An Evaluation of Monthly Mean MSU and ECMWF Global Atmospheric Temperatures for Monitoring Climate

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ABSTRACT

Monthly mean brightness temperature anomalies derived from channel 2 of the microwave sounding units (MSUs) on board NOAA satellites over the past decade are examined and compared with both weighted and pressure-level ECMWF monthly mean temperatures for the 96 months of 1982–89. Very good agreement between the MSU and channel 2 weighted ECMWF anomalies is found over most of the globe with correlation coefficients over 0.9, but the agreement falls off over the tropics, the South Atlantic, and high latitudes of the Southern Hemisphere. The ECMWF analyses agree best with the MSU data in regions of good radiosonde coverage, while lower correlations are found in regions where the analyses depend more heavily on satellite data. Systematic errors introduced into the analyses by the retrieval techniques applied to the radiance data largely explain this apparent contradiction. Additionally, changes to the analysis-forecast system at ECMWF over the decade appear as apparent changes in climate, and these discontinuities most strongly affect the tropics and are evident in regions of fewer observations.

To the extent that the weighted ECMWF data agree with the MSU brightness temperatures the vertical dependence of the MSU data can be examined. Correlations of the MSU data with ECMWF temperature anomalies at individual pressure levels are highest at 300 mb over the globe, a level apparently least affected by the frequent changes and improvements at ECMWF. Over regions of good data coverage, such as the Northern Hemisphere landmasses and Australia, the MSU anomalies correlate very highly with all levels of the troposphere up to 200 mb. Thus, the MSUs appear to be an extremely useful tool for measuring global tropospheric temperature fluctuations on a monthly and longer time scale.

Problems in the ECMWF temperature record since 1982 are examined in detail for the tropics. In September 1982 the introduction of diabatic nonlinear normal-mode initialization resulted in significant temperature increases in the tropical middle troposphere, especially at 500 mb. In May 1985 tropical temperatures at 700 mb (850 mb) increased (decreased) after the implementation of the T106 spectral model with major accompanying changes to physical parameterizations. Tropical temperatures near the tropopause decreased substantially after the May 1986 enhancement of the vertical resolution of the model from 16 to 19 levels with 3 new stratospheric levels. Problems at 1000 mb are present throughout the 96-month study period and are directly related to the manner in which analyzed temperatures are obtained at ECMWF. Comparisons with temperatures obtained from radiosonde stations in the tropics show that the ECMWF analyses have clearly improved with time, especially after May 1985 after which the 1000–200-mb temperatures show much greater coherence. These results show the importance of realizing the inherent problems with operationally based gridded datasets, and they strongly support the need for reanalysis of all data using a state-of-the-art four-dimensional data assimilation system.

1. Introduction

The possibility of inadvertent climate change induced by continuing emissions of carbon dioxide (CO_2) and other greenhouse gases has prompted many recent analyses of historical weather data. Unfortunately, historical atmospheric observations were principally designed to monitor weather rather than climate change. Observations of surface temperature and precipitation have received the most attention in climate studies, largely because long records of these variables exist. A useful summary of a number of systematic and random errors that may have affected these data and, consequently, our ability to understand climate change and variability from them has been given by the Intergovernmental Panel on Climate Change (IPCC 1990). Upper-air data, although available only for the last few decades, have also received increased attention. These data have been subject to serious errors as well, and the utility of radiosonde observations for climate studies has been discussed by Elliott and Gaffen (1991). It is with such biases in mind that there has recently been

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an increasing emphasis on the use of satellites for climate monitoring. Although satellite data currently suffer from shortness of record, satellites do have the ability to provide the global coverage that the historical record lacks. If the problem of drift in instrument calibration can be overcome, satellite measurements may potentially provide a long-term record free of the many sampling errors present in the more conventional datasets. Of course these are essential requirements if we are to ever fully comprehend the background natural variability of the climate system and ultimately study climate change.

One of the purposes of the present paper is to examine and interpret data provided by the microwave sounding units (MSUs) on board NOAA satellites over the last decade (Spencer and Christy 1990, 1992a; Spencer et al. 1990). In particular, we will examine MSU monthly mean brightness temperatures together with European Centre for Medium-Range Weather Forecasts (ECMWF) monthly means. In a parallel paper, Trenberth et al. (1992) (hereafter referred to as TCH) compared global monthly mean brightness temperature anomalies from the MSUs with a near-global surface dataset used by the IPCC in their assessments. Gridpoint correlation coefficients over the 144-month period of 1979–90 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 inherent noise in the surface observations, although physical differences between the MSU and surface data were clearly another reason. In this study we aim to gain a better understanding of the physical nature and the vertical dependence of the MSU data using the ECMWF analyses. As a natural result of this effort, the usefulness of the ECMWF analyses in monitoring monthly mean global temperatures will be also examined.

The potential importance of the MSU data is emphasized by the results of general circulation model (GCM) integrations that predict temperature increases resulting from enhanced greenhouse-gas concentrations will be more widespread and, perhaps, greater in the midtroposphere than at the surface (IPCC 1990). In addition, equilibrium experiments using coupled ocean–atmosphere GCMs have shown that free tropospheric temperatures, together with near-surface temperatures and lower-to-middle tropospheric water vapor content, have a very high signal-to-noise ratio and, therefore, may be useful in detecting anthropogenic climate change (Barnett and Schlesinger 1987; IPCC 1990; Santer et al. 1991).

Observational studies of recent upper-air temperature and thickness deviations have been made by numerous authors. Parker (1985) used approximately 25 years of radiosonde data through 1983 from 21 locations to examine the temporal variation of 50-mb minus 300-mb temperature differences. He found that most stations showed no indication of the tropospheric warming and stratospheric cooling trends predicted in most modeling scenarios of doubled CO_2 concentrations. He suggested that an additional 35 years of radiosonde data was a prerequisite for detecting temperature trends of the magnitude predicted by most GCMs. Sellers and Liu (1988) examined contributions of several different climatic variables to the total variance of the zonally averaged upper-air temperature field using data from 511 radiosonde stations around the world from 1957 through 1985 using an empirical orthogonal function (EOF) analysis. The third eigenvector contained the model-predicted opposition between the stratosphere and troposphere and exhibited a steady upward trend that appeared to be consistent with observed increases in CO_2 concentrations. Karoly (1987, 1989) used radiosonde data from 1964 through 1985 and found warming trends at most stations in the troposphere and cooling trends in the stratosphere. However, as noted in the above studies, the tendency for forcing mechanisms such as the El Niño–Southern Oscillation (ENSO) phenomenon and changes in solar fluxes and CO_2 to produce the same response in the temperature field makes causal identification difficult.

Angell (1988) compiled layer mean temperatures from 63 radiosonde stations well distributed around the globe and showed that globally averaged midtropospheric (850–300-mb) temperatures have significantly increased 0.09°C per decade from 1957 through 1987. Most of the warming, however, was confined to the equatorial region and to the Southern Hemisphere (SH), while no significant warming trend was found north of 10°N. A larger global warming trend (0.24°C per decade) was evident in Angell's data during the period 1973–87, and all latitude zones except for the Northern Hemisphere (NH) polar region showed warming. In the 300–100-mb layer Angell found a steady decline in global temperatures since 1958, which is in general disagreement with model simulations of increased greenhouse-gas concentrations. Global temperatures in the 100–50-mb layer decreased by a significant 0.62°C per decade from 1973 to 1987, and the decrease was three times as large in the SH as in the NH, largely as a result of the Antarctic ozone hole phenomenon. The ability of Angell's 63-station network to capture the climate signal has been examined by Trenberth and Olson (1991). They used nine years of ECMWF analyses on a T42 grid to compare regional and global means computed exactly with means computed using the procedures of Angell (1988). Trenberth and Olson found high correlations between the station network and the true values, but root-mean-square (rms) errors outside of the tropics were also large and were of the same order as the signal being sought. Thus, although the low-frequency fluctuations were reasonably well depicted by the 63-station network, their amplitude was too large, which tended to exaggerate trends. Moreover, Trenberth and Olson pointed out that results from such a spatially wide distribution of

stations can be compromised by missing data because of the low level of redundancy in the network.

This discussion illustrates the intense interest in and the importance of monitoring free-atmosphere temperatures. However, one overriding problem with trend analysis of the upper-air data is that the surface record indicates that trends from the last three decades are not representative of the true long-term trends. Another important point to keep in mind is that temperatures derived from radiosondes are subject to instrumental biases, and little effort has been taken in the aforementioned studies to account for these errors, although many changes in radiosonde instrumentation have occurred over the last three decades (Pratt 1985; Elliott and Gaffen 1991). In addition, differences in observing times, radiation corrections, station distributions, and other errors have all affected the temperature record. To the extent that the MSU data have not been strongly affected by calibration errors (section 2), the usefulness of such global satellite data becomes apparent.

In section 2 we present a description of the MSU and ECMWF datasets, albeit brief since they have been described in detail elsewhere. Comparisons of monthly mean temperature variations from both datasets are contained in section 3 for both vertically weighted and individual level ECMWF data. In section 4 we document and explain some irregularities in the ECMWF analyses that arise from changes to the analysis-forecast system, and a brief summary and conclusions are given in section 5.

2. The MSU and ECMWF datasets

a. MSU data

The technical aspects of the MSU data retrievals have been described by Spencer et al. (1990), and the data specifically used in this study have been described in detail by Spencer and Christy (1992a), hereafter referred to as SC92. The individual channels in the MSU measure a vertically averaged atmospheric thermal emission, or brightness temperature, and, thus, do not represent a thin near-surface layer sensitive only to variable surface effects. Moreover, Spencer et al. (1990) report that the MSU 53.74-GHz channel (channel 2) is sensitive to the thermal emission of molecular oxygen in the middle troposphere, and it is relatively transparent to water vapor and cloud variations. Oxygen is a very good temperature tracer for climate monitoring because it is uniformly mixed and its concentration is very stable in time. The primary loss of data from the MSUs results from filtering out the effects of precipitation-sized ice in thunderstorms. The surface emissivity has a noticeable effect in mountainous regions, but because it is systematic, the interference can mostly be eliminated when the mean annual cycle is removed. Probably the most limiting factor to interpreting the channel 2 MSU data in terms of a tropospheric temperature, however, is the small, but nontrivial, signal received 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. However, the reproducibility of brightness temperatures between different satellites is not as good with the adjusted data as with channel 2. Consequently, only the channel 2 brightness temperatures are utilized in this study.

The stability of the MSU channel 2 data from one satellite to another is a key issue. Over much of the past decade, two MSUs on different NOAA satellites have sampled globally twice daily, although a few periods have existed when only a single satellite has been available. SC92 describe how the multisatellite data have been merged, and they also give an evaluation of instrument stability. Monthly mean channel 2 brightness temperatures averaged over the hemispheres are reproduced to within approximately 0.01°C, indicating a significant lack of instrument drift. In fact, the monthly reproducibility between different satellites at the 2.5° gridpoint resolution was found to be generally better than 0.1°C in the tropics and 0.2°C at higher latitudes. In comparisons with radiosonde data over the decade, SC92 show that no significant spurious trends are present in the satellite data. Moreover, they conclude that the accuracy of the MSU data approaches the precision of individual radiosonde stations in their ability to measure monthly mean temperature anomalies, which they estimated from intercomparisons of closely spaced oceanic stations in the tropical Pacific to be 0.2°C.

In evaluating the ability of the MSUs to measure tropospheric temperature fluctuations, SC92 found that both monthly and annual MSU anomalies from the last decade correlated from 0.90 to 0.98 with those from vertically weighted radiosonde temperature profiles. Root-mean-square differences generally ranged from 0.15°C in the tropics to 0.25°C at high latitudes and improved to 0.10°C and 0.20°C, respectively, for radiosonde data composited into regional profiles. Correlations of the satellite data to radiosonde-measured thickness values were only slightly lower and were best for the 1000–200-mb layer. These results were somewhat limited, however, to stations from the continental United States, Alaska, Hawaii, the Caribbean basin, and the tropical west Pacific. It is the purpose of this work to examine the relationship between the apparent climate records as depicted by the MSU data and the ECMWF analyses on a global scale.

These results seem to indicate that the MSUs are highly suitable for monitoring intraseasonal to interannual temperature variations with global coverage. Channel 2 brightness temperatures were available to us from 1979 through 1990 (144 months), although data from March 1989 are excluded in this study because a limited number of retrievals during the month make the mean temperature unreliable. For compat-

ibility with the archived ECMWF analyses (Trenberth and Olson 1988a), the MSU data have been transformed to and processed on a T42 Gaussian grid.

b. ECMWF data

Four-dimensional data assimilation at ECMWF is used to produce analyses by combining in an optimal fashion information from past analyses carried forward by the numerical weather prediction model with new observations in 6-hour increments. It is important to note that geopotential heights, but not temperatures, are the primary analyzed quantities, while temperatures, and not geopotential heights, are predicted by the model. The optimum interpolation scheme employed at ECMWF uses observations to determine increments of geopotential height on model sigma hybrid (half) levels. Increments of temperature are then computed hydrostatically on full model sigma levels. The hydrostatic temperature increments are then added to the 6-hour forecast first-guess model-level temperatures to obtain the analyzed temperatures. Analyzed snow cover and sea surface temperatures (SSTs) (after July 1982) specify some lower boundary conditions for the model, while surface and near-surface temperatures over land are largely dependent on the relevant physical parameterizations. Postprocessing to standard pressure levels involves an interpolation of temperatures from the two nearest model sigma levels, or if the pressure level is below the model terrain, an extrapolation is invoked using a standard lapse rate. Inherently, larger errors should be expected if extrapolation is required, so one might anticipate larger uncertainties at 1000 mb when surface pressures are less than that, such as over oceanic regions at middle and high latitudes especially during winter.

Monthly data from ECMWF for the period 1979–89 (132 months) were taken from the archived analyses of Trenberth and Olson (1988a), and they were produced from 12-hourly data excluding a few "bad" analyses where problems clearly existed. Prior to 1982, very large and physically unrealistic temperature vari-

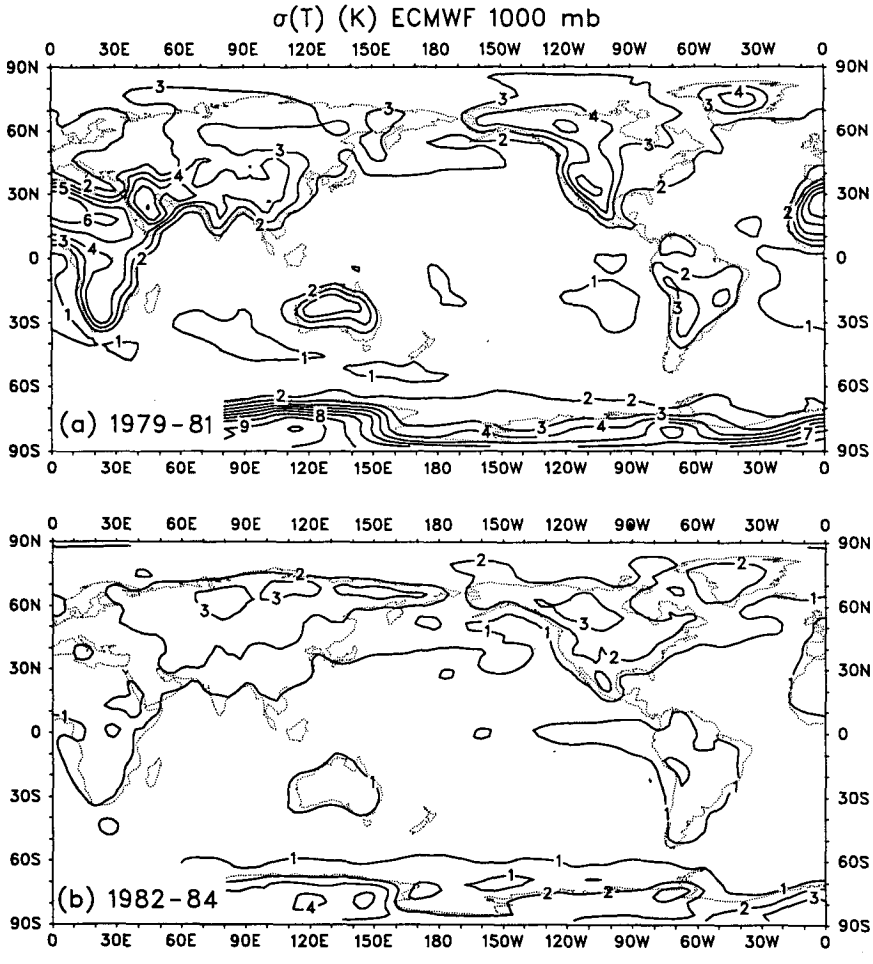

FIG. 1. Standard deviation of ECMWF 1000-mb monthly temperature anomalies from (a) 1979–81 and (b) 1982–84. Contour interval is 1 K.

ations at 1000 mb are present in the ECMWF analyses, as revealed by the standard deviations of 1000-mb monthly mean temperature anomalies for the 3-year periods 1979–81 (Fig. 1a) versus 1982–84 (Fig. 1b). The latter result appears to be more physically realistic, and it is nearly identical to the same plot for the 96 months of 1982–89 (not shown). Moreover, Fig. 1b is in good agreement with a similar figure from TCH (their Fig. 6) of the standard deviation of monthly mean observed surface temperatures for the period 1979–89. The largest standard deviations, in excess of 1 K, occur over the land areas, and values are greater than 2 K over much of North America and Asia. Values over Antarctica and other regions of high elevation have no physical relevance because 1000-mb temperatures are extrapolated below ground. Over the oceans the deviations are much smaller and only exceed 1 K over the eastern tropical Pacific, the northern extratropical sectors of the Pacific and Atlantic, and at the highest latitudes of the Southern Ocean.

It is difficult to account for the source of the uncertainties in the 1000-mb data prior to 1982. Other uncertainties exist in the ECMWF 1000-mb temperature analyses after this time as well, which points to the lack of attention given to surface fields in the operational analyses of the atmosphere and, in particular, to the manner in which temperatures are not analyzed at ECMWF but rather are derived from virtual temperatures estimated from layer thicknesses of geopotential height. These problems are manifested as very poor anomaly correlations and spurious variance in comparisons of ECMWF 1000-mb monthly temperatures with several SST analyses over the oceans. An example is the correlation with monthly anomalies from the Climate Analysis Center (CAC) SST analyses from 1982 to 1989 (Fig. 2). Poor correlations are evident over all ocean regions, and values exceed 0.75 only in the tropical eastern Pacific where the climate signal is large. These aspects are illustrated further for the North Atlantic (20°–50°N, 20°–60°W), a region of good data coverage, by the time series of SST anomalies from the CAC and United Kingdom Meteorological Office (UKMO) analyses plotted along with the 1000-mb ECMWF temperature anomalies (Fig. 3). Note that the variance of the ECMWF product is a factor ~9 larger than for either SST series and is much larger than reasonable. In the North Atlantic, the correlation between the two SST products is 0.97, while the correlations of the 1000-mb data with the SSTs are −0.07 (CAC) and −0.05 (UKMO).

Of course there are physical differences between air and sea surface temperatures, so one would not expect perfect agreement, although on monthly time scales, anomalies should be fairly well correlated. Indeed, TCH found from the Comprehensive Ocean–Atmosphere Data Set (COADS) that monthly mean air and SSTs were correlated 0.89 in the North Atlantic over 1982–88, showing that there is a distinct difference between SST and surface air temperature but that 80% of the variance of one is captured by the other. Moreover, the correlation of the ECMWF 1000-mb monthly temperature anomalies with the COADS air temperature anomalies was 0.0. Evidently, some of the inconsistencies in the ECMWF 1000-mb data occurred from the improper use of single-level data (Per Unden, personal communication, 1991), a problem that was corrected on 29 August 1989. Before that time, surface observations with negative (positive) pressure or height departures from the first guess were placed above (below) the model surface. Where a number of such observations occurred (e.g., from ships), the analysis scheme drew to a significant extent to this artificial vertical height gradient and produced, at times, spurious temperature errors of 1° to 4°C.

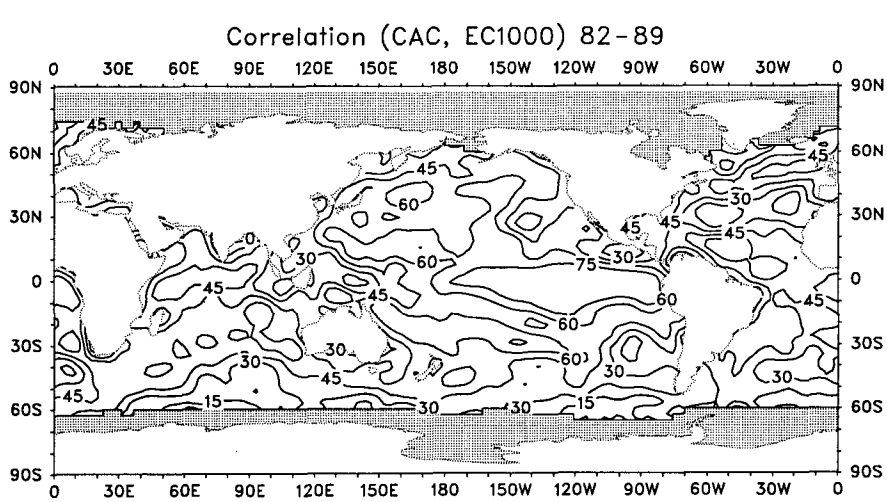

FIG. 2. Correlation over 96 months from 1982 to 1989 for the CAC SST and ECMWF 1000-mb anomaly data. Values have been multiplied by 100, and the contour interval is 15.

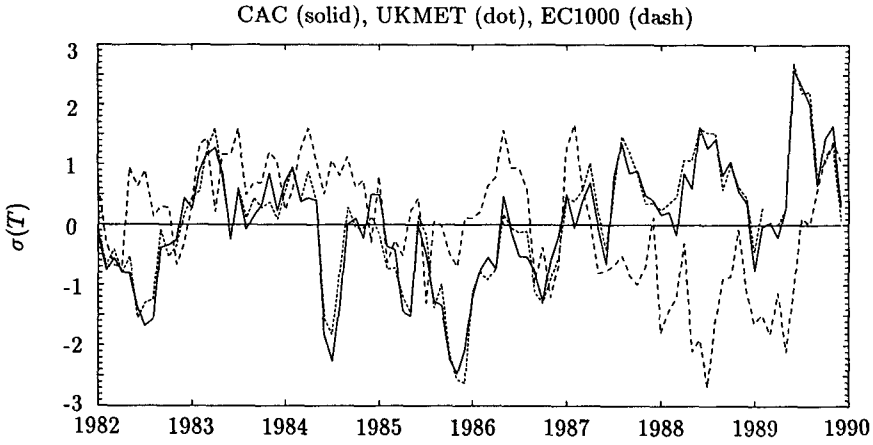

FIG. 3. Time series of standardized monthly temperature anomalies for the North Atlantic region from CAC (solid) and UKMO (dotted) SSTs and ECMWF 1000 mb (dashed). The standard deviation used to normalize each series is 0.21°C for CAC, 0.23°C for UKMO, and 0.63°C for ECMWF.

Clearly, the operational ECMWF analyses were not intended for climate studies, and there are many a priori reasons why the analyzed temperatures should not be appropriate for climate monitoring. As discussed by Bengtsson and Shukla (1988) and Trenberth and Olson (1988a,b), the model-based ECMWF global dataset is a very useful by-product of the operational forecasting mission. As such, discontinuities in the data arise from frequent improvements to the forecast model and the data assimilation system, and these discontinuities are manifested as apparent changes in climate. Trenberth and Olson provide a detailed listing of the changes to the operational system at ECMWF since 1979. They also assess the internal consistency and accuracy of both the National Meteorological Center (NMC) and ECMWF global analyses, and they discuss the usefulness of these data for climate studies. Similarly, Bengtsson and Shukla demonstrate how changes at ECMWF have produced qualitative and quantitative changes in the spatial and temporal variability of the global analyses, especially in the derived quantities.

It is with such points in mind, and the clear problems in the 1000-mb temperatures prior to 1982, that we carefully use the monthly ECMWF level data for the period 1982–89 to better understand the physical nature of the MSU data. Some specific changes to the analysis-forecast system that have clearly impacted the ECMWF analyzed temperature fields will be discussed further in section 4.

c. *The weighting function*

The vertical structure of the MSU channel 2 weighting function is relevant to the comparison. The theoretical calculations presented in Spencer et al. (1990) suggest a weighting function for the nadir scan position that has a broad maximum between 500 and 1000 mb that drops to about half the peak by 300 mb. For off-nadir scans, the peak is higher near 400 mb, with more weight relative to nadir at lower pressures. Based on comparisons with radiosonde data, however, SC92 suggest that a more accurate weighting function at nadir maximizes near 500 mb, and even higher for off-nadir scans (see their Fig. 1). In addition, to retrieve an equivalent channel 2 brightness temperature from multiple-level datasets, they suggest using a simple vertical weighting function that is equal to the channel 2 weighting function, as opposed to more complicated radiative transfer calculations. In this case, the vertically weighted equivalent channel 2 temperature from the ECMWF data is given by

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

(see SC92). Here, the ith layer of the ECMWF data has an average temperature T_i, an average weight w_i taken from Fig. 1 in SC92, 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), and monthly mean surface pressures were used to adjust the normalized weight so that no levels below the surface were used in the calculations.

3. Comparison of the MSU and ECMWF data

a. *Channel 2 weighting*

Gridpoint correlations and rms differences between the 96 monthly MSU and weighted ECMWF temper-

ature anomalies for 1982–89 are presented in Fig. 4. Anomalies in each dataset are defined relative to the annual cycle from this period; therefore, differences between the MSU and ECMWF data are relative to the removed mean annual cycles of each dataset and do not represent absolute differences. It is clear that monthly anomalies between the two datasets are in very good agreement over most of the globe. Outside of the western tropical Pacific, the tropical Atlantic, tropical portions of the continents, the Himalayas, and Antarctica correlations generally exceed 0.8. The lower correlations and large rms differences over some mountain regions may reflect a surface influence in the MSU data, plus the comparison differs in that a smaller depth of the atmosphere is represented. The same reasoning applies to much of Antarctica, where additionally the MSU signal may suffer from stratospheric contamination and problems exist in the ECMWF data (discussed later). Over much of the NH extratropics, correlations are greater than 0.9, and values exceed 0.95 over most of the landmasses and the North Pacific. Correlations in the SH are a bit lower, but still exceed 0.9 in a belt from roughly 20°S to 50°S. The lower correlations throughout the tropical belt probably reflect not only a smaller signal-to-noise ratio but changes to the ECMWF analysis system as well (section 4). These changes apparently have had least influence on the 300-mb analyses so that the MSU vertical weighting function reduces the impact of many of the inconsistencies. The largest rms differences in the tropics are in the eastern tropical Pacific where the variance is large, but rms differences of 0.25°C in the western tropical Pacific and equatorial Atlantic are significant considering the smaller size of the signal.

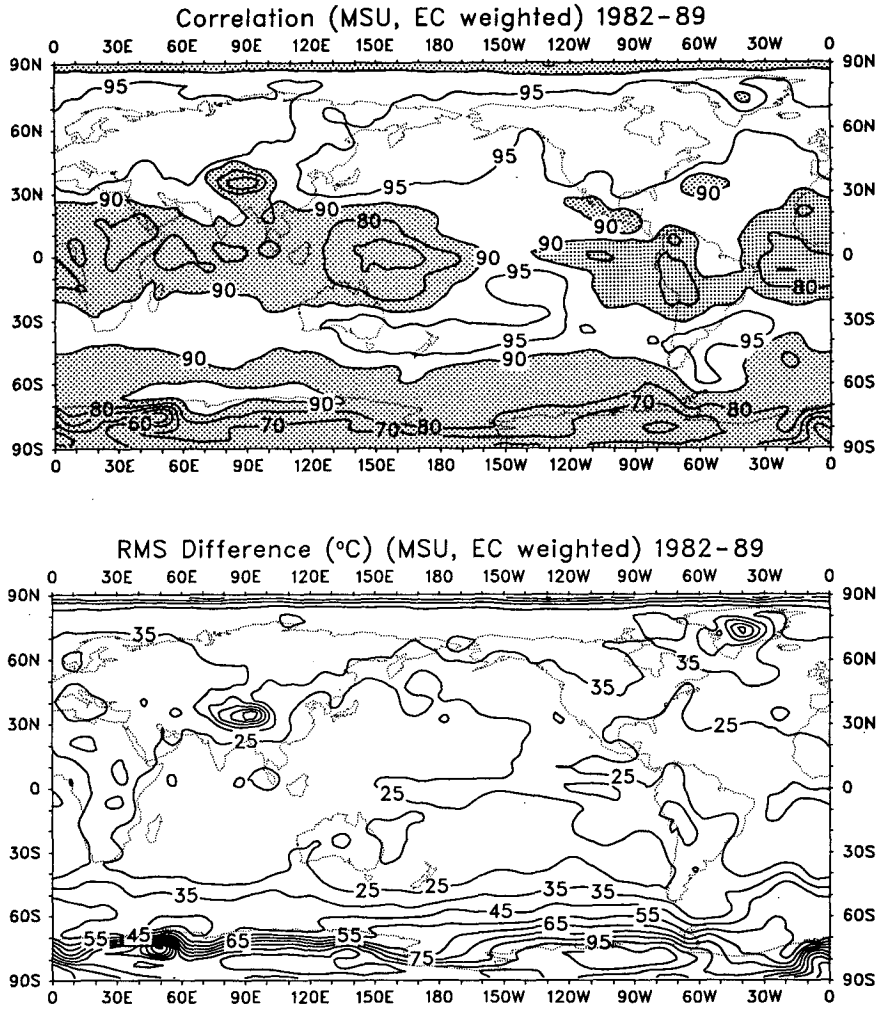

FIG. 4. (a) Correlation and (b) rms differences over 96 months from 1982 to 1989 of the MSU channel 2 and weighted ECMWF temperature anomalies. Values have been multiplied by 100, and the contour interval is 10, except in (a) the 95 contour is included and values less than 90 are shaded.

Area-averaged time series of the monthly mean MSU and weighted ECMWF anomalies are illustrated in Fig. 5 for the globe, the NH and SH extratropics, and the tropics, while zonal means are presented in Fig. 6 and regional mean time series for a few areas are shown in Fig. 7. The latitudinal and longitudinal extent of each region is given in Table 1, which also summarizes the correlation coefficient, the rms difference, and the standard deviation of each time series. Each series plot

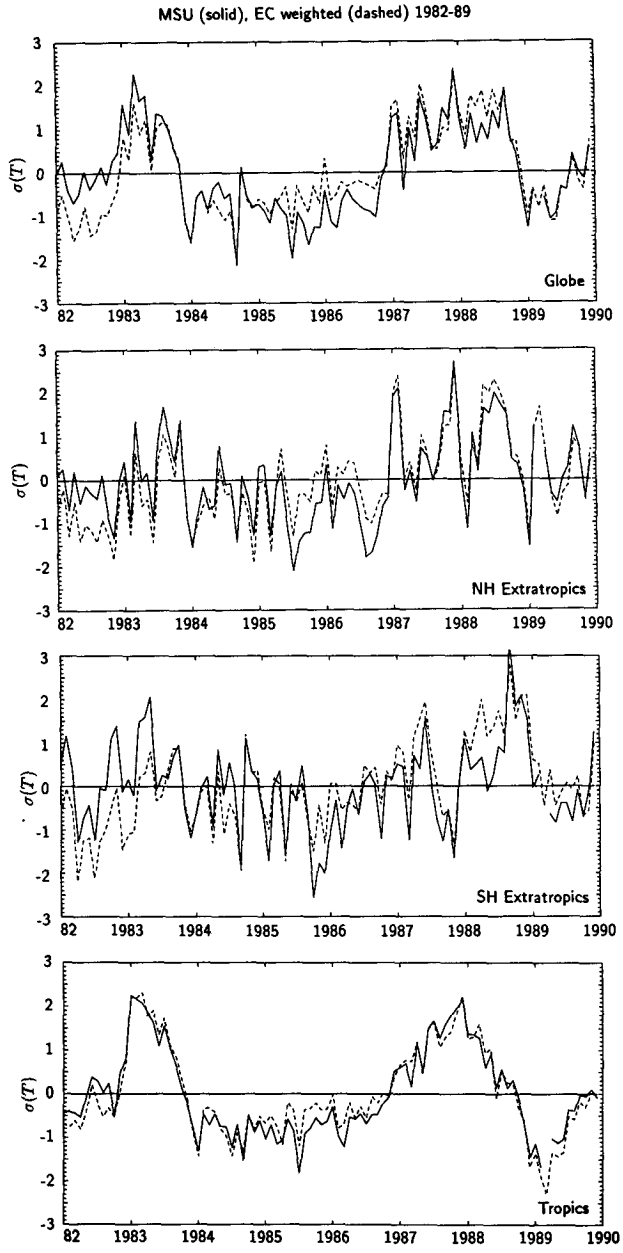

FIG. 5. Time series of monthly temperature anomalies from MSU (solid) and weighted ECMWF (dashed) data for several regions of the globe defined in Table 1. Time series have been normalized by their standard deviations.

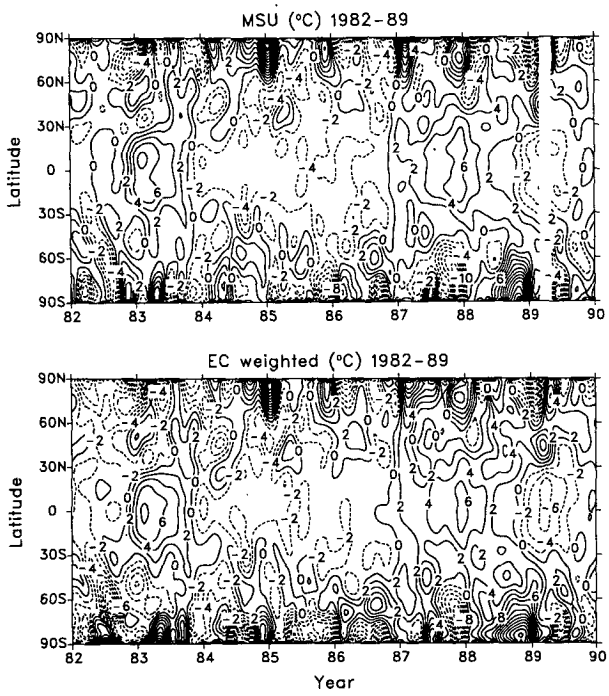

FIG. 6. Zonally averaged temperature anomalies in °C from (a) MSU and (b) weighted ECMWF analyses. No latitudinal cosine weighting has been applied so that values near the poles represent small areas, and all values have been multiplied by 10.

(Figs. 5 and 7) is normalized by its standard deviation, which gives a measure of the signal plus noise in the data. Again, differences are relative and not absolute, and area averages were computed only from grid points where anomalies in both datasets were defined.

Globally, both the MSU and weighted ECMWF data exhibit anomaly fluctuations that are in phase but often differ in magnitude. The weighted ECMWF temperatures tend to be colder, in general, than the MSU anomalies prior to 1985 and warmer afterward, although several extended periods of better agreement do exist. Overall, the correlation is 0.87 and the rms difference is 0.10°C. Note that although the tropical and extratropical regions each comprise about one-third of the total surface area of the earth, the global mean follows the tropical series most closely because of the larger, more coherent signal associated with ENSO variations.

The correlation and rms difference for the NH extratropics are similar to those for the global average, but both are worse for the SH extratropical series. The standard deviations of both datasets are nearly equal over the globe and the NH extratropics, but the weighted ECMWF anomalies over the SH extratropics exhibit more variability (σ = 0.26°C) than the MSU data (σ = 0.20°C). Zonally averaged differences (Fig. 6) between the datasets are largest in the middle and high latitudes of the SH, where absolute values of the

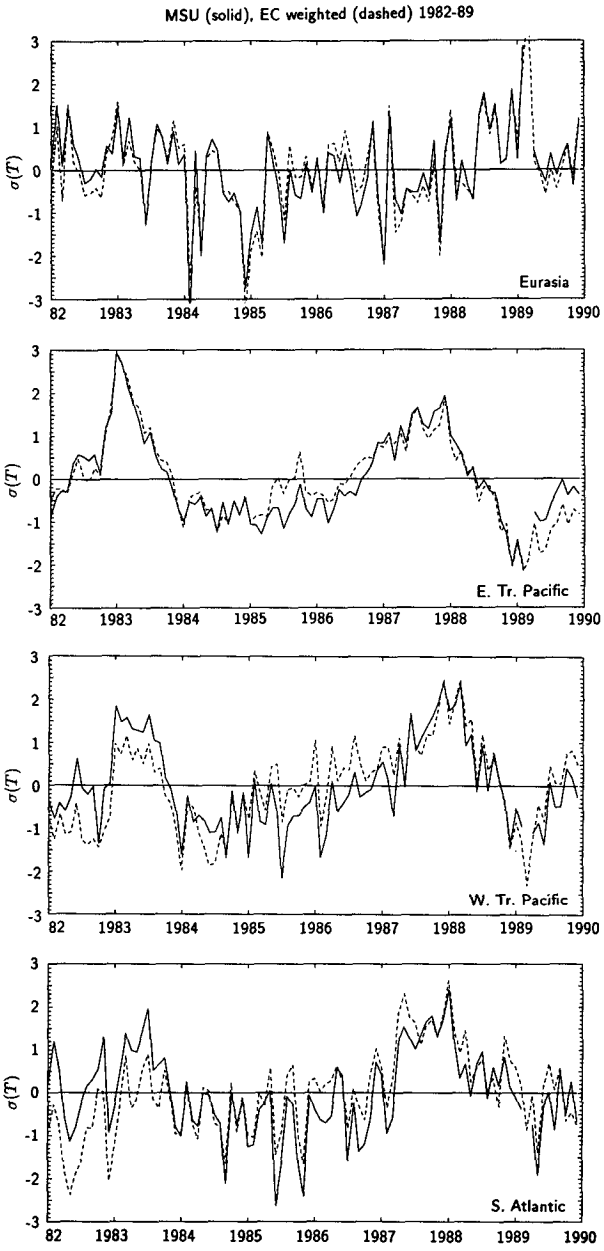

FIG. 7. As in Fig. 5 for more limited land and ocean regions as given by each label and defined in Table 1.

ECMWF weighted anomalies exceed those of the MSU data by as much as 0.8°C. Trenberth and Olson (1988b) confirmed that there were problems with the ECMWF analyses at high latitudes in the SH, especially over Antarctica, that may have arisen partially from shortcomings in data communications. Comparisons with Antarctic station data show pronounced discrepancies prior to 1983 but with errors being systematically reduced throughout the 1980s.

The impact of model and data assimilation changes over the decade can be clearly seen in Figs. 5 and 7. For example, as for the global series, the largest discrepancies between the MSU and ECMWF data averaged over the NH extratropics are prior to the implementation of a diabatic initialization scheme at ECMWF in late September 1982 and for about 18 months following the conversion to a T106 spectral model with major accompanying changes to the physical parameterizations of clouds, convection, and condensation on 1 May 1985. Before the former change, the ECMWF weighted anomalies tended to be cold relative to the MSU data.

Such changes to the analysis-forecast system appear to have had the greatest impact on ECMWF temperatures in the tropics (section 4), and this helps explain the lower gridpoint correlations seen in Fig. 4. On a regional scale, warmer tropical temperatures relative to the MSU data after the May 1985 changes are clearly seen in Fig. 7 for the eastern and western tropical Pacific series, and large (relative) discrepancies are seen after model changes on 2 May 1989, which included modifications to the physical parameterizations of radiation and convective processes. As will be discussed later, the temperature signal in the western tropical Pacific appears to be most strongly affected, and this helps explain the poor agreement between the datasets over this area; gridpoint correlations of less than 0.7 (Fig. 4), an area-averaged correlation of 0.83, and a relatively significant rms difference of 0.17°C. In contrast, good agreement is seen between the weighted ECMWF and MSU data where the climate signal is large, such as over the eastern tropical Pacific, and even for the tropical time series (Fig. 5) where the correlation is 0.97 and the rms difference is 0.09°C. As revealed in Fig. 6, the best agreement is seen during the 1982–83 and 1986–87 El Niño events and the 1988 La Niña event when tropical anomalies in both datasets were on the order of two standard deviations and zonally averaged anomalies exceeded ±0.6°C.

The agreement between the monthly mean MSU and weighted ECMWF temperatures is very good over landmasses with good quality observational networks. For Eurasia (Fig. 7), high-frequency large-amplitude fluctuations are well captured in both datasets ($r = 0.94$ with a rms difference of 0.17°C), and similar results with correlations exceeding 0.95 and rms differences of 0.16°C were found over North America and Australia. Slightly lower correlations with equally large rms differences were found over portions of tropical Africa and South America. Good agreement was evident over the North Pacific and North Atlantic (Table 1), but of the areas considered, the lowest area-averaged correlations were over the South Atlantic sector (Fig. 7).

Given the equal coverage and accuracy of the MSUs over both hemispheres, the lower correlation and the larger rms difference in the SH extratropics indicate the importance of many fairly accurate observations

TABLE 1. For the areas as labeled, given are the correlation r between MSU and weighted ECMWF data over the 96 months 1982–89, the standard deviation of each series σ_{MSU} and σ_{EC} in degrees Celsius, and the rms differences between each series in degrees Celsius.

Area	Latitude	Longitude	r	σ_{MSU}	σ_{EC}	rms diff
Globe	90°N–90°S		.87	.19	.20	.10
NH Extratropics	20°–90°N		.88	.22	.23	.11
SH Extratropics	20°–90°S		.75	.20	.26	.17
Tropics	20°S–20°N		.97	.35	.33	.09
North America	30°–70°N	75°–125°W	.98	.71	.78	.16
Eurasia	40°–70°N	0°–140°E	.94	.41	.48	.17
Australia	15°–40°S	115°–155°E	.96	.41	.47	.16
Africa	35°S–15°N	15°–40°E	.90	.33	.39	.18
South America	0°–30°S	75°–45°W	.88	.39	.27	.18
North Atlantic	20°–50°N	20°–60°W	.88	.37	.45	.22
South Atlantic	0°–55°S	10°E–35°W	.76	.27	.29	.19
North Pacific	30°–50°N	150°E–130°W	.93	.43	.50	.19
Indian Ocean	0°–40°S	45°–110°E	.94	.31	.31	.11
Eastern tropical Pacific	10°N–20°S	85°–150°W	.94	.55	.57	.19
Western tropical Pacific	15°N–15°S	120°–180°E	.83	.27	.30	.17

(radiosondes) to the quality of any model-based global dataset. In an intercomparison of the NMC and ECMWF global analyses, Trenberth and Olson (1988b) found the largest discrepancies in the tropics and SH, while there was fairly widespread agreement in the NH extratropics. In particular, they found much greater differences in the wind field south of 20°N and in geopotential heights south of approximately 30°S. Hoskins et al. (1989) note that ECMWF has invested considerable effort into improving their SH analyses, and the skill of their SH forecasts has shown consistent improvement over the last decade. Specifically, ECMWF has found that satellite data have had a definite positive impact on the SH analyses and forecasts, which implies that these data can help offset the void of conventional data. Impact studies in the NH have had more variable results (Uppala et al. 1984; Kelly and Pailleux 1988; Andersson et al. 1991; Kelly et al. 1991).

In interpreting the results presented in this section, it is important to note that the ECMWF analyses are not independent of the MSU brightness temperatures. While the raw radiance data were not directly incorporated into the analysis system, the temperature and moisture satellite retrievals used by ECMWF 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 the recent studies by 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 ECMWF. Both the statistical retrieval algorithms used by NESDIS prior to September 1988 and the physical retrieval algorithms currently used 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 raw 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. Andersson et al. note that the assimilation system that became operational at ECMWF in July 1988 was more sensitive to data and therefore was more vulnerable to bad data. They showed that the degradation of forecast skill in the NH resulted from quality control procedures that did not remove most of the erroneous satellite retrieval information. Kelly et al. report on new quality control changes that eliminate the largest errors in the satellite data, and these changes were incorporated into the operational assimilation system in January 1989.

Our results are consistent with the foregoing findings. At first thought, one might expect that the highest correlations between the MSU and weighted ECMWF anomalies should occur in data-sparse regions where the analyses depend most heavily on satellite data. However, correlations in the South Atlantic, for instance, are lower than in regions where the analyses are essentially driven by upstream radiosonde data, such as the North Pacific and North Atlantic. Currently, research efforts at ECMWF are directed toward new methods for assimilating satellite radiance data more directly into the model (Eyre, personal communication, 1991). The new techniques involve calculating forecast radiances from the first-guess fields, comparing them to observed radiances, and then using the radiance increments to update temperatures and humidities (Eyre and Lorenc 1989).

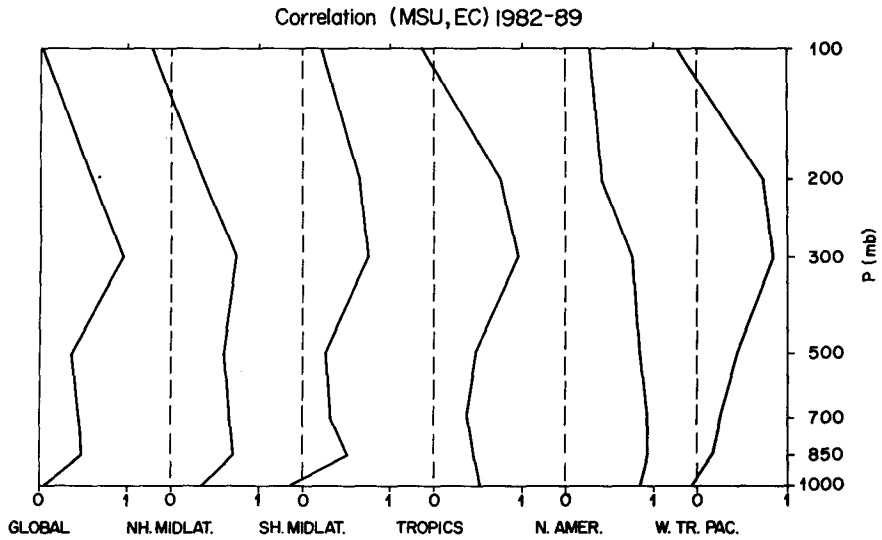

FIG. 8. Correlation profiles over 96 months from 1982 to 1989 of MSU and pressure-level ECMWF temperature anomalies for selected regions defined in Table 1.

b. Individual levels

Vertical profiles of correlations of MSU anomalies with individual pressure-level ECMWF temperatures for selected regions (Fig. 8) reveal that the MSU data correlate best with 300-mb anomalies for the globe ($r = 0.96$), with a secondary maximum at 850 mb. Much of the upper-tropospheric signal is, of course, dominated by the tropics, and this signal dominates hemispheric averages (not shown) as well. Indeed, if averages over the middle latitudes (30° to 70° latitude) are taken, the 300- and 200-mb correlations are reduced. The NH middle-latitude profile also demonstrates considerably higher correlations throughout the mid-troposphere, unlike the tropical and SH profiles. This result is in good agreement with the MSU vertical weighting function, and it probably reflects fewer uncertainties in the NH extratropical ECMWF analyses (Trenberth and Olson 1988a,b; Bengtsson and Shukla 1988; Andersson et al. 1991).

Correlation profiles for North America and the western tropical Pacific are also illustrated in Fig. 8. The North American profile is in very good agreement with the station and regional radiosonde comparisons of SC92. Specifically, correlations greater than 0.75 are evident from 1000–300 mb, with a maximum in the lower troposphere. Similar results were found over Eurasia and Australia (not shown). For the western tropical Pacific, correlations were relatively poor except at 300 and 200 mb. Although the sensitivity of the temperatures to analysis improvements at ECMWF over this region appears to be large, it is worth noting that the radiosonde comparisons of SC92 for the tropical stations of Hawaii and Guam also showed low correlations ($r \approx 0.4$ in the 1000–700-mb layer) between the MSU data and the lower-tropospheric levels. This probably reflects a decoupling of the surface boundary layer from the free atmosphere as a result of the pervasive trade-wind inversion.

Historically, there appears to have been too little coherence between the lower and middle troposphere in the ECMWF analyses throughout the tropical belt.

TABLE 2. Correlation matrices among ECMWF temperature anomalies at standard pressure levels over the period 1982–89.

	1000	850	700	500	300	200	100
				Tropics			
1000	1.00	0.84	−0.33	−0.14	0.66	0.17	0.39
850		1.00	−0.60	−0.13	0.63	0.06	0.49
700			1.00	0.46	0.12	0.53	−0.68
500				1.00	0.33	0.13	−0.45
300					1.00	0.68	0.04
200						1.00	−0.25
				NH Midlatitudes			
1000	1.00	0.24	0.06	0.02	0.17	−0.05	−0.03
850		1.00	0.86	0.66	0.41	−0.08	−0.48
700			1.00	0.86	0.51	0.00	−0.58
500				1.00	0.68	0.04	−0.55
300					1.00	0.42	−0.25
200						1.00	0.31
				SH Midlatitudes			
1000	1.00	−0.22	−0.31	−0.27	−0.33	−0.24	0.13
850		1.00	0.63	0.47	0.54	0.38	−0.15
700			1.00	0.88	0.45	0.09	−0.15
500				1.00	0.46	0.02	−0.15
300					1.00	0.46	0.06
200						1.00	0.51

This is further illustrated in Table 2, which presents correlation matrices for the ECMWF level data over the period 1982–89 for the tropics and the NH and SH midlatitudes. Note the negative correlations in the tropics between the 850- and 700-mb anomalies, which appear to be spurious and tied to changes in the analysis-forecast system (section 4), while the 1000-mb anomalies are highly correlated with the 850-mb level and the upper troposphere. In the middle latitudes of the NH, there is a much stronger coherence of the ECMWF data throughout the troposphere, and this is reflected in higher correlations with the MSU data from 850 to 300 mb. The exception is the 1000-mb anomalies, especially in the SH midlatitudes, which are poorly correlated with the rest of the tropospheric levels. However, the 1000-mb ECMWF data are not reliable (see section 2).

Overall, these results indicate that, in spite of the many changes made to the ECMWF forecast models and data assimilation schemes since January 1982, weighted ECMWF anomalies correlate well with the MSU data. The credibility of the lower correlations of low-level ECMWF anomalies with MSU channel 2 brightness anomalies is compromised by poor quality ECMWF 1000-mb analyses and are not entirely physical, although in the western tropical Pacific such a degradation can be partially ascribed to naturally low interlayer correlations. These results corroborate the limited regional radiosonde comparisons of SC92 and extend them to a more global scale; moreover, these findings seem to indicate that the MSUs can be an extremely useful tool for measuring global tropospheric temperature fluctuations on a monthly, and longer, time scale. Likewise, many aspects of the ECMWF temperature analyses are useful, but only if the known internal inconsistencies are understood and taken into consideration. Some specific inconsistencies are now documented.

4. Internal inconsistencies in the ECMWF analyses

Major problems with the ECMWF 1000-mb temperatures over the last decade have already been discussed in some detail, and the importance of a high number of good-quality observations to the analysis-forecast system has also been pointed out. Problems are especially found over portions of the tropics, where changes to the data assimilation and forecast system tend to have a strong impact on the analyzed fields. To illustrate this, times series of temperature anomalies averaged over 20°S–20°N at the seven archived pressure levels from ECMWF are given in Fig. 9. The vertical scale is in units of standard deviation, but each series is offset by increments of three standard deviations. Several discontinuities in time are evident.

One notable change is with the 100-mb anomalies after May 1986. On 14 May the vertical resolution of the forecast model was increased by three levels in the lower stratosphere. Apparently, this enhanced resolution had a strong impact on the derivation of the 100-mb temperature data, producing a decrease in the tropical temperatures near the tropopause. Tropical temperatures prior to the May 1986 change were approximately 2σ warmer than after, or about 4°–5°C warmer. The relationship between the number and distribution of vertical levels in a forecast model and the resulting analyzed temperature field has recently been demonstrated by Arpe (1988a). Biases arise because of coarse vertical resolution, especially at strong inversions such as the tropical tropopause. Such problems are clearly evident in Fig. 9 at 100 mb, and the

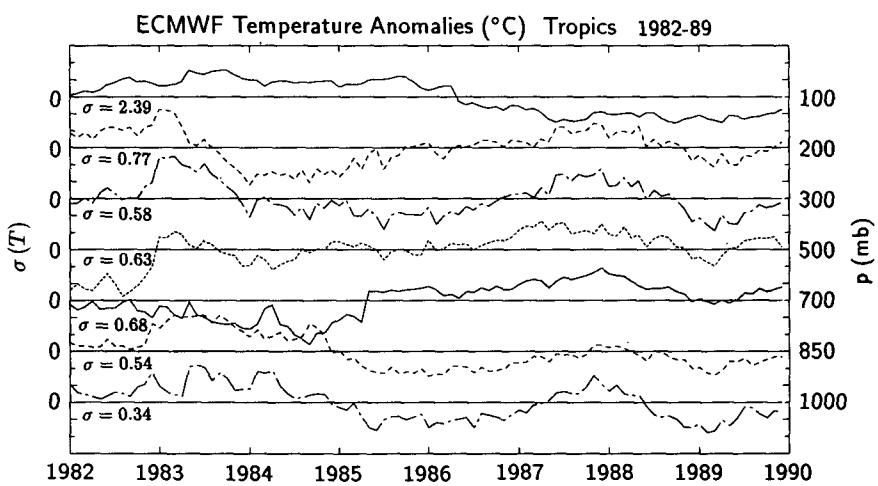

FIG. 9. Time series of ECMWF temperature anomalies at standard pressure levels area averaged over the tropics. Each series has been normalized by its standard deviation and is offset by $\pm 3\sigma$. The standard deviation for each anomaly series is given just below the $\sigma = 0$ line.

impact was also felt at higher latitudes. Arpe (1988b) reports that a change to the parameterization of vertical diffusion in January 1988 resulted in a further reduction of 100-mb temperatures, although the impact was not as great as the May 1986 change.

Another distinct discontinuity in Fig. 9 appears to be related to the introduction of a diabatic nonlinear normal-mode initialization to the data assimilation scheme in September 1982 (Arpe 1988b). This change, apparently, had the largest impact in the middle troposphere. For example, a sharp increase is noted in the 500-mb tropical temperatures immediately after this date. Previously, the 500-mb temperatures appear to be too cold, oscillating around a value of -2σ. Of course, the difficulty is separating out such a signal from the concurrent El Niño warming, although the cooler signal prior to September 1982 appears to be unique to the 500-mb level.

The 1982–83 and 1986–87 El Niño events and the 1988 La Niña cooling are evident in all the time series up to 200 mb, with one notable exception: the 1982–83 warming is absent from the 700-mb anomaly series. At this level a major change is clearly evident on 1 May 1985, which corresponds to the time of implementation of the T106 spectral model with an incorporation of new convective and cloud parameterizations. This date marks the transition from cool to warm anomalies relative to the total 8-year annual cycle. Another concern is the strong tendency for the 850- and 700-mb anomalies to be negatively correlated by −0.60 over the tropical belt (Table 2). Figure 10 illustrates the correlation of these levels over the entire globe. Outside of the tropical belt, correlations generally exceed 0.75 and are greater than 0.90 over much of the NH middle and high latitudes and portions of the southern oceans. Over the western tropical Pacific and the tropical South Atlantic, however, local correlations less than −0.75 are observed. Temperatures at 1000 and 850 mb can be affected by an introduction of higher resolution or enhanced orography that brings the levels closer to the surface or even underground so that temperatures become extrapolated (Hoskins et al. 1989). Thus, tropical 850-mb temperatures increased with the introduction of the T63 model and envelope orography in April 1983, but they decreased in December 1984 with revised radiation and in May 1985 with the T106 model and reduced envelope orography. Substantial revisions to the parameterization of convection (shallow and deep) in May 1985 also appear to have significantly affected the 850-mb temperatures.

An examination of 1000–850-mb- and 850–700-mb-thickness anomalies averaged over the tropics did not reveal the same strong negative correlations (not shown); rather, the anomaly series were highly correlated at $r = 0.86$. Of course there is a physical difference between the above thicknesses and 850-mb and 700-mb temperatures, but the result serves to emphasize again that ECMWF level temperatures are not analyzed but are derived from virtual temperatures estimated from layer thicknesses of geopotential height. Therefore, model changes that affect the predicted moisture fields also affect the level temperatures, but not necessarily the thicknesses. For example, the sudden increase of about 1.2°C in tropical 700-mb temperatures from April to May 1985 was accompanied by an equally dramatic decrease in relative humidity by 20%, which alone would account for roughly 30% of the change in temperature. At the same time, the 1000–850-mb and 850–700-mb thickness (or equivalently virtual temperature) anomalies did not exhibit such a

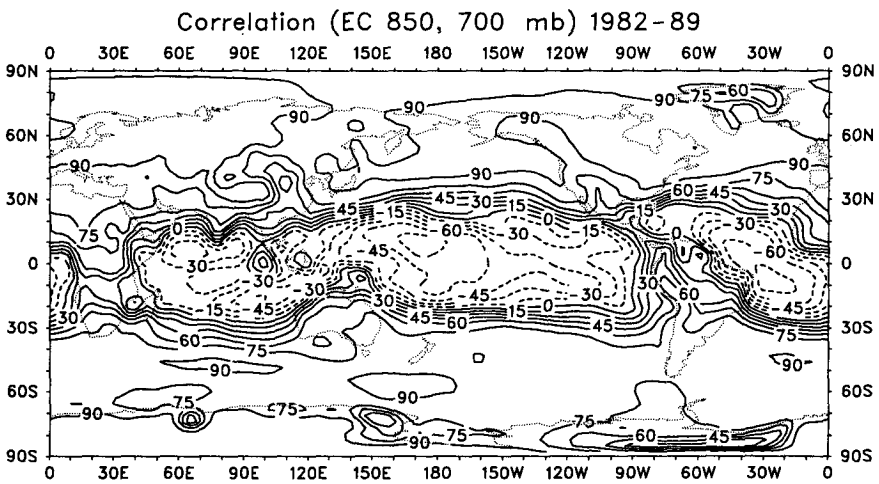

FIG. 10. Correlation over 96 months from 1982 to 1989 of ECMWF 850- and 700-mb temperature anomalies. Values have been multiplied by 100, and the contour interval is 15. Negative correlations are dashed.

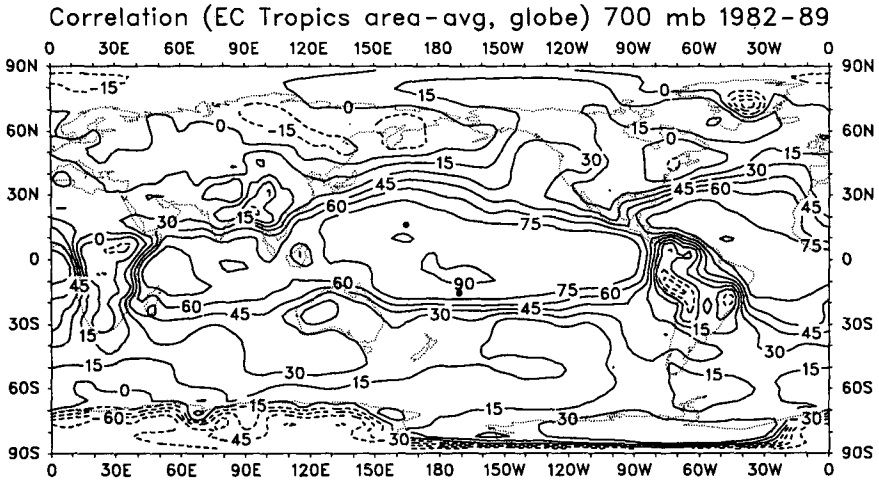

FIG. 11. Correlation over 96 months from 1982 to 1989 of ECMWF 700-mb gridpoint temperature anomalies with the area-averaged tropical 700-mb anomalies. Values have been multiplied by 100, and the contour increment is 15. The locations of Wake Island and Pago Pago are indicated by dots.

discontinuity. Such results imply that there may be compensating differences between the analysis and observed radiosonde profiles over thick layers, but significant biases may exist at individual pressure levels. The 850-mb tropical temperature analysis is especially difficult because it is often influenced by the large trade-wind inversion so that temperatures can change by several degrees over a shallow layer. For example, the 1200 UTC 14 January 1988 sounding at Wake Island (19.3°N, 166.7°E) indicated a strong inversion with temperatures increasing from ~13°C at 860 mb to ~18°C at 840 mb, a feature that was missed in the analysis. Thus, for some purposes the thickness analyses may be more reliable than the temperatures.

To better determine the accuracy of the tropical ECMWF temperatures at the 850- and 700-mb levels, we have compared the ECMWF data to time series from several radiosonde stations within the tropics. To select the stations, we determined which regions of the tropics were contributing the largest signal to the area-averaged series in Fig. 9. Results for the 700-mb level, Fig. 11, reveal correlations exceeding 0.75 over much of the tropical oceans, with the largest contributions found in the western Pacific. It is also interesting to note the low correlations over the tropical landmasses. Based on these results, we have selected several stations in the tropical Atlantic and western Pacific. Results will be presented for only two western Pacific stations, however, since they contained by far the most frequent observations over the last decade. These stations are Wake Island and Pago Pago (14.3°S, 170.7°W), both of which are indicated by the solid dots in Fig. 11 and are at grid points with correlations exceeding 0.85.

Time series for 850- and 700-mb total temperatures at Wake Island are shown in Fig. 12 from 1982 through 1988. The ECMWF series were calculated by averaging the four nearest grid points surrounding the island stations. The seasonal cycle at Wake Island is clearly evident at 850 mb in both datasets, and the ECMWF analyses show a clear improvement with time and are exceptionally good after May 1985. At 700 mb, the

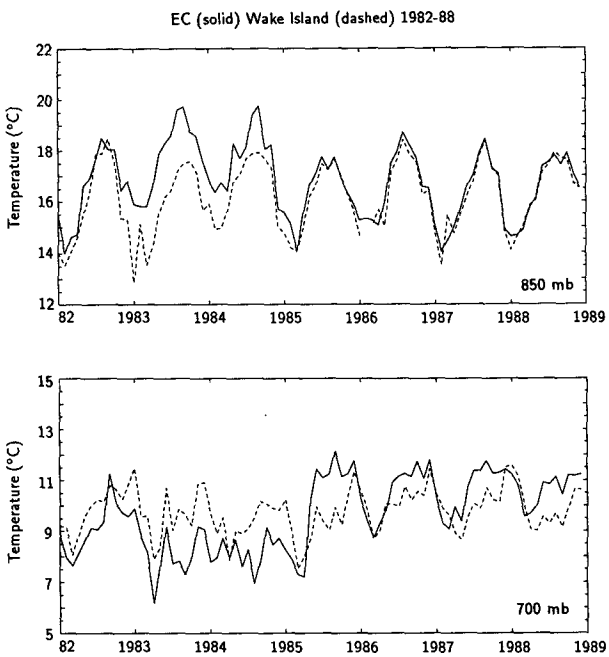

FIG. 12. Time series of monthly temperatures (°C) from ECMWF (solid) and Wake Island (dashed) for (a) 850 mb and (b) 700 mb. The ECMWF temperatures were averaged around the four grid points surrounding the island station.

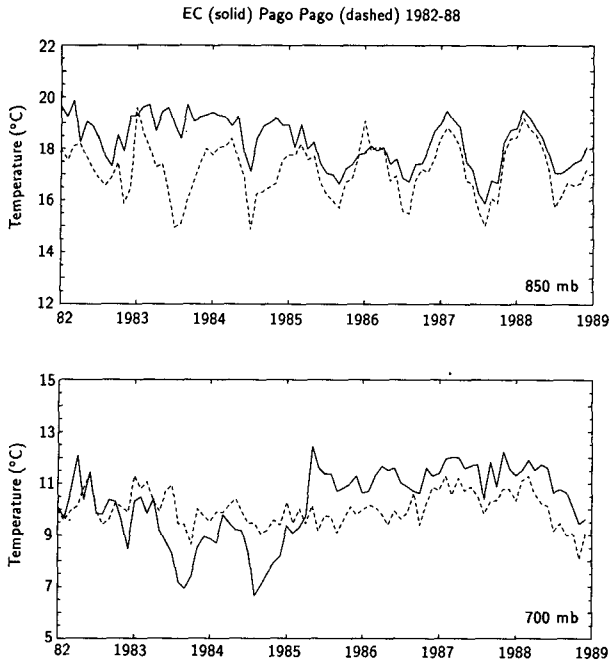

FIG. 13. As in Fig. 12 but for Pago Pago.

seasonal cycle is not as well defined but is clearly seen in the radiosonde data. Again, the ECMWF analyses show a marked improvement after May 1985, but they appear to overestimate the temperatures during the summers. Similar conclusions can be drawn for the Pago Pago series (Fig. 13). The seasonal cycle is again better defined at 850 mb than at 700 mb, and the best agreement with the ECMWF analyses is at 850 mb after 1985. During the entire period, 850-mb temperatures are warmer than the island data, and the same is true at 700 mb after the May 1985 change. When correlation coefficients between anomalies are computed from the island temperatures, the low natural coherence between the 850- and 700-mb levels is evident; $r = 0.17$ at Wake Island and $r = 0.31$ at Pago Pago. These results, however, substantiate the conclusion that the strong negative correlations between the 850- and 700-mb anomalies in the ECMWF data are spurious and result primarily from changes over the decade to the analysis-forecast system. Indeed, when only the period May 1985–December 1989 (56 months) is considered, the correlations of ECMWF 850- and 700-mb temperature anomalies averaged over the four grid points surrounding Wake Island and Pago Pago are 0.08 and 0.29, respectively, compared to −0.55 at both stations for 1982–89 (see Fig. 10). When averaged over the entire tropical belt since May 1985, the correlation of the 850- and 700-mb anomalies is 0.69, compared to −0.60 in Table 2. Thus, it appears that the May 1985 changes greatly improved the tropical temperature analyses. Comparisons of analyzed thickness values to the Pago Pago and Wake Island radiosonde thicknesses from 1982 to 1988 show a better agreement than in Figs. 12 and 13 with smaller biases, especially prior to May 1985.

The results presented in this section illustrate the impact of only a few major data assimilation and forecast system changes at ECMWF on tropical level temperatures. These, and other, changes appear to have had the least impact on the 300-mb temperature field at all latitudes. This result helps to explain not only the high correlation of the MSU channel 2 brightness anomalies with the 300-mb level ECMWF anomalies but, because of the structure of the MSU weighting function, it also helps to explain the high correlation of the MSU data with the weighted ECMWF analyses. It is encouraging that the ECMWF analyzed tropospheric temperatures are improving with time.

5. Summary and conclusions

The purpose of this paper has been to examine monthly mean brightness-temperature anomalies from the MSU channel 2 and both weighted and individual level temperature anomalies from ECMWF. The ability of the MSUs to measure free-atmosphere temperature fluctuations has recently been demonstrated by SC92, and the comparison here gives consistent results. At the outset we had thought we may gain a better feeling for the reliability of the MSU data. The result has been to increase our confidence in those data and instead use them to reveal problems in the ECMWF level temperature analyses. In addition, there seems to be a prospect for monitoring the radiosonde network in a similar fashion using consistently calibrated MSUs as a benchmark. In this way, the impact of changes to the upper-air network may be more directly and accurately measured than is currently possible, and this would represent an important improvement for monitoring free-atmosphere temperature variations over the long term.

We have been able to show that very good agreement exists between the MSU and weighted ECMWF temperatures over the 96-month period 1982–89. Gridpoint correlations around the globe generally exceeded 0.85. Regions of lower correlations and higher rms differences included portions of the tropics and the SH high latitudes, where changes to the analysis-forecast system at ECMWF have apparently had their largest impact.

Comparisons of the MSU data with individual pressure level temperatures from ECMWF revealed high correlations at 300 mb over most of the globe. In regions of good upper-air data coverage, such as the NH landmasses and Australia, correlations were high at all levels from 1000 to 200 mb, in good agreement with the radiosonde comparisons of SC92. In portions of the tropics and the SH, however, lower correlations

throughout the lower troposphere probably reflect problems in the ECMWF data more than the physical relationship with the channel 2 data. Discontinuities at tropospheric pressure levels in the ECMWF temperature analyses can be most clearly seen in the tropical time series, and they can be directly related to several major changes at ECMWF since 1982. Additionally, our results are consistent with the finding at ECMWF that large errors are introduced into the analyses by the retrieval algorithms applied to the satellite radiance data to obtain vertical profiles of moisture and temperature. Correlations with MSU brightness temperatures are best where the analyses are heavily influenced by radiosonde data, and in data void regions, where the analyses rely more on satellite information, the agreement is worse.

This study was in part motivated by the parallel work of TCH in which MSU channel 2 anomalies were correlated with a surface dataset used by the IPCC in their assessments. TCH found very distinctive correlation patterns with values ranging from less than zero to over 0.9. Although a major factor in accounting for the correlation patterns was the spatial variation in the inherent noise in the surface observations, it was a purpose of this paper to examine the extent to which the correlation patterns resulted from physical differences between the MSU and surface datasets. Clear problems exist in the 1000-mb temperature field, especially over the oceans, throughout the entire study period. These problems result from the manner in which the ECMWF temperatures at standard levels are obtained and at least partially from the improper use of single-level data prior to 29 August 1989. Unfortunately, this compromises any statements we might make concerning how well the MSU temperature anomalies are reflected at the surface.

It must be remembered that the ECMWF analysis system, like all operational systems, undergoes continual revision and development in order to fulfill its most important responsibility of providing improved forecasts. As discussed by Bengtsson and Shukla (1988) and Trenberth and Olson (1988a,b), these revisions have led to substantial improvements in analysis and forecast accuracy over the past decade. The model-based global dataset used in this and many other useful diagnostic studies of the general circulation is simply a by-product of the forecast mission. As such, for climate purposes, the ECMWF analyses must be used intelligently with their shortcomings in mind. One must be cautious when trying to determine the natural variability of the climate system using these data, even on interannual time scales. It is in this light that Trenberth and Olson (1988b) and Bengtsson and Shukla (1988) argue for the *reanalysis* of global data using a state-of-the-art data assimilation system with a realistic, high-resolution physical model to produce an internally consistent, homogeneous, multivariate dataset that is more useful for studies of the global climate. The results of this study strongly support the need for reanalysis; only then will the problems of trends discussed in the introduction perhaps become tenable. Shortness of record and changes over time to the observational network will remain key issues, although the impact of the latter can be carefully studied and better understood. Reanalysis projects are planned at both ECMWF and NMC. The results of these efforts will undoubtedly improve our understanding of the atmospheric component of the climate system.

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