Surface Soil Moisture Retrieval and Mapping Using High-Frequency Microwave Satellite Observations in the Southern Great Plains

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ABSTRACT

Studies have shown the advantages of low-frequency (<5 GHz) microwave sensors for soil moisture estimation. Although higher frequencies have limited soil moisture retrieval capabilities, there is a vast quantity of systematic global high-frequency microwave data that have been collected for 15 yr by the Special Sensor Microwave Imager (SSM/I). SSM/I soil moisture studies have mostly utilized antecedent precipitation indices as validation, while only a few have employed limited ground observations, which were typically not optimal for this particular type of satellite data. In the Southern Great Plains (SGP) hydrology experiments conducted in 1997 and 1999, ground observations of soil moisture were made over an extended region for developing and validating large-scale mapping techniques. Previous studies have indicated the limitations of both the higher-frequency data and models for soil moisture retrieval. Given these limitations, an alternative retrieval technique that utilizes multipolarization observations was implemented and tested for the SGP region. A technique for extracting algorithm parameters from the observations was developed and tested. The algorithm was then used to produce soil moisture maps of the region for the two study periods.

1. Introduction

The potential of passive microwave remote sensing for measuring surface soil moisture has been demonstrated over a range of microwave frequencies (Choudhury and Golus 1988; Paloscia et al. 1993; Lakshmi et al. 1997; Drusch et al. 2001) and a variety of platforms (Wang 1985; Jackson et al. 1999; Jackson and Hsu 2001). These studies clearly show the advantages of low-frequency (<5 GHz) microwave sensors for this application. Although low-frequency sensors are recognized as the best direction for future soil moisture measurement systems, there is still a good reason in the meantime to consider the use of higher frequencies: the vast quantity of global systematic high-frequency microwave data that have been collected for the past 15 yr by the Special Sensor Microwave Imager (SSM/I).

Despite the fact that high-frequency microwave sensors will have limited retrieval capabilities, there are some conditions under which these observations can provide useful soil moisture information. Most studies using SSM/I and other passive microwave satellite systems to estimate soil moisture have utilized antecedent precipitation indices (APIs) as validation (Choudhury and Golus 1988; Ahmed 1995; Teng et al. 1993; Owe et al. 1992). Morland et al. (2001) compared APIs to soil moisture in estimating SSM/I emissivity. In that study they found APIs to be less correlated to emissivity and concluded that rapid drying of the soil layer, which determines the microwave emission was not adequately reflected in APIs.

A few investigations have employed limited observations from ground networks that were not optimally designed for this particular type of satellite data. The ground networks were either sparse, such as in Koike et al. (2000) (one measurement station per one SSM/I footprint) and in Vinnikov et al. (1999) (17 soil moisture stations for the entire state of Illinois), or the soil moisture layer observed was much deeper than that which determines the microwave response, such as in Owe et al. (1992) (20 cm) and in Vinnikov et al. (1999) (10 cm).

As part of the Southern Great Plains (SGP) hydrology experiments conducted in 1997 (SGP97) and 1999 (SGP99), ground observations of soil moisture were made over an extended region in order to contribute to the validation and demonstration of large-scale mapping of soil moisture using SSM/I data. In a previous investigation the use of a single-channel soil moisture retrieval algorithm was evaluated with limited datasets collected over the region in 1992 and 1994 (Jackson 1997). An investigation by Drusch et al. (2001) used the SGP97 SSM/I data and a more sophisticated radi-

TABLE 1. SSM/I satellite platforms.

Satellite	Dates of operation	Ascending equatorial crossing time (UTC)
F8	Jun 1987–Apr 1994	0612
F10	Dec 1990–Nov 1997	2215
F11	Nov 1991–May 2000	1925
F13	Mar 1995–present	1754
F14	Apr 1997–present	2046
F15	Dec 1999–present	2120
F16	2003 launch	TBD

ative transfer approach that fully considered atmospheric effects to study soil moisture and brightness temperature relationships.

These previous studies have indicated the limitations of both the high-frequency data and the models used for soil moisture retrieval. In the current investigation an alternative retrieval technique utilizing multipolarization observations and based upon the work of Njoku and Li (1999) was implemented and tested for the SGP region. Available information on parameters needed by the soil moisture retrieval algorithm at high frequencies is lacking. As part of the current investigation, a technique for extracting algorithm parameters from the observations was developed and tested. The algorithm was then used to produce soil moisture maps of the region for the two study periods.

2. The SSM/I instrument

The SSM/I is a conical scanning total power microwave radiometer system operating at a look angle of 53° at four frequencies: 19.4, 22.2, 37, and 85.5 GHz. The 22.2-GHz channel operates in V polarization and the other three channels in both V and H polarization. Spatial resolution [effective field of view (EFOV) 3-dB beamwidth] ranges from 69 km by 43 km at 19.4 GHz to 15 km by 13 km at 85.5 GHz. The orbital period is about 102 min, which results in 14.1 orbits per day. For a given satellite, coverage is possible twice a day approximately 12 h apart on the ascending and descending passes. Additional information can be found in Hollinger et al. (1990).

SSM/I instruments have been a component of the Defense Meteorological Satellite Program since 1987. Table 1 summarizes some aspects of the data records available from this series of satellites.

7. Conclusions

Previous studies have suggested that microwave data with frequencies higher than 10 GHz are not appropriate for soil moisture estimation since the vegetation will strongly mask surface information. However, a number of investigations using SSM/I data have presented evidence that there is a usable soil moisture signal under some conditions. Much of this work has been qualitative in nature, relying on indices and not the surface soil moisture for validation.

There are well-established theories describing the microwave emission of the land surface. Vegetation is important in these models but is less significant at low frequencies. At higher frequencies the vegetation is a more dominant feature, and soil moisture retrievals are more sensitive to the representation and parameterization of vegetation effects. Estimating algorithm parameters a priori, as suggested for low frequencies, may not be reliable. For this reason we evaluated a retrieval technique utilizing dual-polarization observations.

Data collected in two field experiments in the Southern Great Plains of the United States were used with SSM/I measurements to better understand the behavior of soil moisture and emissivity at these higher frequencies. The region used for the investigation was well suited to the limitations of using 19-GHz data to estimate soil moisture.

For each of three study areas, a linear relationship was observed between soil moisture and emissivity. Areas with lighter vegetation and the use of H-polarization data produced better linear regression results based on correlation and standard error of estimate values.

An attempt was made to describe the observed linear trends using a radiative transfer model in which the vegetation parameters were optimized. This is essentially the same as using the single-polarization approach described in Jackson (1997). Analysis resulted in values of the vegetation optical depth and the single-scattering albedo that were reasonable based upon published data. The single-channel algorithms had higher SEE than the linear regressions but low bias. These results suggest that there is a limitation on accuracy that is attributed to either the model structure or the quality of the ground observations. Both causes are considered possible.

The dual-polarization algorithm explicitly incorporates parameters that were lumped in the single-channel optimization. It utilizes the same equations but makes assumptions about the effects of polarization on some parameters. If these assumptions on vegetation effects are valid, it is a potentially robust solution. The most significant problem in applying this approach is reducing the number of unknowns to two (i.e., soil moisture and the vegetation parameter b).

The availability of data to perform atmospheric corrections and to estimate effective soil temperature at the time of SSM/I observation may add some restrictions to the application of this approach to areas without meteorological network and radiosonde observations. As an alternative to estimating temperature, van de Griend (2001) demonstrated that effective temperature could be estimated using 37-GHz V-polarization brightness temperature and some climatologic records over semiarid areas. The *Aqua* satellite, recently launched by NASA, includes sensors that can provide atmospheric profile information. With these additional measurements this approach can be extended to other areas with sparse vegetation.

An error analysis of the dual-polarization algorithm revealed that it produced good results for two of the test areas (CF and LW) but poor results at ER. This is attributed to the sources of error identified in previous investigations (Jackson et al. 2002).

Subject to the assumptions made in its implementation, the dual-polarization algorithm worked well in these tests with SSM/I data. We acknowledge that conditions in the SGP region are benign for the frequency used. However, it is anticipated that with lower-frequency channels available with AMSR that the assumptions and limitations imposed by vegetation on soil moisture estimation will be improved.