Satellite versus Surface Estimates of Air Temperature since 1979

JAMES W. HURRELL AND KEVIN E. TRENBERTH

National Center for Atmospheric Research, Boulder, Colorado*

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ABSTRACT

A comparison of near-global monthly mean surface temperature anomalies to those of global Microwave Sounding Unit (MSU) 2R temperatures for 1979–95 reveals differences in global annual mean trends that are shown to be largely attributable to important physical differences in the quantities that are measured. Maps of standard deviations of the monthly mean anomalies, which can be viewed as mostly measuring the size of the climate signal, reveal pronounced differences regionally in each dataset. At the surface, the variability of temperatures is relatively small over the oceans but large over land, whereas in the MSU record the signal is much more zonally symmetric. The largest differences are found over the North Pacific and North Atlantic Oceans where the monthly standard deviations of the MSU temperatures are larger by more than a factor of 2. Locally over land, the variance of the surface record is larger than that of the MSU. In addition to differential responses to forcings from the El Niño–Southern Oscillation phenomenon and volcanic eruptions, these characteristics are indicative of differences of the response to physical processes arising from the relative importance of advection versus surface interactions and the different heat capacities of land and ocean. The result is that the regions contributing to hemispheric or global mean anomalies differ substantially between the two temperature datasets. This helps to account for the observed differences in decadal trends where the surface record shows a warming trend since 1979 of 0.18°C per decade, relative to the MSU record. While a common perception from this result is that the MSU and surface measurements of global temperature change are inconsistent, the issue should not be about which record is better, but rather that both give a different perspective on the same events.

1. Introduction

Reconstructions of global surface air temperature from the instrumental record have indicated that recent years have been among the warmest since at least the late nineteenth century, and 1995 was the warmest year on record (Fig. 1, see also Hansen et al. 1996). From 1979 through 1995, the rate of global surface warming estimated from annual mean anomalies has been 0.13°C per decade. This warming rate differs substantially from the cooling trend observed in global lower-tropospheric temperatures derived from satellite Microwave Sounding Unit (MSU) measurements. The decadal trend in MSU temperatures over the same 17-yr period is −0.05°C (Fig. 1; see also Christy et al. 1995). Linear global trends calculated over such short periods are simplistic and unreliable measures of temperature change because they are highly dependent on the periods of time examined and are sensitive to a number of sources of error (e.g., Karl et al. 1994). Nevertheless, Hansen et al. (1995) used data from a 3000-yr run of a global climate model to show that a difference in globally averaged decadal trends of surface and tropospheric temperature of the observed magnitude is not likely to occur by chance. Their conclusion is that the observed difference is probably meaningful and requires a physical explanation.

Reasons for differences between the global surface and MSU temperature records have been a matter of spirited debate. Claims and counterclaims have been made primarily concerning issues related to sampling and data reliability (e.g., Hansen and Wilson 1993; Hansen et al. 1995; Christy and Spencer 1995). Other studies have examined the differential effect of volcanic eruptions and the El Niño–Southern Oscillation (ENSO) phenomenon on trends in global surface and tropospheric air temperatures. Removing the linear influence of these phenomena leads to better agreement between the global MSU and surface temperature trends (Christy and McNider 1994; Jones 1994), but significant differences still exist.

An important point is that the MSU is monitoring a different physical quantity than surface air temperature, and the vertical structure of the temperature anomalies is one major factor in the expected differences between the climate signals in the two datasets. Time series of monthly 850–300-mb temperature anomalies from radiosondes are in good agreement with monthly MSU anomalies, and the 17-yr (1979–95) radiosonde trend

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Corresponding author address: Dr. James W. Hurrell, NCAR, P.O. Box 3000, Boulder, CO 80307-3000.

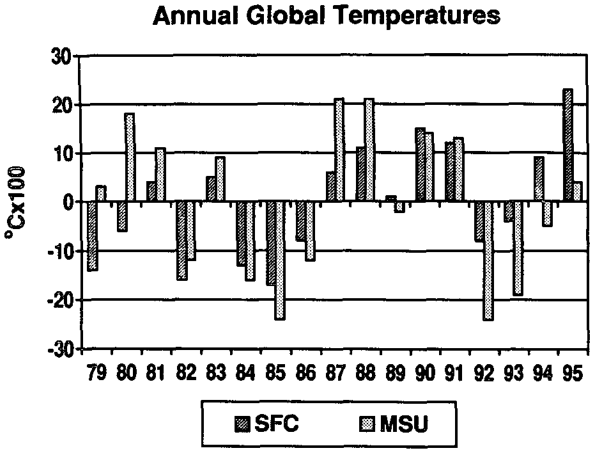

FIG. 1. Global annual mean temperature anomalies (×100°C) from the MSU 2R and surface datasets relative to the 1979–95 means.

is also ~ −0.05°C per decade (see also Christy 1995). The physical differences between the MSU and surface records has been addressed by Trenberth et al. (1992, hereafter TCH), and Hansen et al. (1995) have also proposed some physical reasons for the differences in trends. TCH compared surface air temperatures to data from MSU channel 2, which measures a vertically averaged atmospheric thermal emission that extends from the surface to the lower stratosphere. Based on comparisons with radiosonde data, Spencer and Christy (1992a) show that the channel 2 temperature weighting function peaks near 500 mb. Removal of the nontrivial stratospheric influence is obtained through a linear combination of channel 2 data from different view angles to provide an adjusted vertical weighting function (called MSU 2R), which peaks lower in the troposphere near 700 mb (Spencer and Christy 1992b). The MSU 2R data have been used in most of the more recent comparisons to surface air temperatures (e.g., Jones 1994; Christy 1995; IPCC 1996).

It is the purpose of this paper to expand upon some of the points made by TCH through a comparison of the surface to MSU 2R records and to clarify reasons for observed differences (Fig. 1). A considerable asset of the MSUs is that they obtain many observations globally each month to provide a highly consistent record. In contrast, the spatial and temporal coverage of surface observations is more sporadic, and large areas of the globe (such as the southern oceans) cannot be reliably analyzed (TCH; Karl et al. 1994). Our analysis shows, however, that a principle cause of the discrepancies in the MSU and surface trends arises from the physical differences in the quantities being measured. Large differences exist regionally in the size of the climate signal, as measured by the standard deviation of the monthly mean temperature anomalies, in each dataset. The result is that the regions contributing to the global mean anomalies differ substantially between the surface and MSU records. Thus, it becomes clear that the two estimates of global temperature anomalies differ even in the absence of sampling errors. This point seems to be frequently obscured, especially by those who point to the satellite record as proof that the surface temperature measurements cannot provide an adequate measure of climate change (e.g., Singer 1996).

2. The surface and MSU datasets

a. *Surface data*

Some studies of surface air temperature change have been made using the land-based meteorological station network (e.g., Hansen and Lebedeff 1987), but more often the surface data are a combination of near-surface air temperature anomalies over land areas merged with in situ sea surface temperature anomalies over marine areas. The surface dataset we use is of the latter type, and it is a version of the dataset used in the Intergovernmental Panel of Climate Change assessments (e.g., IPCC 1996). The development of this dataset has been documented in many papers, the most recent being Jones and Briffa (1992) and Parker et al. (1994).

Because sampling is a major problem over most oceanic regions and SSTs have much greater persistence, it has typically been preferred to use SSTs for monitoring anomalies in surface air temperatures. Large differences occur between marine air temperature (MAT) and SST in some places at certain times of the year, notably off the east coasts of North America and Asia and off Antarctica during winter where mean differences exceed 4°C (e.g., Trenberth et al. 1989), but it is generally expected that anomalies of MAT and SST will go hand in hand. TCH used data from the Comprehensive Ocean–Atmosphere Data Set (COADS, Slutz et al. 1985) and found this to be true for regional averages over the well-sampled northern oceans. Correlation coefficients between SST and MAT anomalies averaged over the North Atlantic and North Pacific basins were ~0.9, indicating that while there is a distinct difference between SST and MAT, 80% of the variance of one is captured by the other (see also Bottomley et al. 1990). Locally, however, the correlations are lower, especially in the Tropics (Fig. 2). In addition to the physical difference between SST and MAT, the patterns in Fig. 2 relate to the size of the climate signal versus the noise in each variable.

The noise in monthly mean SSTs depends on inherent uncertainties in individual measurements and their representativeness of a grid box average. TCH estimated that individual SST measurements from COADS are representative of the monthly mean in a 2° box to within a standard error ranging from 1.0°C in the Tropics to 1.4°C in the North Pacific. The total standard error of the monthly mean in each box is reduced approximately by the square root of the total number of observations. Overall noise was estimated by TCH to

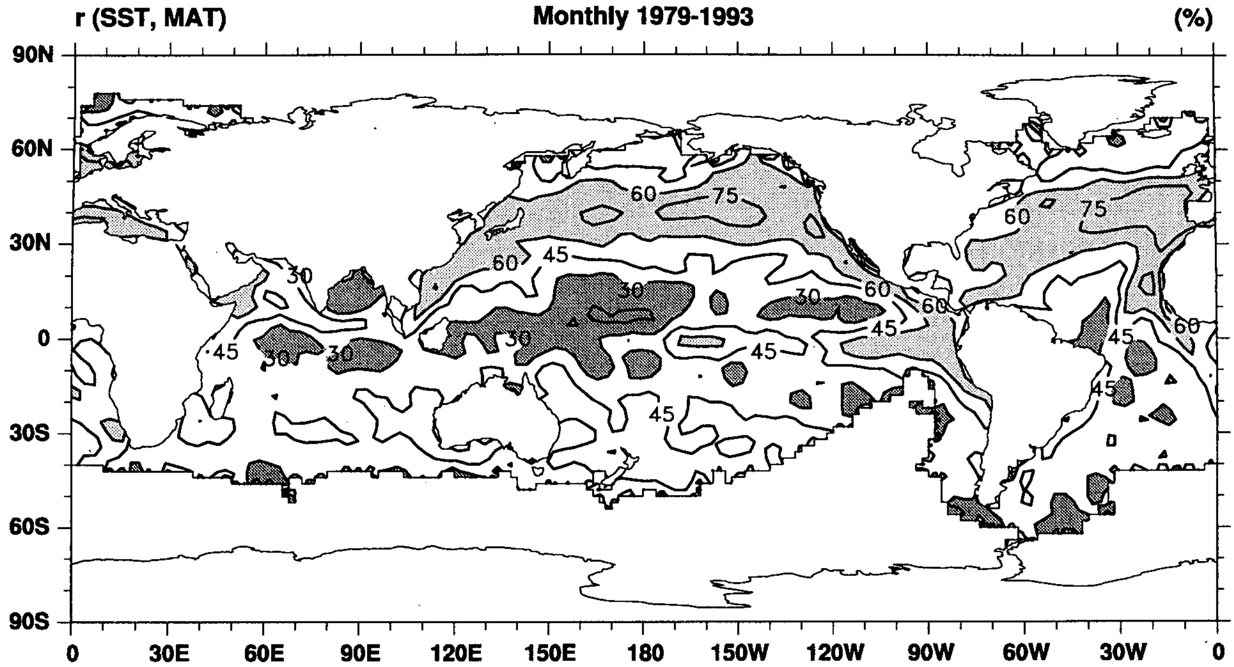

FIG. 2. Correlation coefficients over 180 months of COADS sea surface temperature and marine air temperature anomalies. Monthly anomalies were computed relative to the mean annual cycle for 1979–93. Coefficients less than 30% are indicated by the dark shading, and values greater than 60% are indicated by the light shading. The contour increment is 15%, and regions of insufficient data are not contoured. A nine-point smoother was applied to the results in this and all subsequent figures.

be ~0.06°C in the North Atlantic, with values a factor of 2 or more larger in regions of strong SST gradient such as the Gulf Stream. Noise estimates are ~0.1°C in the North Pacific and tropical Indian and Atlantic Oceans, but two to three times larger for the tropical and South Pacific and South Atlantic north of about 30°S. Farther south the noise generally exceeds 0.5°C except in ship tracks. For MAT, the diurnal cycle is larger than for SSTs, so more observations are needed to resolve the climate signal. The diurnal cycle is especially poorly sampled south of about 20°N where COADS data indicate that nearly 70% of MAT observations occur during daylight hours, and the percentage increases to nearly 90% south of about 40°S (not shown). Because of the contaminating effects of on-deck solar heating, only nighttime MATS have been preferred (Bottomley et al. 1990), but these data are not readily available from COADS. The within-month variance and the seasonal variability are also larger for MAT than for SST, which further contributes to a higher level of noise in MAT. Over the North Atlantic on average, TCH estimate that a factor of 2 to 3 more observations of MAT would be required to produce the same standard error of the monthly mean as for SST.

b. MSU data

The MSU 2R data are described by Spencer and Christy (1992b). The stability of the MSU data from one satellite to another is a key issue. Over much of the record since 1979, two MSUs on different National Oceanic and Atmospheric Administration (NOAA) satellites have sampled globally twice daily, although a few periods have existed when only a single satellite has been available (see Fig. 1 of Christy et al. 1995). Spencer and Christy (1992a) describe how the multisatellite data have been merged and how the effects of different satellite equator-crossing times, and thus diurnal cycle effects, are removed. They also show that the hemispheric means of tropospheric temperatures through 1990 are reproduced between different satellites to within approximately 0.01°C. Recent systematic problems with *NOAA-11* and *NOAA-12* resulted in a trend in the MSU 2R record, however, but the data we have accessed incorporate corrections for the spurious drift (Christy et al. 1995).

In evaluating the ability of the MSUs to measure tropospheric temperature fluctuations, Spencer and Christy (1992a) found that both monthly and annual MSU anomalies correlated from 0.90 to 0.98 with those from vertically weighted radiosonde temperature profiles from selected regions. Hurrell and Trenberth (1992) compared monthly MSU anomalies to weighted European Centre for Medium-Range Weather Forecasts monthly means and found that correlations exceeded 0.9 over most of the globe [see also Basist et al. (1995) for a comparison to National Centers for Environmental Prediction (NCEP) analyses]. The standard error of measurement for monthly gridpoint MSU 2R anomalies ranges from less than 0.1°C in the Tropics to 0.3°C over continental areas (Spencer and Christy 1992b; Christy and Spencer 1995), and monthly global anomalies are known to within 0.04°C. The conclusion is that the MSUs are highly suitable for monitoring intraseasonal to interannual temperature variations with global coverage.

For our purposes, MSU 2R temperatures were averaged into 5° boxes to coincide with the resolution of the surface data. The mean annual cycle for 1979–95 was subtracted from each dataset, with 12 years required to define the annual cycle, so that the analysis is of anomalies defined as the departures from the monthly means. The treatment of missing data can affect estimates of global annual mean anomalies by ~0.01°C (Fig. 1).

3. Comparison of the MSU and surface data

The correlation coefficients between the 204 monthly anomalies on the 5° grid reveal a very distinctive spatial pattern, with values ranging from near zero to over 0.9 (Fig. 3). The small differences between Fig. 3 and the correlations in TCH (their Fig. 1) occur because of updates to the surface and MSU datasets and because of differences in the vertical atmospheric profiles that contribute energy to the MSU 2R versus channel 2 data used in TCH. As expected, with the removal of the stratospheric influence, correlation coefficients between MSU 2R and surface anomalies are slightly higher than with channel 2 anomalies, which is why the MSU 2R data have been used in many of the recent comparison studies.

The highest correlation coefficients, of >0.75, are found across the middle and high latitudes of Europe, Asia, and North America (Fig. 3). Correlations are generally much less (~0.5) over the tropical continents and the North Atlantic and North Pacific Oceans. Correlations of less than 0.3 occur over the tropical and southern oceans and are lowest (<0.15) in the tropical western Pacific. Relatively high correlation coefficients (>0.6) are found over the tropical eastern Pacific where the ENSO signal is large.

Differences between the MSU and surface records are found where there is some degree of decoupling in the vertical between the surface and the lower to middle troposphere. For instance, Spencer and Christy (1992a) found that monthly mean temperatures for the layer from 1000 to 700 mb were correlated with MSU values < 0.4 at Hawaii and Guam in the tropical Pacific, resulting from the trade wind inversion that decouples the surface boundary layer from the free atmosphere over much of the Tropics. Shallow temperature inversions are also commonly found over land in winter, especially in high latitudes, and this contributes to occasional large discrepancies in individual monthly anomalies (see Fig. 5 in TCH).

More important than correlations for trends, however, are the absolute and root mean square (rms) dif-

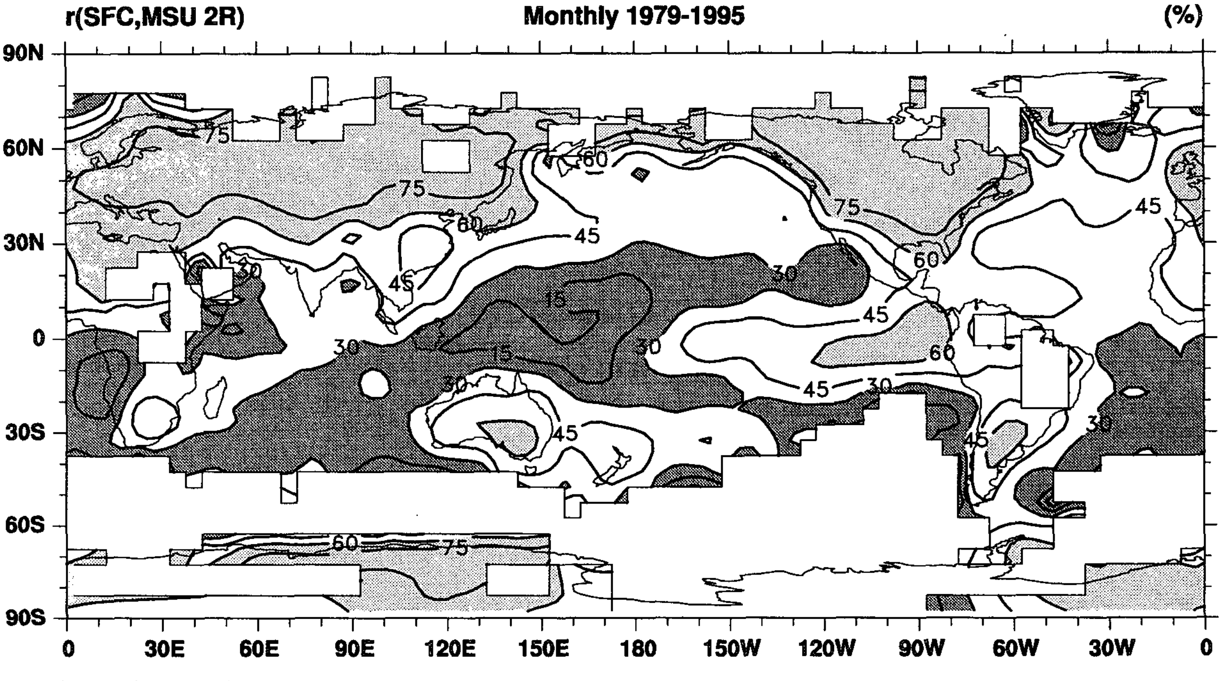

FIG. 3. Correlation coefficients over 204 months of MSU 2R and surface temperature anomalies. Monthly anomalies were computed relative to the mean annual cycle for 1979–95. Values less than 30% are indicated by the dark shading, and values greater than 60% are indicated by the light shading. The contour increment is 15%, and regions of insufficient data are not contoured.

ferences between the two records. These also help to account for the differences in correlation coefficient because of the size and persistence of the signal, relative to the noise in the data. A map of standard deviations of monthly mean anomalies from the surface and MSU 2R records (Fig. 4) shows that the largest signal in both datasets is over the Northern Hemisphere (NH) continents. The MSU 2R standard deviations are more zonally symmetric, however. The standard deviation over the oceans in the surface dataset is much smaller than over land except where the ENSO phenomenon is prominent. The lowest correlation coefficients in Fig. 3 occur where the standard deviation is small in the surface data, implying that noise arising from errors in measurements, and spatial and temporal sampling might account for a substantial part of the total variance in these regions.

The differences in Fig. 4 are highlighted by the ratio of the standard deviations of the monthly anomalies (Fig. 5). The largest ratios are found over the North Pacific and North Atlantic, where the MSU 2R standard deviations are larger by more than a factor of 2. Over the NH continents the ratios are closer to unity, but with the MSU 2R anomalies exhibiting slightly less variance

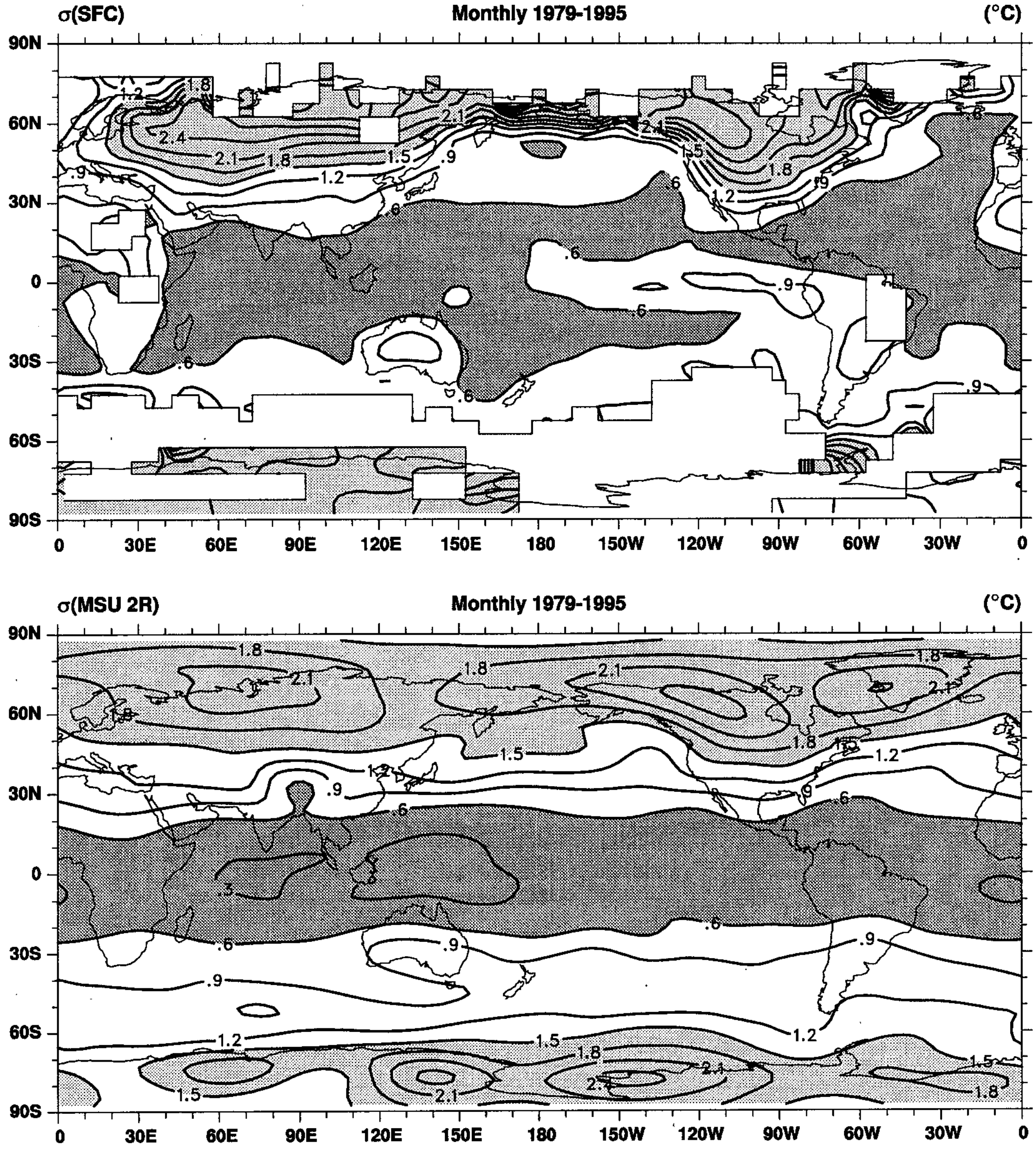

FIG. 4. The standard deviation over 204 months (1979–95) of (top) surface temperature anomalies and (bottom) MSU 2R anomalies. The contour increment is 0.3°C, values less than 0.6°C are indicated the dark shading, and values greater than 1.5°C are indicated by the light shading. Regions of insufficient data are not contoured in the top panel.

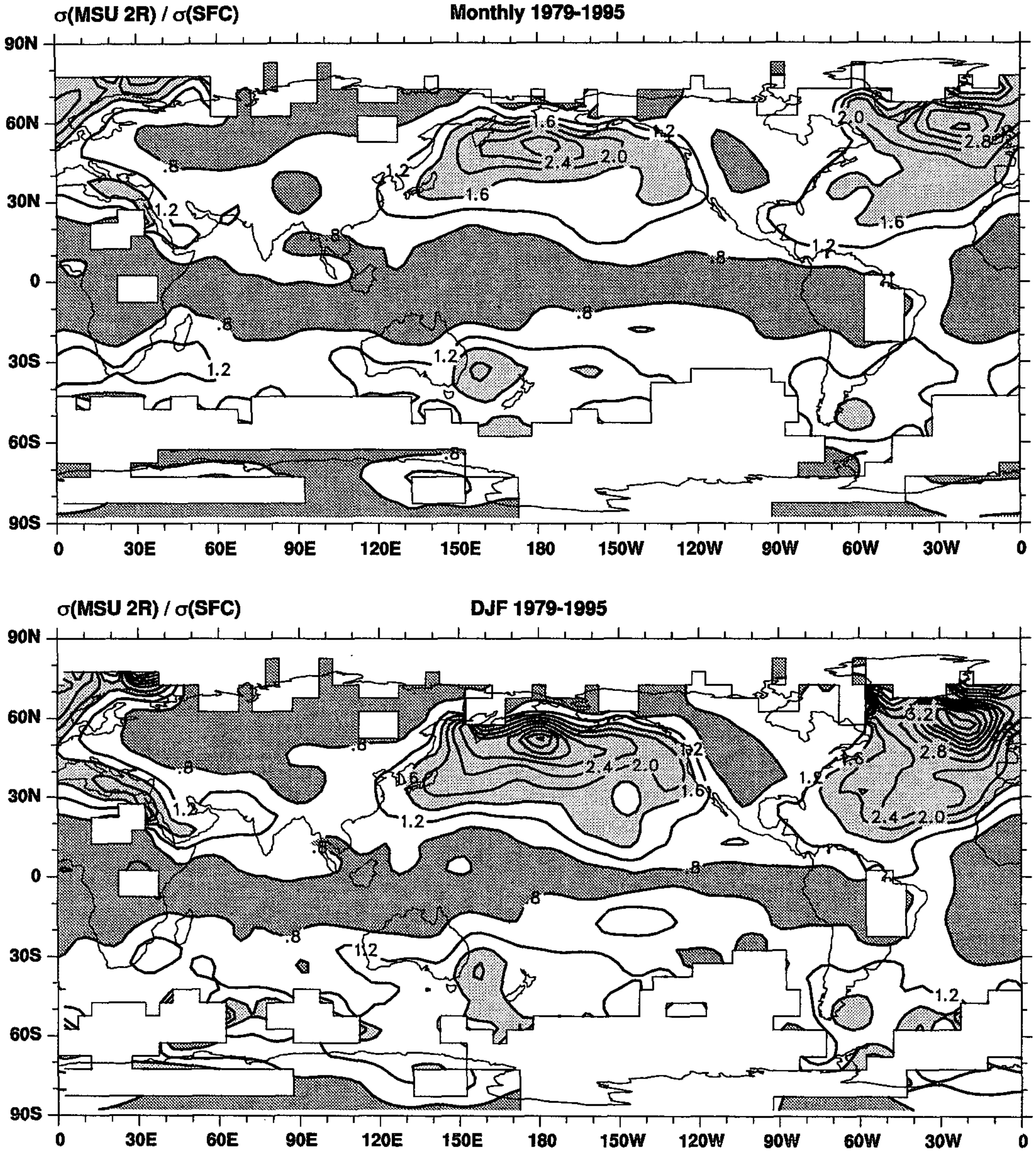

FIG. 5. The ratio of the standard deviations of the MSU 2R and surface temperature anomalies over (top) the 204 months from 1979 to 1994 and (bottom) the 48 winter months (December–February) over the same years. The contour increment is 0.4, and regions of insufficient data are not contoured. Values less than 0.8 are given by the dark shading, and values greater than 1.6 by the light shading.

than the surface temperatures (see also Table 1 of TCH and Table 3 of Christy 1995). These characteristics are most pronounced during northern winter (Fig. 5), especially over the northern oceans where the standard deviations of temperatures from MSU 2R are more than three times larger than those for the surface.

4. Physical reasons for differences

The different patterns of temperature variance at the surface and in the lower troposphere (Figs. 4 and 5), and therefore in the static stability of the atmosphere, are indicative of differences in physical processes over the oceans versus the continents. It is not the purpose of this paper to fully document this aspect, but we provide a brief discussion of the processes involved. Of particular importance are the roles of the land surface and ocean as the lower boundary for the atmosphere, their very different heat capacities and, thus, the different surface fluxes into the atmosphere, as well as the role of the atmospheric winds that help to ameliorate the differences through heat advection and convergence as the flow goes between the land and the ocean.

The differences in heat capacity are well known and relate to ''continentality.'' Over land, heat storage and heat penetration into the surface involves only the upper few meters. The specific heat of soils is roughly a factor of 4.5 less than that of sea water, although the factor is probably closer to 2 for moist soils (Trenberth 1993). Consequently, the heat capacity of a land surface is less than that of 2 m of the ocean. Similarly, the heat capacity of the atmosphere is equivalent to that of only about 3 m of the ocean. In contrast, mixing and convection in the ocean result in an active mixed layer typically of 50-m depth but ranging from about 20 m or so in summer to over 100 m in winter (e.g., Meehl 1984). Therefore, the same heating over land, when confined to a vertical column, is apt to result in a greater response in temperature change over land by a factor of >25. This reasoning neglects the partitioning of heating into sensible and latent components, but serves to illustrate the point that this factor is much greater than the observed factor of up to 5 (Fig. 5), and the reason is the atmospheric winds.

The evidence for the moderating influence of the atmospheric winds can be seen in the heat budget computations of Trenberth and Solomon (1994). We have used the NCEP reanalyses (Kalnay et al. 1996) to reevaluate the heat budget and the total vertically integrated energy transport by the atmosphere in January 1986, which is a typical northern winter month (Fig. 6). The energy transport includes a very small component from kinetic energy, but the largest component in the extratropics is from the dry static energy, which dominates over the latent energy component (Trenberth and Solomon 1994). In addition to the strong poleward component (Fig. 6), there is a pronounced divergence of heat from over the northern oceans in winter to a convergence of heat over the continents of about 100 W m^{-2} (see Fig. 13 of Trenberth and Solomon 1994). Therefore, advection by winds contributes to the more zonally symmetric variances in the MSU 2R temperatures, while surface processes play a more dominant role in the determination of surface temperatures, as follows.

The largest differences in the variances of MSU 2R and surface temperature anomalies are apparent in the northern winter (Fig. 5) when the MSU 2R record has somewhat lower variance over the northern continents but much larger variance over the northern oceans. At this time of year, the continents are the source of cold and dry air masses. When they migrate eastward over the adjacent oceans, large sensible and latent heat fluxes occur from the ocean into the atmosphere that can reach >1000 W m^{-2} in individual events over the course of a day (e.g., Smith and Dobson 1984; Neiman and Shapiro 1993) and over 300 W m^{-2} over monthly and seasonal averages off the east coasts of North America and Asia (e.g., Trenberth and Solomon 1994; Da Silva et al. 1994). These fluxes warm and moisten the low layers of the atmosphere and typically lead to shallow cellular cumulus convection, so that increases in both water vapor and cloud contribute further to warming through a greenhouse effect. At the same time, although the heat loss from the ocean surface triggers surface cooling, wind-induced mixing and convection in the ocean occur often down to several hundred meters, so that the result is only small changes in SST (e.g., Killworth 1983; Large et al. 1986). A consequence of these processes is that the SST and near-surface air temperatures are considerably moderated in response to such cold-air outbreaks over the northern oceans, much more so than for tropospheric temperatures.

Alternatively, when relatively moist and warm maritime air masses are advected over the continents in winter, the absence of heat storage in the ground means that radiative cooling, especially associated with the diurnal cycle, will quickly modify the surface air by cooling and drying the atmosphere through a shallow layer. The formation of temperature inversions allows much larger variations in surface conditions than in the free atmosphere, and the latter is decoupled from the surface. Thus, even though the MSU and surface temperature records are highly correlated over the northern continents (Fig. 3), the magnitude of the signal is quite different, and large discrepancies are found in the monthly means (TCH).

In recent years, the predominant warming in the northern winter has occurred over the continents, while negative temperature anomalies are found over the North Atlantic and North Pacific Oceans (Hurrell 1996). These patterns of surface temperature change are related to the tendency for strong positive values of the North Atlantic Oscillation (Hurrell 1995) and negative values of the Southern Oscillation, accompanying persistently above-average SSTs in the tropical Pacific (Trenberth and Hoar 1996). Changes in atmospheric circulation account for 47% of the variance in surface temperature anomalies north of 20°N (Hurrell 1996) and indicate that there has been an amplification of the upward trend in surface temperatures because of the factors listed above (see also Wallace et al. 1995). At the same time, the cooling over the oceans contributes much more to the MSU record, so that these changes help account for the discrepancy between trends in MSU 2R and surface air temperatures.

These aspects are further illustrated in Fig. 7, which shows the correlation coefficients between the globally averaged monthly anomalies and the monthly anomalies on the 5° grid for both the surface and MSU 2R records. The highest correlations in the surface data (~0.4) occur over the NH continents, and correlations elsewhere are generally much lower. In contrast, the globally averaged MSU 2R anomalies are most strongly correlated with gridpoint anomalies throughout the Tropics. The lower correlation coefficients

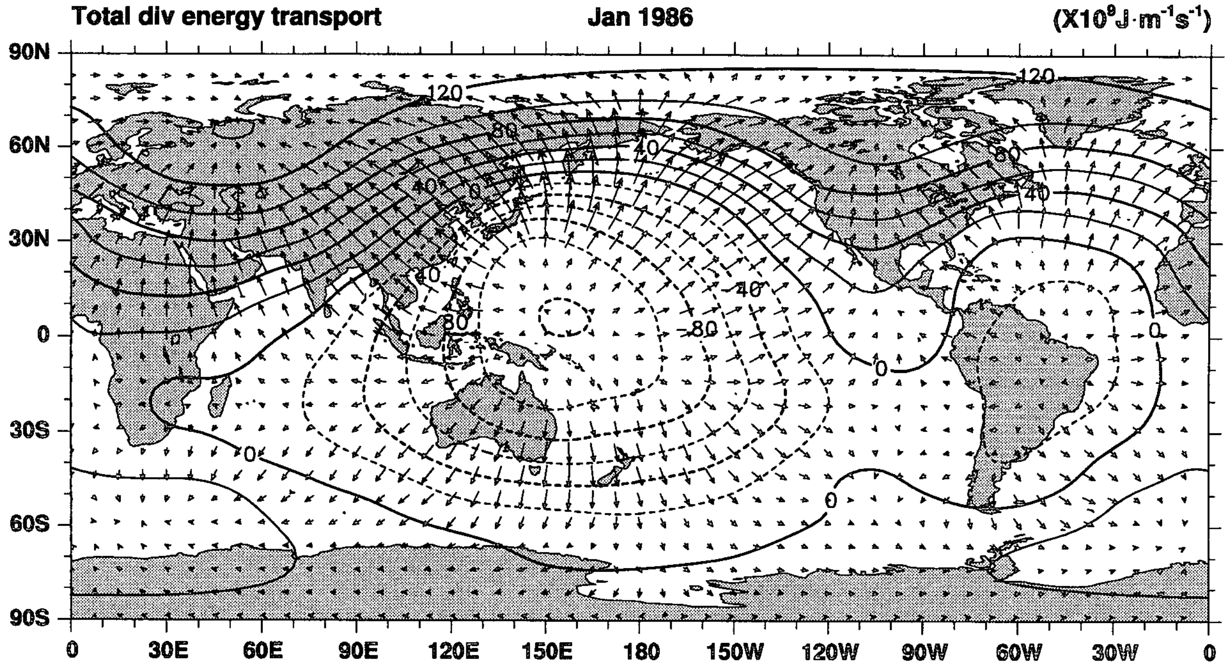

FIG. 6. Total (stationary plus transient) divergent energy transport for January 1986 truncated to T31 resolution. The largest vector corresponds to 0.6 × 10^9 J m^{-1} s^{-1}, and the potential function is in 10^{13} J s^{-1}.

throughout the extratropics of both hemispheres illustrates the cancellation of large regional anomalies in the MSU 2R record.

Dividing the globe into three roughly equal parts helps provide further insight. Over the NH extratropics (20°–90°N) the decadal trend since 1979 in the MSU 2R record is 0.07°C compared to 0.25°C in the surface record, which exemplifies the larger contribution of the cooling over the oceanic regions in the satellite data. Over the Tropics (20°S–20°N) and the Southern Hemisphere (SH) extratropics (90°–20°S), however, the MSU 2R linear trends are both −0.11°C per decade, while the rate of tropical and SH extratropical surface warming is 0.10°C and 0.03°C per decade, respectively. Therefore, the downward trend in MSU 2R anomalies relative to the surface record is global and cannot be fully accounted for by the aforementioned physical differences between the two quantities.

5. Discussion and conclusions

At the core of the debate of anthropogenic climate change is the observation that global mean surface temperatures have risen 0.2° to 0.3°C over the past four decades when the surface measurements are considered to have been most accurate (IPCC 1996). Moreover, results of climate model integrations indicate that temperature increases resulting from enhanced greenhouse gas concentrations will be more widespread and, perhaps, greater in the lower to middle troposphere than at the surface (IPCC 1996). Yet, the decadal trend in MSU 2R temperatures since 1979 shows cooling, albeit over a limited number of years (Fig. 1). It should be noted that tropospheric temperatures from radiosonde information have increased since 1958 by 0.09°C per decade, so that the longer-term trend is distinctly upward and equivalent to that of the surface (Jones 1994; IPCC 1996). When ENSO and volcanic effects are removed from the MSU and surface records, both show warming since 1979, but the surface still warms at about 0.08°C per decade, relative to the MSU data (Jones 1994). Questions arise, therefore, as to whether the observed differences point to problems in the surface record because of measurement errors and other sampling issues, or possibly to systematic errors and noise in the MSU record. While this may be the case, this paper emphasizes that there are other factors that need to be considered that help account for the differences.

There are a number of sources of the discrepancy between the trends in the MSU and surface temperature records. The surface record is not fully global (the main areas missing are shown in Fig. 3), so estimates of the global mean temperature will be biased; however, sampling biases are not large enough to account for the observed differences in trend (e.g., Madden and Meehl 1993). Karl et al. (1994) have shown that a positive bias of ~0.05°C per decade exists in the global surface temperature trend since 1979, as a result of an oversampling of the NH midlatitudes and the undersam-

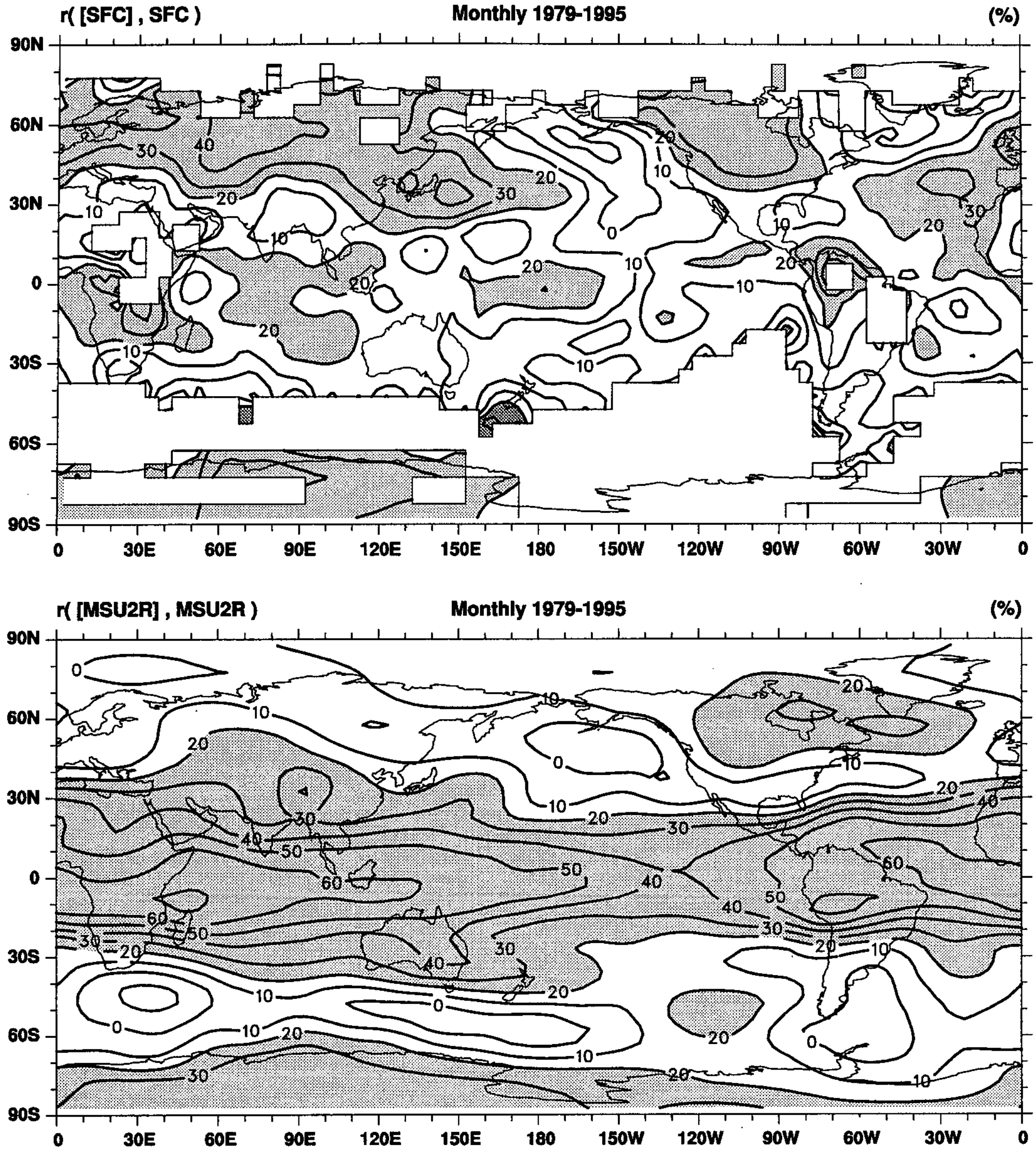

FIG. 7. Correlation coefficients over 204 months between globally averaged monthly anomalies and the monthly gridpoint anomalies for (top) the surface temperature record and (bottom) the MSU 2R record. Monthly anomalies were computed relative to the mean annual cycle for 1979–95. Values less than −20% are indicated by the dark shading, and values greater than 20% are indicated by the light shading. The contour increment is 10%, and regions of insufficient data are not contoured in the top panel.

pling of the Tropics and the high latitudes of the SH. Also, with the exception of the eastern tropical Pacific, where the large El Niño signal is easily detected, the signal-to-noise level of the in situ observations decreases substantially south of about 10°N, and the overall local noise in monthly mean SSTs exceeds 0.5°C over the ocean south of about 35°S (TCH). There are potential shortcomings of the MSU record as well. Several sources of noise, such as differing numbers of observations available on a daily basis, discontinuities associated with changes in satellites, different satellite equator-crossing times that result in sampling biases associated with the diurnal cycle, contamination of the MSU signal from precipitation-sized ice in deep convection, cloud water, water vapor and surface emissivity (Spencer et al. 1990), and instrumental drift (Christy et al. 1995) might all contaminate the MSU record. Moreover, MSU 2R retrievals contain greater noise than MSU channel 2 because of the magnification of small differences between the relatively large radiances from multiangle views. MSU 2R retrievals also lack limb correction and retain fewer observations. Careful steps have been taken, however, to ensure that these problems have been documented and corrections have been applied.

We have shown that very important sources of differences between the MSU 2R and surface temperature records are the physical differences between the quantities being measured that arise from the relative importance of advection versus surface interactions and the effects of continentality (revealed by Figs. 4 and 5). At the surface, the variability of temperatures over land is much greater than that over the oceans (Fig. 4), which reflects the very different heat capacities of the underlying surface and the depth of the layer linked to the surface. Consequently, temperature changes tend to be amplified over the continents in response to changes in circulation. Hemispheric or global averages of mean surface air temperature are, therefore, largely determined by the temperature of the continents (Figs. 4 and 7). The standard deviation of the monthly MSU 2R anomalies has a much more zonally symmetric structure (Figs. 4 and 5), so that relative to the surface there is a much larger contribution from the northern oceans and a generally smaller contribution over land and near the equator to the hemispheric and global means. Changes in circulation over the past two decades have resulted in a surface temperature anomaly pattern of warmth over the continents and coolness over the oceans (Wallace et al. 1995; Hurrell 1996). This pattern of temperature change helps account for the discrepancy between trends in MSU 2R and surface air temperatures. The surface record is dominated by the continental warming, whereas the cooling over the oceans contributes much more to the MSU record.

In addition, physical differences between the two measures of temperature are evident in their dissimilar responses to volcanic eruptions, ENSO, and changes in stratospheric ozone. Of particular note are the much colder anomalies in the MSU record in 1992 and 1993 over the entire globe (Fig. 1), which evidently occur in part from the greater effect of Mt. Pinatubo on tropospheric temperatures. During these 2 years, MSU 2R anomalies were ~0.15°C colder than surface anomalies over the Tropics (20°S–20°N). Differences in tropical anomalies of this magnitude have also persisted over the past 2 years for reasons not as well understood since cooling from Mt. Pinatubo should have diminished. The largest positive disparity between tropical temperatures occurred during 1979 and 1980 when MSU 2R anomalies were more than 0.25°C warmer than the surface record. Hansen et al. (1995) have suggested that the effects of depletion of stratospheric ozone on the MSU record could be important, and the warm years of 1979–80 correspond to a period of relatively high ozone levels. While the vertical profiles of ozone changes are uncertain, Ramaswamy et al. (1996, manuscript submitted to *Nature*) have shown how tropospheric temperatures are cooled by stratospheric ozone losses. In addition, in the Tropics where differences in trends remain substantial, the surface is disconnected from the free troposphere by the trade wind inversion, so that differences in response to ENSO are not surprising. Nevertheless, the added warmth in MSU 2R at the beginning of the record and the relative cooling in recent years magnifies the trend difference, which is not fully explained. It is, therefore, the subject of ongoing research.

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REFERENCES

Basist, A. N., C. F. Ropelewski, and N. C. Grody, 1995: Comparison of tropospheric temperature derived from the Microwave Sounding Unit and the National Meteorological Center analysis. *J. Climate,* **8,** 668–681.

Bottomley, M., C. K. Folland, J. Hsiung, R. E. Newell, and D. E. Parker, 1990: *Global Ocean Surface Temperature Atlas.* U.K. Meteorological Office, 20 pp. and 313 plates.

Christy, J. R., 1995: Temperature above the surface layer. *Climate Change,* **31,** 455–474.

——, and R. T. McNider, 1994: Satellite greenhouse warming. *Nature,* **367,** 325.

——, and R. W. Spencer, 1995: Assessment of precision in temperatures from the microwave sounding units. *Climate Change,* **30,** 97–102.

——, ——, and R. T. McNider, 1995: Reducing noise in the MSU daily lower-tropospheric global temperature dataset. *J. Climate,* **8,** 888–896.

Da Silva, A. M., C. C. Young, and S. Levitus, 1994: *Atlas of Surface Marine Data 1994.* Vol. 3, *Anomalies of Heat and Momentum Fluxes,* National Oceanic and Atmospheric Administration, 413 pp.

Hansen, J., and S. Lebedeff, 1987: Global trends of measured surface air temperature. *J. Geophys. Res.,* **92,** 13 345–13 372.

——, and H. Wilson, 1993: Commentary on the significance of global temperature records. *Climate Change,* **25,** 185–191.

——, ——, M. Sato, R. Ruedy, K. Shah, and E. Hansen, 1995: Satellite and surface temperature data at odds? *Climate Change,* **30,** 103–117.

——, R. Ruedy, M. Sato, and R. Reynolds, 1996: Global surface air temperature in 1995: Return to pre-Pinatubo level. *Geophys. Res. Lett.,* in press.

Hurrell, J. W., 1995: Decadal trends in the North Atlantic oscillation regional temperatures and precipitation. *Science,* **269,** 676–679.

——, 1996: Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperature. *Geophys. Res. Lett.,* **23,** 665–668.

——, and K. E. Trenberth, 1992: An evaluation of monthly mean MSU and ECMWF global atmospheric temperatures for monitoring climate. *J. Climate,* **5,** 1424–1440.

IPCC, 1996: *Climate Change 1995: The Science of Climate Change.* Cambridge University Press, 572 pp.

Jones, P. D., 1994: Recent warming in global temperature series. *Geophys. Res. Lett.,* **21,** 1149–1152.

——, and K. R. Briffa, 1992: Global surface air temperature variations over the twentieth century. Part 1: Spatial, temporal and seasonal details. *Holocene,* **2,** 174–188.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Karl, T. R., R. W. Knight, and J. R. Christy, 1994: Global and hemispheric temperature trends: Uncertainties related to inadequate spatial sampling. *J. Climate,* **7,** 1144–1163.

Killworth, P. D., 1983: Deep convection in the world ocean. *Rev. Geophys. Space Phys.,* **21,** 1–26.

Large, W. G., J. C. McWilliams, and P. P. Niiler, 1986: Upper ocean thermal response to strong autumnal forcing in the northeast Pacific. *J. Phys. Oceanogr.,* **16,** 1524–1549.

Madden, R. A., and G. A. Meehl, 1993: Bias in the global mean temperature estimated from sampling a greenhouse warming pattern with the current surface observing network. *J. Climate,* **6,** 2486–2489.

Meehl, G. A., 1984: A calculation of ocean heat storage and effective ocean surface layer depths for the Northern Hemisphere. *J. Phys. Oceanogr.,* **14,** 1747–1761.

Nieman, P. J., and M. A. Shapiro, 1993: The lifecycle of an extratropical marine cyclone. Part I: Frontal-cyclone evolution and thermodynamic air–sea interaction. *Mon. Wea. Rev.,* **121,** 2153–2176.

Parker, D. E., P. D. Jones, C. K. Folland, and A. Bevan, 1994: Interdecadal changes of surface temperatures since the late 19th century. *J. Geophys. Res.,* **99,** 14 373–14 399.

Ramaswamy, V., M. D. Schwarzkopf, and W. J. Randel, 1995: An unanticipated climate change in the global lower stratosphere due to ozone depletion. *Nature,* in press.

Singer, S. F., 1996: Climate change and consensus. *Science,* **271,** 581–582.

Slutz, R. J., S. J. Lubker, J. D. Hiscox, S. D. Woodruff, R. L. Jenne, D. H. Joseph, P. M. Steurer, and J. D. Elms, 1985: COADS: Comprehensive Ocean–Atmosphere Data Set. Tech. Release 1, 262 pp. [Available from NOAA/ERL/CDC, 325 Broadway, Boulder, CO 80303.]

Smith, S. D., and F. W. Dobson, 1984: The heat budget at ocean weather station Bravo. *Atmos.–Ocean,* **22,** 1–22.

Spencer, R. W., and J. R. Christy, 1992a: Precision and radiosonde validation of satellite gridpoint temperature anomalies. Part I: MSU channel 2. *J. Climate,* **5,** 847–857.

——, and ——, 1992b: Precision and radiosonde validation of satellite gridpoint temperature anomalies. Part II: A tropospheric retrieval and trends during 1979–90. *J. Climate,* **5,** 858–866.

——, ——, and N. C. Grody, 1990: Global atmospheric temperature monitoring with satellite microwave measurements: Method and results 1979–1984. *J. Climate,* **3,** 1111–1128.

Trenberth, K. E., 1993: Northern hemisphere climate change: Physical processes and observed changes. *Earth System Responses to Global Change: Contrasts Between North and South America.* H. A. Mooney, E. R. Fuentes, and B. I. Kronberg, Eds., Academic Press, 35–59.

——, and A. Solomon, 1994: The global heat balance: Heat transports in the atmosphere and ocean. *Climate Dyn.,* **10,** 107–134.

——, and T. J. Hoar, 1996: The 1990–1995 El Niño–Southern Oscillation event: Longest on record. *Geophys. Res. Lett.,* **23,** 57–60.

——, J. G. Olson, and W. G. Large, 1989: A global ocean wind stress climatology based on ECMWF analyses. NCAR Tech. Note NCAR/TN-338+STR, 93 pp. [Available from NCAR, P.O. Box 3000, Boulder, CO 80307.]

——, J. R. Christy, and J. W. Hurrell, 1992: Monitoring global monthly mean surface temperatures. *J. Climate,* **5,** 1405–1423.

Wallace, J. M., Y. Zhang, and J. A. Renwick, 1995: Dynamic contribution to hemispheric mean temperature trends. *Science,* **270,** 780–783.