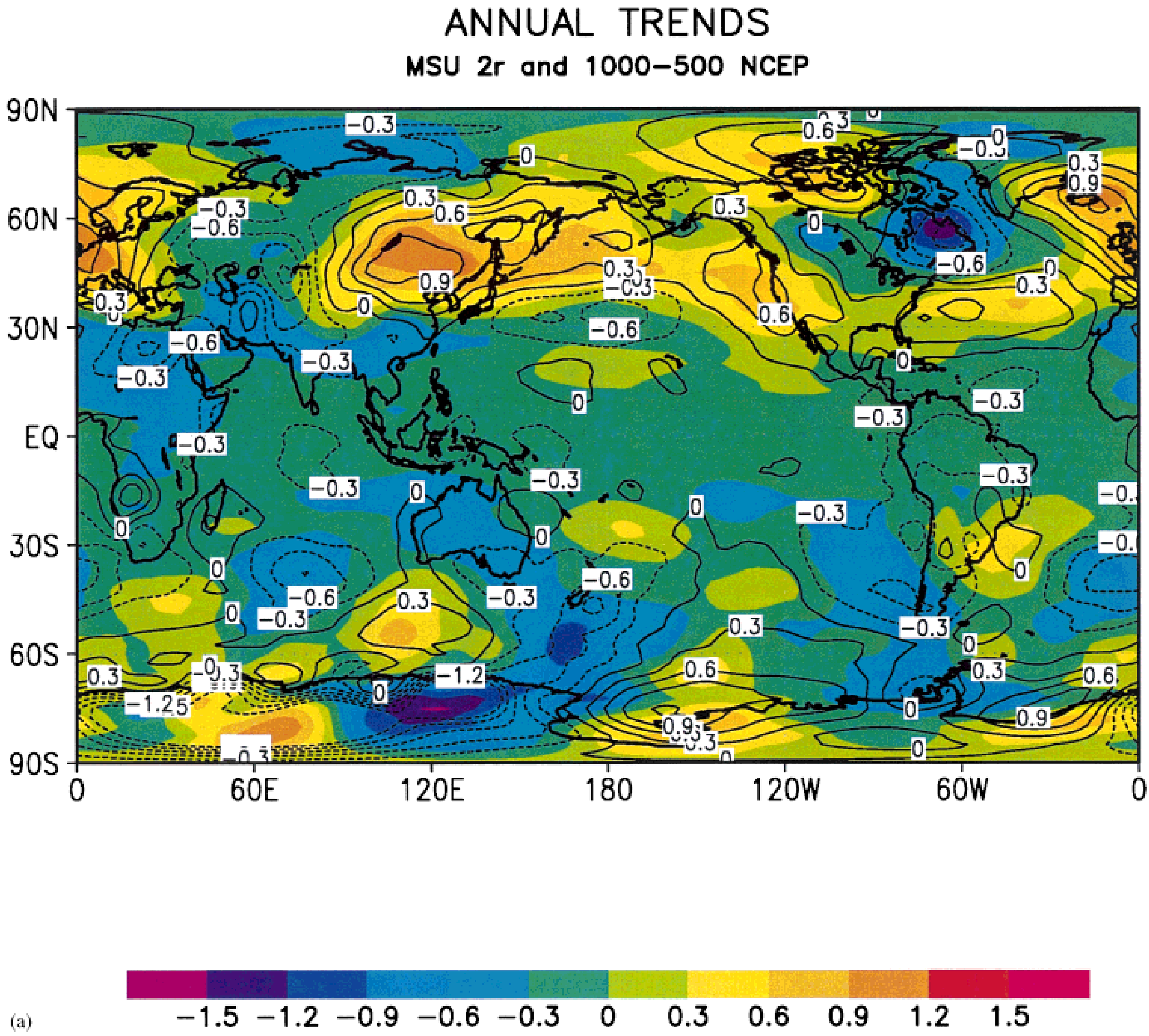
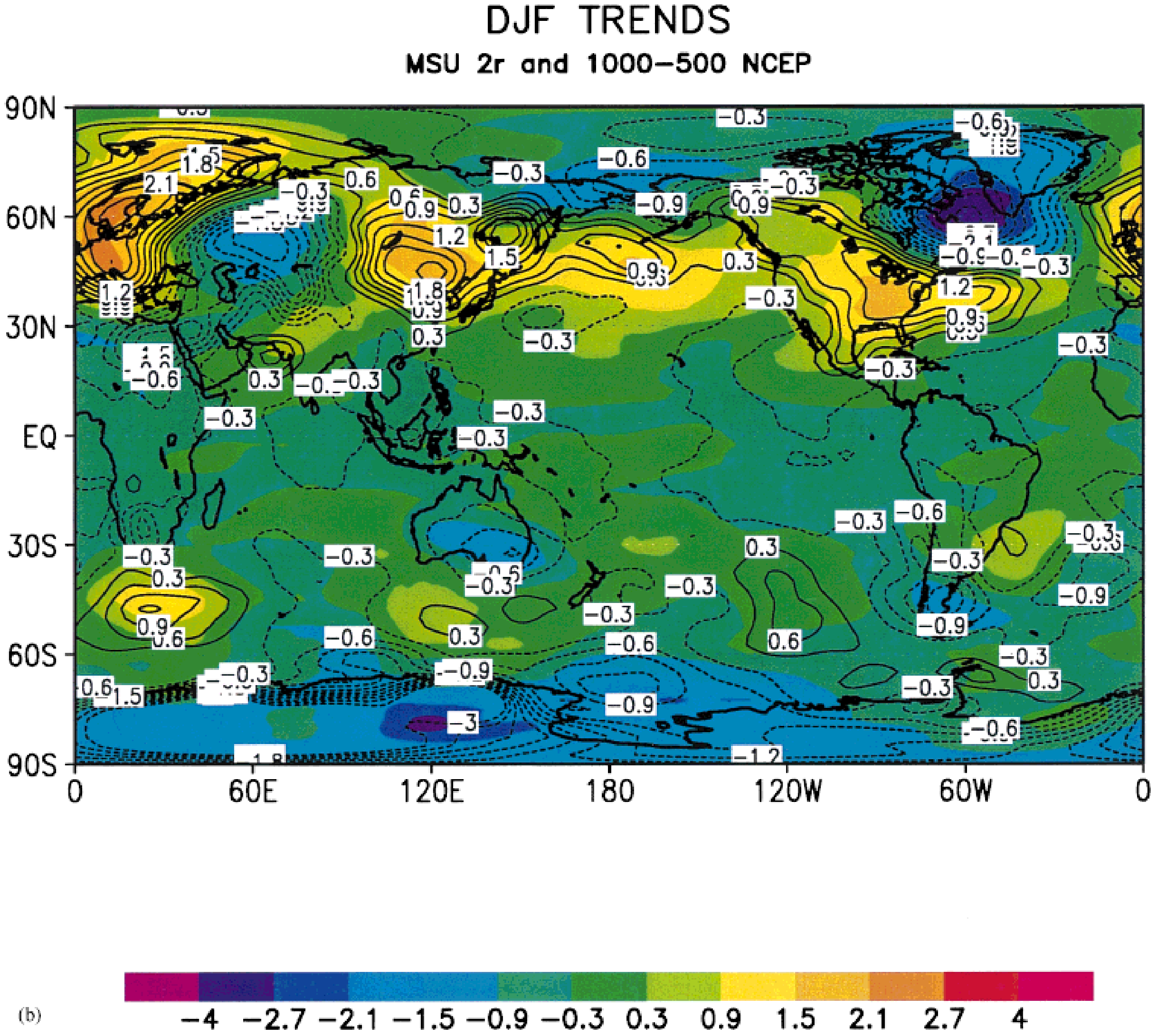
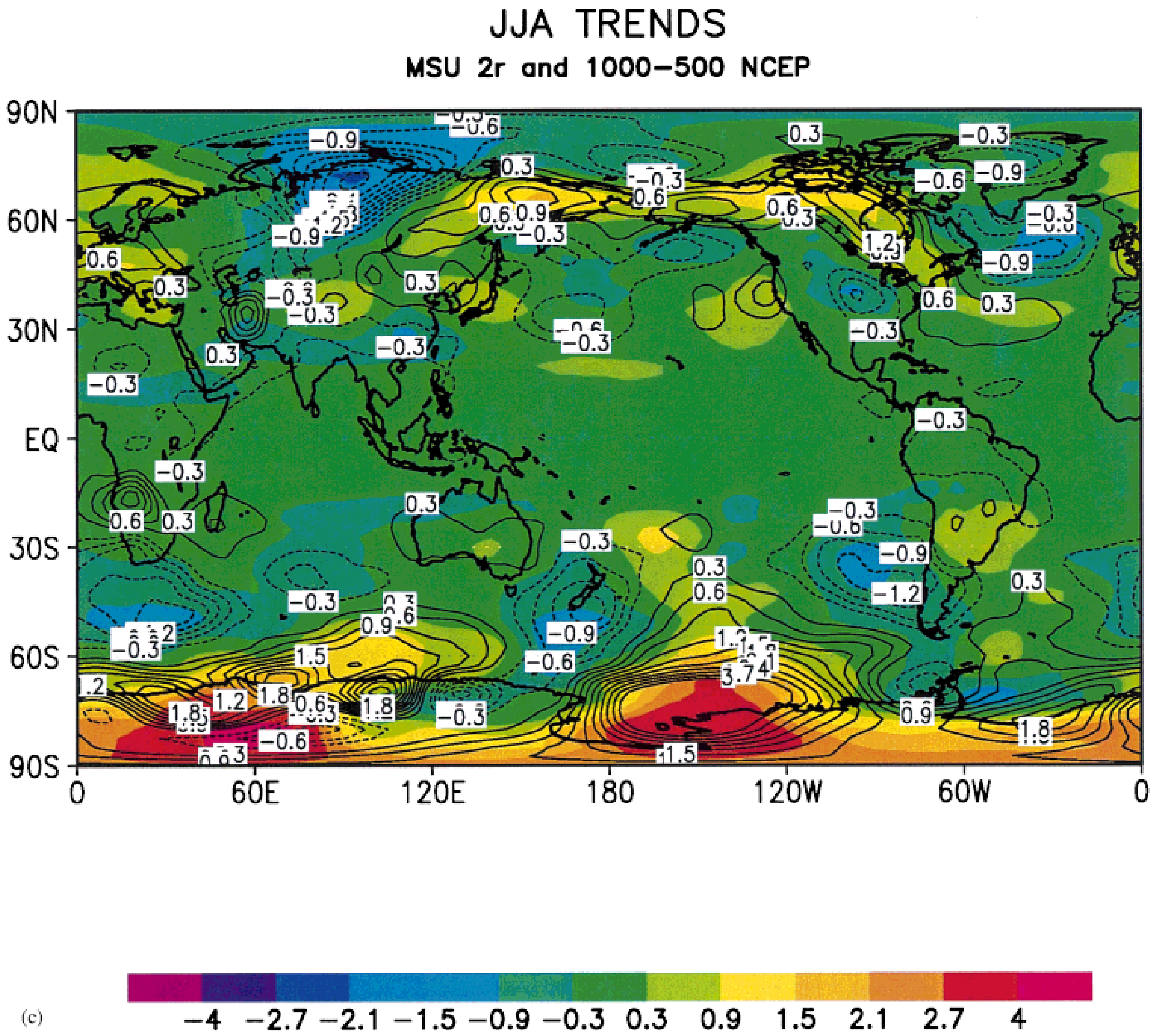


Plate 1. MSU (coloured) and NCEP 1000–500 mb (contoured) trends in °C/19 years for (a) annual average, (b) DJF average and (c) JJA average



(b)

Plate 1 (*Continued*)

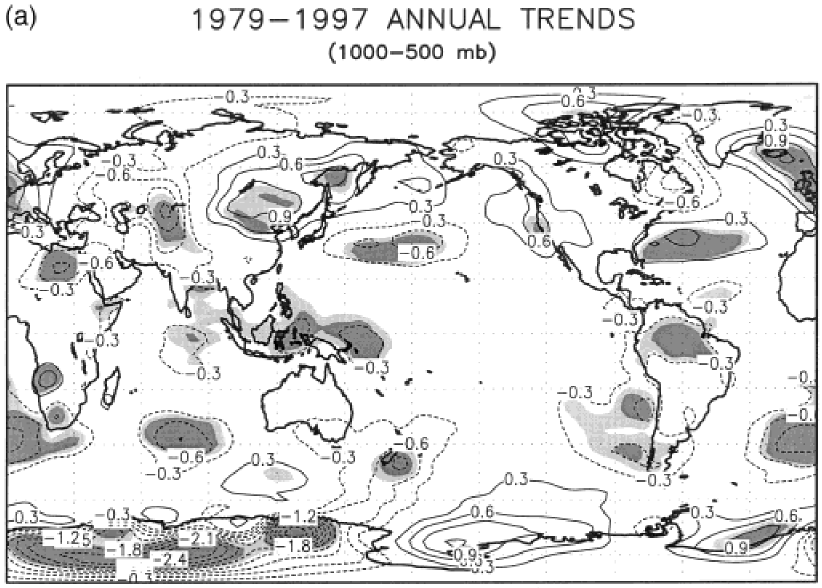


(c)

Plate 1 (*Continued*)

US, Western Europe, central North Atlantic and south of Australia appear in both datasets. Cooling centres in eastern Canada (statistically insignificant in the NCEP data) and in the Southern Hemisphere oceans also show substantial positional agreement. Important discrepancies between the two datasets are several regions of cooling. These include cooling centres in central Asia, the central North Pacific and Amazonia, which are significant in the NCEP data but not in the MSU data. A cooling centre in tropical Africa is significant in MSU but not in NCEP.

In the DJF season (Figures 1(b) and 2(b)), warming trends in east central Asia, the eastern US and adjacent ocean and Western Europe appear in both datasets. A cooling centre in eastern Canada is significant in the DJF season in both datasets. In the Southern Hemisphere, warming off the southern coast of Africa and cooling in southern South America and Australia also appear in both datasets.


(a) 1979–1997 ANNUAL TRENDS
(1000–500 mb)

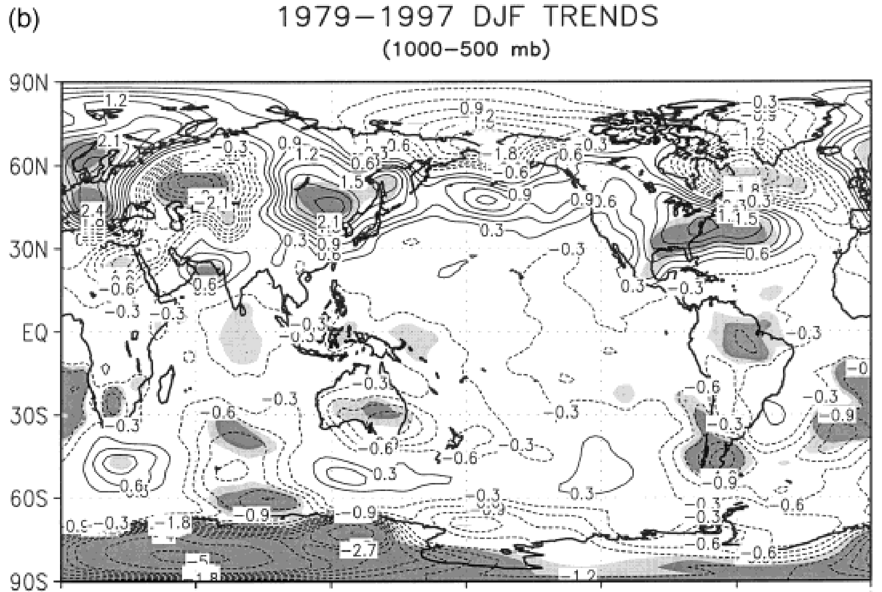

(b) 1979–1997 DJF TRENDS
(1000–500 mb)

Figure 2. As in Figure 1, but for the NCEP 1000–500 mb layer-average temperature

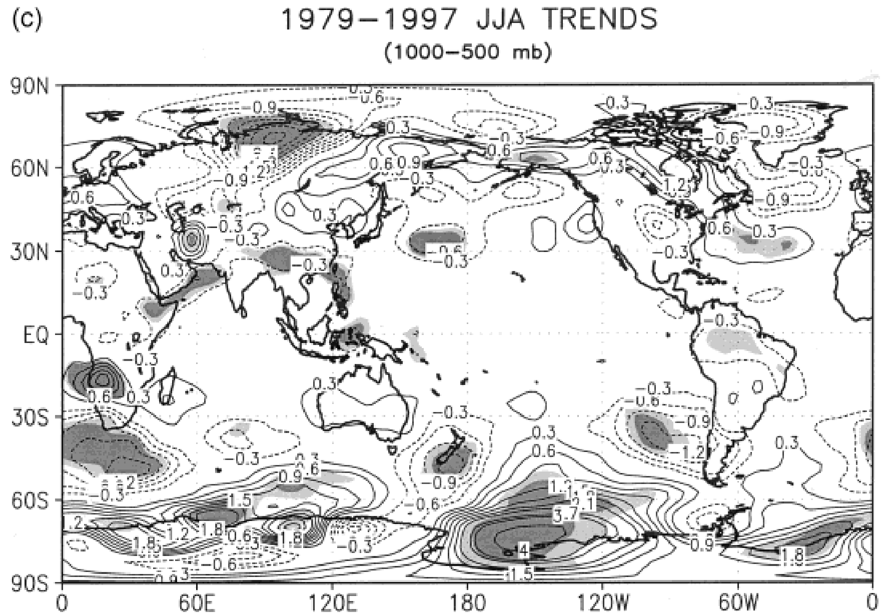


Figure 2 (*Continued*)

Regional trends which are in disagreement include the cooling centre in west central Eurasia which appears in both datasets in this season but is insignificant in the MSU data. Most tropical regions show cooling in both datasets, although the MSU data has a larger region of the tropics cooling significantly.

For the JJA season (Figures 1(c) and 2(c)), a large, strong cooling centre in north central Asia appears in both datasets, as does cooling in southcentral and southeastern Asia. Four significant cooling centres in the Southern Hemisphere oceans also appear in the NCEP data, although only three of these are significant in the MSU data. A warming in the central North Atlantic and in western Alaska also shows up in both datasets, although this warming is insignificant in the MSU data. Regions of significant disagreement in the JJA season include a strong warm trend in southern Africa and a cooling in Amazonia in the NCEP data, which is not indicated in the MSU data.

6. HIGHER AMPLITUDE TRENDS

Because our selection of a bias cutoff for strong, reliable trends is arbitrary (particularly in the case of the NCEP reanalysis), and is based on debated estimates of globally-averaged biases rather than on regional biases for the most part, we compare significant regional trends at higher amplitude cutoff values than the ± 0.1°C/19 years discussed in Sections 3 and 4 and shown in Tables I and II. Table IV shows annual average results when only trends greater than 0.3°C/19 years and 0.5°C/19 years are included in the analysis. For comparison, the difference in global trends between the MSU data and the surface record during this time period is nearly 0.4°C/19 years (Tables I and VI); the difference between global trends in

Table III. Correlation between MSU and NCEP 1000–500 layer-averaged trends by latitude band

	Globe	60°S–90°N	90–60°S	60–30°S	30°S–0°	0°–30°N	30–60°N	60–90°N
Annual	0.50	0.74	0.17	0.61	0.10	0.49	0.80	0.78
DJF	0.79	0.87	0.59	0.73	0.48	0.67	0.89	0.92
JJA	0.71	0.79	0.31	0.84	0.31	0.31	0.74	0.88

Table IV. As in Table I but a comparison of spatial MSU and NCEP 1000–500 mb annual trends at increasing minimum trend level

Threshold (°C/19 years)	Significant trends	Global average significant trends	Global average trends
MSU 2r			
0.1	−0.16	−0.02	−0.08
0.3	−0.14	−0.01	−0.08
0.5	0.00	0.00	−0.08
NCEP (1000–500 mb)			
0.1	−0.32	−0.05	−0.11
0.3	−0.33	−0.05	−0.11
0.5	−0.35	−0.03	−0.11

the NCEP and the ECMWF reanalyses over the period of overlap is approximately 0.26°C/19 years (Santer *et al.*, 1999) and claims of remaining biases in the MSU data can be as large as 0.30°C/19 years (e.g. Prabhakara *et al.*, 1996; Wentz and Schabel, 1999).

For the annual MSU trends, all trends of higher amplitude still show average cooling although the magnitude of the trends become less negative as the cutoff value increases. For the 1000–500 mb NCEP trends, a similar pattern of consistently negative trends emerges. These, however, become slightly more negative as the amplitude of the cutoff increases.

7. COMPARISONS WITH SHALLOWER NCEP LAYERS

Because depth-averaging may remove real differences in atmospheric vertical structure, we examine shallow layer annual averages in the NCEP data and compare them with the 1000–500 mb layer results shown in Figure 1(a). Figure 3 shows the NCEP reanalysis annual averages for the 1000–850 mb layer (Figure 3(a)) and for the 1000–925 mb layer (Figure 3(b)). The shallowest layer generally exists only over oceans or land areas near sea level and is provided for comparisons in these regions. Both figures show a similar distribution of significant regional trends as the 1000–500 mb layer.

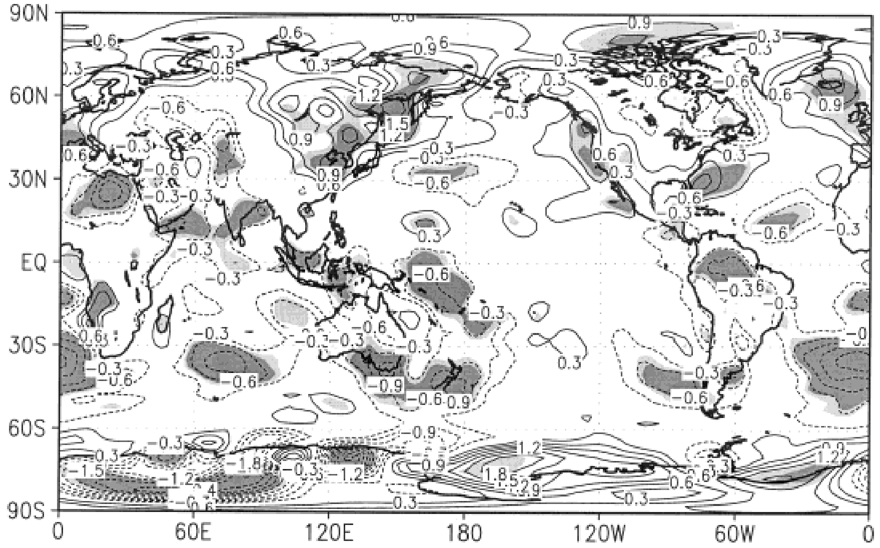
The strength, statistical significance and area affected by significant trends of both signs generally increases as the depth of the layer decreases, although this is not universally the case. For instance, the warm anomaly in east central Asia in Figure 2(a) is of lesser magnitude and covers a smaller area than the corresponding anomaly in the 1000–850 mb (Figure 3(a)) layer. Warming in northern Canada also increases with decreasing layer depth, as does cooling in the four cooling centres in the Southern Hemisphere oceans and the cooling centre over and to the west of the maritime continent. However, a warming centre in Western Europe diminishes in magnitude and area of significance with decreasing layer depth.

Table V compares average annual values for each layer discussed in this section and shows cooling dominates in all three layers to varying degrees. The regional trends do not systematically increase or decrease with depth. The shallowest layer shows the strongest cooling, followed closely by the deepest layer in regions of significant trends.

8. COMPARISON WITH THE SURFACE TEMPERATURE RECORD

For comparison purposes a similar analysis is performed on the surface temperature record described in Parker *et al.* (1994) over the same time period. While caution needs to be exercised when applying these data to both point and regional scales (Jones, 1995) because of missing values and uncorrected discontinuities, an attempt is made to identify where regionally significant trends agree with tropospheric data presented in previous sections.

(a) 1979–1997 NCEP ANNUAL TRENDS
(1000–850 mb)



(b) 1979–1997 ANNUAL TRENDS
(1000–925 mb)

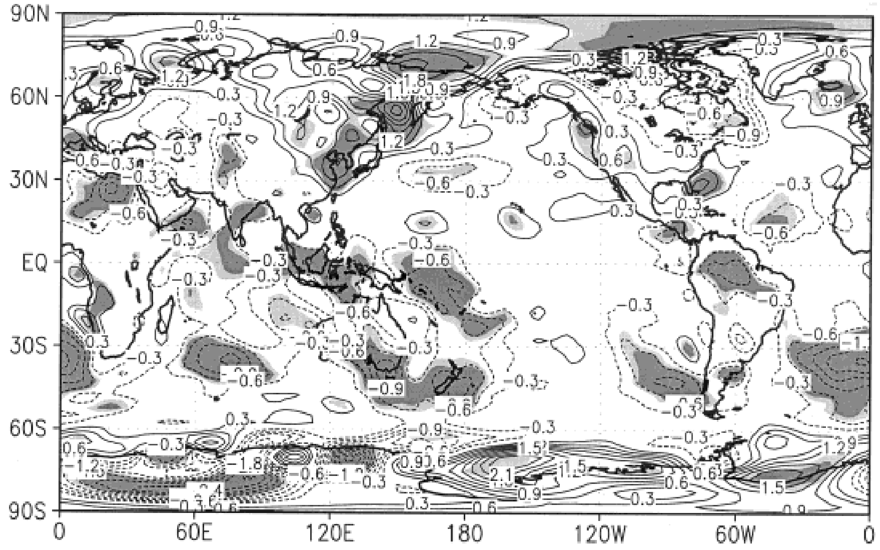


Figure 3. As in Figure 1, but for annual NCEP (a) 1000–850 mb and (b) 1000–925 mb layer-averaged temperature

Figure 4 shows the annual, the DJF and the JJA trends in the surface data network. In the annual trends (Figure 4(a)), the surface network shows the broad area of warming in eastern Asia evident in both the MSU and the NCEP data. Trends in this region, however, are stronger than in the other two datasets and are significant over a much larger area, which extends across the North Atlantic and far into southeast Asia. Both the MSU and the NCEP datasets show cooling in southeast Asia and over much of the maritime continent. A warming trend in the western US is also shared between all three datasets, although again in the case of the surface data the area covered is more extensive and the amplitude of the trends are usually larger. The region of significant warming spreads far into the tropical Pacific and far

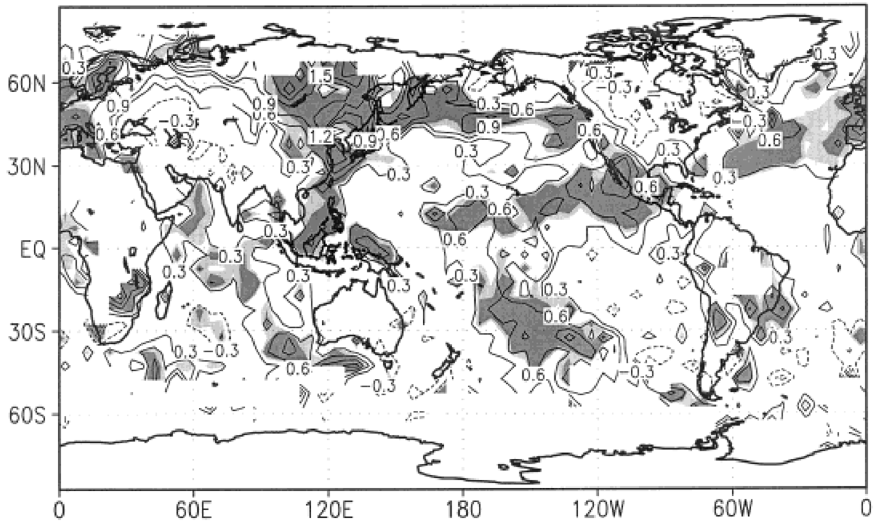
Table V. As in Table I but a comparison of annual NCEP regional trends in various vertical layers

mb	Significant trends	Global average significant trends	Global average trends
1000–500	−0.32	−0.05	−0.11
1000–850	−0.29	−0.06	−0.07
1000–925	−0 33	−0.07	−0.08

south into Mexico, which is not shown in the other two datasets. A warming in Western Europe into the far North Atlantic also shows up in all three datasets and again is generally stronger in the surface data than in either tropospheric dataset. A warming in the North Atlantic off the eastern coast of the US of

(a) 1979–1997 ANNUAL TRENDS

SURFACE



(b) 1979–1997 DJF TRENDS

SURFACE

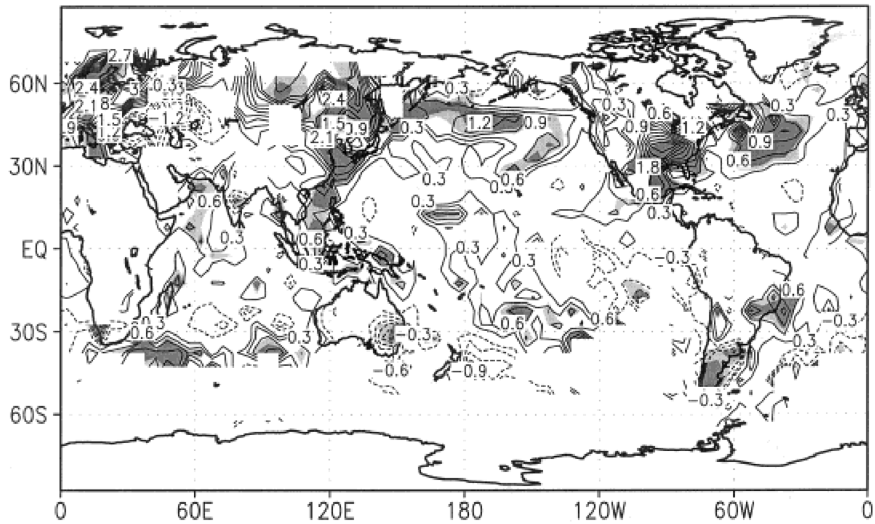
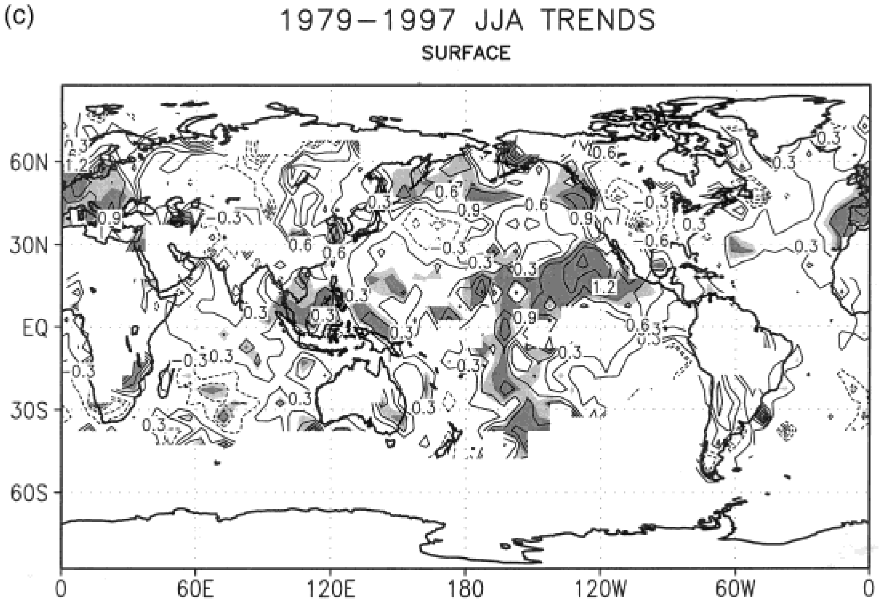


Figure 4. As in Figure 1, but for the surface observational network. Regions not contoured indicate no available data



(c) 1979–1997 JJA TRENDS

SURFACE

Figure 4 (*Continued*)

approximately equal magnitude also appears in all datasets. In the case of the surface data, these two significant regions of warming are connected.

The region of cooling in central Asia shown in both the MSU 2r and NCEP datasets, while hinted at in the surface data, is insignificant. The surface data has small areas of significant cooling at the southern tips of Africa, which are shared in the NCEP data but not in MSU. Small areas of significant cooling are also shared by all datasets in the southern oceans at about 10°W and about 60°E, although these trends tend to be weaker in the surface data than in the other two datasets. The surface data show large areas of the southern oceans covered by significant warming. The region south of Australia shows significant warming in all three datasets, although the significant warming in the surface record appears to extend further to the north relative to the other datasets. The region where warming is centred in the two tropospheric datasets is affected by missing data in the surface record, which makes an assessment of trends here ambiguous. All other warming trends in the surface record are not replicated in the tropospheric datasets.

In the annual average, the surface network shows a general tropical warming among significant regional trends which is directly at odds with the tropospheric datasets, both of which show a general tropical cooling. This is interesting because atmospheric general circulation model (AGCM) simulations of increased greenhouse gas forcing simulate tropical warming trends to increase with height in the troposphere, which is often explained to result from the so-called lapse-rate feedback effect (e.g. Manabe *et al*., 1991; Boer *et al*., 1992). In the present study, this simulated change in tropical vertical structure should manifest itself as an amplification of significant surface record warming trends in the deep-layer tropospheric datasets. However, in no case is a regionally significant, tropical surface trend mirrored or amplified in either of the two tropospheric datasets.

In the DJF season (Figure 4(b)), regionally significant trends are still evident in the surface observations in eastern Asia and across the eastern US and continuing across the North Atlantic, which show up in all three datasets. The warming in eastern Asia tends to be stronger over larger areas in both tropospheric datasets than in the surface data in regions where they agree. However, the surface data has a larger maximum to the north of the eastern Asian region of significance in the tropospheric data. The northern Atlantic warming off the eastern US is stronger over larger regions in the NCEP data than in both the surface and the MSU data, while in the surface data the warming extends much further north than in the other two datasets. The surface data show warming extending into southeast Asia and the maritime continent which is not corroborated by the other two datasets. A cooling in northeastern Canada shows up in all datasets, although there are few data in the surface record in this region so that the northern extent of the cooling is ambiguous at the surface. Warming is also evident in Western Europe in the surface data and this again shows up in both of the other datasets, although it is somewhat weaker and has lesser northern extent in the MSU data than in the other two datasets.

In the Southern Hemisphere, cooling is shared in all three datasets in the southern tip of Africa and is strongest in the surface data even though it is of limited spatial extent. The southern tip of South America also cools in all three datsets, with the strongest cooling in the NCEP data. A cooling of nearly equal magnitude occurs in all datasets for southeastern Australia. A warming region off the southern coast of Africa also appears in all datasets, although its magnitude is difficult to ascertain in the surface record because of missing data to the south. Again, isolated regions of warming in the tropical oceans are in no case amplified in either of the tropospheric datasets.

JJA season trends (Figure 4(c)) show the largest discrepancies between the surface record and the two tropospheric datasets. A small region of warming across the North Atlantic near 30°N appears in all datasets. A warming in the tropical North Pacific west of Baja California, which extends into the Southern Hemisphere extratropics in the surface record, does not appear in the NCEP data, although there is a hint of the Northern Hemisphere warming in the MSU data in two small, weakly significant centres. A strong Western Europe warming in the surface record shows up weakly in both upper-air datasets in this season, although this is insignificant. A large region of warming over the maritime continent does not appear in the MSU data and appears as isolated cooling centres in NCEP. In JJA, significant, tropical surface warming trends are in no case amplified in the tropospheric datasets.

Table VI gives the area-averaged trends of greater magnitude than ±0.1°C/19 years for the surface network. All area-averaged trends are positive in the surface observations. The globally-averaged trend commonly cited for global change applications typically includes all regional data (e.g. IPCC, 1996), both significant and insignificant. During the period of this study, this warming trend is approximately halved in DJF, in JJA and in annual averages when only regionally significant trends are considered.

Comparison between the NCEP and the MSU data and the surface observational network shows significant disagreement as to regions where significant trends occur and their amplitude. This was shown previously in the Jones *et al.* (1997) comparison of the MSU 2r data with the surface record for the period 1979–1996. Significant regional trends cover very small portions of the globe and in almost no instance in that study did significant trends in the two datasets occur in the same place (refer to figure 1a, b in Jones *et al.*, 1997). Therefore, global, hemispheric and zonal averages calculated in that study are not only composed overwhelmingly of areas of the planet where trends are indistinguishable from zero but, where a trend is identifiable, it is not agreed upon in the two datasets. The agreement between the surface and the MSU is somewhat better with the addition of another year of data in the present study. However, many of the significant trends in the surface data appear over oceans in very poorly sampled regions and are not mirrored in either the MSU 2r or the NCEP datasets.

Spatial correlations for all available data between the surface data and MSU and NCEP (tropospheric data was regridded to surface data format) are provided in Table VII and indicate that all three datasets are more highly correlated at mid latitudes than in the tropics. The correlations in the highest latitude bands are based on relatively few points because of missing data in the surface observations and are, therefore, unreliable.

Table VI. As in Table I but for surface observational network trends

	Significant trends	Global average significant trends	Global average trends
Annual	0.65	0.17	0.30
DJF	0.83	0.12	0.28
JJA	0.78	0.13	0.33

Table VII. Spatial correlation between surface observations and MSU, and between surface and NCEP 1000–500 layer-averaged trends by latitude band (MSU/NCEP)

	Globe	90–60°S	60–30°S	30°S–0°	0°–30°N	30–60°N	60–90°N
Annual	0.41/0.30	0.15/0.09	0.33/0.40	0.14/0.15	0.20/0.19	0.61/0.59	0.07/−0.04
DJF	0.50/0.38	−0.21/−0.01	0.36/0.47	0.39/0.38	0.35/0.31	0.54/0.56	0.68/0.58
JJA	0.15/0.19	−0.02/−0.06	0.31/0.29	0.19/0.09	0.25/0.32	0.30/0.39	0.49/0.55

Most surface data is missing in the 60–90°N and 60–90°S latitude bands.

9. DISCUSSION AND CONCLUSIONS

All observational datasets are likely to have biases, some documented, some unknown. It is not argued that any one of the datasets considered here is intrinsically better because there is no objective standard with which to make that judgement. Rather, it is assumed that all the datasets have difficulties, especially when attempting to identify small trends in noisy data. In an effort to circumvent the issue of spurious trends, only those trends that are significantly larger than documented linear biases in the respective datasets were examined. Because global trends are a construct of regional changes, regional trends are a more appropriate diagnostic for climate change assessment and for comparison with model simulations. This is particularly important given the contradictory results among major observational datasets as to recent tropospheric temperature trends (e.g. Santer *et al.*, 1999). The additional fact that regional trends can be quite large in amplitude raises confidence in their reality, despite known problems in the observational record and inadequately quantified regional biases.

We have shown regional trends in both the MSU and the 1000–500 mb NCEP reanalysis which are much larger in magnitude than the documented, average systematic biases of the datasets. These trends are of both sign and are clearly not favouring an increase in temperature as would be expected should carbon dioxide (CO_2) induced warming be a dominant forcing on this timescale. On average, there is a cooling in both the DJF season and in the annual average among the most reliable trends in both datasets, although in many cases these trends are not in the same regions. A weaker JJA season warming is also present in both datasets, which becomes an average cooling if Antarctica and adjacent regions south of 60°S are excluded from the average. Assuming an average bias of up to 0.5°C/19 years still results in an average cooling in these data.

In the case of the surface data, regionally significant trends show warming, although to a lesser magnitude than when all regions, regardless of significance, are considered. However, many regions with significant trends occur in areas with limited observations over oceans and are not confirmed by the other two datasets. Tropical regions in which significant warming occurs in the annual surface data are in no instance mirrored by larger magnitude warming in either of the two tropospheric datasets. AGCM simulations of the effects of elevated CO_2 suggest an enhanced warming with altitude in the tropics, which is the opposite response to that seen here.

We have also shown that the regional trends of both sign in the NCEP data tend to become stronger as the layer becomes shallower, although this is not universally the case. This, in addition to the fact that no systematic warming exists in shallower NCEP layers relative to deeper layers, is an indication that the disagreement between the MSU and the NCEP datasets and the surface record is not necessarily a global-scale difference in atmospheric response at different atmospheric levels (i.e. a large-scale change in static stability) but instead points to a highly regional response. This view is further strengthened when regional trend discrepancies between the surface data and the tropospheric data show no systematic differences (e.g. consistently stronger or weaker in one dataset in regions where they agree). It appears unlikely that a small number of systematic biases in the satellite record could be responsible for the differences between the surface and the tropospheric datasets.

While the majority of the globe is not considered in this analysis because of insignificant trends, it is possible that a real and coherent but statistically insignificant trend could overwhelm those regions of significance. This does not appear to be the case, however, as the globe as a whole is also cooling in both tropospheric datasets. In addition, regionally specific biases, particularly in the NCEP and the surface data, are a likelihood. A systematic bias could then be dominating the signal and might be larger than the thresholds considered here. This is less likely where all the datasets agree and are most independent. Regional disagreement in the tropics as to strength and/or sign of significant trends is also problematic. This is the region responsible for much of the global cooling signal in the tropospheric data and the warming in the surface data. It is possible that errors here could change the sign of the globally-averaged trends in all datasets. The existence of these regional trends in the tropics will have to be confirmed by comparisons with other data, including a careful assessment of local observational bias. The lack of agreement between the observational data in the tropics and the existing physical models is also an indication that the coupling between surface temperature changes and those at higher levels in the troposphere may not be fully understood.

Finally, this study highlights the point that a global trend results from regional-scale trends which may be either real or spurious. Consideration of significant regional trends, which also exceeded reasonable bias thresholds, resulted in little qualitative change in global averages, although it did move global trends in all three datasets towards zero. The two tropospheric datasets show high spatial coherence, particularly at higher latitudes, which is also shared by the surface data. This coherence breaks down in the tropics where the tropospheric data are most dependent and where the surface network is most limited. This, in addition to the fact that significant trends have no obvious systematic changes with depth or with latitude band, indicate that significant trends are likely to be regional in nature and are neither the result of large-scale changes in atmospheric vertical structure nor are they the result of large-scale biases in the satellite observations.

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