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Estimating soil moisture from satellite microwave observations: Past and ongoing projects, and relevance to GCIP

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E. T. Engman¹

Abstract. On the basis of a series of studies conducted in Botswana and preliminary results from an ongoing study in Spain, developments in microwave remote sensing by satellite, which can be used to monitor near-real-time surface moisture and also study long-term soil moisture climatology, are described. A progression of methodologies beginning with single-polarization studies and leading to both dual polarization and multiple frequency techniques are described. Continuing analysis of a 9 year data set of satellite-derived surface moisture in Spain is ongoing. Preliminary results from this study appear to provide some evidence of long-term desertification in certain parts of this region. The methodologies developed during these investigations can be applied easily to other regions such as the GCIP area and could provide useful databases for simulation and validation studies. Additionally, they have strong potential for global applications such as climate change studies.

1. Introduction

Surface moisture is an important link between the land surface and the atmosphere. It has direct influence on the exchange of heat and moisture between these two sinks and as such is an important element in the global circulation process. Surface soil moisture has been identified as a parameter of significant potential for improving the accuracy of large-scale land-surface-atmosphere interaction models. However, soil moisture is quite difficult to measure accurately in both time and space, especially at large spatial scales. It changes constantly as a result of precipitation events, evaporation processes (which includes extraction by vegetation), and redistribution within the soil. Spatially, soil moisture is highly variable on both the small and the large scale, due to the variability of precipitation and the heterogeneity of the land surface (e.g., vegetation, soil physical properties, topography, etc.). While point sampling of soil moisture is generally thought to be the most accurate, the observed value is representative only of a relatively small area immediately surrounding the measurement. Subsequent areal averaging of these measurements, especially at scales of 10^2 – 10^3 km², will often introduce large errors. Since remotely sensed land surface measurements are already a spatially averaged or areally integrated value, they are a logical input parameter to regional or larger-scale land process models. Regular and improved estimates of soil moisture have been shown to significantly enhance the performance of general circulation models (GCMs) [Shukla and Mintz, 1982] and certain mesoscale models, such as flood forecast models.

In recent years a number of international research programs

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have been conducted to study land-surface-atmosphere interactions, with a special emphasis on remote sensing. Several of these programs have concentrated their efforts in arid and semiarid regions. Two of these studies, which were conducted in Botswana and Spain, focused heavily on remote sensing applications and demonstrated the potential of space-borne passive microwave radiometers for monitoring land surface wetness [Van de Griend and Owe, 1989; Bolle *et al.*, 1993]. These studies have provided highly promising results, not only for near-real-time monitoring of surface moisture but also for long-term climatological applications. This paper reviews some of the more significant results of these studies and how they might be applied to current research programs such as the GEWEX (Global Energy and Water Cycle Experiment) Continental-Scale International Project (GCIP).

2. Theory

Remote sensing systems, which monitor the natural microwave emission from a radiating source, are called passive remote sensing systems. This technology is based on the measurement of the thermal radiation from the surface in the centimeter wave band and is determined by the physical temperature of the radiating body and its emissivity. In the microwave region the emitted radiation is extremely low as compared to longwave infrared radiation. An approximation for the Planck equation, at low frequencies ($f < 117$ GHz), is the Rayleigh-Jeans approximation and can be shown to lead to

$$T_B \cong eT \quad (1)$$

where T_B is the observed microwave brightness temperature, T is the physical (thermometric) temperature of the emitting layer, and e is its emissivity. For a more thorough treatment of electromagnetic theory the reader is referred to Ulaby *et al.* [1986].

The microwave region is the only part of the electromagnetic spectrum that permits truly quantitative estimates of soil moisture using physically based models. Microwave technology is the only remote sensing method that measures a direct re-

sponse to the absolute amount of water in the surface soil. The basis for microwave technology in the measurement of soil moisture follows from the dielectric properties of soil-water mixtures and their effect on the natural microwave emission from the soil [Schmugge, 1985]. The dielectric constant is an electrical property of matter and is a measure of the response of a medium to an applied electric field. At low microwave frequencies the dielectric constant of fresh water is around 80, while the dielectric constant of dry soil is usually less than 5. This large difference accounts for the measurable range in emissivity from dry to wet conditions and lends itself well to satellite remote sensing application. The parameter is also a complex number, and therefore it is somewhat difficult to validate with field measurements. In a nonhomogeneous medium, such as soil, the dielectric constant is a combination of the dielectric constants of its individual components (i.e., air, water, rock, etc.). The soil dielectric constant may be calculated from a number of popular models [Wang and Schmugge, 1980; Dobson et al., 1985].

Various other factors such as soil physical properties and vegetation also have a significant effect on the microwave emissivity from the land surface. One of the most important of the soil properties is the surface roughness. Roughness results in an increase in surface area, thereby reducing the reflectivity and increasing the absorptivity and emissivity of the surface. Roughness also reduces the sensitivity of emissivity to soil moisture variations and thus reduces the range in the emissivity from dry to wet conditions. Surface roughness is a function of the root-mean-square (rms) height variation of the surface and the correlation length [Choudhury et al., 1979]. It has been found that surface roughness is less important at satellite scales, as long as the observations are not in mountainous regions [Van de Griend and Owe, 1994a].

The effects of vegetation on the microwave emission as measured from above the canopy is twofold. The vegetation may absorb or scatter the radiation emanating from the soil, but it will also emit its own radiation. In areas of sufficiently dense canopy the measured emissivity may be due entirely to the vegetation. The magnitude of the absorption depends on the wavelength and the water content of the vegetation. The most frequently used wavelengths for soil moisture sensing are in the *L*- and *C*-bandwidths ($\lambda \approx 21$ cm and 5 cm), although only *L*-band sensors are able to penetrate vegetation of any significant density. While observations at all frequencies are subject to scattering and absorption and require some correction if the data are to be used for soil moisture retrieval, shorter wave bands are especially susceptible to vegetation influences.

Numerous canopy models have been developed to account for the effects of vegetation [Kirdiashev et al., 1979; Mo et al., 1982; Theis and Blanchard, 1988; Ulaby et al., 1986]. These basic models have been modified and applied successfully by a variety of investigators, using data from primarily ground-based radiometer systems over agricultural fields [Jackson et al., 1982; Pampaloni and Paloscia, 1986; Jackson and O'Neill, 1990]. Radiative transfer characteristics of vegetation can be expressed in terms of the transmissivity Γ and the single-scattering albedo ω . The transmissivity is defined in terms of the optical depth τ , such that

$$\Gamma = e^{-\tau/\cos\mu} \quad (2)$$

The emitted radiation, as observed from above the canopy, may be expressed in terms of the radiative temperature T_B and is given by [Mo et al., 1982]

$$T_B = T_s \varepsilon \Gamma + (1 - \omega) T_C (1 - \Gamma) + R(1 - \omega) T_C (1 - \Gamma) \Gamma \quad (3)$$

where ε is the soil emissivity, R is the soil reflectivity, and T_s and T_C are the thermometric temperatures of the soil and the canopy, respectively. The first term of the above equation defines the radiation from the soil as attenuated by the vegetation. The second term accounts for the upward radiation directly from the vegetation, while the third term defines the downward radiation from the vegetation, reflected by the soil and again attenuated by the canopy.

The optical depth is related to the canopy density and, for frequencies less than 10 GHz, has been shown to be a linear function of vegetation water content. Typical values of τ for agricultural crops have generally been given as less than 1 [Mo et al., 1982; Jackson and O'Neill, 1990]. Theoretical calculations have shown that the sensitivity of above-canopy brightness temperature measurements to variations in soil emissivity decreases with increasing optical thickness [Ulaby et al., 1986]. This is because the emission from the vegetation canopy tends to saturate the signal with increasing optical depth. This results in decreased sensor sensitivity to soil moisture variations.

The single-scattering albedo describes the scattering by the vegetation of the soil emissivity. The albedo is a function of plant geometry, frequency, and polarization and, consequently, varies according to species and plant associations. Experimental data for this parameter are limited, and values for selected crops vary from 0.04 to ~ 0.12 [Brunfeldt and Ulaby, 1984; Mo et al., 1982; Jackson and O'Neill, 1990]. Values for natural vegetation are even more scarce, although Becker and Choudhury [1988] estimated a value of 0.05 for a semiarid region in Africa.

The influence of polarization on vegetation optical depth has received relatively little attention, although there is some experimental evidence that differences in the transmissivity at horizontal and vertical polarization are dependent on incidence angle. These differences are observed mainly over vegetation elements that exhibit some systematic orientation such as vertical stalks in tall grasses, grains, and maize [Ulaby et al., 1986]. At a nadir (0°) incidence angle the stalks are not visible and appear only as small randomly oriented disks. However, as the incidence angle increases, the stalks become more prominent, resulting in an increased effect on vertically polarized emissions. In general, however, the canopies for most crops and naturally occurring vegetation are randomly oriented, and it is reasonable to assume that the leaf absorption loss factor is for the most part polarization independent. This tendency of vegetation to reduce the polarization difference with increasing biomass is the basis for the microwave polarization difference index (MPDI) [Becker and Choudhury, 1988].

3. Satellite Microwave Data

The microwave data are from the scanning multichannel microwave radiometer (SMMR) onboard the Nimbus-7 satellite. The instrument began transmitting data in November 1978 and was deactivated in August 1987. Because of power constraints onboard the satellite the SMMR instrument could only be activated on alternate days. The satellite orbited the Earth

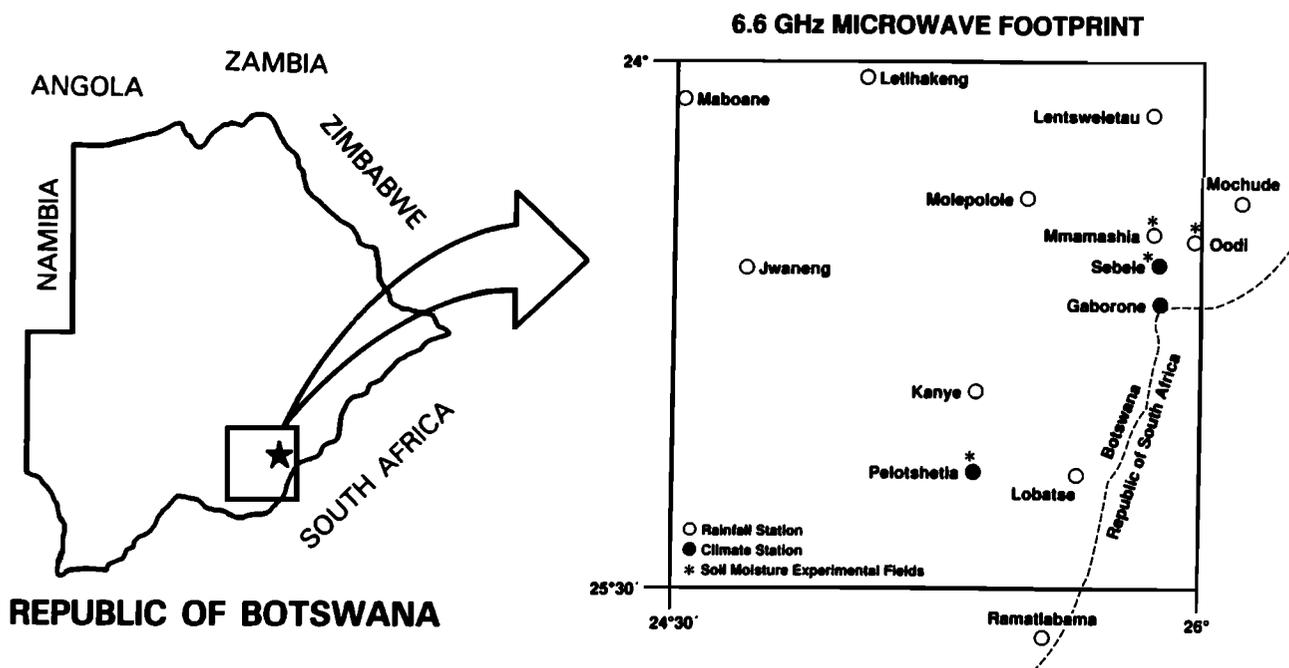


Figure 1. A map of the Botswana study site showing locations of ground data stations.

~14 times in 1 day, with a local noon and midnight equator crossing, and a swath width of about 780 km. Brightness temperatures were measured at five frequencies from 6.6 GHz ($\lambda = 4.5$ cm) to 37 GHz ($\lambda = 0.8$ cm) at both horizontal and vertical polarization, resulting in 10 different channels. Although complete coverage of the Earth required 6 days, sufficient overlapping would occur during this period, especially at latitudes away from the equator, to result in repeat coverage over small sites about 2–3 times per week. The 24 hour on-cycle of the instrument resulted in both day and night observations, which for research purposes was an ideal feature. While the spatial resolution of SMMR was rather coarse (from ~25 km at 37 GHz to 150 km at 6.6 GHz), these data still have highly useful applications, especially at regional and global scales.

4. Monitoring Surface Moisture in the African Savanna

A long-term cooperative research program to study land surface processes in semiarid regions was initiated by the Vrije Universiteit Amsterdam and NASA Goddard Space Flight Center in Botswana during 1988 [Van de Griend *et al.*, 1989]. The emphasis of this program was on satellite remote sensing, with an especially strong focus on microwave remote sensing of surface soil moisture. This research collaboration is still ongoing and has evolved considerably since its beginning.

4.1. Study Area and Ground Data

The 150 km² study area is located in southeastern Botswana and corresponds in size approximately to a scanning multichannel microwave radiometer (SMMR) footprint at 6.6 GHz (Figure 1). The cover consists primarily of tree and shrub savanna with an undergrowth of savanna grasses interspersed with cultivated fields. The region has been characterized as

semiarid, with annual precipitation averaging between 300 and 500 mm.

A 3 year data set of daily surface moisture was derived with a physically based model from available climate and radiation data and calibrated with weekly field measurements of soil moisture [Owe and Van de Griend, 1990; Owe *et al.*, 1992]. The soil moisture data were collected at four experimental sites within the study area. Each site covered about 20 km² and consisted of 40–50 measurement locations for a variety of surface cover conditions. Model calibrations were conducted for all cover types. Using a partial area approach with the 11 precipitation stations located throughout the study area, it was felt that highly accurate estimates of daily pixel-average soil moisture were achieved.

4.2. Physical Surface Temperature

Satellite microwave observations are generally recorded as brightness temperatures, which must be normalized by the physical temperature of the emitting layer. For semiarid regions it has been noticed [Owe *et al.*, 1992] that nighttime brightness temperatures displayed a significantly higher response to variations in surface moisture content than daytime brightness temperatures. Several factors appear to account for this phenomenon. First, daytime surface heating is extremely high and variable in these regions. This usually causes severe drying of the surface layer and increases the difficulty in making accurate spatially representative surface temperature estimates. At night some moisture is restored to the surface as it attempts to regain some equilibrium with the remaining profile. Additionally, the temperatures of the air, soil surface, and canopy also approach equilibrium, making it less difficult to estimate spatial averages of surface temperature.

4.3. Single-Polarization Microwave Analysis

To derive soil moisture information from satellite microwave observations, it is necessary to use a model, such as the

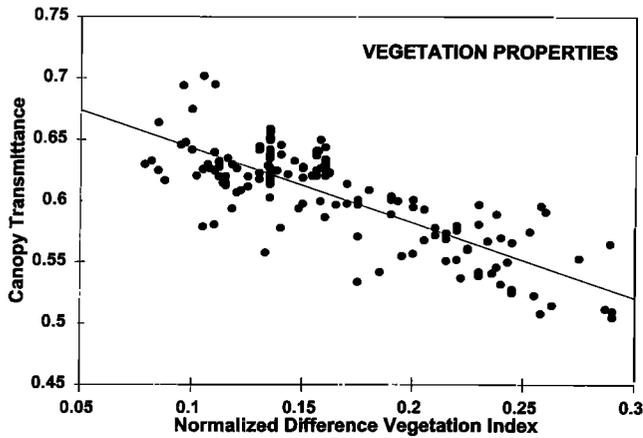


Figure 2. Relationship between the normalized difference vegetation index and the vegetation canopy transmittance derived from data acquired over the Botswana savannas.

simple radiative transfer model given in (3). The relationship between soil moisture and surface emissivity is more or less linear, especially within the range of commonly observed moisture values. While this linearity holds for vegetated surfaces as well as for bare surfaces, adjustments in both slope and offset must be made for different vegetation densities. Correcting for vegetation influences requires an independent method to estimate the canopy optical depth or transmittance and also the scattering albedo. A frequently used method for estimating the

biophysical properties of vegetation is the normalized difference vegetation index (NDVI). The relationship between NDVI and canopy transmittance was found to be approximately linear (Figure 2), at least for regions such as the African savanna, and was derived from actual data [Van de Griend and Owe, 1993]. However, the savanna region has rather low vegetation biomass, and as biomass increases, NDVI will eventually reach saturation.

A major disadvantage of the NDVI results from the compositing process and the fact that the index is a monthly value. This is especially true in semiarid regions, where dominant vegetation species such as grasses may react very quickly to small precipitation events which may subsequently result in significant greening. Some of these vegetation species will also lose their greenness during antecedent dry periods. The monthly NDVI is unable to capture these short-term fluctuations which may occur during the month. Inaccurate estimates of vegetation biomass and subsequent canopy optical depth may lead to significant errors in calculating soil moisture.

A 3 year time series of soil moisture was derived from horizontally polarized 6.6 GHz SMMR brightness temperatures and monthly NDVI values, by inverting (3) and solving for the soil emissivity, which then leads to the soil moisture (Figure 3). For this analysis it was assumed that the single-scattering albedo was zero. This is not an unreasonable assumption, since the effect of the scattering albedo is relatively small compared to the optical depth and is more or less constant over the range of commonly observed soil moisture values [Owe et al., 1992]. When compared to ground observations of soil moisture, how-

Single Polarization Approach

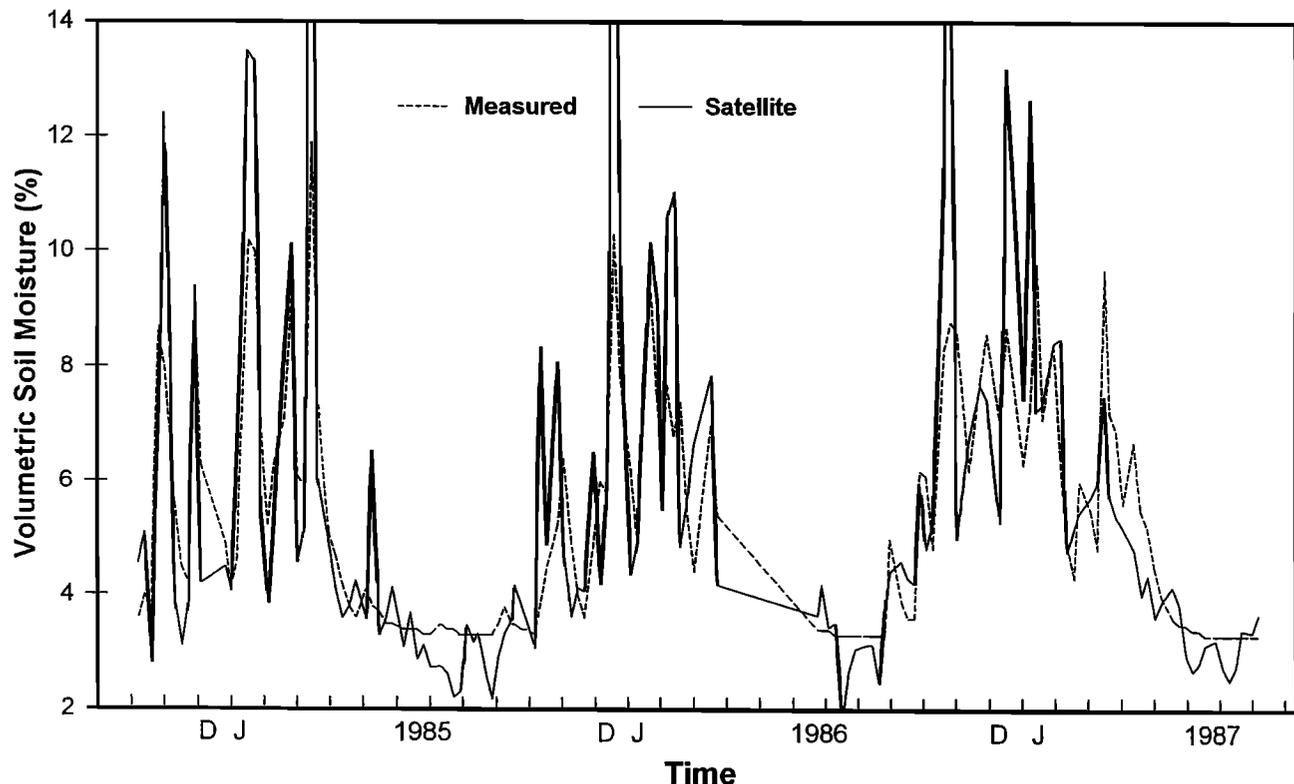


Figure 3. Comparison of 3 year time series of measured and satellite-derived soil moisture, using only horizontally polarized SMMR data and NDVI to estimate canopy properties.

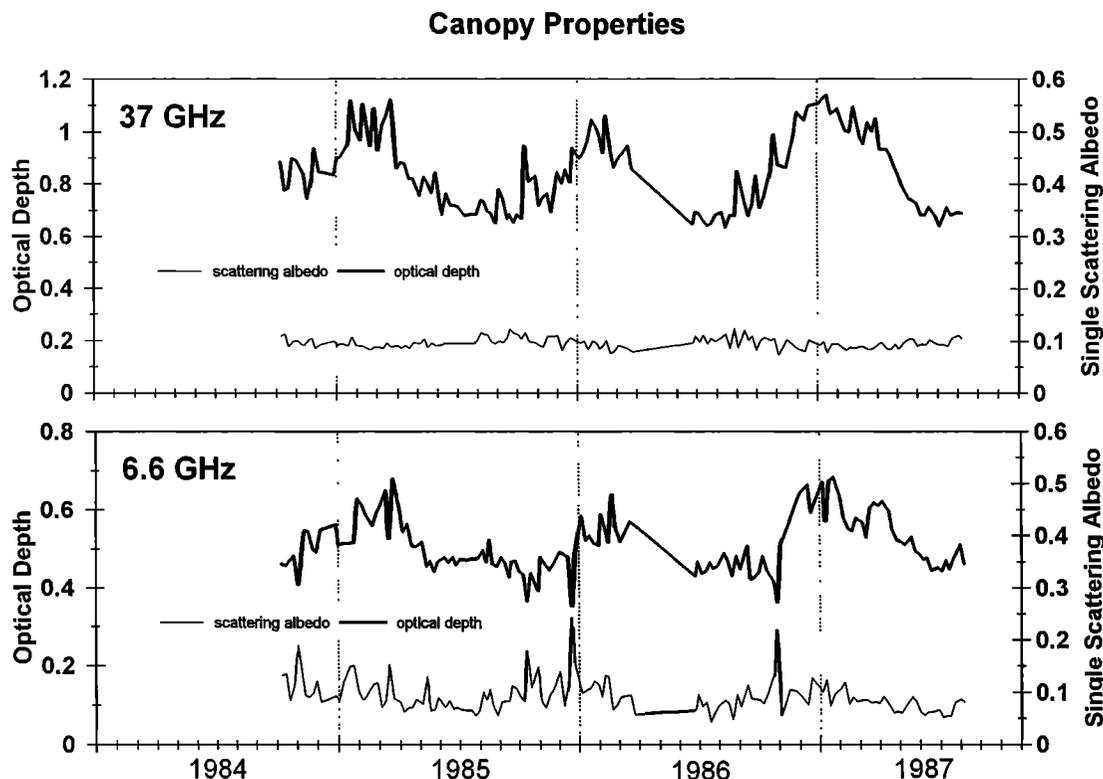


Figure 4. Comparison of vegetation optical depths and single-scattering albedos calculated from 6.6 GHz and 37 GHz SMMR data.

ever, one notices that the satellite-derived surface moisture is frequently overestimated. The standard error of estimate for these data is $\sim 5\%$ absolute soil moisture [Van de Griend and Owe, 1994a]. The reason for these high-moisture values is due to a large extent to an overestimate of the vegetation for much of any given month. This is an inherent disadvantage with the NDVI compositing process, whereby the highest recorded value during any given month determines the average value for that month. This may lead to significant errors in estimating the canopy transmittance, especially in semiarid regions, where vegetation greenness is extremely variable and highly reactive to small localized precipitation events.

4.4. Dual-Polarization Microwave Analysis

A radiative transfer model was also used to investigate and compare the seasonal variation in the vegetation optical depth and the single-scattering albedo at C-band and Q-band (37 GHz). For this analysis it was assumed that both the optical depth and the scattering albedo were independent of polarization. Again, for vegetation canopies, which possess a totally random structure, this is not unreasonable. The optical depth at both frequencies displays a distinct annual course, although the 6.6 GHz data appear to contain somewhat more noise (Figure 4). This clearly follows from the fact that the microwave signal at the longer wavelength is also significantly affected by the soil emission, whereas the signal at the shorter wavelength is due predominantly to the canopy emission. The vegetation canopy is much less transparent to the shorter wavelength signal, which is evidenced by the greater optical depth values at 37 GHz. However, the scattering albedo displays the same average value for the 3 year time series for both frequencies. An annual course in the scattering albedo is also not

evident for either wavelength, although there exists considerably more noise in the 6.6 GHz data. The reason for this is not entirely clear.

Because of the nonideal nature of using monthly NDVI to estimate the vegetation transmission properties and since polarization independence of the optical depth and scattering albedo had also not yet been conclusively demonstrated, a new numerical approach was developed to solve for the soil moisture and which uses both horizontal and vertical polarization brightness temperatures. This new approach is referred to as the dual polarization approach and utilizes the radiative transfer equation (equation (3)) written in both polarizations in a nonlinear optimization scheme [Van de Griend and Owe, 1994a; Van de Griend et al., 1996]. Results from this analysis saw a significant improvement in soil moisture estimation. The 3 year time series of satellite-derived soil moisture obtained by this new approach is compared to the observed ground data with a standard error of 1.2% absolute moisture content (Figure 5).

5. Monitoring Long-Term Temporal Changes of Soil Moisture

Many results from the previous studies in semiarid southern Africa are currently being applied to an ongoing desertification monitoring study in Spain. One of the objectives of this study is to investigate temporal changes in long-term soil moisture, quantify the changes, and attempt to relate them to specific land use changes or physiographic characteristics.

The full 9 year data set of SMMR observations was analyzed. Only horizontally polarized C-band brightness temperatures were used in calculating the land surface moisture. Both hor-

Dual Polarization Approach

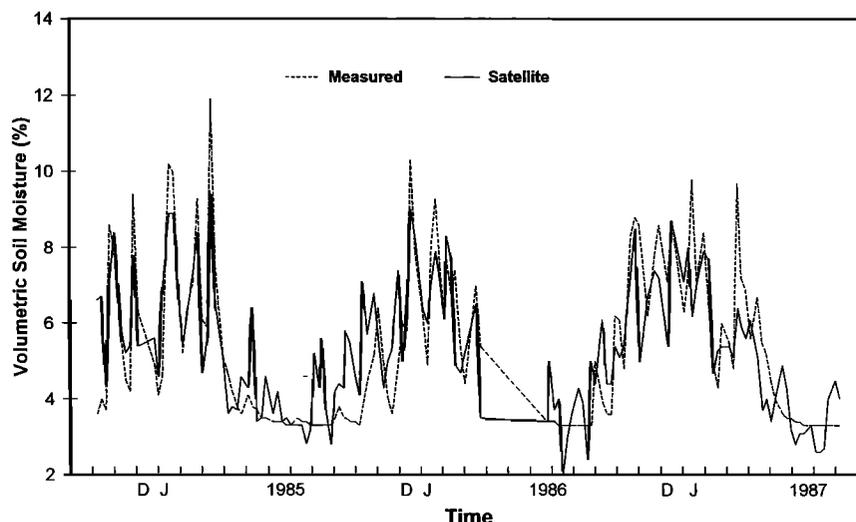


Figure 5. Comparison of 3 year time series of measured and satellite-derived soil moisture using the dual-polarization approach.

horizontal and vertical polarization brightness temperatures were used for the 37 GHz frequency data for the purpose of calculating the MPDI, while the vertical polarization data were also used to estimate the physical temperature of the emitting layer.

On the basis of data from the Botswana studies, relationships were developed between the radiative transfer characteristics of the vegetation and the various satellite-derived vegetation indices [Van de Griend and Owe, 1994b]. From these relationships the canopy transmissivity was then derived from the MPDI for each grid cell over Spain. Since both Botswana and much of Spain are somewhat similar climatically and are also characterized by large areas of bare soil, discontinuous vegetation, and agriculture, this approach seemed reasonable. The MPDI has many advantages and may be a more appropriate measurement of vegetation biomass for shorter time-scale (i.e., daily) modeling applications. Specifically, the MPDI is less hampered by clouds, thereby permitting simultaneous acquisition with the longer wavelength C-band data and eliminating the necessity for compositing images in the visible and near-infrared channels. Since no distinct annual course was found in the Botswana studies for the single-scattering albedo, an average value derived from the 3 year analysis was used [Van de Griend and Owe, 1993].

The physical temperature of the emitting layer was estimated from the 37 GHz vertical polarization data for the entire study period. A procedure was developed, which was based on a series of relationships derived from daily maximum and minimum air temperatures, ground-based surface temperatures, and Meteosat infrared surface temperatures (M. Owe and Van de Griend, manuscript in review, 1998). These measurements were acquired during the international climate-research field program, EFEDA, which was conducted in central Spain during 1991 [Bolle et al., 1993].

The vegetation-corrected surface emissivity was derived by inverting the radiative transfer equation (equation (3)). The relationship between the soil moisture content and the soil dielectric constant for representative soils in Spain was determined from both laboratory measurements and modeled estimates of the dielectric constant. The soil emissivity was subse-

quently calculated from the dielectric constant by the Fresnel equations [Schmugge, 1985] in order to define the relationship between soil moisture and soil emissivity (Figure 6). A 9 year time series of satellite-based soil moisture was then calculated, resulting in ~10–12 observations per month for each grid cell. In order to reduce the high variability inherent in daily values, all the observations for a given month were averaged to obtain a 9 year time series of mean monthly soil moisture.

Trends in soil moisture content over time can then be analyzed by a variety of methods. A simple technique, such as calculating the slope of the time series over the period of observation, will provide a reasonable indication of changes in soil moisture. More sophisticated techniques, such as Fourier analysis, may also be performed and may be very appropriate for quantifying long-term data sets which exhibit some periodicity such as annual cycles. They may provide important information, such as the magnitude and amplitude of the average annual cycle, and trends in the intra-annual cycle such as phase shifts.

Preliminary results indicate that the surface soil moisture has decreased significantly during the 9 year period from 1978 to 1987 in certain locations, while having remained unchanged or even increased in others. While considerable variability exists in the annual cycle from year to year, long-term trends are readily apparent in the time series data for those situations where they exist. An example of a decreasing trend in surface soil moisture is illustrated in a time series of mean monthly soil moisture from an area in the northeast part of Spain (Figure 7). In contrast, another time series from the western central part of the country illustrates a constant trend in mean monthly soil moisture during the same period (Figure 8).

Efforts are currently in progress to quantify existing soil moisture trends for the entire country. Also, long-term trends in the vegetation will be investigated by analyzing both NDVI and MPDI time series data. Attempts will then be made to relate the observed surface moisture conditions over time to predominant land cover classes. It may then be possible to infer what types of cover conditions, land use practices, or other factors are associated with the different trends in surface moisture which have been observed during the period of study.

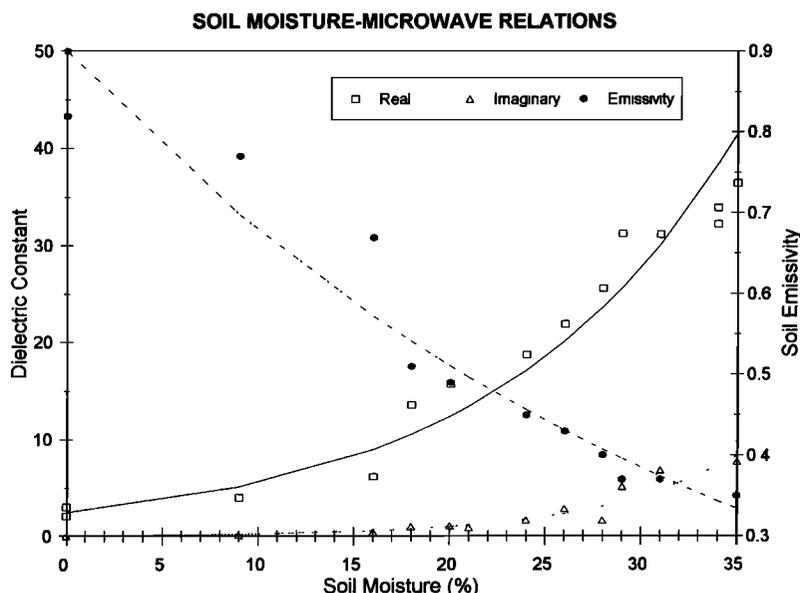


Figure 6. Relationship among the horizontal emissivity, the real and imaginary parts of the soil dielectric constant, and soil moisture for an average soil from central Spain. All values reflect a frequency of 6.6 GHz and an incidence angle of 50°.

6. Application to the GCIP Area

The work presented above illustrates how passive microwave remote sensing is capable of identifying long-term desertification from estimates of the surface soil moisture. This approach offers the potential for meeting some of the science objectives identified by the GCIP soil moisture primary research activity (PRA). The objectives of this PRA which could be, at least in part, addressed with SMMR- and SSM/I-derived soil moisture data are (1) to improve the understanding and estimation of the space-time structure of soil moisture, the relationship between model estimates of soil moisture and observations of soil moisture, and to produce soil moisture fields for the GCIP area to be used as diagnostic and input data for modeling initiatives; (2) to assess the role of soil moisture in hydrological models and develop an understanding of the relationship between model soil moisture state variables and observation-based values of soil moisture; that is, is the model-produced value of soil moisture anything like that what we can measure?; and (3) to develop improved remote sensing techniques for areal estimation of soil moisture.

Although it is recognized that data from these satellites are not ideal for measuring soil moisture in situations where there is significant vegetation cover, the Botswana and Spain studies illustrate that a soil moisture signal can be detected, especially in arid and semiarid locations. There is a definite need to follow up on these studies and produce a soil moisture data set for the GCIP area that covers the time period from the launch of SSMR to the present. This data set would give modelers a valuable resource for simulation and validation studies. At this time it is not clear how much of the GCIP area would be covered with valid estimates of soil moisture, but it seems likely that most of the large study areas for the southwest and northwest (LSA-SW and LSA-NW) would be covered. Furthermore, these would be the only remotely sensed soil moisture data available until the year 2000 or later.

7. Summary

A number of international field programs have been conducted in recent years, which have contained strong satellite remote sensing components aimed at improving the interpre-

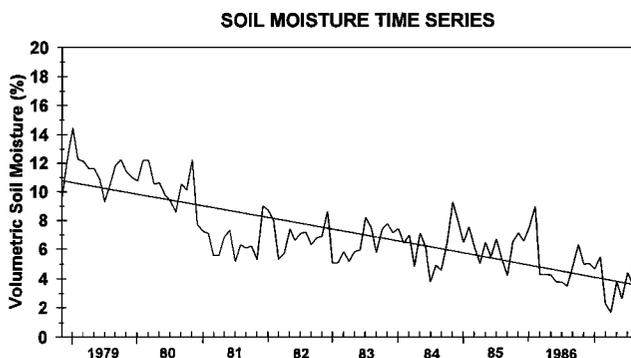


Figure 7. Nine year time series of mean monthly soil moisture, illustrating a decreasing trend in moisture content.

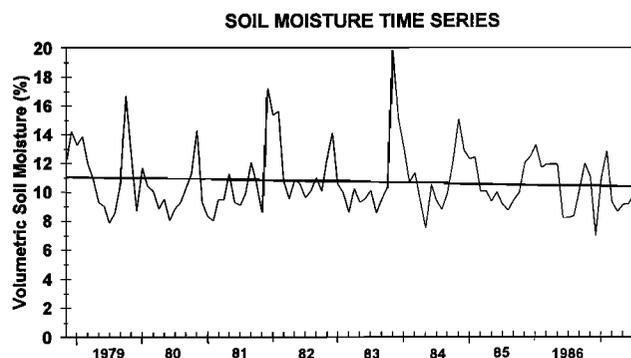


Figure 8. Nine year time series of mean monthly soil moisture, illustrating a constant trend in moisture content.

tation of passive microwave observations of the land surface. Recent developments in the application of these data, especially in the area of inverse modeling, have resulted in improved techniques for estimating important land surface parameters such as soil moisture and vegetation canopy properties. Knowledge of these vegetation properties such as single-scattering albedo and optical depth are crucial because they tend to mask and distort the microwave signal, and their effect must be removed in order to obtain accurate estimates of soil moisture.

Surface soil moisture is a key factor in the partitioning of incoming radiation at the land surface. It is also the common link between the moisture and the energy balances, which are the physical basis for modeling of the Earth system. While the importance of this parameter is fully realized, independent spatial estimates at local to global scales are still largely unavailable. This inability to quantify soil moisture has had an adverse impact on environmental modelling efforts. Passive microwave remote sensing presents the greatest potential for providing this information at a global scale and at regular time intervals. Spatially accurate estimates of surface moisture should provide the necessary input for improved predictions of global circulation. Real-time estimates should improve weather and climate modeling efforts, while the creation of historical data sets will provide necessary information for simulation and validation of long-term climate and global change studies. Additional applications of these data include desertification and drought monitoring, agricultural forecasting, and flood potential prediction.

Results from the above research programs have demonstrated the potential for deriving soil moisture from C-band satellite microwave signatures and should provide a basis for further development and application of inverse modeling techniques. This is especially important in light of upcoming new microwave sensors, such as planned for the EOS-PM platform.

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