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Research Article

Precise Monitoring of Global Temperature Trends from Satellites

ROY W. SPENCER AND JOHN R. CHRISTY

Passive microwave radiometry from satellites provides more precise atmospheric temperature information than that obtained from the relatively sparse distribution of thermometers over the earth's surface. Accurate global atmospheric temperature estimates are needed for detection of possible greenhouse warming, evaluation of computer models of climate change, and for understanding important factors in the climate system. Analysis of the first 10 years (1979 to 1988) of satellite measurements of lower atmospheric temperature changes reveals a monthly precision of 0.01°C, large temperature variability on time scales from weeks to several years, but no obvious trend for the 10-year period. The warmest years, in descending order, were 1987, 1988, 1983, and 1980. The years 1984, 1985, and 1986 were the coolest.

ACCURATE ESTIMATES OF GLOBAL ATMOSPHERIC TEMPERATURES are needed for evaluation of global climate models, detection of climate changes, and a better understanding of the climate system. Global temperatures have generally been estimated from surface temperature records, but there has been much debate regarding, for example, whether these data provide evidence of recent greenhouse warming (*1*). The primary source of uncertainty is the relatively sparse distribution of thermometers over the surface of the earth. Most of the earth is covered by oceans, and vast oceanic areas go unmeasured. Even over land, the coverage is greatest where the population is greatest; therefore, remote land areas also go unmeasured. An additional problem is that urban sites, which represent only a small part of the globe but where many long-term measurements have been made, have warmed because of heat from man-made structures, and thus these records are difficult to interpret (*2, 3*). Depending upon how the thermometer data are analyzed, various answers can be expected. In contrast to surface thermometers, sensors on satellite platforms can provide nearly complete earth coverage in as little as one day and can obtain measurements from various levels of the atmosphere. Calibration of satellite sensors is particularly difficult, however. For climate temperature monitoring a precision of 0.1°C is needed, a goal that has been perceived as difficult for any earth viewing radiometer. The difficulty arises from uncertainty about the long-term stability of satellite sensors. In this article, we show that accurate long-term global temperature measurements can be obtained from satellites now operating and discuss data obtained from 1979 to 1988.

Methodology. In late 1978, a series of passive microwave radiometers was launched aboard the TIROS-N series of National Oceanic and Atmospheric Administration (NOAA) satellites. These radiometers, or microwave sounding units (MSUs), are Dicke-type radiometers designed to measure the thermal emission of radiation by atmospheric O_2 at four frequencies near 60 GHz (*4*). The atmospheric concentration of O_2 is constant in both space and time (*5*), and thus O_2 provides a stable temperature tracer. The strong interaction of radiation from 50 to 70 GHz with O_2 through rotational energy transitions causes absorption and emission. As the channel frequency of the MSU approaches the 60-GHz peak in this absorption complex, higher levels in the atmosphere will be measured (Fig. 1) (*6*). We have analyzed data from MSU channel 2, which measures the temperature of the middle troposphere at 53.74 GHz. At 57.95 GHz, MSU channel 4 can be used to monitor temperatures of the lower stratosphere. MSU channels 1 and 3 are more difficult to interpret for climate purposes because channel 1 is too sensitive to surface effects on the earth and cloud water, whereas channel 3 detects radiation from a strong temperature-transition region between the troposphere and stratosphere (the tropopause). The four channels have traditionally been used to obtain vertical profiles of temperature in remote regions of the earth where weather balloon data are not available. However, because the weighting

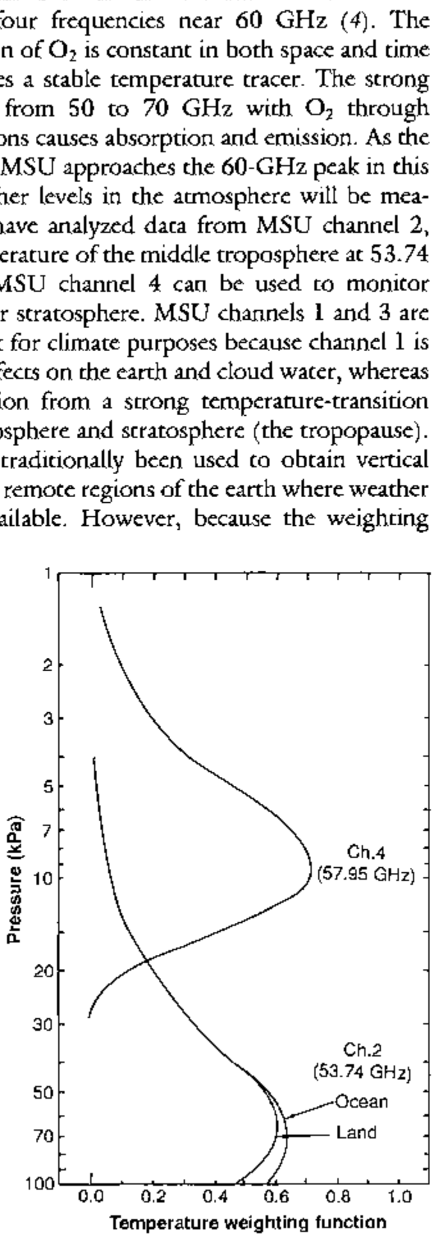

Fig. 1. Temperature weighting functions (unitless) for MSU channels 2 (mid-troposphere) and 4 (lower stratosphere). Also shown are the different channel 2 weighting functions for ocean and land surfaces, which arise because the less emissive ocean reflects more of the downwelling atmospheric radiation back upward. Sensitivity to the surface radiation itself cannot be implied from the magnitudes at the intersection of the curves with the surface. [Adapted from (*6*)]

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functions for each channel are vertically broad (Fig. 1), retrieval of adequate data on the vertical temperature structure of the atmosphere that are needed for computer modeling of the weather has been difficult. The temperature measurement within a constant-pressure depth, however, rather than at traditionally measured specific pressure levels, is completely adequate, even preferable in some respects, for climate monitoring.

The MSUs are externally calibrated, after each earth scan of the instrument, by measurement of the cosmic background radiation (for our purposes, constant at 2.7 K), and a warm target in the instrument that has its temperature monitored with redundant platinum resistance thermometers. This calibration design is considered to be the best available for microwave radiometers because any temperature changes in the instrument components are canceled out. The earth-viewing measurements are then calculated as a "brightness temperature" (T_b) by interpolation between these two reference extremes. The term "brightness temperature" acknowledges that the temperature measurement is actually based upon radiative brightness and is only equal to a thermometric temperature when the emitting body is completely "black" (nonreflective). This condition is nearly true of measurements of the atmosphere from MSU channel 2.

Satellite intercomparison. Because two MSUs have usually been simultaneously operating on separate satellites, a comparison between them shows how different sensors agree in their measurements and gives an estimate of errors. The NOAA-6 and NOAA-7 MSUs were simultaneously operating during a period of nearly 2 years (29 June 1981 to 16 April 1983). These satellites are in sun-synchronous, near-polar orbits, and have constant local crossing times of 7:30 a.m. and p.m. and 2:30 a.m. and p.m., respectively. The precession rates of their orbits are quite different so that in a single day there are many differences (but also many overlaps) in the areas of the globe sampled by the two satellites. The MSUs scan across the satellite subtrack, and thus paint out swaths of coverage about 2000 km wide beneath the satellites.

We averaged the channel 2 T_b data from the separate satellites at 2-day intervals over both the Northern and Southern hemispheres in 2.5°-latitude bands with cosine-latitude weighting to account for the decrease in surface area of these bands toward the poles. We reduced contamination of the measurements by large thunderstorm complexes, which cause infrequent depressions in T_b over small areas (*6, 7*), by excluding any scan lines that had individual footprint measurements that deviated by more than 1.5°C from their average relationship to both neighboring footprint measurements. The resulting variations in the 2-day averages are dominated by the seasonal change of temperature (*8*), termed the annual cycle. This annual cycle is sinusoidal in shape, and a smoothed cycle was computed for each satellite individually. Then this cycle was subtracted from the original 2-day time series to arrive at the anomalies in temperature, that is, the temperature deviations from the average temperature for a particular time of year. A period of data considerably longer than 2 years is necessary for a more representative annual cycle (and thus, more representative anomalies), but the short-term data are utilized only for satellite intercomparison. Several revealing observations can be made from the data (Fig. 2):

1) The standard deviation (SD) of the sums of the data from the two satellites is much larger than the SD of their differences. This relation means that both satellites were measuring nearly the same temperature variations and implies that hemispheric temperature anomalies can be measured with relatively little error from a single satellite. The 2-day average difference between these satellites was about 0.05°C, and for monthly averages, the difference improved to about 0.011°C. Similar noise was found in monthly comparisons between data acquired from sensors on (i) TIROS-N and NOAA-6 (0.012°C), (ii) NOAA-7 and NOAA-9 (0.012°C), (iii) NOAA-9 and NOAA-10 (0.006°C), and (iv) NOAA-10 and NOAA-11 (0.008°C), although much shorter overlap periods were available. Thus, we estimate that the precision of monthly satellite measure-

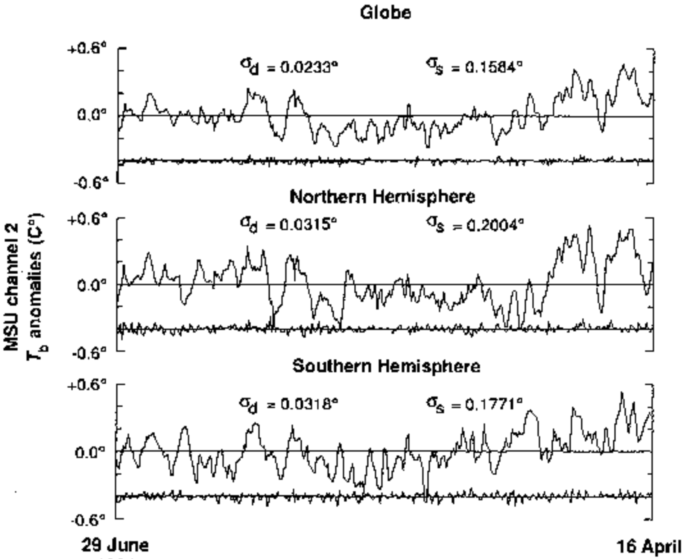

Fig. 2. Comparison between global MSU channel 2 T_b values from NOAA-6 and NOAA-7 during a nearly 2-year period (29 June 1981 to 16 April 1983) when both satellites had MSUs operating. Time series of global and hemispheric satellite averages (sum divided by 2) and differences (difference divided by 2) are shown by the large-variation and small-variation curves, respectively. The difference time series are offset −0.4°C for legibility. The SD of the two-satellite sums (σ_s) and differences (σ_d) are also listed.

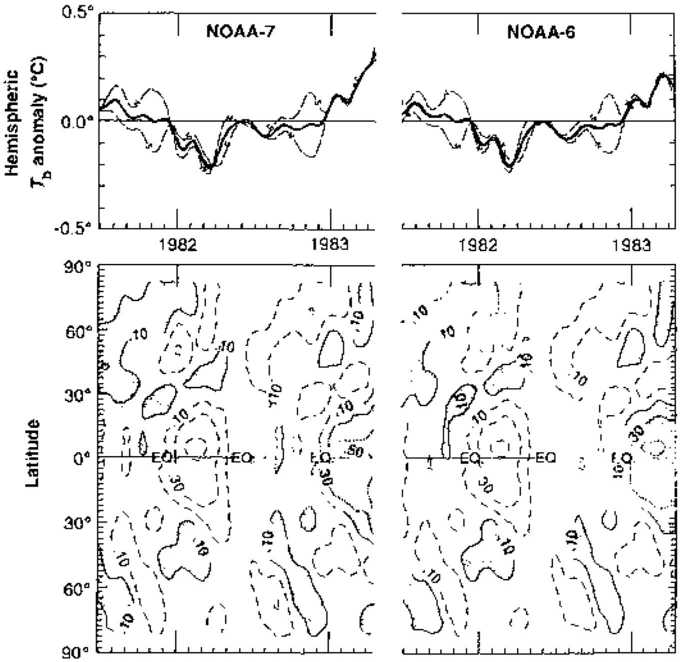

Fig. 3. Low-pass filtered hemispheric (top) and zonally averaged (bottom) MSU channel 2 T_b anomalies during the 2-year overlap period of NOAA-6 (right) and NOAA-7 (left); "N" and "S" labels represent Northern and Southern hemispheres, respectively, and the global time series is the heavy line. The time series do not agree near the beginning and end of the period because of the low-pass filter and the lack of data past the end of the period for NOAA-6 or before the beginning of the period for NOAA-7. Warm zonally averaged anomalies are stippled.

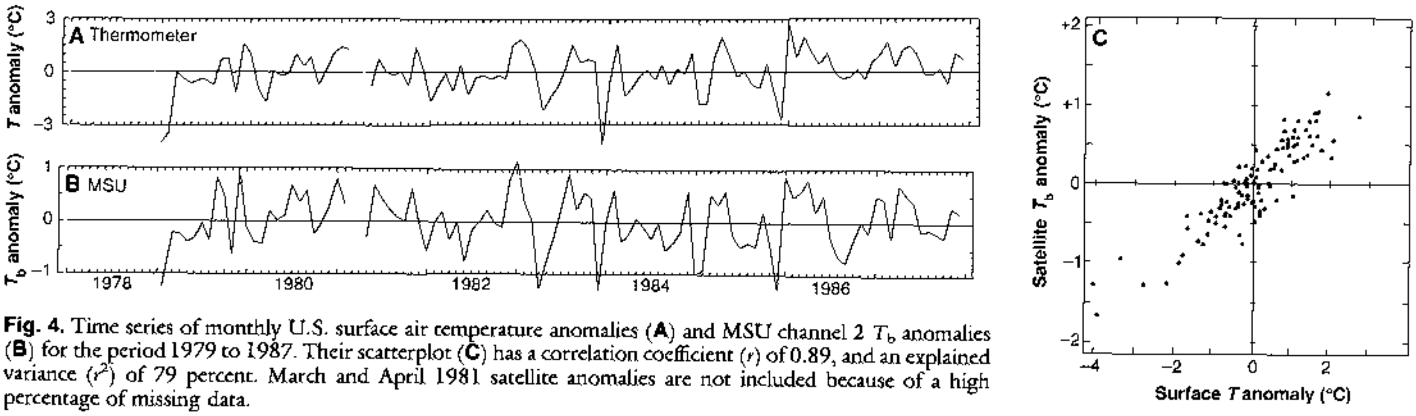

Fig. 4. Time series of monthly U.S. surface air temperature anomalies (**A**) and MSU channel 2 T_b anomalies (**B**) for the period 1979 to 1987. Their scatterplot (**C**) has a correlation coefficient (r) of 0.89, and an explained variance (r^2) of 79 percent. March and April 1981 satellite anomalies are not included because of a high percentage of missing data.

ments is about ±0.01°C for the globe.

2) The sums of the two sets of data reveal that dramatic globally averaged warming and cooling events of greater than 0.5°C can occur in less than 2 weeks. The warmings, representing huge energy exchanges, are possibly associated with stormy periods when large amounts of latent heat were released in precipitation of moisture previously evaporated from the sun-warmed ocean. The coolings might be from formation of widespread low-level cloudiness, which reflects significant amounts of incoming solar radiation.

3) The long-term drift of one instrument relative to the other, seen in the difference time series in Fig. 2, is so small that it is virtually unmeasurable. Any trend is less than ±0.01°C for the 2-year period. This high degree of stability was unexpected. The four other satellite overlaps mentioned above also gave no indication of drift.

Further evidence that the measurements were repeatable is shown by low-pass filtered (*9*) times series of hemispheric (and global) temperature anomalies from NOAA-7 and NOAA-6 data and the zonally averaged distribution of those anomalies (Fig. 3). The zonal averages allow examination of which latitude bands of the earth were responsible for the warm or cool events seen in the hemispheric and global time series. The zonal average patterns are nearly identical between satellites. Such agreement improves our confidence that even regional areas can be studied to find the origins of the hemispheric anomalies.

Comparisons with United States and global thermometer measurements. Although the above results indicate that the sampling provided by a single satellite is geographically extensive and that the measurements are radiometrically stable enough to be useful for monitoring climate, it still must be demonstrated that MSU measurements are closely related to temperature. Earlier investigators have made point comparisons between weather balloon data and satellite measurements (*10–12*). The differences between individual radiosonde and satellite measurements are generally less than 1.0°C. These differences are usually attributed to (i) the isolated balloon sampling compared to the large area represented by a single satellite measurement (a circular footprint 110 km in diameter); (ii) errors in calibration of the balloon thermometer before its release; (iii) the random noise of a single MSU measurement, about 0.3°C; and (iv) time mismatches between the satellite and balloon observations. We compared the 1980 through 1988 MSU observations to T_b data obtained from radiosondes launched twice daily by 66 National Weather Service offices around the United States. The T_b data were calculated with the radiative transfer equation for MSU channel 2, and thus the radiosondes had to reach a fairly high-pressure altitude, 2 kPa or less. Only MSU data within 200 km of the radiosonde location and within 3 hours of its release time were included. The comparisons revealed that there were biases of up to ±1°C between the two data sets; the biases are most easily related to the difference in time between the release time of the radiosondes (all simultaneous at 00 and 12 GMT) and the MSU observation times, which are sun synchronous. After correction for these biases on a station-by-station basis, we found no long-term trend in the 9 years of differences between MSU and radiosonde-calculated T_b values and a monthly SD of 0.068°C.

The MSU data also can be compared to records of temperature variability from near-surface thermometers. Even though they are different variables, their common variability helps to assess how well coupled the near-surface temperature variations are to the deep layer variations. Although the global distribution of thermometers is suspected by many researchers as being inadequate for accurate monitoring, the distribution over the United States is widely

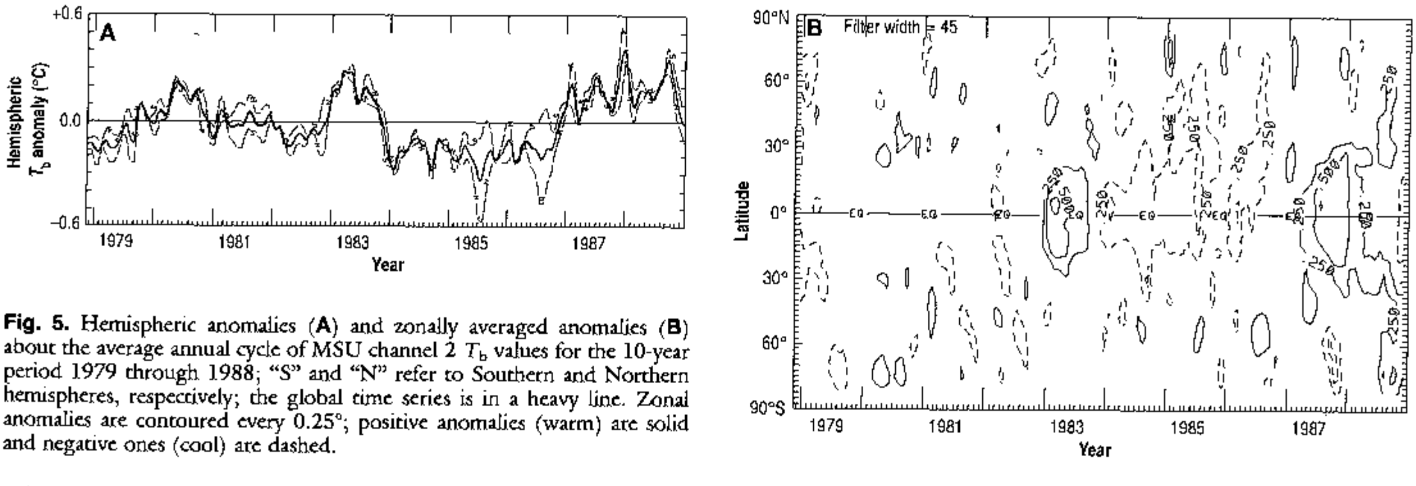

Fig. 5. Hemispheric anomalies (**A**) and zonally averaged anomalies (**B**) about the average annual cycle of MSU channel 2 T_b values for the 10-year period 1979 through 1988; "S" and "N" refer to Southern and Northern hemispheres, respectively; the global time series is in a heavy line. Zonal anomalies are contoured every 0.25°; positive anomalies (warm) are solid and negative ones (cool) are dashed.

accepted as good enough for climate work. We compared monthly temperature anomalies from thermometers over the contiguous United States for the period 1979 through 1987 (*13*) to our monthly mid-tropospheric temperature anomalies from the satellites. The resulting anomaly time series (Fig. 4, A and B) are similar, as verified by a scatterplot (Fig. 4B) and a correlation coefficient of 0.89. This correlation agrees with those between radiosonde near-surface and upper air measurements, for which monthly temperature anomalies range from 0.8 for the eastern United States to greater than 0.9 for the western United States. The surface anomalies are typically two to three times as great as the MSU anomalies. This relation is probably a result of daytime solar heating and nighttime cooling of the surface, which largely control the deeper air mass temperatures over the United States on monthly and seasonal time scales.

Two major research groups have been responsible for hemispheric calculations of temperature anomalies from thermometer measurements, and we refer to them by their leading authors names: Jones (*14, 15, 16*) and Hansen (*17*). Their results have been sufficiently different to spark debate in the climate community and have led to conflicting reports in the popular press regarding global temperature trends. We have compared our satellite-measured hemispheric anomalies to the thermometer-based anomalies from these two groups (Table 1). Again, when the separate systems are viewed as a bivariant distribution in which we wish to determine the level of common variability, these comparisons reveal that the level of agreement between the calculations by Jones and the satellite data is about 40% better than that between the calculations by Hansen and the satellite data. As might be expected for two land-dominated data sets, the Jones and Hansen data are much better correlated with each other, with an explained variance of 94%, than either is with the MSU data. The much lower explained variances for the hemispheres and globe (Table 1) compared to the United States are the result of both poor thermometer coverage over much of the earth and weak thermal coupling between the middle and lower troposphere over much of the oceans. This latter effect was deduced from radiosonde near-surface and deep layer temperature comparisons: When monthly surface temperature anomalies from radiosonde are compared to the corresponding radiosonde-calculated channel 2 anomalies for United States–controlled ocean stations, the explained variances drops to about 35% for the Caribbean, 0 to 20% for the tropical Pacific, and 25% for the tropical south Atlantic. Although there are few high-latitude ocean radiosonde stations, the data suggest that the thermal coupling increases poleward (for example, 52% in Iceland), probably because of the wider range of air mass temperatures encountered there. Thus we would not expect as good agreement between MSU anomalies and tropical ocean surface air temperature anomalies as are obtained over land, even if the oceanic thermometer coverage were adequate. This conclusion is substantiated by the somewhat poorer agreement between the satellite data and combined thermometer and sea surface temperature data from

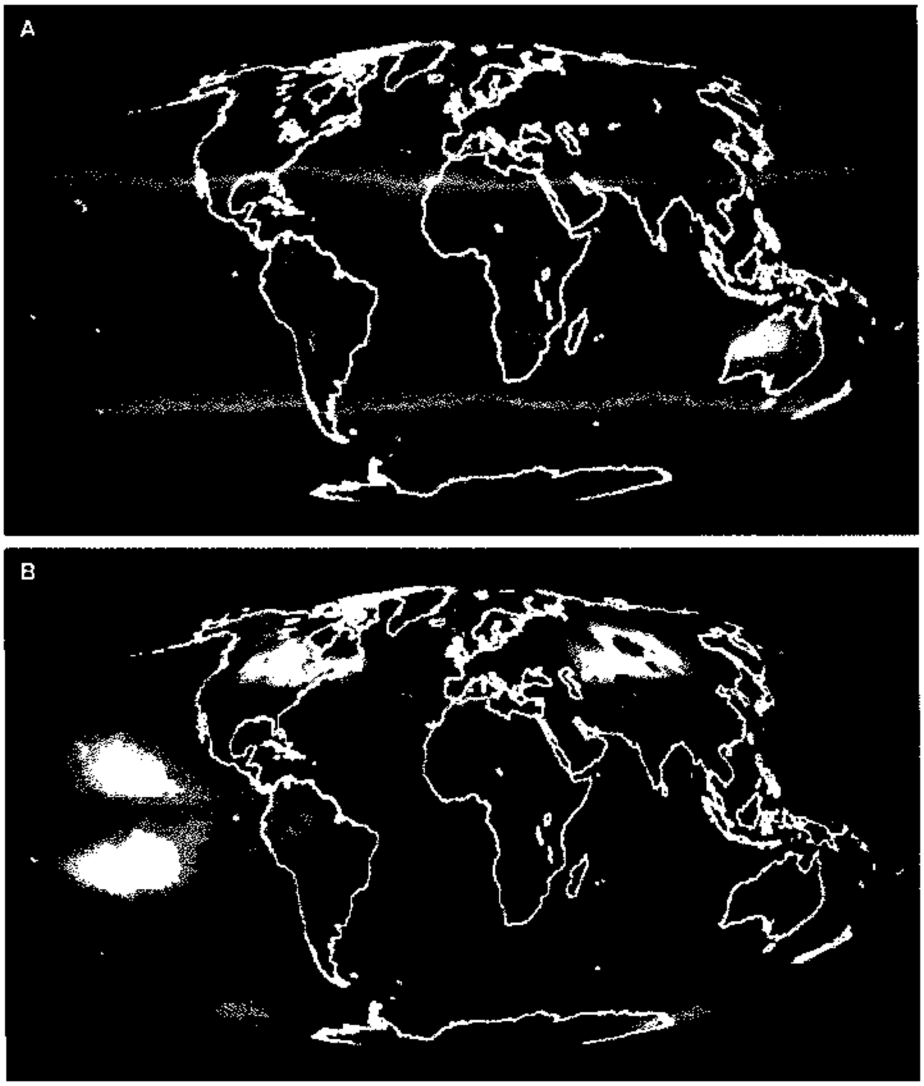

Fig. 6. Average MSU channel 2 T_b (**A**) during the 10-day period 26 January to 5 February and temperature anomalies (**B**) for the same 10-day period during the 1983 ENSO climate anomaly. Temperatures range in top image is gray, representing 235 K, to red, representing 260 K, in 1 K increments; temperature anomalies in bottom image change color every 0.25 K, the blue side of dark gray is colder, red side is warmer.

Table 1. Monthly and annual explained variances (in percent) between MSU and thermometer-measured temperature anomalies for United States (U.S.), Northern (NH) and Southern (SH) hemispheres, and the globe from 1979 to 1988. Thermometer-based calculations for the United States are from Karl (*13*); monthly and annual hemispheric and global thermometer anomalies are from Jones (*14–16*); annual anomalies are from Hansen and Lebedeff (*17*), and hemispheric and global anomalies, which also include sea surface temperatures, are from Farmer *et al.* (*18*).

Source	U.S.	NH	SH	Globe
		Monthly		
Karl	77			
Jones		33	10	35
Farmer		26	11	28
		Annual		
Karl	77			
Hansen		67	27	53
Jones		72	66	74
Farmer		77	24	69

Farmer *et al.* (*18*) (Table 1). The poor agreement raises the important issue of whether near-surface temperatures or deep layer temperatures should be monitored for detection of climate change. Because they are often different from one another over the tropical oceans, it would be best to monitor both in order to gain an understanding of how the entire troposphere behaves. Indeed, it might well be that the oceanic surface air layer is so strongly coupled to sea surface temperature variations that a deep layer mean would provide an earlier signal of possible greenhouse warming.

Global temperature anomalies 1979 to 1988. The first 10 years of satellite data reveal large fluctuations in the hemispheric and global temperatures (Fig. 5A). The Northern and Southern hemispheres trends follow each other for the slower, interannual trends, but often oppose each other on monthly to seasonal time scales. The warmest years, in decreasing order, were 1987, 1988, 1983, and 1980. There is no obvious long-term trend, and anomalies during the first 5 years nearly balance those during the last 5 years. The 1988 warm event was traced to the mid-latitudes, as was the 1980 warm anomaly. Both years included summer heat waves in the United States. The largest warm anomaly in the Northern Hemisphere for the 10-year record occurred in 1987 and 1988 (Fig. 5B). The 1987 and 1983 warm events were associated with El Niño/Southern Oscillation events [ENSOs (*19*)]. During the 1983 ENSO, transfer of heat from record-setting sea surface temperatures in the eastern Pacific to the atmosphere caused major changes in atmospheric flow that impacted weather conditions worldwide. Warming locally exceeded 2°C in two Pacific anticyclones (Fig. 6) that straddled an equatorial zone of intense convective activity caused by the warm water. This event caused globally averaged temperatures to rise more in several months than what is expected within several decades if enhanced greenhouse warming is occurring. Although the 1987 ENSO has been considered weaker than the 1983 ENSO, it was associated with higher temperatures that were more uniformly spread throughout the tropics. The mid-latitudes in both the Southern and Northern hemispheres in 1988 experienced warm conditions that appear to be coupled to the 1987 tropical warmth. The period 1984 to 1986 was dominated by cooler than normal tropical air. The 10-year time series exhibits bifurcation in that there are nine cool or warm years, and only one year (1981) that could be considered "average." This pattern makes the definition of what is "normal" for global temperatures uncertain, for as shown above normal can mean either warm or cool conditions.

The future. Our data suggest that high-precision atmospheric temperature monitoring is possible from satellite microwave radiometers. Because of their demonstrated stability and the global coverage they provide, these radiometers should be made the standard for the monitoring of global atmospheric temperature anomalies since 1979. Their use will allow relatively precise monthly determinations of the locations and magnitudes of temperature change events. The resulting data should provide a greater focus of scientific debate on why temperature anomalies occur rather than whether they occur. The advanced microwave sounding units (AMSU) will replace the MSU on NOAA satellites in the mid-1990s, and these units will allow extension of the time series into the next century. Various computerized climate models, which predict future changes through time-dependent equations representing physical processes, can now be evaluated with accurate global temperature measurements. These data should result in improved specification of processes in these models, which still require independent verification. These improvements should facilitate more informed policy decisions concerning the effects of anthropogenic greenhouse gas production.

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9. Low-pass filtering of the time series allows isolation of the more slowly varying temperature variations that are of interest to climatologists. Here, the filter retains 50 percent of the power of cycles having 90-day periods, progressively less power of periods shorter than 90 days, and more power of longer periods.
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20. R. Jenne and D. Joseph provided the MSU data used in this study; R. Hood provided data processing and programming support; N. Grody collaborated on portions of this research and provided general advice; F. Wentz provided updated sea surface emissivity estimates; P. Olsen, F. Soltis, and P. Swanson assisted us in obtaining technical data on the MSU; G. Wilson helped obtain the satellite data sets; discussions with J. Dodge and R. McNider led to the present research.

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