2.1 THE ROLE OF PASSIVE MICROWAVE RADIOMETERS IN CLIMATE MONITORING

Roy W. Spencer
Earth System Science Center
The University of Alabama in Huntsville
National Space Science and Technology Center
Huntsville, AL 35805

1. INTRODUCTION

Passive microwave radiometers have been at the forefront of the emerging field of climate applications of satellite data. Even though the pool of researchers is considerably smaller in passive microwave remote sensing than it is in visible and infrared remote sensing, the characteristics of microwave radiometers in some ways lend themselves more readily to climate applications. I will review some of the important advances this area has seen in the last thirty years, and what the future holds.

2. HISTORICAL CONTEXT

The first launch of a passive microwave radiometer for measurement of natural Earth emissions was accomplished by the U.S.S.R. on a Cosmos satellite in September, 1968. This followed the successful U.S. flyby mission past Venus with a microwave radiometer aboard Mariner-2 in December, 1962. On the U.S. side, these events were followed by a series of window-frequency and sounding (oxygen channel) frequency radiometers on the NASA Nimbus satellite series, starting with the Nimbus-5 Electrically Scanning Microwave Radiometer (ESMR-5) in 1972. ESMR-5 demonstrated the utility of microwave window frequencies (in this case, 19.35 GHz) to measure the warm thermal emission of rain cells against the low microwave emissivity ocean background (Wilheit et al., 1977), a concept first advanced by Buettner (1963). On the same satellite, the first temperature sounder, the Nimbus-E Microwave Spectrometer (NEMS) was flown to measure the emission by molecular oxygen at three frequencies near 60 GHz (e.g. Staelin, 1969). This set the stage for operational satellite monitoring of global atmospheric air temperatures.

Two important events in the eventual use of microwave radiometers for climate monitoring were the first launches of the Microwave Sounding Unit (MSU) in late 1978, and of the Special Sensor Microwave Imager (SSM/I) in mid-1987. Although designed for the day-to-day weather monitoring needs of NOAA and DoD, respectively, the design of these instruments turned out to be sufficiently well thought out, both in terms of calibration and longevity, to allow long-term monitoring of interannual to decadal climate variations. The MSUs, built by the Jet Propulsion Laboratory (JPL), followed on the heritage of the earlier, experimental microwave temperature sounders flown by NASA on the Nimbus-5, -6, and –7 satellites. The MSU was a four channel instrument with center frequencies at 50.3, 53.74, 54.96, and 57.95 GHz, allowing sensitivity to air temperatures from near the surface to the lower stratosphere.

Critical for climate applications, the MSUs had an “external” calibration design, which featured a two-point linear calibration strategy involving a view of the cosmic background at 2.7 K, and a high emissivity on-board warm target whose temperature was monitored with redundant platinum resistance thermometers (PRTs). These calibration measurements were made through the same antenna system (offset parabolic reflector and feedhorn) as were the Earth measurements. This design results in the variable thermal emissions by the radiometer hardware canceling out in the calibration equation. This is an important element in climate monitoring since the decaying or drifting orbit of a single satellite over the course of years causes long-term changes in the solar heating and thus temperature of the satellite and the radiometer. Monitoring and adjusting for these effects was found to be extremely difficult, e.g. in the case of the Nimbus-7 and SeaSat Scanning Multichannel Microwave Radiometer (SMMR). The use of the MSUs for monitoring decadal scale tropospheric temperature variations to about 0.01 deg. C per year was demonstrated by Spencer *et al.* (1990). But along with better sensors came a greater sensitivity to smaller instrument calibration effects. A small nonlinearity of the MSUs response caused instrument-temperature dependent biases, through the specification of the original calibration nonlinearity based upon a single gain state as measured pre-launch. Since the gain of the MSUs Dicke-style radiometer is directly related to the instrument temperature, as the orbits of the NOAA TIROS-N satellites drifted to different times of day, the instrument temperature changed. if not adjusted for, this causes a spurious drift on the long-term record of brightness temperatures (Christy *et al*., 2000).

There are a series of temperature sounders on the DMSP satellites, also flying since 1979, called the Special Sensor Microwave Temperature (SSM/T) instruments. Partly because early data from these instruments were never archived, there are no climate products being investigated from them. A more recent raw data archive from SSM/T, since the mid-1980’s, is kept by NOAA/NESDIS.

The SSM/I was an externally-calibrated window frequency radiometer, and was first flown on the DMSP F8 satellite. The SSM/I measures dual linear-polarized (H and V) brightness temperatures at 19.35, 22.235, 37, and 85.5 GHz. It features a conical scan pattern, which results in a constant Earth incidence angle across the data swath. This allows more accurate retrieval of surface and atmospheric quantities since the variability of the Earth's microwave emissivity with incidence angle is complex, and not well understood. In the years following the launch of the first SSM/I, the field of satellite microwave remote sensing expanded considerably. What was once a field containing maybe two dozen researchers now numbers in the hundreds.

Obviously, a decadal-scale dataset requires one or more copies of an instrument to be operating during the time period. If multiple copies of the same instrument are flown, it is important to have at least one year of overlap between them to allow for accurate intercalibration while on-orbit.

Finally, the algorithms for turning calibrated satellite measurements into estimates of a geophysical parameter will always be imperfect. The climate demands on their accuracy are in some ways more stringent than for weather monitoring applications. For example, it is important that there be little algorithm "cross-talk" between different parameters. For example, an algorithm for the retrieval of any non-temperature parameter (e.g. sea ice) should have little change in the diagnosed sea ice parameter when only the temperature of the sea ice changes. Similarly, an algorithm for oceanic wind speed should be relatively insensitive to changes in water vapor.

3. THE MICROWAVE RADIOMETER "ADVANTAGE" FOR CLIMATE APPLICATIONS

An important practical aspect of all of these microwave radiometers that lend themselves well to climate monitoring is a low data rate. Since these instruments measure frequencies so much lower than visible or infrared radiometers, antennas of any practical size (generally from several centimeters to near 1 m in diameter) yield spatial resolutions from about 15km to over 100 km (depending on the channel frequency). Thus, not nearly as many radiometer measurements are required to cover the entire Earth. Since frequent reprocessing of multi-decadal satellite datasets is required to thoroughly understand their characteristics, current computer limitations give the data processing advantage to datasets whose volumes do not exceed tens of gigabytes of data. Clearly, as computer and data storage device access speeds increase, this will become less of an advantage.

A second, but arguable, advantage is the lack of cloud effects in the microwave temperature sounders. The "cloud-clearing" problem with infrared temperature sounders is a formidable one, and much work has been devoted to the removal of cloud effects from those measurements. The microwave sounder channels in the 50-60 GHz oxygen absorption region are insensitive to cirrus clouds, and are only slightly sensitive to cloud water contamination.

4. CLIMATE PRODUCTS AVAILABLE TODAY

While there are many researchers that now provide products from measurements made by several satellite microwave radiometer systems, we will highlight those few datasets that I am aware of that have been routinely available, and kept up-to-date with recent satellite data. Also, since strictly speaking a climate dataset could include as little as two months of data (from, say, two successive Januarys, thus allowing analysis of interannual variability) I will make special mention of only those datasets that span a decade or more. Times series of some of these datasets will be shown at the conference.

4.1 *from MSU*

The MSU global lower tropospheric and lower stratospheric deep-layer temperature datasets are now in their twenty-third data year, comprised of data from nine separate MSUs. The MSUs have now been replaced by the Advanced Microwave Sounding Units (AMSUs) on the NOAA-15 and NOAA-16 satellites. With fifteen temperature sounding channels instead of four, and higher spatial resolution (50 km versus 110 km for the MSU, both at nadir), the AMSUs are providing a rich source of new information, while allowing continuation of the time series started with the MSUs.

4. 2 *from SSM/I*

The dataset with the greatest heritage has been the "ocean product" suite developed by Wentz (1997). Available since shortly after the launch of the first SSM/I in 1987, these products include oceanic surface wind speed, total integrated cloud water, total integrated water vapor, and now precipitation rate. Because the emissivity variations of the ocean background are better understood, and therefore better modeled, than the land background, "ocean" products have a much longer heritage than do "land" products.

There are several researchers that now provide nearly complete rainfall retrieval records from the SSM/I instruments. This has been the area with possibly the greatest amount of research funding in recent years, and numerous investigators have developed their own algorithms, some of which provide routine products to the research community. Specifically, an SSMI-only dataset developed and maintained by NOAA/NESDIS, and a Global Precipitation Climatology Project (GPCP) dataset that includes SSM/I rainfall estimates, are worthy of mention. The precipitation products are particularly difficult to make an accurate long term record of since, generally speaking, the polar-orbiting spacecraft they come from are at different times during the diurnal cycle, and these times change as the satellites' orbits drift. This can cause the drift through the diurnal cycle in rainfall (even over the ocean) to be falsely interpreted as a climate trend in the rainfall estimates. To my knowledge, these effects have not been adjusted for in any of the decadal-scale precipitation datasets from SSM/I. Indeed, the drift of "sun-synchronous" satellites through the diurnal cycle remains as possibly the largest single source of error in the use of these datasets for climate purposes.

The two best-known sea ice datasets that come from SSM/I (and even extend back to 1979 with SMMR) come from NASA. The so-called "NASA Team" algorithm (Cavalieri *et al*., 1991) and the "bootstrap" algorithm (Comiso, 1995) have been applied to the SSM/I data record and have allowed estimates of decadal scale sea ice changes in the Arctic and around Antarctica.

Climate datasets of additional parameters (e.g. land surface temperature, snow cover, vegetation, soil wetness) will be addressed at the conference.

4.3 *TRMM*

Although designed as a three-year mission, the Tropical Rain Measuring Mission (TRMM) has been providing unique tropical measurements since late 1997. TRMM deserves special mention for several reasons. It carries the TRMM Microwave Imager (TMI), a modified SSM/I design, which includes the first externally calibrated channels below 11 GHz. This now allows sea surface temperature (SST) retrievals through clouds that could provide a basis for climate monitoring of cloudy SSTs from future microwave radiometers. There has been a recent decision to boost the TRMM satellite to a significantly higher orbit (from its nominal 350 km altitude) that will reduce atmospheric drag sufficiently that TRMM could conceivably provide a 10-year dataset before satellite reentry. Since TRMM is not sun-synchronous, it should provide important information on the diurnal cycle in tropical rainfall to allow diurnal adjustments to datasets built from the polar-orbiting radiometers. TRMMs first flight of a precipitation radar is providing a unique validation opportunity of the passive-microwave based precipitation datasets, and will pave the way for a future high-latitude orbiting radar as part of the NASA Global Precipitation Mission (GPM).

5. CLIMATE PRODUCTS IN THE FUTURE

There are more microwave radiometers in operational use now than ever before, and the situation will improve even further in the future. Within the next year or so, new satellite systems will include the research missions involving the Advanced Microwave Scanning Radiometer (AMSR), a Japanese-built instrument to be flown on the NASA Aqua satellite and on the Japanese ADEOS-II satellite. More operational copies of AMSU will be flown by NOAA and on the European MetOp satellite, as well as on Aqua. The first SSM/IS (an SSM/I-style instrument but with both temperature sounding and window channels) will be launched to begin replacing the SSM/I line of instruments. Farther in the future, probably after 2010, the National Polar Orbiting Environmental Satellite System (NPOESS) will carry a line of Conically-scanning Microwave Imager Sounders (CMIS), with 2 m antennas and frequencies ranging from 6 GHz to around 200 GHz, as well as a through-nadir scanning microwave temperature sounder.

In summary, the important elements necessary to the construction of useful decadal-scale datasets from sun-synchronous polar-orbiting satellites include:

1. stable calibration design
2. instrument longevity
3. overlap between successively launched copies of instruments (to allow intercalibration)
4. a stable orbit (or procedures for adjustment of the radiometer measurements for drift through the diurnal cycle)
5. well-designed retrieval algorithms with a minimum of cross-talk between different geophysical parameters.

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