Difficulties in Obtaining Reliable Temperature Trends: Reconciling the Surface and Satellite Microwave Sounding Unit Records

JAMES W. HURRELL AND KEVIN E. TRENBERTH

National Center for Atmospheric Research, Boulder, Colorado*

(Manuscript received 10 March 1997, in final form 28 August 1997)

ABSTRACT

A chronic difficulty in obtaining reliable climate records from satellites has been changes in instruments, platforms, equator-crossing times, and algorithms. The microwave sounding unit (MSU) tropospheric temperature record has overcome some of these problems, but evidence is presented that it too contains unreliable trends over a 17-yr period (1979–95) because of transitions involving different satellites and complications arising from nonatmospheric signals associated with the surface. The two primary MSU measures of tropospheric temperature contain different error characteristics and trends. The MSU channel 2 record exhibits a slight warming trend since 1979. Its broad vertical weighting function means that the temperature signal originates from throughout the troposphere and part of the lower stratosphere; intersatellite comparisons reveal low noise levels. Off-nadir channel 2 data are combined to provide an adjusted weighting function (called MSU 2R) without the stratospheric signal, but at a cost of an increased influence of surface emissions. Land surface microwave emissions, which account for about 20% of the total signal, depend on ground temperature and soil moisture and are subject to large variations associated with the diurnal cycle. The result is that MSU 2R noise levels are a factor of 3 larger than for MSU 2 and are sufficient to corrupt trends when several satellite records are merged.

After allowing for physical differences between the satellite and surface records, large differences remain in temperature trends over the Tropics where there is a strong and deterministic coupling with the surface. The authors use linear regression with observed sea surface temperatures (SSTs) and an atmospheric general circulation model to relate the tropical MSU and surface datasets. These and alternative analyses of the MSU data, radiosonde data, and comparisons between the MSU 2R and channel 2 records, with estimates of their noise, are used to show that the downward trend in tropical MSU 2R temperatures is very likely spurious. Tropical radiosonde records are of limited use in resolving the discrepancies because of artificial trends arising from changes in instruments or sensors; however, comparisons with Australian radiosondes show a spurious downward jump in MSU 2R in mid-1991, which is not evident in MSU 2. Evaluation of reanalyzed tropical temperatures from the National Centers for Environmental Prediction and the European Centre for Medium-Range Weather Forecasts shows that they contain very different and false trends, as the analyses are only as good as the input database.

Statistical analysis of the MSU 2R record objectively identifies two stepwise downward discontinuities that coincide with satellite transitions. The first is in mid-1981, prior to which only one satellite was in operation for much of the time so the diurnal cycle was not well sampled. Tropical SST anomalies over these years were small, in agreement with the Southern Oscillation index, yet the MSU 2R values were anomalously warm by ~0.25°C. The second transition from *NOAA-10* to *NOAA-12* in mid-1991 did not involve an overlap except with *NOAA-11*, which suffered from a large drift in its equator-crossing times. MSU 2R anomalies have remained anomalously cold since mid-1991 by ~0.1°C. Adding the two stepwise discontinuities to the tropical MSU 2R record allows it to be completely reconciled with the SST record within expected noise levels. The statistical results also make physical sense as the tropical satellite anomalies are magnified relative to SST anomalies by a factor of ~1.3, which is the amplification expected following the saturated adiabatic lapse rate to the level of the peak weighting function of MSU 2R.

1. Introduction

Global temperatures estimated from 850- to 300-mb radiosonde data have increased on average by 0.09°C decade^{-1} since 1958, a trend that is distinctly upward and equivalent to the observed rate of warming at the surface (Jones 1994; IPCC 1996). Over the much shorter period 1979–95, however, the rate of global surface warming has been 0.13°C decade^{-1}, compared to a cooling of −0.05°C decade^{-1} in global lower-tropospheric temperatures derived from satellite microwave sounding unit (MSU) measurements known as MSU 2R (see section 3) (Hurrell and Trenberth 1996; see also Christy 1995). The absence of upward trends in the recent satellite record has been used by some as ''proof'' that global warming is not occurring and that the instru-

* The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Corresponding author address: James W. Hurrell, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307.
E-mail: jhurrell@ncar.ucar.edu

mental record of surface temperatures cannot provide a reliable measure of climate change. Such hyperbole is centered on arguments concerning issues of sampling and data reliability of the surface record, implying that the only credible estimates of recent temperature trends are attainable through the global coverage of the MSUs. Results from this study challenge this view and show that, in reality, a number of factors contribute to the differences between the two records of temperature, including problems with the MSU record that cast doubt on the reliability of the satellite trends.

One issue often overlooked is that there is no *single* MSU record and different tropospheric measures of temperature from the MSUs contain different trends and different error characteristics. For instance, the trend since 1979 in global anomalies from MSU channel 2, which is representative of the middle troposphere and is believed to be more reliable than the MSU 2R record for reasons discussed below, is 0.02°C decade^{-1}. Certainly, linear global trends calculated over such short (i.e., 17 yr) 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).

Another important factor is that the surface and MSU records measure different physical quantities so that decadal trends should not be expected to be the same (Hansen et al. 1995; Hurrell and Trenberth 1996), especially in the presence of strong interannual variability associated with volcanic eruptions and El Niño–Southern Oscillation (ENSO) events (Christy and McNider 1994; Jones 1994). Both the surface and the satellite temperature records, furthermore, have advantages and disadvantages. The surface record extends back to the middle of the last century, but the spatial and temporal coverage is sporadic and large areas of the globe cannot be reliably analyzed (Trenberth et al. 1992; Karl et al. 1994). The space-based measurements are derived from many observations globally each month, yet they suffer from discontinuous segments from different satellites, and the MSUs sample layers of the atmosphere that include nontrivial contributions from the surface and/or the stratosphere. These factors lead to problems that make decadal trends from satellite measurements unreliable.

In this paper we specify and attempt to resolve these issues with a focus on the discrepancies that remain between the MSU and surface records after physical differences between them are taken into account. The discrepancies are especially evident in the Tropics in regions where there are few reliable radiosonde records from which to gain insight. In fact, we have not been able to fully resolve all of the questions, but we use global reanalyses from the National Centers for Environmental Prediction (NCEP; Kalnay et al. 1996) and the European Centre for Medium-Range Weather Forecasts (ECMWF; Gibson et al. 1996), simulations with the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM3) integrated with specified observed sea surface temperatures (SSTs), alternative analyses of the MSU data, radiosonde data, and comparisons between the different MSU records of tropospheric temperature along with estimates of their noise (as borne out by intersatellite comparisons) to show that the cumulative evidence is strongly suggestive that the downward trend in MSU lower-tropospheric temperatures is spurious and arises from difficulties in matching records between satellites compounded by surface emission influences. The latter add considerable noise, especially over land, while the merging of satellite records requires long overlaps between different satellites and stable orbits that are not always achieved (Christy et al. 1995; Christy et al. 1998).

In section 2 we summarize some factors that contribute to discrepancies between the surface and MSU records. These include physical differences between temperature records at the surface and in the troposphere, and the quality of the records, especially with respect to spatial sampling. We also explain why trends computed from radiosonde data are, in general, limited in their ability to validate the MSU trends. Section 3 provides a very brief description of the MSU data. Results from comparisons between MSU and surface records, between different MSU retrievals, between records from MSU and CCM3 simulations, NCEP and ECMWF reanalyses and selected radiosonde records, and results from an alternative analysis of the MSU data are given in section 4. Discussion of the comparison results is provided in section 5, along with a more detailed analysis of the MSU data with foci on the issues of merging different satellite records and contamination from surface emissions. Concluding remarks are given in section 6. The validity of using the CCM3 as a tool in the analysis is briefly demonstrated in appendix A, while the utility of radiosonde data from Australia is discussed in appendix B.

2. Background

a. Physical differences

The physical differences between the MSU and surface records were first addressed by Trenberth et al. (1992), and Hansen et al. (1995) have also proposed some physical reasons for the differences in decadal trends. Trenberth et al. (1992) compared surface air temperatures with data from MSU channel 2, which has a weighting function that peaks near 500 mb (Fig. 1; Spencer and Christy 1992a). They found that gridpoint correlation coefficients between monthly surface and MSU anomalies revealed very distinctive patterns, with values ranging from less than zero to over 0.9. These patterns were explained in part by spatial variations in the climate signal and its masking by inherent noise in the surface observations, and in part by differences between the two temperature records, which were es-

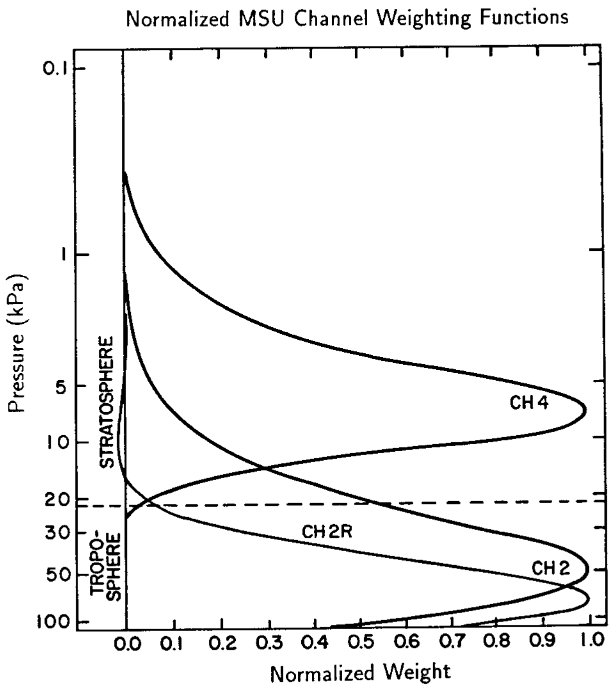

FIG. 1. Normalized weighting functions for MSU channels 2 (53.74 GHz), 4 (57.95 GHz), and MSU 2R for a 22° view angle through a *U.S. Standard Atmosphere.* The dashed line represents the level of the tropopause.

pecially evident in regions where there is some degree of decoupling in the vertical between the surface and the lower to middle troposphere. For instance, a pervasive trade wind inversion over the Tropics indicates local decoupling of the surface mixed boundary layer from the free atmosphere where large-scale subsidence occurs outside of the convective regions. The correlation between monthly mean temperatures for the layer from 1000 to 700 mb and MSU channel 2 values is less than 0.4 at Hawaii and Guam (Spencer and Christy 1992a), which indicates a clear physical difference between the MSU and surface data. Shallow temperature inversions are also found over land in winter, especially at high latitudes, and this contributes to large discrepancies in individual monthly anomalies [see Fig. 5 in Trenberth et al. (1992)].

For trends, however, the absolute and root-mean-square differences between the two records are more important than correlations. These also help to account for differences in correlation coefficients because of the size and persistence of the signal relative to the noise in the data. Hurrell and Trenberth (1996) revealed pronounced differences regionally in the standard deviations of monthly mean anomalies from both the surface record and MSU 2R, which has a weighting function that peaks lower in the troposphere near 700 mb (Fig. 1; Spencer and Christy 1992b). At the surface, the variability of temperatures over land is much greater than over the oceans, which reflects the very different heat capacities of the underlying surface and the depth of the layer linked to the surface. Consequently, changes in surface temperatures tend to be amplified over the continents in response to changes in atmospheric circulation. In contrast, relative to the surface, the global mean monthly MSU 2R anomalies contain a much larger contribution from over the northern oceans and a generally smaller contribution from over land [see Figs. 4, 5, and 7 of Hurrell and Trenberth (1996)] because of the relative importance of advection versus surface interactions. Since the late 1970s, changes in atmospheric circulation have resulted in surface warmth over the northern continents and coolness over the oceans (Wallace et al. 1995; Hurrell 1996), which therefore helps account for the discrepancy between trends because the recent surface record is dominated by the continental warming, whereas the cooling over the northern oceans contributes much more to the MSU record.

Physical differences between the two measures of temperature are also evident in their dissimilar responses to volcanic eruptions and ENSO. Both phenomena have a greater effect on tropospheric than surface temperature, especially over the oceans (Jones 1994). Removing their linear influence leads to better agreement between the global MSU and surface trends (Christy and McNider 1994), but the surface still warms at ~0.08°C decade^{-1} since 1979 relative to the MSU data (Jones 1994). Changes in concentrations of stratospheric ozone could also be important, as the troposphere is cooled more by observed ozone depletion than is the surface (Hansen et al. 1995; Ramaswamy et al. 1996).

b. Sampling of the surface record

Sampling issues contribute to the discrepancies between the surface and MSU records as well. A considerable asset of the MSUs is that they obtain many observations globally each month to provide a highly consistent record. In contrast, surface temperatures over large areas of the globe, such as the southern oceans, are not reliably observed. Karl et al. (1994) estimate that a positive bias of ~0.05°C decade^{-1} exists in the global surface temperature trend since 1979 as a result of an oversampling of the Northern Hemisphere (NH) midlatitudes and an undersampling of the Tropics and the Southern Hemisphere (SH). Noise in the data and the number of observations also affect the surface record. Over oceans, SSTs are often used as a surrogate for surface air temperature because they have much greater persistence so that fewer observations are needed to get a representative value. The noise in monthly mean SSTs depends on inherent uncertainties in individual measurements and their representativeness of a grid box average. Individual SST observations 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 (Trenberth et al. 1992). The standard error of the monthly mean is proportional to the reciprocal of the square root of the number of observations. With the exception of the eastern tropical Pacific, the signal-to-noise level of in situ measurements 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 (Trenberth et al. 1992).

c. Utility of radiosonde records

Radiosonde releases provide the longest record of upper-air measurements, and these data have been used to validate the MSU temperatures (e.g., Spencer and Christy 1992a). Unfortunately, vast regions of the oceans and portions of the landmasses (especially in the Tropics) are not monitored so that there is always a component of the global or hemispheric mean temperature that is missing (Trenberth and Olson 1991; Karl et al. 1994). Moreover, measurement errors and sampling issues affect the radiosonde record as well (Elliott and Gaffen 1991). The two main sources of temperature data derived from radiosondes employ different methodologies. Angell (1988) has analyzed the mean layer virtual temperature (geopotential thickness) derived from a set of 63 widely distributed radiosonde sites but values are influenced by changes in moisture. Elliott et al. (1994) estimate that improved radiosonde humidity sensors have led to a spurious cooling since 1958 of −0.01°C to −0.03°C decade^{-1} in Angell's data.

The datasets of Oort and Liu (1993) rely on as many radiosonde sites as possible to produce an objective global analysis of temperature on several pressure levels. While their analysis is not affected by changes in humidity, it is sensitive to changes in the temperature sensors, and some data are missing. Gaffen (1994) examined several sources of inhomogeneities in radiosonde temperature records and documented spurious changes from several tenths to as high as several degrees Celsius. The net effect of such inhomogeneities, which are most common at tropical and SH sites, is difficult to assess as the discontinuities do not always act in the same sense.

Such problems complicate the comparison of the radiosonde and MSU records, especially when the issue concerns the reliability of trends over short time intervals, and particularly over the Tropics where there are few reliable radiosonde records (e.g., Parker and Cox 1995). Using statistical change-point detection schemes and historical station information, Gaffen et al. (1997) conclude that only three stations out of 91 examined between 30°S and 30°N have homogeneous temperature records over the period 1979–92 (Wake Island, Hilo, and Koror). Stations throughout Australia and parts of New Zealand, for example, changed to Vaisala RS80-15 radiosondes during 1987 and 1988, and this change resulted in a spurious stepwise cooling of stratospheric temperatures (Tett et al. 1996; Parker at al. 1997) and a warming of tropospheric temperatures (see section 4d and appendix B). For such reasons analyses of radiosonde data should (but usually do not) include estimates of the accuracy to which the mean temperatures are known.

Over the recent period 1979–95, global temperatures estimated from 850- to 300-mb radiosonde data updated from Angell (1988) have cooled at a rate of −0.05°C decade^{-1}, in agreement with the global MSU 2R trend. When the MSU data are sampled at radiosonde sites, however, discrepancies between the two records emerge. Hansen and Wilson (1993) compared MSU 2R temperatures at grid points near the 63 radiosonde sites of Angell (1988) and found that the MSU 2R trend through 1993 cooled by −0.1°C decade^{-1} relative to the radiosonde trend, leading them to conclude that the better agreement with the "global" MSU record may be accidental. Moreover, noting that the trend difference arose mainly from stations within the Tropics, Hansen et al. (1995) compared MSU 2R anomalies at grid points nearby five U.S.-controlled radiosonde stations between 10°N and 30°N and found that MSU temperatures cooled relative to the radiosonde data at a rate of 0.42°C decade^{-1}. Some of the differences could be associated with inhomogeneities in the radiosonde records (Christy and Spencer 1995; Christy 1995), but other evidence presented below implicates the MSU record as well.

3. The MSU data

The technical aspects of the MSU data retrievals have been described by Spencer et al. (1990), and the data used in our analysis have been described by Spencer and Christy (1992a,b) and Christy et al. (1995). The individual channels in the MSU measure a brightness temperature, or vertically averaged atmospheric thermal emission, by molecular oxygen in the atmosphere at different spectral intervals in the oxygen absorption complex near 60 GHz. Oxygen is a very good temperature tracer for climate monitoring because it is uniformly mixed and its concentration is very stable in time. The deep-layer nature of the MSU measurements is illustrated by the channel weighting functions at nadir shown in Fig. 1 for channels 2 (53.74 GHz), 4 (57.95 GHz), and 2R.

Probably the most limiting factor to interpreting the MSU channel 2 data in terms of a tropospheric temperature is the small, but nontrivial, signal from the lower stratosphere. This is especially true at high latitudes where the height of the tropopause is lower. The stratospheric influence on the channel 2 data is addressed by Spencer and Christy (1992b), who propose a retrieval technique to remove it. Essentially, the off-nadir data, which have a somewhat different vertical weighting function, can be used to remove the stratospheric influence and thus provide an adjusted, narrower vertical weighting function (MSU 2R) that peaks slightly lower in the troposphere but is more sensitive to surface effects (Fig. 1). The outer eight of the 11 MSU scan positions are used to construct the MSU 2R data, and different vertical profiles from each scanning angle have been processed separately by J. Christy (1997, personal communication; see

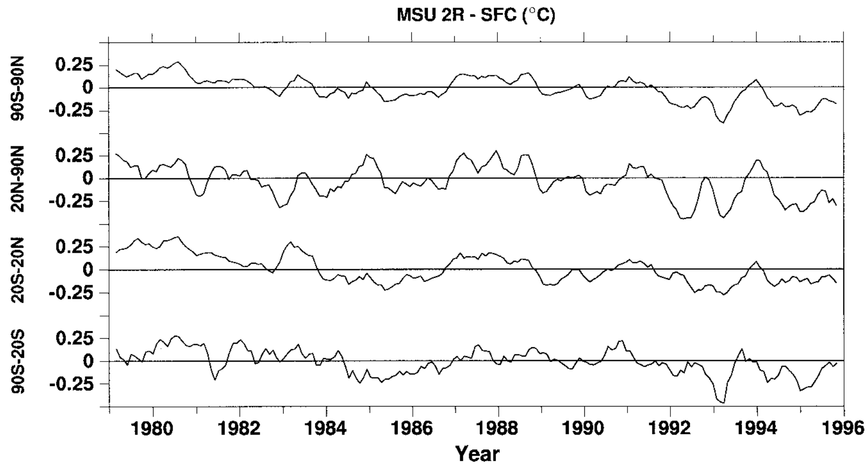

FIG. 2. Five-month running mean differences (°C), MSU 2R minus surface temperature anomalies, relative to the 1982–91 means averaged over the globe (90°S–90°N), the Northern Hemisphere extratropics (20°–90°N), the Tropics (20°S–20°N), and the Southern Hemisphere extratropics (20°–90°S).

also Goldberg and Fleming 1995). 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; Hurrell and Trenberth 1996). Other aspects of the MSU data, including the merging of records across multiple satellites and influence of nonatmospheric emissions, are discussed in section 5.

4. Comparisons

a. Surface versus MSU temperatures

The differences between the MSU 2R and surface temperature records are shown in Fig. 2 for the globe (90°S–90°N), the Tropics (20°S–20°N), and the extratropics (20°–90° lat) of both hemispheres. In this figure and most others, a 5-month running mean has been applied to eliminate high-frequency noise and small lag effects. The anomalies in both the MSU and surface datasets are relative to the decade 1982–91; therefore, differences are relative to the removed mean annual cycles of each dataset and do not represent absolute differences. The surface data are a combination of near-surface air temperature anomalies over land areas merged with in situ SST anomalies over marine areas, and it is an updated version of the dataset used in the Intergovernmental Panel of Climate Change assessments (e.g., IPCC 1996). The development of the surface dataset has been documented in many papers, the most recent being Jones and Briffa (1992) and Parker et al. (1994).

As described in section 2, global tropospheric temperature anomalies tend to be larger than surface anomalies during ENSO events, and the much colder anomalies in the satellite record during 1992 and 1993 occur in part from the smaller effect of the Mt. Pinatubo eruption (June 1991) at the surface (Jones 1994). The signal of the El Chichón eruption in April 1982 is more difficult to identify in both temperature records because the sulfate aerosol-induced cooling is masked by the 1982–83 ENSO warming. Over the NH extratropics the MSU 2R anomalies exhibit cooling relative to surface anomalies at the linear rate of -0.18°C decade^{-1}, which exemplifies the larger contribution of continental warming in the surface record and cooling over the oceans in the satellite data (Hurrell and Trenberth 1996). Over the SH extratropics the linear trend of the monthly differences is -0.14°C decade^{-1}, although this number is compromised by the poor sampling of the southern oceans in the surface record, which also contributes to the noisier behavior of the difference time series.

It is clear from Fig. 2 that the downward trend in MSU 2R anomalies relative to the surface record is global and cannot be fully accounted for by the aforementioned sampling of the surface record and physical differences between the two quantities. The Tropics contribute the most to the global trend difference: the MSU 2R record cools relative to the surface at a rate of -0.21°C decade^{-1} since 1979 (Table 1). Within this third of the globe, there is a fairly direct tropospheric response to SST anomalies, and there is a large interannual signal associated with ENSO. Unlike the extratropics, masking by natural internal atmospheric variability is small and the tropical Pacific appears to be predictable 6–12 months in advance (e.g., Shukla and Fennessy 1988; Chen et al. 1995; also see appendix A and Fig. A1). For these reasons, our focus will be on discrepancies between the two temperature records over this portion of the globe.

Differences in response to ENSO and volcanic eruptions are expected and seem to be identifiable in Fig. 2. However, a cooling trend is evident in the difference time series even after ENSO and volcanic effects are taken into account. When detrended anomalies are compared, the correlation coefficient between tropical MSU 2R and

TABLE 1. Linear trends (°C decade⁻¹) from monthly anomalies averaged over 20°S–20°N for 1979–95. Trends over the shorter period 1979–94 are given in parentheses, the period of record of the CCM3 data. The ECMWF trends were computed over 1979–93. Values in bold (italics) are significant at the 99% (95%) level. The significance was estimated accounting for the correlation in the monthly residuals from the linear trend fit following Cryer (1986, 38).

Quantity	Trend °C decade⁻¹
Surface	**0.10** (*0.07*)
SST	0.05 (0.03)
MSU 2R	−0.11 (*−0.14*)
land	**−0.24**
ocean	−0.07
MSU 2	0.05 (0.02)
land	0.01
ocean	0.07
NCEP 2R	*−0.09* (*−0.12*)
NCEP 2	−0.10 (−0.10)
ECMWF 2R	*0.25*
ECMWF 2	0.18
CCM3 2R	(0.09 ± 0.02)
CCM3 2	(0.12 ± 0.03)

tropical surface anomalies is 0.84 over the 17-yr period. The largest disparities between tropical temperatures occurred during 1979 and 1980 when annual MSU 2R anomalies were relatively ~0.25°C warmer than the surface record (Fig. 3). Tropical Pacific SST anomalies during these 2 yr were only slightly above the 1951–80 mean (see also Fig. A1), so the much warmer satellite temperatures are difficult to explain. Moreover, MSU 2R anomalies have been colder than surface anomalies over the past several years, which serves to magnify the trend difference. Since 1992, annual MSU 2R anomalies averaged over the Tropics have been ~0.15°C colder than surface anomalies (Fig. 3).

b. MSU 2R versus channel 2 using SSTs

From 1979–95, the linear trend in MSU 2R brightness temperature anomalies averaged over the Tropics is −0.11°C decade⁻¹, in contrast to the surface warming rate of 0.10°C decade⁻¹ (Figs. 2 and 3; Table 1). Physical differences cannot account for this discrepancy. Another way of examining the relationship between the MSU and surface anomalies is through simple linear regression. Using the reconstructed SST analyses of Smith et al. (1996) through 1981, and the optimally interpolated (OI) SST analyses of Reynolds and Smith (1994) thereafter, tropical SSTs with a 1-month lead were regressed against the MSU channel 2 and 2R data over the decade 1982–91 (Fig. 4). Variations in tropical SSTs explain 77% of the MSU channel 2, 61% of the MSU 2R temperature variance over the full 17-yr period, and 86% of the variance in both MSU records over the decade 1982–91. It is apparent that there is a strong cooling trend in the MSU 2R anomalies after the linear effects of the SST variations are removed. Very similar results are obtained with other SST analyses such as those based only on in

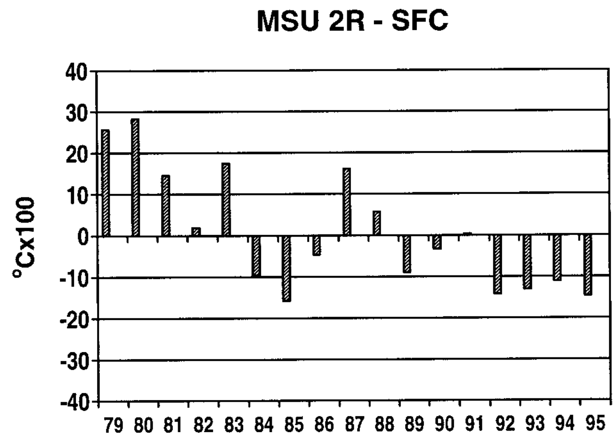

FIG. 3. Tropical (20°S–20°N) annual mean temperature anomaly differences (×100°C), MSU 2R minus surface, relative to the 1982–91 means.

situ data (see section 5). In particular, MSU 2R anomalies are much warmer than would be expected from the SSTs prior to 1982 and are colder after 1991. The channel 2 residual is also positive prior to 1982, but not as much as the MSU 2R residual, and it does not show the nearly stepwise cooling evident in the MSU 2R data in mid-1991. Variations in tropical SSTs linearly explain nearly 75% of the variance of detrended MSU 2R anomalies. A curiosity in the MSU 2R residual is the ~12-month variation that may have arisen from nonlinearities in the response associated with the annual cycle (e.g., land contribution or satellite platform heating).

The two monthly MSU records are directly compared in Fig. 5. The linear trend in tropical channel 2 anomalies since 1979 is 0.05°C decade⁻¹, which is closer to the observed rate of warming in the surface record and matches the linear trend in the SSTs of Fig. 4 (Table 1). Moreover, MSU 2R anomalies are warmer than channel 2 anomalies early in the record and are colder over the past several years. The differences, MSU 2R − MSU 2, are 0.16°C averaged over 1979–80, 0.01°C over 1981–91, and −0.13°C over 1992–95. Moreover, differences over tropical land contribute significantly to the differences in trends. The 17-yr MSU 2R trend is −0.24°C decade⁻¹ over land compared with −0.07°C decade⁻¹ over the oceans, while the corresponding land and ocean trends in channel 2 data are 0.01°C and 0.07°C decade⁻¹, respectively (Table 1). The trends in tropical gridpoint anomalies are shown for both channels in Fig. 6. Differences between the two records are very large locally, especially over land, and the cooling in MSU 2R is more widespread.[1]

[1] The MSU data used here are the so-called version b data. Christy et al. (1998) describe several changes in the merging procedures for the latest release, version c, for which decadal trends in tropical MSU 2R (MSU 2) temperatures are ~0.04°C (0.01°C) warmer. Version c gridpoint datasets are created using different techniques from those used to create the zonal-mean datasets, and local MSU 2R trends differ significantly from those shown in Fig. 6.

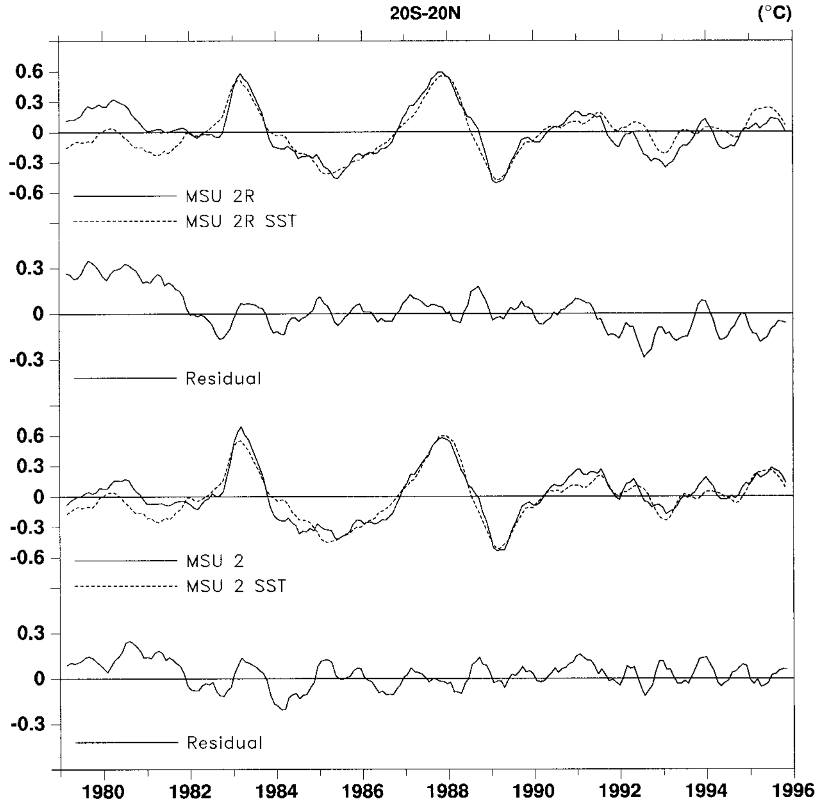

FIG. 4. Five-month running mean MSU channel 2 and 2R temperature anomalies area-averaged over the Tropics (20°S–20°N). The dashed lines represent the MSU anomalies associated with SST variations (leading by one month) from linear regression over the period 1982–91. Also shown are the residuals after removing the linear SST effects for MSU 2R (top) and MSU channel 2 (bottom).

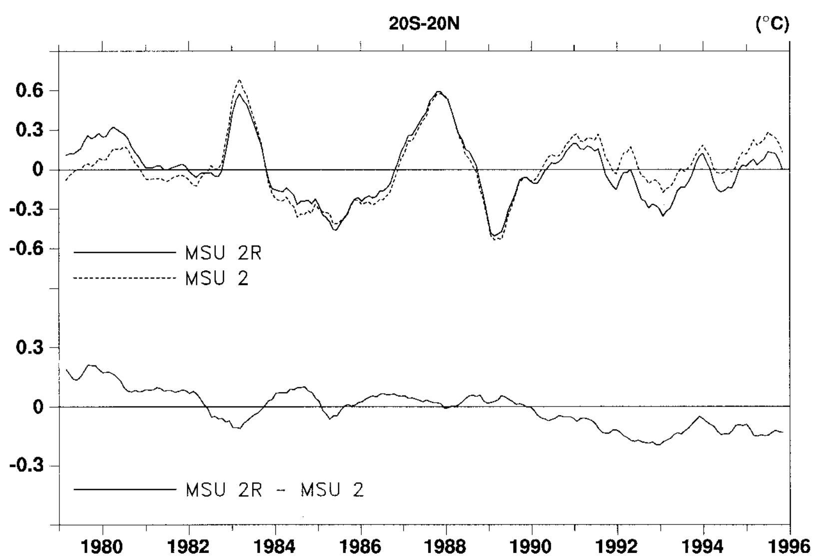

FIG. 5. Five-month running mean MSU channel 2 and 2R temperature anomalies, and the differences (MSU 2R − MSU 2), area-averaged over the Tropics (20°S–20°N). The anomalies are relative to the 1982–91 means.

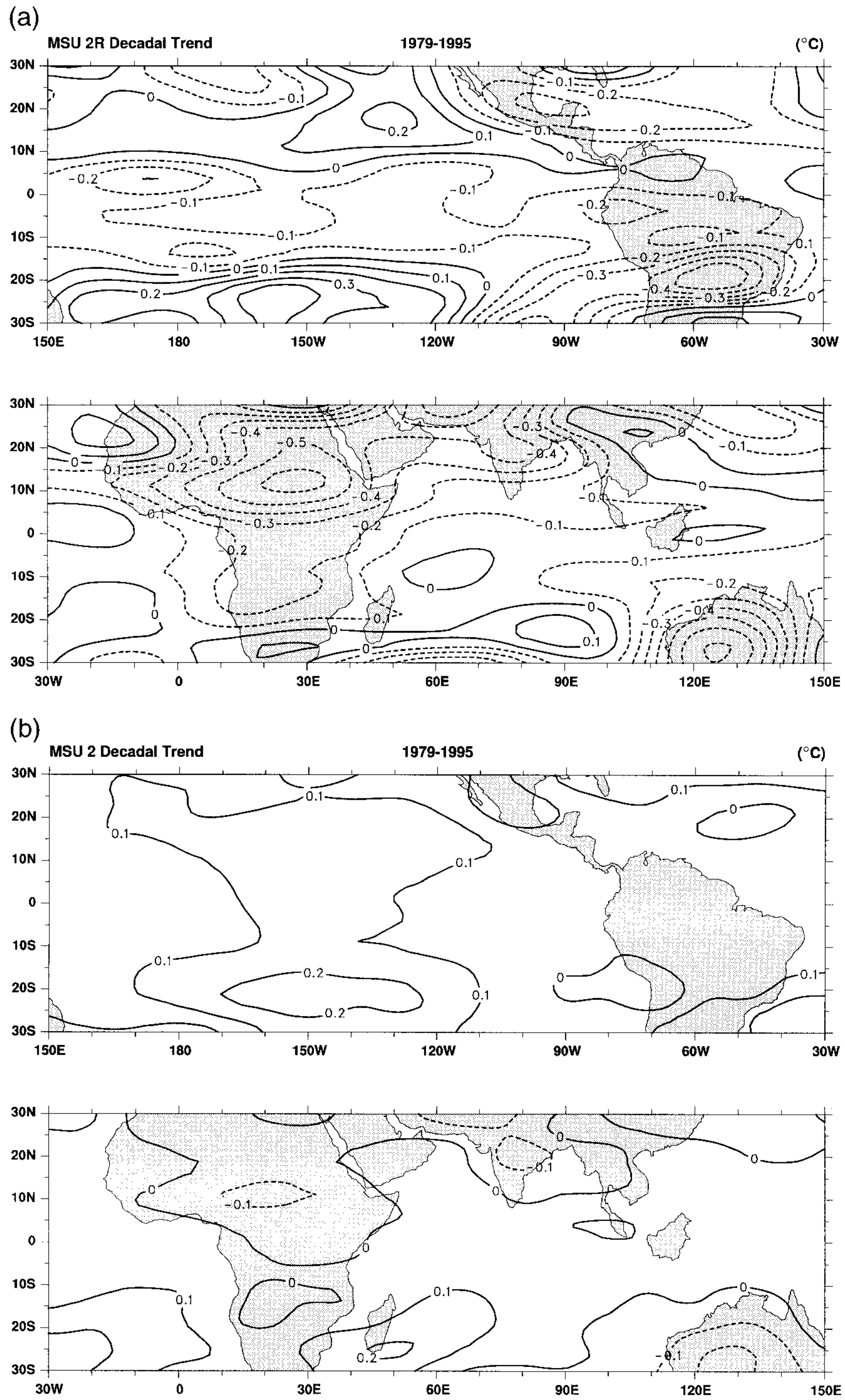

FIG. 6. Linear trends (°C decade^{-1}) in (a) MSU 2R temperatures and (b) MSU channel 2 temperatures computed from monthly anomalies over the period 1979–95. Negative trends are dashed, and the contour increment is 0.1°C decade^{-1}.

c. MSU and CCM

The CCM forced with observed SSTs can be thought of as a nonlinear transfer function for converting the SST record into a temperature record equivalent to that of the MSUs. Version 3.0 (CCM3) is the fourth generation in the series of NCAR community climate models. A detailed description of the model is provided by Kiehl et al. (1996). The standard model configuration uses a triangular wavenumber 42 (T42) horizontal spectral resolution (approximately a 2.8° × 2.8° transform grid) with 18 unequally spaced vertical (hybrid) levels. Here we analyze the last 16 yr of a five-member ensemble of 45-yr integrations forced with observed monthly SSTs that are assigned to the midmonth date and updated every time step at each ocean grid point using linear interpolation. The integrations cover the period 1950–94 and are forced with the reconstructed SST analyses through 1981 and the OI analyses thereafter. Three integrations were performed with global SSTs, and two were forced with observed SSTs between 30°S and 30°N relaxed to climatology poleward of 40° lat. The results of all five simulations were linearly averaged since attention will be limited to the Tropics, and the spread of the individual simulations was also examined.

To retrieve an equivalent channel 2 or 2R brightness temperature, simple vertical weighting functions that are equal to the MSU weighting functions (Fig. 1) were applied to the CCM3 multilevel temperatures, as suggested by Spencer and Christy (1992a). After first interpolating CCM3 temperatures to pressure surfaces, the vertically weighted equivalent channel 2 and 2R temperature were obtained from

$$T = \frac{\sum_{i=1}^{N} w_i T_i \ln(p_{i-1/2}/p_{i+1/2})}{\sum_{i=1}^{N} w_i \ln(p_{i-1/2}/p_{i+1/2})}, \qquad (1)$$

where the *i*th layer of the CCM3 data has an average temperature T_i, an average weight w_i taken from Fig. 1, and bounding pressures $p_{i-1/2}$ and $p_{i+1/2}$. In addition, small adjustments were made to the weights to account for the different emissivities of ocean and land surfaces (Spencer et al. 1990; Shah and Rind 1995), and monthly mean CCM3 surface pressures were used to adjust the normalized weight so that no data from pressure levels on or below the model surface were used in the calculations.

The usefulness of the MSU to CCM3 comparison is dictated by the ability of the model to realistically simulate the interannual variability associated ENSO. This issue is briefly addressed in appendix A, and the results give us confidence that the CCM3 is a very effective tool to help interpret the tropical MSU record.

The ensemble mean CCM3 2R and channel 2 anomalies and their spread from the five integrations are shown in Fig. 7 together with the MSU data averaged over the Tropics (20°S–20°N). Over the decade 1982–91, MSU 2R anomalies lie within the CCM3 spread with only a few minor exceptions in spite of large ENSO-related excursions, and the correlation with the ensemble mean is 0.92. Over the entire record, however, the correlation falls to 0.73 because of large discrepancies during 1979–80 and after 1991. For channel 2, simulated temperature anomalies agree better with the MSU record and the 1979–94 correlation coefficient from monthly anomalies is 0.87. Although the model temperatures are colder than MSU channel 2 early in the record, the difference time series (CCM3 − MSU) oscillates about zero over the remaining period. Moreover, simulated 2R and channel 2 anomalies vary hand-in-hand over the entire period, so there is no significant difference in simulated trends, unlike the MSU data (Table 1). It is important to note that the standard deviation of CCM3 tropical temperatures arising from chaotic internal atmospheric effects is about 0.04°C (Table 1), a factor of 7 less than the ENSO-related signal, reinforcing the view that the tropical temperature response to SST forcing is fairly deterministic.

Other comparisons between the MSU record and tropospheric temperatures simulated with atmospheric general circulation models (AGCMs) show similar results although only global-mean values have been analyzed. For instance, Stendel and Bengtsson (1997) computed simulated 2R brightness temperatures from a five-member ensemble with an AGCM (ECHAM4) forced with the SSTs used in the Atmospheric Model Intercomparison Project (AMIP; Gates 1992). They concluded that the much warmer global MSU 2R temperatures early in the record were indicative of uncertainties in the SST analyses prior to 1982, while they assigned the colder MSU anomalies after 1991 to the effects of the Mt. Pinatubo eruption. S. Tett (1996, personal communication) has examined a four-member ensemble from the Hadley Center AGCM forced with AMIP SSTs through 1988 and has also found that simulated global 2R anomalies could not capture the relative warmth evident in the MSU 2R data prior to 1982. Differences in global anomalies are more difficult to interpret than tropical differences, however, given the large internal component of variability over middle and high latitudes. In addition, discontinuities in the specification of the SST and sea ice boundary conditions used in the AMIP integrations [e.g., see Fig. 11 in Hansen et al. (1996)] contaminate calculation of global temperature trends.

d. MSU and Australian radiosondes

The comparison of MSU and radiosonde data over the Tropics is severely limited by the number of reporting stations and the lack of continuous and homogeneous records. Over the tropical continents, where the strongest cooling in MSU 2R temperatures occurs (Fig. 6), the number of reports of monthly standard-level data from sparsely distributed stations throughout Africa and South America has been declining since the mid-1970s (Parker and Cox 1995), so the best coverage and the most complete records available come from Australia. As previously discussed, however, temperature trends computed from Australian data are unreliable because past changes in instruments and observing practices have induced temporal inhomogeneities (see Gaffen 1993). Nevertheless, we have reconstructed (as detailed in appendix B) the records at Darwin (130.9°E, 12.4°S) and Alice Springs (133.9°E, 23.8°S) in an attempt to gain further insight into the MSU channel 2 and 2R records.

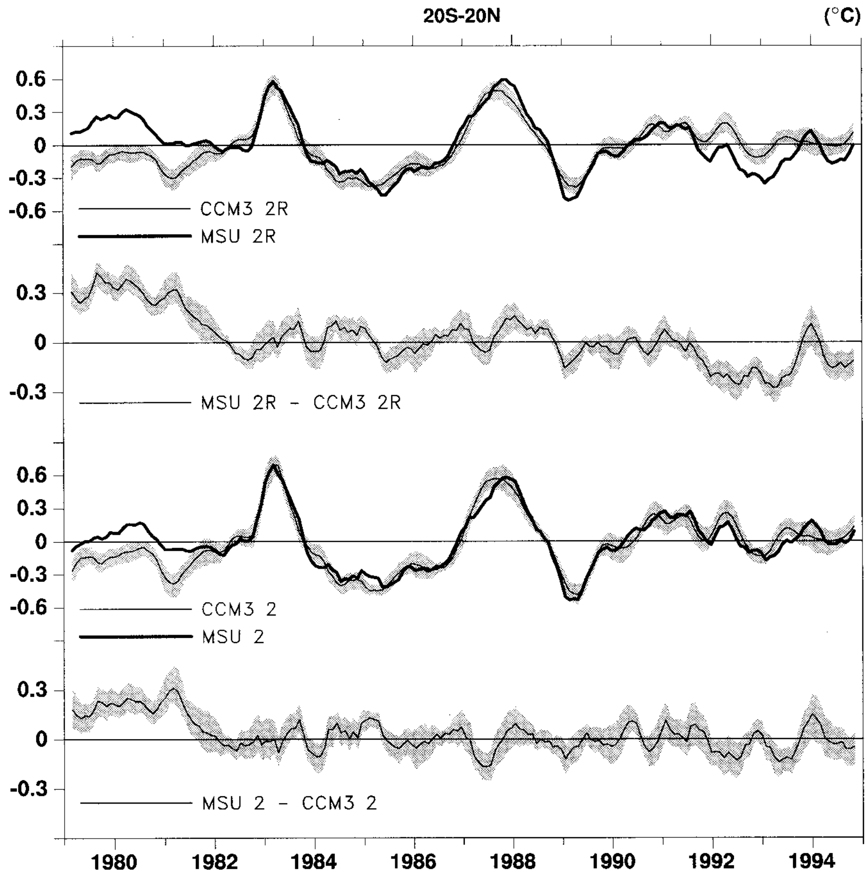

FIG. 7. Five-month running mean MSU channel 2 and 2R temperature anomalies (heavy solid) and the five-member ensemble mean equivalent MSU anomalies from CCM3 integrations (thin solid) and the range about the means (stippled) area-averaged over the Tropics (20°S–20°N). Also shown are the differences (MSU − CCM) for MSU 2R (top) and MSU channel 2 (bottom).

Equivalent MSU temperatures at each station were obtained from (1) using monthly pressure-level data at standard levels, expressed as departures from the 1982–91 mean annual cycle. Signals common to collocated MSU and radiosonde records are evident in plots of the sum of the monthly anomalies, while plots of monthly differences (station minus MSU) are a simple way to identify inconsistencies. A large discontinuity occurs at Darwin (not shown) in June 1987, the month of the transition from the Philips Mark III radiosonde model to the Vaisala RS80-15. Afterward, vertically weighted Darwin anomalies remain warmer than collocated MSU 2R and channel 2 temperatures through 1995. Otherwise, neither the channel 2 nor the 2R comparisons at Darwin show any systematic differences.

The same is not true of the Alice Springs comparison (Fig. 8), however, where the MSU 2R cooling trend is ~ -0.6°C decade^{-1} (see also Fig. 6a). As for Darwin, a spurious stepwise warming in the radiosonde data relative to the satellite data is evident in late 1987 (the transition to the Vaisala model occurred in August 1987). Subsequently, the relative differences for MSU 2 are uniformly ~0.4°C through 1995. Differences of similar magnitude are evident in the MSU 2R comparison through mid-1991, but since then the satellite data are colder than the equivalent 2R record at Alice Springs by nearly 0.8°C on average. As no changes in instruments or observation practices were reported at Alice Springs between 1989 and 1993 (Gaffen 1996), the relative cooling of the satellite record must have some other origin.

e. MSU and reanalyzed temperatures

Comparisons between satellite and radiosonde data are limited by the sparse distribution of upper-air stations and unreliable, long-term records, especially over the Tropics. In an attempt to study the climate record depicted by the MSUs on a global scale, Hurrell and Trenberth (1992) compared monthly MSU channel 2 anomalies to weighted ECMWF monthly means and found that correlations exceeded 0.9 over most of the globe. Basist et al. (1995) performed a similar study with the operational global analyses from NCEP. Both of these studies, however, primarily revealed spurious changes in the analyzed temperatures that resulted from operational changes to the analysis-forecast systems at

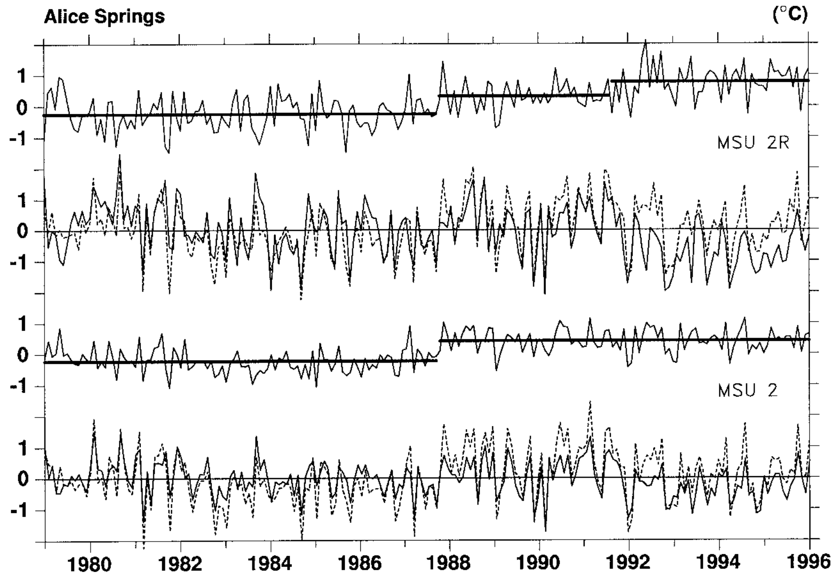

FIG. 8. Monthly mean temperature anomalies from MSU (solid) and Alice Springs (dashed), and the differences (Alice Springs minus MSU), for MSU 2R (upper two curves) and MSU 2 (lower two curves). Also indicated are the mean differences (heavy) before and after August 1987 for MSU 2, as well as before and after June 1991 for MSU 2R. The anomalies are relative to the 1982–91 means.

both centers. The problems were especially evident in regions of fewer observations such as the Tropics.

A purpose of the NCEP–NCAR and ECMWF reanalysis projects is to eliminate spurious climate jumps associated with changes in the data assimilation system by using a state-of-the-art analysis/forecast system that is frozen in time (Kalnay et al. 1996; Gibson et al. 1996). Analyzed SSTs, snow cover, sea ice, and surface albedo specify some lower boundary conditions for the assimilating models, while soil wetness and surface and near-surface temperatures over land are largely dependent on the relevant physical parameterizations. We use the postprocessed values on standard pressure levels produced from 6-h data averaged into monthly means. Equivalent channel 2 or 2R brightness temperature were retrieved from (1) in the same way as for CCM3.

The vertical structure of tropospheric temperature anomalies over the Tropics is revealed through time series of NCEP reanalyzed pressure-level and MSU normalized anomalies for 1979–95 (Fig. 9). Differences in the vertical structure of the anomalies are evident, which might give insight into the differences in MSU 2R and channel 2 trends. For instance, the cooler MSU channel 2 anomalies relative to MSU 2R early in the record are consistent with a larger influence from the upper troposphere and lower stratosphere where temperatures were anomalously cold during 1979–80. However, the relative cooling in the NCEP temperatures over the past several years is inconsistent with the MSU channel 2 record.

These points are further highlighted by contrasting the vertically weighted NCEP anomalies with the MSU data averaged over the Tropics (Fig. 10). The NCEP 2R anomalies are highly correlated with the MSU 2R measurements over the 17 yr ($r = 0.95$) but are systematically colder prior to 1982 and after mid-1992. The differences in Fig. 10 are more apparent through a singular value decomposition analysis applied to the temporal covariance matrix between tropical NCEP 2R and MSU 2R records (not shown). The additional insights provided by this analysis indicate that the lower NCEP temperatures prior to 1982 are significant, during the 1982–83 warm event MSU 2R is warmer than NCEP 2R, and from 1984 through mid-1986 and 1990 through mid-1991 satellite temperatures are colder than NCEP. The agreement is better overall with channel 2 data (Fig. 10). A large, stepwise relative difference appears after mid-1991, however, with the NCEP analyses much colder than the satellite data, as also found by Basist and Chelliah (1997). As for the CCM3 MSU weightings, there is no significant trend in the difference of weighted NCEP temperatures (Table 1).

Equivalent anomalies from the ECWMF reanalysis project have also been included for comparison in Fig. 10. The ECMWF data are available only through 1993 and exhibit poor agreement with both the NCEP and MSU anomalies. The correlation coefficient between monthly ECMWF and MSU 2R (NCEP 2R) anomalies is 0.71 (0.74) over the 15 yr, and 0.90 (0.84) for MSU 2 (NCEP 2). The largest differences relative to MSU 2R and channel 2 temperatures occur after 1989 when the ECMWF data are much warmer, while ECMWF anomalies are generally colder than the satellite data prior to 1987. As a result, both ECMWF 2R and 2 exhibit strong positive decadal trends relative to MSU since 1979 (Table 1). Throughout the record ECMWF tropical temperatures

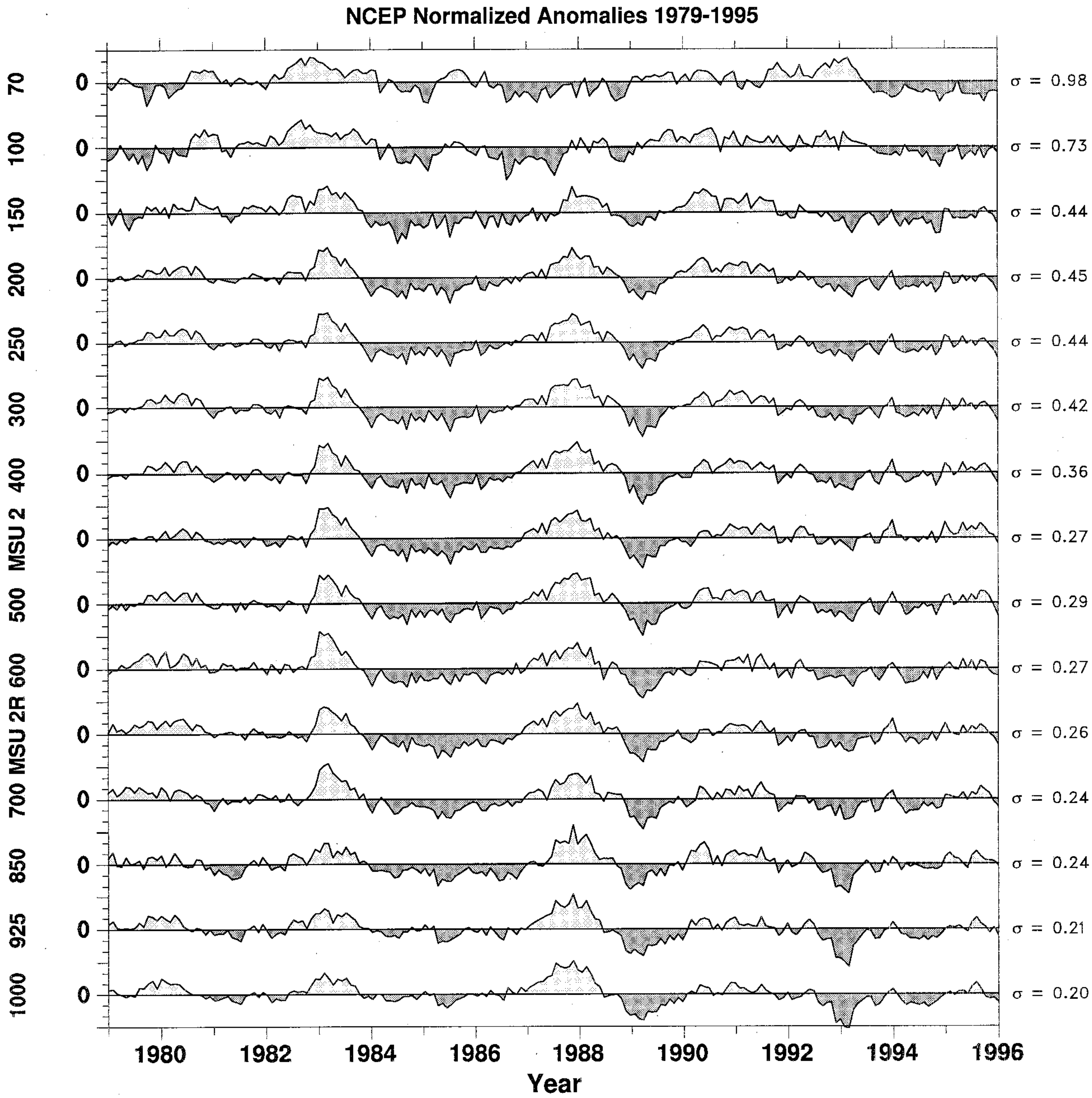

FIG. 9. Normalized tropical (20°S–20°N) temperature anomalies relative to the 1979–95 means of NCEP reanalyzed temperatures at pressure levels from 1000 to 70 mb. The standard deviations (°C) of the monthly anomalies are given on the right axis, and the tick marks on the left axis are every 3σ. The observed MSU 2R and MSU channel 2 normalized anomalies are also provided near the pressure levels of the peaks in their respective weighting functions. Negative anomalies are given by the darker shading.

display much more variability at all timescales than either NCEP or MSU, and local standard deviations (not shown) reveal considerably higher variance over the radiosonde sparse tropical Pacific east of 150°W than either MSU or NCEP temperatures. Evaluation of precipitable water and precipitation from NCEP reanalyses shows that they substantially underestimate the observed variability associated with ENSO in the Tropics (Trenberth and Guillemot 1998), although the variances of both NCEP 2 and 2R temperatures are close to those of MSU (not shown).

The significantly different character of the two reanalyzed products, and their differences from the MSU products, emphasizes that the results are only as good as the input databases used in the reanalyses, and large uncertainties remain, as also noted by Basist and Chelliah (1997). As discussed in section 2c, there were major

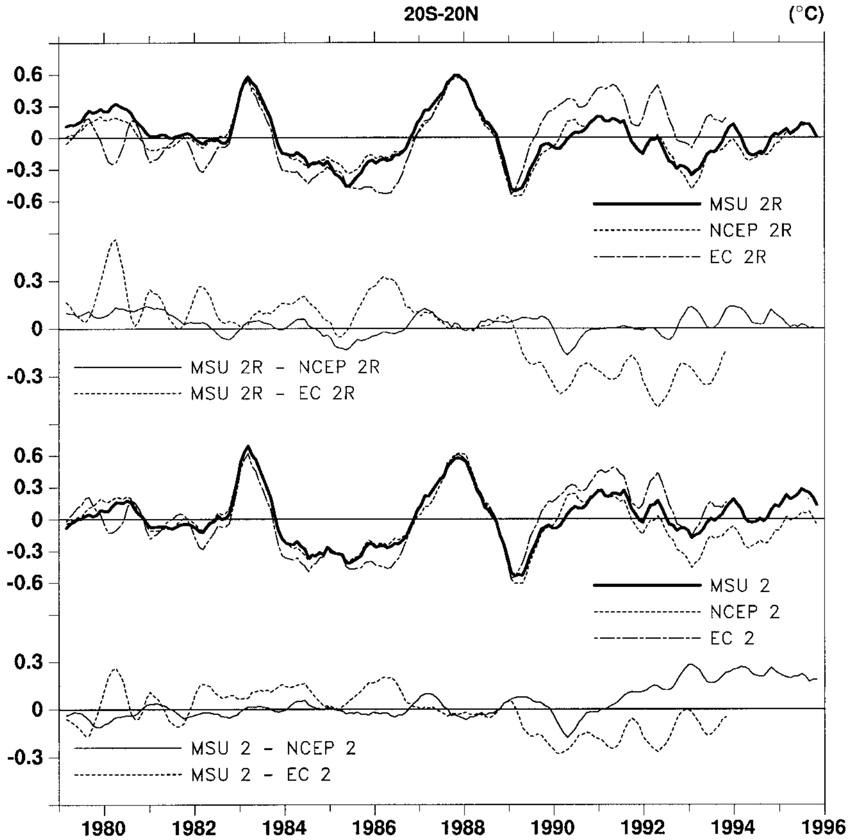

FIG. 10. Five-month running mean MSU channel 2 and 2R temperature anomalies (solid) and the equivalent anomalies from the NCEP (dashed) and ECWMF (dash–dot) reanalyses area-averaged over the Tropics (20°S–20°N). Also shown are the differences (MSU − NCEP) and (MSU − ECWMF) for MSU 2R (top) and MSU channel 2 (bottom).

changes in radiosonde instruments throughout this period so that the radiosonde records are unreliable for establishing trends. In addition, major changes in satellite retrievals occurred that affect the NCEP results, while only the cloud-cleared radiances were assimilated by ECMWF. When interpreting the comparisons, it should be noted that the reanalyses are not independent of the MSU brightness temperatures. While the radiance data are not directly incorporated into the analysis system at NCEP as they are at ECMWF, the temperature satellite retrievals do include MSU data in clear, partly cloudy, and cloudy retrievals. In cloudy regions the retrievals depend entirely on MSU data. Profile information produced from operational retrieval techniques is needed because of the historical design of analysis schemes to make full use of radiosonde data. Eyre (1987) has documented the error characteristics of retrieval algorithms from a theoretical standpoint, and Andersson et al. (1991) and Kelly et al. (1991) have identified large errors and biases in the operational retrievals produced at the National Environmental Satellite Data and Information Service (NESDIS) and used at NCEP. Both the statistical retrieval algorithms used by NESDIS prior to September 1988 and the current physical retrieval algorithms are very sensitive to the initial atmospheric state used in the schemes and often force the retrieved profiles to contain a priori information that is not accurate. Thus, the NESDIS retrievals in many regions exhibit large differences from the model first-guess fields and are clearly wrong, while the MSU radiance data and the estimated radiances computed from the first guess fields agree closely. This presents serious problems when trying to use either the retrieval data or the analyses generated from them in climate studies. Accordingly, during the second phase of reanalysis, NCEP will assimilate the satellite radiance data directly into the analyses (Kalnay et al. 1996).

A contributing factor to the stepwise cooling in the NCEP temperatures may indeed be a major change in the cloudy algorithms over oceans in April 1992 (Reale et al. 1994; Basist and Chelliah 1997). Note that the 5-month running mean applied in Fig. 10 blurs the change. Prior to this time, SSTs were used as a lower boundary condition in the retrieval algorithms, but because it is more important for the algorithms to have a priori knowledge of boundary layer temperatures, the SSTs were replaced by forecasted potential temperatures while forecast surface air temperature is used over land

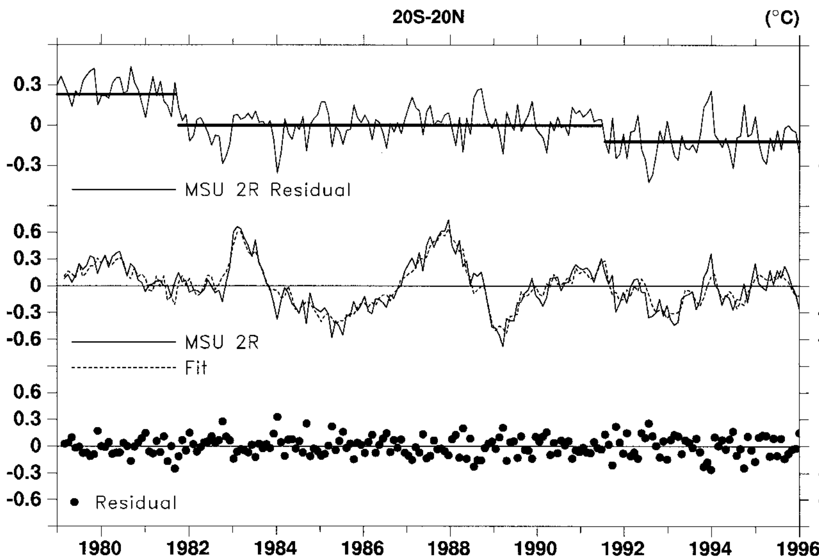

FIG. 11. (Top) Monthly MSU 2R residuals after removing the SST effects through linear regression, as in Fig. 4, and the means of the residuals determined before and after the two breakpoints identified by an objective change-point analysis technique (heavy lines); (middle) monthly MSU 2R anomalies (solid) with fitted values (dashed); (bottom) residuals obtained from the linear model described in the text.

(W. Planet 1996, personal communication). The result was a significant reduction in the spatial discontinuity between clear and cloudy retrievals over the oceans. Aerosols from the Mt. Pinatubo eruption could have also played a role, but only for a short time (perhaps 3 months) after June 1991 since the retrieval algorithms use collocated satellite and radiosonde observations to tune for satellite drift. However, this methodology means that discontinuities in the radiosonde record, such as those associated with changes in instruments, are also included in the record. The salient point is that the strong cooling at the end of the NCEP record has a spurious component, so the utility of the MSU comparisons are limited and the agreement with MSU 2R is fortuitous. It is worthwhile emphasizing the very different satellite data that went into the NCEP and ECMWF reanalyses; however, the large differences between the two are puzzling and are the topic of ongoing work beyond the scope of this paper.

5. Issues with the satellite record

We have statistically analyzed the tropical MSU 2R record using the SST record going beyond the analysis in section 4b. After first removing the SST effects using linear regression as in Fig. 4, the change-point analysis technique of Jones and Dey (1995)[2] was applied to the MSU 2R residual time series. Two change points were objectively identified. We associate the first with the beginning of the *NOAA-7* record in June 1981, while the second change-point corresponds to the *NOAA-10* to *NOAA-12* transition in August 1991.[3] These times were then used as ''indicator'' variables in a linear statistical model that was fitted to the tropical MSU 2R record. The independent variables were SST at zero lead and leading by one month to allow for delayed responses, which appear to be a week or two (Deser and Timlin 1997). The results of the linear fit are shown in Fig. 11. The coefficients of the indicator variables suggest biases of 0.23°C prior to June 1981 and −0.12°C after August 1991, both of which are statistically significant. The residuals are small enough to be consistent with known sources of noise in both records and, moreover, they are fitted by a first-order autoregressive process and thus would be very small if a 5-month running mean were applied as in many earlier figures. With the offsets included as adjustments to tropical MSU 2R anomalies, the variance accounted for by linear regression against tropical SSTs rises from 61% to 81% and the decadal trend is 0.08°C. The regression also indicates that MSU 2R anomalies are amplified relative to SST anomalies by a factor of ~1.3. For a temperature of 25°C at 1000 mb, an amplification factor of 1.3 is equivalent to the temperature change expected at ~670 mb following the saturated adiabatic lapse rate, which is appropriate in the Tropics (Stone and Carlson 1979)

[2] The statistical procedure starts by fitting a straight line without change points. Next a line with a single change point is fit to the data, and a statistical test is used to determine if the line with a single change point provides a significantly better fit to the data than the line with no change points. This is then followed by fitting a line with two change points, etc.

[3] The same breakpoints are present in the version c data described by Christy et al. (1998).

and is near the peak weighting function of MSU 2R (Fig. 1). Thus, these statistical results make sense physically.

We have also performed the statistical analysis using in situ SSTs from the Comprehensive Ocean–Atmosphere Data Set (Slutz et al. 1985) and the reconstructed analyses of Kaplan et al. (1998). The results are very similar to those shown in Fig. 11, indicating that the two stepwise decreases in the MSU 2R data relative to the SSTs do not arise from uncertainties in the bias-corrected satellite data used in the OI analyses of Reynolds and Smith (1994). The two change points demand explanations, and the second coincides with that found at Alice Springs (Fig. 8). Therefore, we have reexamined the procedures for producing the satellite record. Two significant issues emerge in particular.

a. Merging records from different satellites

The stability of the MSU data from one satellite to another is a key issue. As shown in section 4, discrepancies between the MSU 2R record and several other sources of information appear in the form of two step functions, both of which occur about the time of satellite merges. The first, in mid-1981, is *NOAA-6* to *NOAA-7* and the second, in mid-1991, is *NOAA-10* to *NOAA-12*. The way in which the multisatellite data have been merged are described by Spencer and Christy (1992a) and Christy et al. (1995). The standard configuration of the MSUs is to sample globally twice daily from each of two satellites with different equator-crossing times, one in a morning orbit (0730 LT) and one in an afternoon orbit (1430 LT). However, periods exist when only one satellite was in operation [see Fig. 1 in Christy et al. (1995)]. While the morning crossing times have been relatively stable, those of the afternoon orbiters have tended to degrade over the years. For example, *NOAA-11* drifted by 4 h, creating potentially serious consequences, especially for trends (Christy et al. 1995).

The following discussion, summarized from Christy et al. (1995), describes how a single time series is obtained. Reference annual cycles over the period September 1981–August 1982 are determined separately for the morning (*NOAA-6*) and afternoon (*NOAA-7*) passes. Because of the *NOAA-11* drift, this is the only 12-month period common to both a morning and afternoon satellite since 1979. The other morning (*NOAA-6, -10, -12, -14*) and afternoon (*TIROS-N, NOAA-7, -9,* and *-11*) records are then standardized by subtracting the *NOAA-6* and *NOAA-7* annual cycles. In this way the diurnal cycle effects peculiar to morning or afternoon orbits are mostly removed from the data. Next, biases that arise from the systematic offset of one instrument versus another, determined as the average difference between temperatures of the MSUs at each latitude during overlap periods, are sequentially accumulated and removed. All anomalies are then recomputed relative to the 1982–91 base period. ''Corrections'' for the drift in *NOAA-11* are treated separately by linearly removing the trend (over the period January 1990–February 1994) in *NOAA-11* relative to *NOAA-10* and *NOAA-12* anomalies as a function of latitude. The time drift in *NOAA-11*, which began operation in late 1988, was not noticeable until after 1990 when a spurious global warming trend of 0.03°–0.04°C yr^{-1} became evident. Other ad hoc corrections, related to variations in the amount of missing data, residual harmonics of the annual cycle unique to particular satellites, and ''median'' filtering of daily data were applied to reduce the noise in the data while leaving the signal with as much of its original variance as possible. The data used in this study include all of these corrections.

It should be noted that the linear adjustment applied to the *NOAA-11* record is of limited usefulness and could lead (through extrapolation) to spurious temperature trends. Such problems would be most pronounced over dry, sunny regions or over high terrain because of strong diurnal variations in surface skin temperature, which are not linear and are much larger than diurnal variations in tropospheric emissions. Corrections for drifts in other satellite orbits (e.g., *NOAA-6* by 1 h and *NOAA-7* by 1.75 h) have not been applied,[4] although they too will have an impact through aliasing of the diurnal cycle. Such drift problems have been identified and corrected in the tropical outgoing longwave radiation (OLR) record from the same NOAA satellites: the *NOAA-7* and *NOAA-11* drift effects were especially large (Waliser and Zhou 1997). Since OLR also depends on cloud-top temperatures, the corrections do not translate directly to the MSU record, except perhaps over cloudless regions such as the Sahara where the greatest negative trends in the tropical MSU-2R record arise (Fig. 6) and, consequently, are suspect.

The agreement between two MSUs concurrently operating on different satellites gives an indication of instrument stability. Spencer and Christy (1992a,b) examined the 20-month overlap between *NOAA-6* and *NOAA-7* and computed rms differences of anomalies between the two satellites. They found that monthly mean channel 2 brightness temperatures at 2.5° gridpoint resolution were reproduced to within a standard error of better than 0.05°C in the Tropics and 0.15°C at higher latitudes. For MSU 2R, monthly gridpoint anomalies were reproduced to within 0.15°C over tropical oceans and 0.3°–0.5°C over tropical land and at higher latitudes. The agreement between different satellites during other overlaps, however, is not as good. This is illustrated by the zonal means of the rms anomaly differences between different satellites for five overlap periods (Fig. 12), and the local rms differences for the 34-month overlap of *NOAA-10* and *NOAA-11* are shown

[4] A linear adjustment for the orbital drift in *NOAA-7* is included in the version c data.

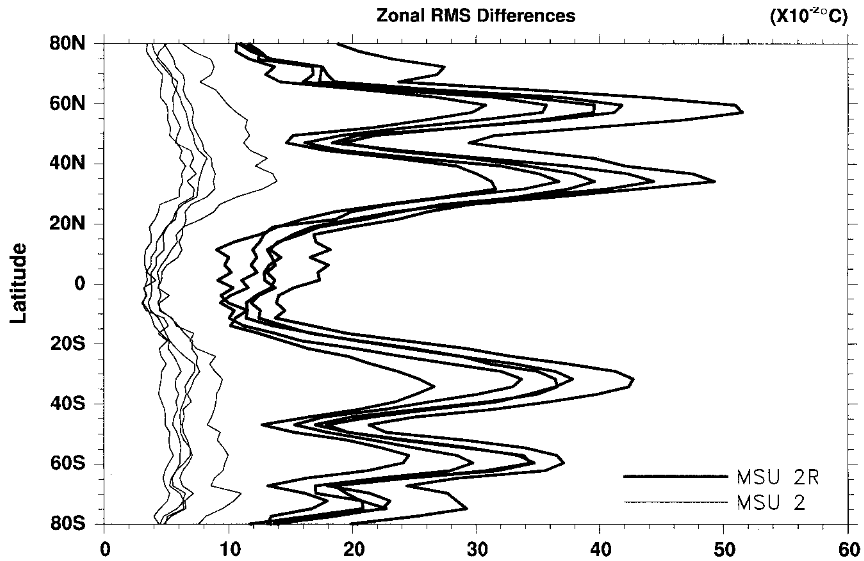

FIG. 12. Zonal means of the rms anomaly differences ($\times 10^{-2}$°C) between different satellites for five overlap periods for MSU 2R (heavy lines) and MSU 2. The data were kindly provided by J. Christy.

in Fig. 13. The comparisons that involve *NOAA-11* are made after the linear adjustment for the drift in the equator-crossing times (Christy et al. 1995).

An important point evident in Figs. 12 and 13 is that 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 (Spencer and Christy 1992b) and because of the greater influence of surface emissions. MSU 2R retrievals also lack limb correction and retain fewer observations, so that the reproducibility of brightness temperatures between different satellites is not as good with the adjusted data (Fig. 12).

Using the technique of Overland and Preisendorfer (1982) to determine if the eigenvalues of an empirical orthogonal function analysis can be distinguished from those produced from a spatially and temporally uncorrelated random process, we estimate from the MSU channel 2 (2R) data that there are roughly 5 (8) spatially independent estimates of tropical tropospheric temperatures (see also Jones et al. 1997a). The results are identical when the CCM3 deep-layer temperatures are used. Moreover, the low-frequency nature of the ENSO variations means that the number of months needed to gain an extra degree of freedom, or effectively the time between independent observations, is 6 months (Trenberth 1984). Monthly mean area-averaged tropical (20°S–20°N) MSU 2R temperature differences between two satellites therefore have a standard error of the mean of ~0.15°C (Fig. 12) divided by $\sqrt{8}$, or ~0.05°C so that biases are known to ~±0.1°C, which is large enough to corrupt long-term trends when several satellite records are merged, especially when the overlap is short as is often the case.

Of particular concern is the transition between the morning satellites *NOAA-10* and *NOAA-12* in August 1991. Both could be matched to the afternoon satellite *NOAA-11*, but the drift in the *NOAA-11* orbit degrades the matching process. The issue is illustrated by Fig. 14, which shows tropical MSU 2R temperatures after the adjustments of Christy et al. (1995) against those independently estimated at the National Oceanic and Atmospheric Administration (NOAA) by Goldberg and Crosby (1995). In the NOAA data, the *NOAA-12* temperatures were calibrated against *NOAA-10* using a 3-month overlap (June–August 1991), so that the time series is based only on morning satellites. The anomalies in both datasets are relative to the 1987–94 mean, and the correlation coefficient between the 96 monthly anomalies is 0.88. The difference shows up as essentially a step function in mid-1991 with the NOAA estimates warmer after the transition. The procedures for matching the NOAA records can be questioned, but there is no doubt they give different results and highlight the difficulties in merging satellite records.

b. Effects of surface emissions

Another concern has been how much of the MSU signal arises from nonoxygen emission. For MSU channel 2, the theoretical calculations of Spencer et al. (1990) predict small contaminating influences from interannual variations in precipitation-size ice in deep convection, cloud water, water vapor, and surface emissivity, which might corrupt monthly brightness temperature anomaly signals in regional areas by 0.1°C or more. The largest effects come from precipitation-sized ice in deep convection, which can cause brightness temperature de-

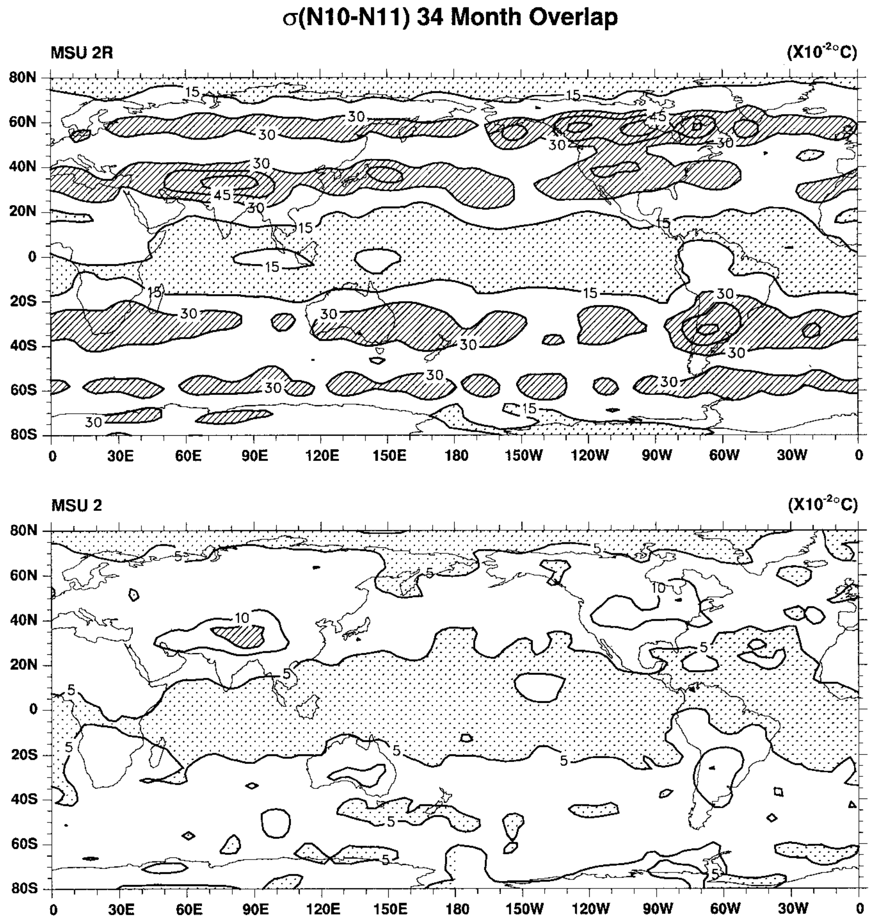

FIG. 13. Gridpoint rms anomaly differences (×10⁻²°C) for the 34-month overlap of *NOAA-10* and *NOAA-11* for (top) MSU 2R and (bottom) MSU channel 2. Values less than 0.15°C (0.05°C) are stippled and values greater than 0.30°C (0.15°C) are hatched in the top (bottom) panel.

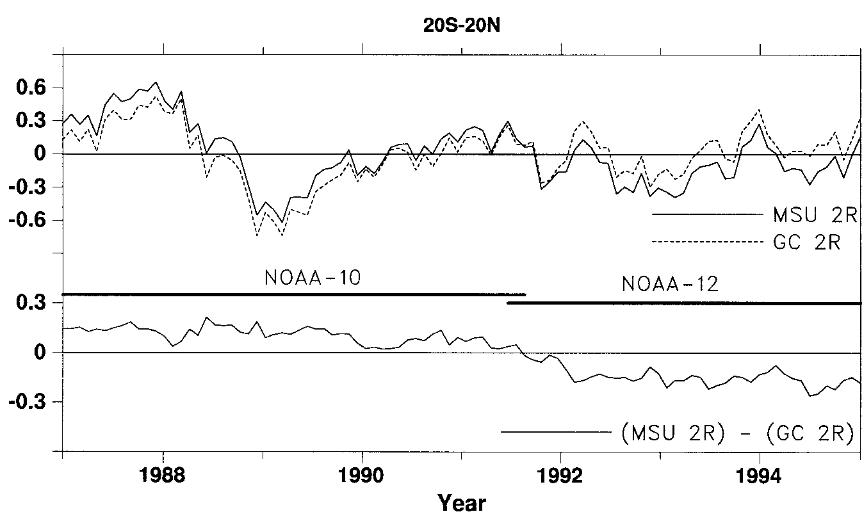

FIG. 14. (Top) Monthly anomalies from Christy et al. (1995) (MSU 2R) and from Goldberg and Crosby (1995) (GC 2R) relative to the 1987–94 means, and (bottom) their difference (°C), MSU 2R−GC 2R. Also indicated are the periods of operation for *NOAA-10* and *NOAA-12.*

pressions of up to several degrees Celsius. Therefore, the MSU data have been filtered to remove this particular contamination, but the matter is a topic of ongoing debate. Prabhakara et al. (1995), and Prabhakara et al. (1996) suggest that a substantial hydrometeor effect still exists in the MSU records, while their analysis is critiqued by Spencer et al. (1996), who argue that the residual hydrometeor contamination effects are greatly overestimated. Variations in water vapor have a smaller effect on MSU brightness temperatures, although the effect is largest for tropical air masses. The estimated MSU 2 (2R) sensitivity to a 20% increase in water vapor concentration over a tropical site is ~ -0.09°C (-0.10°C) over land and ~ 0.08°C (0.18°C) over ocean (Spencer et al. 1990; Shah and Rind 1995). Large regional variations in water vapor occur in response to ENSO, but for interannual variations over the Tropics as a whole such effects would be small.

Channel 2 brightness temperatures receive roughly 90% of their full signal from the atmosphere and 10% from surface emissions over land at sea level, while 95% of the signal is atmospheric over oceans (Spencer et al. 1990). Because of its increased sensitivity to the lower troposphere, surface emission contributes nearly 20% of the signal to MSU 2R over land and 10% over oceans (Shah and Rind 1995). Surface emissions have a much larger effect in mountainous regions, but removal of the mean annual cycle can eliminate the interference where the effect is systematic. Nevertheless, MSU 2R standard errors between different satellites in the Himalayan region can exceed 0.6°C (Fig. 13). Also, significant variations in surface emissivity arise from changes in surface skin temperature, wetness, snow cover, and vegetation and thereby affect measures of interannual variability and trends.

Soil wetness can reduce a dry land microwave surface emissivity by 20%–50% locally, making the land appear colder (Spencer et al. 1990; Shah and Rind 1995), although such effects are mitigated in vegetated regions because the soil moisture is masked. For a change in surface emissivity of -0.2 at an unvegetated tropical land site, the channel 2 bias is ~ -0.8°C and the MSU 2R bias is ~ -1.6°C (Shah and Rind 1995).

The sensitivity of the MSU channels to a 1°C change in tropical land skin temperature is 0.1° and 0.2°C for MSU 2 and 2R, respectively (Shah and Rind 1995). Spencer et al. (1990) point out that changes in surface temperature also result in changes in atmospheric temperature, however, so the issue is whether the average coupling of the surface to the free atmosphere changes in such a way as to cause a misinterpretation of a skin temperature anomaly as an atmospheric anomaly. One example of a change in coupling would be widespread anomalous drought. In this case, much steeper-than-normal lapse rates would add noise to the MSU measurements by producing positive brightness temperature anomalies. Very large diurnal skin temperature variations in desert areas or regions of high topography are another source of noise. Diurnal variations in skin temperature over deserts and mountains are on the order of 20°C, which would add 1°–2°C of daily variability to channel 2 temperatures and twice that for MSU 2R (Shah and Rind 1995). Clear evidence for the noise in the MSU record from these sources comes from the rms differences between satellites over tropical land where noise levels are 0.3°–0.5°C and are roughly double the values over adjacent oceans (Fig. 13). Nor is this noise likely to be random because tropical soil moisture, for instance, is affected by ENSO. However, because surface emissivity influences are obfuscated by the procedures used for removing the diurnal cycle in the MSU record, it is not possible to deconvolve the signal.

6. Conclusions

Changes in the vertical temperature structure of the atmosphere may serve as a useful indicator of anthropogenic climate change and are being used in detection studies (e.g., Santer et al. 1996; Tett et al. 1996). Consequently, reasons for differences between the surface and MSU temperature trends over the past 17 yr have been a matter of spirited debate. While a principal cause of the discrepancies relates to physical differences in the quantities being measured (Hurrell and Trenberth 1996), differences continue to exist and are highlighted in the Tropics where the atmosphere has a very strong direct connection to SSTs. MSU 2R anomalies are much warmer than would be expected from the SSTs prior to 1982 and are colder after 1991 (Fig. 4). Moreover, such features are not as evident in the MSU channel 2 record, which warms relative to the MSU 2R data at a rate of 0.16°C decade^{-1} since 1979 over the Tropics (Fig. 5), nor are they evident in CCM3 simulations forced with observed SSTs (Fig. 7). Radiosonde records almost universally contain temporal inhomogeneities arising from changes in instruments or sensors during the period of interest and are therefore of limited usefulness in resolving the discrepancies, especially throughout the Tropics. Nevertheless, evidence of a spurious downward discontinuity in the MSU 2R record emerges when compared with radiosonde data at Alice Springs after 1991. Moreover, global reanalyses from NCEP also contain artificial trends because they depend upon the radiosondes both directly and through satellite-retrieved soundings. The latter, in particular, have undergone changes in methodology, which contribute to a spurious downward trend in the reanalyzed temperatures. Reanalyzed temperatures from ECMWF show poor agreement with both NCEP and MSU records, which highlights the difficulties in obtaining reliable temperature trends over the Tropics.

We have shown that the surface and MSU temperature records can be completely reconciled in the Tropics provided that two stepwise discontinuities are added to the record. The extensive surface database from many different platforms and several alternative analyses of these

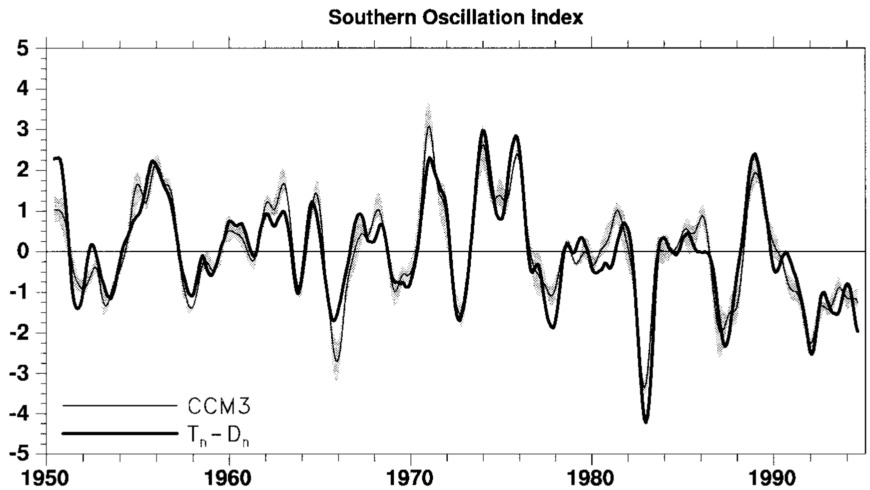

FIG. A1. Observed (heavy solid) and the five-member ensemble mean (thin solid) equivalent Southern Oscillation index from CCM3 integrations and the range about the means (stippled). The values were smoothed with a low-pass 11-term filter that eliminates fluctuations of less than 8 months but retains periods exceeding 24 months (Trenberth 1984).

data provide no evidence that these discontinuities arise from the SST record. Therefore, we have argued that the downward trend in MSU 2R temperatures is spurious and is associated with two discontinuities coincident with changes in satellites and different satellite equator-crossing times that result in sampling biases associated with the diurnal cycle. Matching problems and noise are magnified in the MSU 2R record relative to MSU 2 because of the retrieval method, which eliminates the nontrivial stratospheric influence on channel 2 temperatures but at the expense of contamination of the MSU signal from surface emissions.

Area-averaged monthly mean tropical MSU 2R biases between satellites are known only to an accuracy of ~±0.1°C, so errors of this magnitude can occur in merging records from different satellites. Therefore, there is no a priori reason to expect that only two discontinuities would emerge from our analyses. The magnitude of the discrepancy prior to June 1981 (~0.25°C) is larger than can be explained at present. The warmth in the MSU 2R record relative to surface anomalies before mid-1981 is global and is fairly uniformly distributed (Jones et al. 1997b). It is also reflected in MSU channel 2 anomalies although with much smaller magnitude. Over the Tropics there are few reliable upper-air records to help resolve the differences. During the first half of 1979 afternoon passes of *TIROS-N* provided the only MSU data, while morning passes from *NOAA-6* were the only data source throughout nearly all of 1980 and the first half of 1981, so that the diurnal cycle was not well sampled. Another factor may be that drifts of 1–2 h in the equator-crossing times of both *NOAA-6* and *NOAA-7* clearly influence the OLR record (Waliser and Zhou 1997), but corrections have not been applied to the MSU record. Tropical SST anomalies during this period were only slightly above the 1951–80 mean and agree with an index of the Southern Oscillation based on surface pressures (see Fig. A1), so the much warmer MSU 2R temperatures are difficult to explain physically. Nevertheless, the results raise a serious question concerning the matchup between *NOAA-6* and *NOAA-7* and indicate that the discrepancy can be explained by a discontinuity coincident with the beginning of the *NOAA-7* record.

The noise in the MSU 2R record makes it unsuitable for trend analysis, especially over short (17 yr) periods, although it is in this context that the data are most frequently referenced. Discrepancies in trends from different records are ~0.2°–0.3°C decade^{-1} over the Tropics (Table 1). The accumulated evidence indicates that there should be a small positive trend in MSU 2R, such as found for MSU 2 and the SST record. A positive tropical trend would also be more consistent with the observed retreat of tropical alpine glaciers and ice caps (Thompson et al. 1995) and changes in freezing levels (Diaz and Graham 1996). Because the errors are quite small relative to the interannual signal, the MSU records are otherwise excellent for studies of the interannual variability of tropospheric temperature (e.g., Yulaeva and Wallace 1994).

Acknowledgments. We thank Dr. John Christy for providing the MSU data, including those shown in Figs. 12 and 13. We also thank Liz Stephens for preparing Fig. 3 and Mark Berliner, Chris Wilde, Tim Hoar, and Barbara Bailey for their assistance on the statistical analysis, in particular Fig. 11 and Table 1. Dennis Shea and Doug Lindholm assisted with the preparation and analysis of the Australian radiosonde data. We thank the anonymous reviewers for their critical comments and suggestions. This research is partly sponsored by NOAA

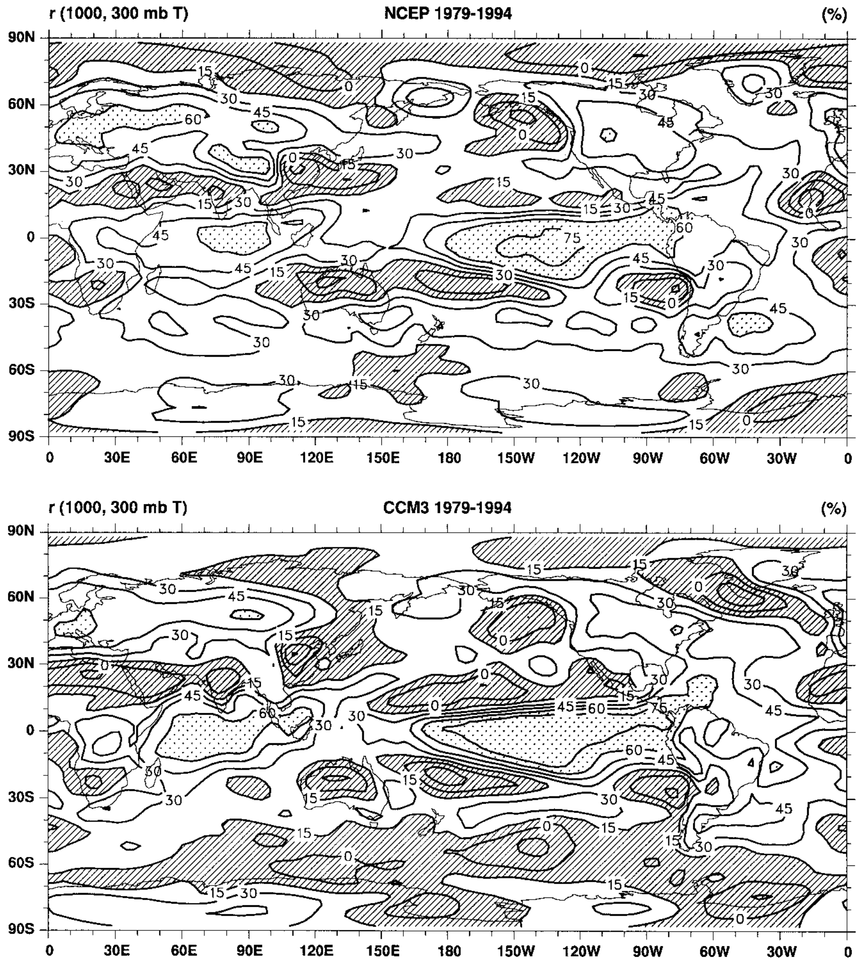

FIG. A2. Correlation coefficients (%) over 192 months between 1000- and 300-mb temperature anomalies from (top) the NCEP reanalyses and (bottom) three-member ensemble mean anomalies from CCM3 integrations forced with observed global SSTs. Monthly anomalies were computed relative to the mean annual cycle for 1982–91. Values less than 15% are hatched and values greater than 60% are stippled.

under Grant NA56GP0247 and by NASA under NASA Order No. W-18,077.

APPENDIX A

CCM3

The utility of the tropical brightness temperatures simulated by CCM3 forced with observed SSTs is dependent upon the ability of the model to realistically mimic atmospheric variability associated with ENSO. Variations in the SO can be measured from the inverse variations in pressures at Darwin (12.4°S, 130.9°E) in northern Australia and Tahiti (17.5°S, 149.6°W) in the South Pacific. Annual mean pressures at these two stations are correlated at -0.79, and an index of the SO can be defined as $T_N - D_N$, where T and D refer to the departure from long-term (1950–94) monthly mean sea level pressures at Tahiti and Darwin, respectively, and N represents the normalization by the annual mean standard deviation of each time series (Trenberth 1984). The observed and simulated SO indices (Fig. A1) show good agreement, especially over several large excursions since 1979. The CCM3 SO index was computed from the five-member ensemble mean pressures at the model grid points nearest to Darwin and Tahiti.

While there is a fairly direct response in tropospheric temperatures to SST changes when area averages are taken over the Tropics, the same is not true locally. During ENSO events, for example, the entire tropical troposphere warms up a few months after the event (Newell and Weare 1976; Horel and Wallace 1981), following the SST signal in the central and eastern tropical Pacific. However, SST anomalies in the western tropical Pacific may actually have the reverse sign, as in the composite for the mature phase of an El Niño in Rasmusson and Carpenter (1982). The surface can also be locally disconnected from the free atmosphere as a result of the tropical trade wind inversion. The local corre-

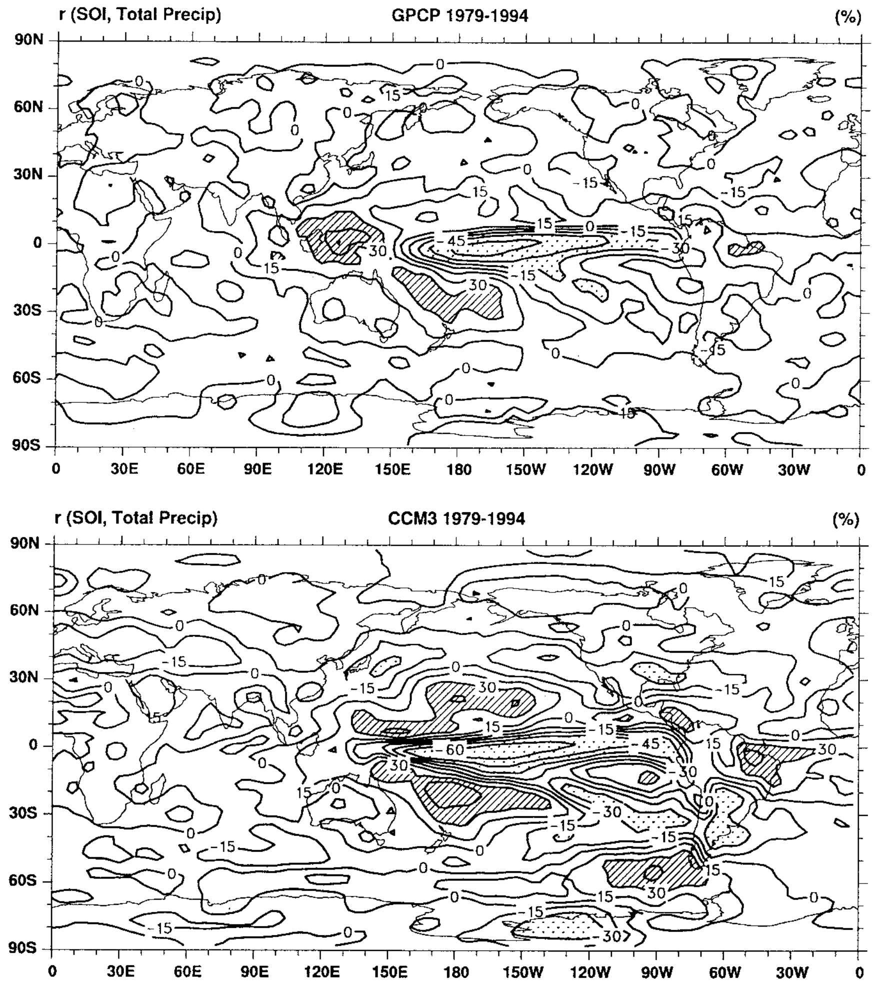

FIG. A3. Correlation coefficients (%) over 192 months between the observed Southern Oscillation index (as defined in the text) and (top) total precipitation from the Global Precipitation Climatology Project (see Xie and Arkin 1996) and (bottom) three-member ensemble mean anomalies from CCM3 integrations forced with observed global SSTs. Values less than −30% are stippled and values greater than 30% are hatched.

lation coefficients between 1000- and 300-mb temperature anomalies show these relationships over the period 1979–94 (Fig. A2). The patterns of correlation from the CCM3 simulations are similar to those from NCEP reanalyzed temperatures, including correlations higher than 60% over the tropical central and eastern Pacific and Indian Oceans, and low correlations throughout the subtropics. Observed shifts in tropical and subtropical convergence zones and monthly rainfall anomalies associated with variations in the SO index are also well simulated by the CCM3 (Fig. A3), in spite of the considerable uncertainties in the deduced ''observed'' values (Chiu et al. 1993). Simulated rainfall anomalies over subtropical subsidence regions are more widespread and are larger than observed except over the western tropical Pacific. The essence of the results in Figs. A1–A3 is that the CCM3 is revealed to be a capable tool for translating the SST record into tropospheric temperatures and is useful in helping to interpret the tropical MSU record.

APPENDIX B

Australian Radiosonde Records

The major discontinuity evident in radiosonde temperature records from Australia involves the introduction of the Vaisala RS80-15 radiosonde in May 1987 at capital cities and at remaining stations throughout the next two years, replacing earlier Philips models, which were biased cold in the troposphere because of significant mean bias errors in pressure of more than 2 mb (Schmidlin and Finger 1987). Initially, daily data from eight tropical or subtropical stations throughout Australia were obtained in order to compare to collocated MSU data. Since the Vaisala instruments were introduced during different months at all eight stations, the initial goal was to estimate the biases introduced into the temperature records through comparisons of anomalies at nearby locations. This approach was not tenable, however, because five of the station records contained large gaps in the daily time series. At Broome (18.0°S, 122.2°E), for example, at least 25 days of data were available for only ~68% of the months since 1979, and ~11% of the monthly means were based on less than 15 days of data. Often, the missing days were consecutive so that monthly mean data could be strongly biased. The most complete records since 1979 were available from Darwin, Alice Springs, and Giles (25°S, 128.3°E), so for those stations missing temperatures were interpolated from collocated daily NCEP reanalysis data and monthly averages were computed based on 0000 UTC values (the 1200 UTC records were much more sparse). Monthly anomalies at one station were then compared at standard levels to the other two stations through linear regression, but the fits were not good enough to attempt to remove biases from the Vaisala transition. Moreover, for reasons that are not clear at this time, the monthly anomalies from Giles show little relationship to those from Darwin and Alice Springs, and they also disagree with data provided independently by D. Gaffen. For this reason, we have not included the Giles data in our analysis. Such problems do, however, highlight the care that must be taken when comparing the MSU temperatures to radiosonde data, especially when stations are averaged together to form regional means.

REFERENCES

Andersson, E., A. Hollingsworth, G. Kelly, P. Lönnberg, J. Pailleux, and Z. Zhang, 1991: Global observing system experiments on operational statistical retrievals of satellite sounding data. *Mon. Wea. Rev.,* **119,** 1851–1864.

Angell, J. K., 1988: Variations and trends in tropospheric and stratospheric global temperatures, 1958–87. *J. Climate,* **1,** 1296–1313.

Basist, A. N., and M. Chelliah, 1997: Comparison of tropospheric temperature derived from the NCEP/NCAR reanalysis, NCEP operational analysis and the Microwave Sounding Unit. *Bull. Amer. Meteor. Soc.,* **78,** 1431–1447.

——, 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.

Chen, D., S. E. Zebiak, A. J. Busalacchi, and M. A. Cane, 1995: An improved procedure for El Niño forecasting: Implications for predictability. *Science,* **269,** 1699–1702.

Chiu, L. S., A. T. C. Chang, and J. Janowiak, 1993: Comparison of monthly rain rates derived from GPI and SSM/I using probability distribution functions. *J. Appl. Meteor.,* **32,** 323–334.

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.

——, ——, and E. Lobi, 1998: Analysis of the merging procedure for the MSU daily temperature time series. *J. Climate,* in press.

Cryer, J. D., 1986: *Time Series Analysis.* Duxbury Press, 286 pp.

Deser, C., and M. Timlin, 1997: Atmosphere–ocean interaction on weekly time scales in the North Atlantic and Pacific. *J. Climate,* **10,** 393–408.

Diaz, H. F., and N. E. Graham, 1996: Recent changes in tropical freezing heights and the role of sea surface temperature. *Nature,* **383,** 152–155.

Elliott, W. P., and D. J. Gaffen, 1991: On the utility of radiosonde humidity archives for climate studies. *Bull. Amer. Meteor. Soc.,* **72,** 1507–1520.

——, ——, J. D. W. Kahl, and J. K. Angell, 1994: The effect of moisture on layer thicknesses used to monitor global temperatures. *J. Climate,* **7,** 304–308.

Eyre, J. R., 1987: On systematic errors in satellite sounding products and their climatological mean values. *Quart. J. Roy. Meteor. Soc.,* **113,** 279–292.

Gaffen, D. J., 1993: Historical changes in radiosonde instruments and practices. WMO/TD-No. 541, Instruments and Observing Methods Rep. 50, World Meteorological Organization, 123 pp.

——, 1994: Temporal inhomogeneities in radiosonde temperature records. *J. Geophys. Res.,* **99,** 3667–3676.

——, 1996: A digitized metadata set of global upper-air station histories. NOAA Tech. Memo. ERL ARL-211, 38 pp. [Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.]

——, R. E. Habermann, and J. R. Lanzante, 1997: Toward estimating stratospheric temperature trends with radiosonde data. Stratospheric processes and their role in climate (SPARC). *Proc. First SPARC General Assembly,* Melbourne, Australia, World Meteorological Organization, 197–200.

Gates, W. L., 1992: AMIP: The Atmospheric Model Intercomparison Project. *Bull. Amer. Meteor. Soc.,* **73,** 1962–1970.

Gibson, R., P. Kållberg, and S. Uppala, 1996: The ECMWF Re-Analysis (ERA) Project. *ECMWF Newsletter,* **73,** 7–17.

Goldberg, M. D., and D. S. Crosby, 1995: NOAA's MSU time series for detecting climate change. *Proc. 20th Annual Climate Diagnostics Workshop,* Seattle, WA, NOAA/Climate Prediction Center and the Joint Institute for the Study of Atmosphere and Ocean, University of Washington, 345–348.

——, and H. E. Fleming, 1995: An algorithm to generate deep-layer temperatures from microwave satellite observations for the purpose of monitoring climate change. *J. Climate,* **8,** 993–1004.

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

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

——, and Coauthors, 1996: A Pinatubo climate modeling investigation. *Global Environmental Change,* G. Fiocco, D. Fua', and G. Visconti, Eds., NATO ASI Series, Vol. 42, Springer-Verlag, 233–272.

Horel, J. D., and J. M. Wallace, 1981: Planetary scale atmospheric phenomena associated with the Southern Oscillation. *Mon. Wea. Rev.,* **109,** 813–829.

Hurrell, J. W., 1996: Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperatures. *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.

——, and ——, 1996: Satellite versus surface estimates of air temperature since 1979. *J. Climate,* **9,** 2222–2232.

IPCC, 1996: *Climate Change 1995: The Science of Climate Change.* Cambridge University Press, 570 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.

Jones, R. H., and I. Dey, 1995: Determining one or more change points. *Chem. Phys. Lipids,* **76,** 1–6.

——, T. J. Osborne, and K. R. Briffa, 1997a: Estimating sampling errors in large-scale temperature averages. *J. Climate,* **10,** 2548–2568.

——, ——, T. M. L. Wigley, P. M. Kelly, and B. D. Santer, 1997b: Comparisons between the MSU 2R temperature record and the surface temperature record over 1979 to 1996: Real differences or potential discontinuities? *J. Geophys. Res.,* **102,** 30 135–30 145.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Kaplan, A., M. A. Cane, Y. Kushnir, A. C. Clement, M. B. Blumenthal, and B. Rajagopalan, 1998: Analyses of global sea surface temperature 1856–1991. *J. Geophys. Res.,* in press.

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.

Kelly, G., E. Andersson, A. Hollingsworth, P. Lönnberg, J. Pailleux, and Z. Zhang, 1991: Quality control of operational physical retrievals of satellite sounding data. *Mon. Wea. Rev.,* **119,** 1866–1880.

Kiehl, J. T., J. J. Hack, G. B. Bonan, B. A. Boville, B. P. Briegleb, D. L. Williamson, and P. J. Rasch, 1996: Description of the NCAR Community Climate Model (CCM3). NCAR Tech. Note NCAR/TN-420+STR, 152 pp. [Available from NCAR, P.O. Box 3000, Boulder, CO 80307-3000.]

Newell, R. E., and B. C. Weare, 1976: Factors governing tropospheric mean temperatures. *Science,* **194,** 1413–1414.

Oort, A. H., and H. Liu, 1993: Upper-air temperature trends over the globe, 1958–1989. *J. Climate,* **6,** 292–307.

Overland, J. E., and R. W. Preisendorfer, 1982: A significance test for principal components applied to a cyclone climatology. *Mon. Wea. Rev.,* **110,** 1–4.

Parker, D. E., and D. I. Cox, 1995: Towards a consistent global climatological rawinsonde data-base. *Int. J. Climatol.,* **15,** 473–496.

——, 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.

——, M. Gordon, D. P. N. Cullum, D. M. H. Sexton, C. K. Folland, and N. Rayner, 1997: A new global gridded radiosonde temperature data base and recent temperature trends. *Geophys. Res. Lett.,* **24,** 1499–1502.

Prabhakara, C., J. J. Nucciarone, and J.-M. Yoo, 1995: Examination of ''Global atmospheric temperature monitoring with satellite microwave measurements.'' Part 1: Theoretical considerations. *Climate Change,* **30,** 349–366.

——, J.-M. Yoo, S. P. Maloney, J. J. Nucciarone, A. Arking, M. Cadeddu, and G. Dalu, 1996: Examination of ''Global atmospheric temperature monitoring with satellite microwave measurements.'' Part 2: Analysis of satellite data. *Climate Change,* **33,** 459–476.

Ramaswamy, V., M. D. Schwarzkopf, and W. J. Randel, 1996: Fingerprint of ozone depletion in spatial and temporal patterns of recent lower stratospheric cooling. *Nature,* **382,** 616–618.

Rasmusson, E. M., and T. H. Carpenter, 1982: Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Mon. Wea. Rev.,* **110,** 354–384.

Reale, A., M. Chalfant, R. Wagoner, T. Gardner, and L. Casey, 1994: TOVS operational sounding upgrades: 1990–1992. NOAA Tech. Rep. NESDIS 76, U.S. Department of Commerce, NOAA, Washington, DC, 67 pp. [Available from National Environmental Satellite, Data, and Information Service, Washington, DC 20233.]

Reynolds, R. W., and T. M. Smith, 1994: Improved global sea surface temperature analyses using optimum interpolation. *J. Climate,* **7,** 929–948.

Santer, B. D., and Coauthors, 1996: A search for human influences on the thermal structure of the atmosphere. *Nature,* **382,** 39–46.

Schmidlin, F. J., and F. G. Finger, 1987: Conclusions and recommendations resulting from the WMO international radiosonde comparison. *Proc. Sixth Symp. on Meteorological Observations and Instrumentation,* New Orleans, LA, Amer. Meteor. Soc., 459–462.

Shah, K. P., and R. Rind, 1995: Use of microwave brightness temperatures with a general circulation model. *J. Geophys. Res.,* **100,** 13 841–13 874.

Shukla, J., and M. J. Fennessy, 1988: Prediction of time-mean atmospheric circulation and rainfall: Influence of Pacific sea surface temperature anomaly. *J. Atmos. Sci.,* **45,** 9–28.

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. Release 1, 262 pp.

Smith, T. M., R. W. Reynolds, R. E. Livezey, and D. C. Stokes, 1996: Reconstruction of historical sea surface temperatures using empirical orthogonal functions. *J. Climate,* **9,** 1403–1420.

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.

——, ——, and ——, 1996: Analysis of 'Examination of ''Global atmospheric temperature monitoring with satellite microwave measurements.''' *Climate Change,* **33,** 477–489.

Stendel, M., and L. Bengtsson, 1997: Toward monitoring the tropospheric temperature by means of a general circulation model. *J. Geosphys. Res.,* **102,** 29 779–29 788.

Stone, P. H., and J. H. Carlson, 1979: Atmospheric lapse rate regimes and their parameterization. *J. Atmos. Sci.,* **36,** 415–423.

Tett, S. F. B., J. F. B. Mitchell, D. E. Parker, and M. R. Allen, 1996: Human influence on the atmospheric vertical temperature structure: Detection and observations. *Science,* **274,** 1170–1173.

Thompson, L. G., E. Mosley-Thompson, M. E. Davis, P.-N. Lin, K. A. Henderson, J. Cole-Dai, J. F. Bolzan, and K.-B. Liu, 1995: Late glacial stage and holocene tropical ice core records from Huascarán, Peru. *Science,* **269,** 46–50.

Trenberth, K. E., 1984: Signal versus noise in the Southern Oscillation. *Mon. Wea. Rev.,* **112,** 326–332.

——, and J. G. Olson, 1991: Representativeness of a 63-station network for depicting climate changes. *Greenhouse-Gas-Induced Climatic Change: A Critical Appraisal of Simulations and Observations,* M. E. Schlesinger, Ed., Elsevier Science, 249–260.

——, and C. J. Guillemot, 1998: Evaluation of the atmospheric moisture and hydrological cycle in the NCEP reanalyses. *Climate Dyn.,* in press.

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

Waliser, D. E., and W. Zhou, 1997: Removing satellite equatorial crossing time biases from the OLR and HRC datasets. *J. Climate,* **10,** 2125–2146.

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

Xie, P., and P. A. Arkin, 1996: Analyses of global monthly precipitation using gauge observations, satellite estimates, and numerical model predictions. *J. Climate,* **9,** 840–858.

Yulaeva, E., and J. M. Wallace, 1994: The signature of ENSO in global temperature and precipitation fields derived from the Microwave Sounding Unit. *J. Climate,* **7,** 1720–1736.