obal Atmospheric Temperature Monitoring with Satellite Microwave Measurements: Method and Results 1979–84

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ABSTRACT

A method for measuring global atmospheric temperature anomalies to a high level of precision from satellites is demonstrated. Global data from the Microwave Sounding Units (MSUs), flying on NOAA satellites since late 1978, have been analyzed to determine the extent to which these data can reveal atmospheric temperature anomalies on bidaily and longer time scales for regional and larger space scales. The global sampling provided by the MSUs is an important asset, with most of the earth sampled bidaily from each of (typically) two instruments flying concurrently on separate satellites at different solar times. The primary source of tropospheric thermal information is from the MSU 53.74 GHz channel. This channel is primarily sensitive to thermal emission from molecular oxygen in the middle troposphere, with relatively little sensitivity to water vapor, the earth's surface, and cloud (especially cirrus) variations. The long-term stability of the oxygen mixing ratio in the atmosphere makes it an ideal tracer for climate monitoring purposes. Lower stratospheric temperature anomalies are derived from the MSU 57.95 GHz channel.

Comparisons between monthly MSU temperature anomalies and corresponding thermometer-measured anomalies for the United States reveal a high (0.9) correlation, but hemispheric anomalies show much lower correlations. This results from some combination of poor thermometer sampling of remote regions and weak coupling of surface and deep-tropospheric temperature anomalies in tropical areas.

Analysis of data from two of the MSUs (on NOAA-6 and NOAA-7), whose operational periods overlapped by two years, reveals that hemispheric temperature anomalies measured by the separate instruments are very similar (to about 0.01°C) on monthly time scales. Their combined time series of unfiltered two-day hemispheric averages show standard deviations of their mean of 0.15°–0.20°C and standard deviations of their average difference of 0.02°–0.03°C, indicating a signal-to-noise ratio of 40 for the Southern Hemisphere and 45 for the Northern Hemisphere. The intercomparison period also reveals no evidence of calibration drift between satellites at the 0.01°C level. This was substantiated by two 15-month comparisons of NOAA-6 with rawinsonde data from 45 stations in the eastern United States, which revealed 0.013°C net difference over five years. Monthly averaged comparisons between individual rawinsonde and NOAA-6 data from 1980 through 1982 reveal a monthly standard deviation of their difference of 0.04°C. The statistical and geophysical portions of this noise are found to be about equal in magnitude, 0.03°C. The single-satellite noise due to imperfect sampling for ten-day, 2.5° gridpoint temperatures was calculated by measuring the standard deviation of the difference between two satellites with ranges from 0.2°C in the tropics to 0.4°C in middle latitudes.

The period of analysis (1979–84) reveals that Northern and Southern hemispheric tropospheric temperature anomalies (from the six-year mean) are positively correlated on multiseasonal time scales but negatively correlated on shorter time scales. The 1983 ENSO dominates the record, with early 1983 zonally averaged tropical temperatures up to 0.6°C warmer than the average of the remaining years. These natural variations are much larger than that expected of greenhouse enhancements, and so it is likely that a considerably longer period of satellite record must accumulate for any longer-term trends to be revealed.

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he problem

hanges in the global climate system have received igh level of scientific, political, and public visibility in the last several years. The possibilities of rising ocean levels and significant regional changes in climate due to anthropogenic greenhouse enhancements have captured widespread attention. Unfortunately, the potentially inadequate geographical distribution of thermometers has resulted in much uncertainty (and thus controversy) about whether temperature anomalies on a hemispheric basis can even be confidently inferred from conventional data. Sparsely populated regions are

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either poorly measured or not measured at all. Changes in thermometer exposure due to urbanization are known to result in apparent warming of well populated locations (Karl et al. 1988; Balling and Idso 1989). Unfortunately, correction for this urbanization effect is difficult since the majority of land station locations have likely experienced some sort of local increase in exposure to man-made structures. Of course, most oceanic areas go unmeasured. Thus, we are faced with the task of understanding what portion of climate change is to be attributed to man versus "natural" variations, when we cannot even quantify with confidence what the background natural variability is.

b. Satellites to monitor climate?

In contrast to conventional measurements, satellites can provide the global coverage that is needed to monitor the earth's atmosphere. Unfortunately, the issue of satellite instrument calibration has typically been a source of great concern and uncertainty. However, possibly the best calibrated instruments in earth orbit to date have direct application to the global atmospheric temperature monitoring issue. These are the Microwave Sounding Units (MSUs), built by the Jet Propulsion Laboratory (JPL) for the National Oceanographic and Atmospheric Administration's (NOAA) operational weather monitoring needs. Because these instruments measure a vertically averaged atmospheric temperature, we feel that they have the potential for significantly augmenting the surface-based thermometer record by providing a measurement representing a significant depth of the troposphere, rather than just a thin near-surface layer sensitive to variable surface effects (urbanization, desertification, etc.). This paper provides detailed technical aspects of the MSUs utility as a climate monitoring device. A related paper (Spencer and Christy 1990) summarizes the global temperature anomalies observed during 1979–88.

c. Theory

The MSUs are designed to measure the thermal emission by molecular oxygen in the atmosphere at different spectral intervals in the oxygen absorption complex near 60 GHz (Meeks and Lilley 1963). Because the oxygen abundance in the atmosphere is very stable in both space and time (Warnek 1988) it makes an ideal tracer for radiometric atmospheric temperature monitoring. As Machta and Hughes (1970) state, "all reliable oxygen data since 1910 fall in the range of 20.945%–20.952% by volume," with the instrumental accuracy of in situ measurements being ±0.006% by volume. In contrast, infrared temperature monitoring methods depend upon thermal emission from CO_2, the mixing ratio of which is much more variable in space and time.

At microwave frequencies, radiance is directly proportional to the temperature of the emitting body. The
radiometer output is usually converted to a
temperature" (T_b). The term "brightness tem
acknowledges that the measurement is based
diative brightness that equals a thermometric
ature only when the measured object is radi
black body (unit emissivity, and thus zero ref

While T_b is measured directly by the satelli
tive transfer theory can be used to evaluate the
radiation emission and scattering processes wh
to the measured T_b. Conceptually, the trans
diation leading to the satellite measurement at
frequencies involves three "sources": 1) a dom
direct (upward) thermal emission by the atm
and smaller contributions from 2) an
(downward) atmospheric emission reflected
surface back up to the satellite, and 3) a surfac
sion shining through the (mostly opaque) atmo
Based upon the theory for nonscattering atmos
the T_b at a given frequency, $T_b(\nu)$, depends
vertically integrated atmospheric temperature
between the satellite and the earth's surface,

$$T_b(\nu) = \int_{\ln p_s}^{+\infty} T(p)[d\bar{\tau}_\nu(p)/d\ln p]\,d\ln p +$$

The integral is written in pressure coordinates, p,
p_s is the surface pressure and T_s is the surfac
temperature. For conciseness, an "effective trans
tance function" is defined which is virtually inde
dent of temperature

$$\bar{\tau}_\nu(p) = [1 + (1 - e_s(\nu, \theta)) \times (\tau_\nu(p_s)/\tau_\nu(p))^{2\sec\theta}]\tau_\nu(p)$$

where $\bar{\tau}_\nu(p_s) = \tau_\nu(p_s)^{\sec\theta} e_s$ represents the surface
sion term in Eq. 1, e_s is the surface emissivity
is the Earth incidence angle.

Equation 2 contains the atmospheric transmi
function, $\tau_\nu(p)$, which is the exponential abso
along the vertical path between the satellite a
arbitrary pressure level. As a satellite instrumen
away from nadir (vertical), the increased abso
due to longer path lengths is accounted for by the
terms. Also, the contribution due to the reflec
diation by the surface is contained in the term
the factor $(1 - e_s)$. As discussed below, a compen
surface effect is contained in the surface emission
$\tau_\nu(p_s)^{\sec\theta} e_s T_s$, in (1).

In (1), T_b is expressed as a vertically (p
weighted atmospheric temperature, where the w
ing function is defined as $-d\tau_\nu(p)/d\ln p$ (see
In typical applications of the four channels of
data, (1) is inverted to retrieve the atmospheric
perature profile $T(p)$. We depart from this app
by interpreting the MSU channel 2 and 4 T_b fo
nearly what they are, a vertically averaged tempe
measurement of the atmosphere. However, to