Estimating long term surface soil moisture from satellite microwave observations in Illinois, USA

MANFRED OWE
MC 974, NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771, USA
e-mail: owctojhsb.gsfc.nasa.gov

RICHARD DE JEU & ADRIAAN VAN DE GRIEND
Faculty of Earth Sciences, Vrije Universiteit, Amsterdam, The Netherlands

Abstract A database of long-term soil moisture was compared to satellite microwave observations over a test site in the midwestern United States. Night-time microwave brightness temperatures were observed at a frequency of 6.6 GHz by the Scanning Multichannel Microwave Radiometer (SMMR). At 6.6 GHz, the instrument provides a spatial resolution of approximately 150 km, and a temporal frequency over the test area of about two to three night-time orbits per week. Vegetation radiative transfer characteristics, such as the canopy transmissivity, were estimated from vegetation indices such as the NDVI and the MPDI. Because the time of satellite coverage does not always coincide with the ground measurements of soil moisture, the existing ground data were used to calibrate a water balance for the top 10 cm surface soil layer in order to interpolate daily surface moisture values. Passive microwave remote sensing presents the greatest potential for providing regular spatially representative estimates of surface soil moisture at global scales.

Key words microwave; optical depth; remote sensing; SMMR; soil moisture

INTRODUCTION

Soil moisture is a key component of the water and energy balances of the Earth's surface, and 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 often somewhat difficult to measure accurately in both space and time, especially at large spatial scales. Soil moisture is highly variable, and while point measurements are typically quite accurate, subsequent areal averaging of these measurements often leads to large errors. Passive microwave remote sensing presents the greatest potential for providing spatially representative estimates of surface soil moisture at global scales on a recurring basis.

Microwave remote sensing has been used to monitor surface soil moisture with varying degrees of success. Both ground-based and airborne observations have usually lead to good results, while results from satellite-based studies have been mixed. Results from satellite remote sensing studies are highly dependent upon the quality of the ground measurements used for calibration, validation, or other comparisons. The usefulness of soil moisture data is typically determined by a variety of factors, e.g. measurement technique, depth, spatial coverage, temporal frequency, and associated land use characteristics. Ground-based and aircraft measurement campaigns are generally accompanied by intensive soil moisture measuring programmes, to ensure
optimum spatial representation for comparison. On the other hand, long-term satellite remote sensing studies at larger spatial scales usually do not have regular observations of soil moisture which are spatially representative of pixel-sized (or greater) areas.

A database of long-term soil moisture was compared to satellite microwave observations over a test site in the midwestern United States. The test site is located in southeastern Illinois (38°N, 89°15'W), and covers an area of approximately 150 km square (Fig. 1). The site contains three soil moisture sampling stations and is represented by two nearby meteorological stations which provided hourly temperature and solar radiation. Additionally, over 30 precipitation stations are located in or near the test site. The region is primarily agricultural in nature, and corrections for vegetation influences are also made. Real time estimates of soil moisture should improve weather and climate modelling efforts, while the development of historical soil moisture data sets will provide necessary information for model initialization, simulation, and validation of long-term climate and global change studies.

![Study Area Map](image)

**Fig. 1** Location of the Illinois test sites and various ground data stations.

**DATA DESCRIPTION**

Soil moisture observations were obtained from a dataset collected by the Illinois State Water Survey. These measurements were made several times per month at 19 locations throughout the state of Illinois since 1981, and have been described in considerable detail elsewhere (Hollinger & Isard, 1994). Measurements of average volumetric soil
moisture were made at regular intervals within the soil profile down to a depth of 2 m, however, only the average soil moisture in the top 10 cm was used for this study.

Microwave data were obtained from the Scanning Multichannel Microwave Radiometer (SMMR) (Gloersen & Barth, 1977), which flew onboard the Nimbus 7 satellite. Brightness temperatures were measured at five frequencies, from 6.6 GHz ($\lambda \approx 4.5$ cm) to 37 GHz ($\lambda \approx 0.8$ cm) at both horizontal and vertical polarization, resulting in ten different channels. Soil moisture was derived from 6.6 GHz horizontally polarized night-time microwave brightness temperatures.

National Climatic Data Center (NCDC) hourly and daily precipitation, temperature, and radiation datasets were used for water balance calibrations for the two test sites.

Vegetation radiative transfer characteristics such as the canopy transmissivity and the single scattering albedo were estimated from two common vegetation indices. The Normalized Difference Vegetation Index (NDVI) (Tucker et al., 1985) and the 37 GHz Microwave Polarization Difference Index (MPDI) (Becker & Choudhury, 1988) were both tested to determine which index provided the best estimate of the vegetation properties. While both indexes have been shown to work well, each has its inherent advantages and disadvantages. Because of frequent cloud contamination problems, the NDVI is typically reported as a 15-day or monthly composite. While it is unable to quantify short-term temporal variability in the vegetation character, the NDVI is very useful for monitoring long term trends. On the other hand, microwave observations are less hampered by clouds, making the MPDI better suited for use with other daily orbit data.

WATER BALANCE CALIBRATION AND INTERPOLATION

Because the time of satellite coverage does not always coincide with the ground measurements of soil moisture, the existing ground data were used to calibrate a water balance model for the top 10 cm surface layer in order to interpolate daily surface moisture values for days of satellite coverage. Such a climate-based approach is often more appropriate for estimating large-area average soil moisture, and has been used successfully in other studies. Meteorological data are generally more spatially representative of large areas than isolated point measurements of soil moisture. Daily soil moisture for the study period was derived in a manner similar to that described by Owe & Van de Griend (1990) and Owe et al. (1992).

MICROWAVE MODELLING

Theory

Remote sensing systems that measure the natural microwave emission from a radiating source are referred to as passive systems. This technology is based on the measurement of the thermal radiation from the surface in the centimetre 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 long-wave infrared radiation. An approximation for the Planck equation at low frequencies ($f < 117$ GHz), is the Rayleigh-Jeans approximation:
Estimating long-term surface soil moisture from satellite microwave observations

\[ T_b = eT \]  
(1)

where \( T_b \) is the observed microwave brightness temperature, \( e \) is the emissivity and \( T \) is the thermometric temperature of the emitting layer. The emitted microwave radiation, as observed from above the ground may be given as (Mo et al., 1982):

\[ T_b = T_s e_s \Gamma + (1 - \omega)T_c (1 - \Gamma) + R_s (1 - \omega)T_c (1 - \Gamma) \Gamma \]  
(2)

where \( e_s \) is the soil emissivity, \( T_s \) and \( T_c \) are the temperature of the emitting soil layer and the canopy respectively, \( R_s \) is the soil reflectivity, \( \omega \) is the canopy single scattering albedo, and \( \Gamma \) is the canopy transmissivity. For a more comprehensive treatment of microwave theory, the reader is referred to Schmugge (1985) and Ulaby et al. (1986).

Vegetation relations

When using night-time data, one may assume that the physical temperatures of both the canopy and the surface soil layer are similar, and may be approximated by the same value (Owe et al., 1982). The above model (equation (2)) was then optimized on the two canopy properties, \( \omega \) and \( \Gamma \), which remained as the only unknowns. The transmissivity and the single scattering albedo are then plotted against both the 15-day NDVI and the MPDI (Fig. 2). The MPDI appears to provide a somewhat better relationship with the transmissivity. While the 15-day NDVI composite data provide a somewhat better temporal resolution than the monthly NDVI composite data, the 15-day data are still unable to capture the temporal variability in vegetation biomass necessary for daily soil moisture modelling. The result is that NDVI frequently overestimates or

Fig. 2 Relationship between the canopy radiative transfer characteristics and two common vegetation indices, NDVI and MPDI, are illustrated.
underestimates the biomass during the composite period. Consequently, significant errors in soil moisture estimation may result, since the vegetation component of the radiative transfer model is quite significant. The single scattering albedo demonstrates no clear relationship with either vegetation index. This result is also consistent with other studies, which found that the scattering albedo exhibited no clear relationship with the annual course in vegetation biomass or other measured biophysical properties (Van de Griend & Owe, 1993).

**Satellite derived soil moisture**

Having quantified the vegetation relations, the soil moisture is derived from the 6.6 GHz horizontally polarized night-time microwave brightness temperatures by inverting equation (2) and solving for the soil emissivity and applying dielectric curves which are representative of the soil types found in this region. The 9-year time series of satellite derived soil moisture is then compared to the average soil moisture for the test site as determined by the observational and modelled data (Fig. 3).

![Satellite derived soil moisture graph](image)

**Fig. 3** A 9-year time series illustrating average daily soil moisture for the southern test site in Illinois (continuous line) and the remotely sensed soil moisture derived from horizontally-polarized 6.6 GHz microwave brightness temperatures from SMMR.

**SUMMARY AND CONCLUSIONS**

A nine-year database of Nimbus/SMMR 6.6 GHz microwave brightness temperature observations was used to derive surface soil moisture over a test site in southeastern Illinois. The satellite-derived surface moisture values were compared to the average
surface moisture as determined from a combination of physically-based modelling and an extensive data set of in situ moisture observations. The satellite data were adjusted for vegetation influences by deriving relationships for the canopy transmissivity and single scattering albedo. Soil moisture measurements taken during the months of December, January, and February were excluded from the soil moisture calibration in order to minimize the influence of snow and frozen soils. While some differences are noticed between the satellite derived surface moisture and the observational values, the overall relationship appears to be very good. Improvements in the relationship are expected with refinements in the calibration procedure. Prospects for near-real-time soil moisture derived from microwave sensors, which are expected to be launched within the next several years, remain high.

REFERENCES


