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Journal of Hydrology xx (2004) 1–12

Journal
of
Hydrologywww.elsevier.com/locate/jhydrol

Microwave remote sensing of soil moisture: evaluation of the TRMM microwave imager (TMI) satellite for the Little River Watershed Tifton, Georgia

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Received 29 January 2004; revised 15 October 2004; accepted 29 October 2004

Abstract

Soil moisture plays a critical role in many hydrological processes including infiltration, evaporation, and runoff. Satellite-based passive microwave sensors offer an effective way to observe soil moisture conditions over vast areas. There are currently several satellite systems that can detect soil moisture. Calibration, validation, and characterization of data received from these satellite systems are an ongoing process. One approach to these requirements is to collect and compare long-term *in situ* (field) measurements of soil moisture with remotely sensed data. The *in situ* measurements for this paper were collected at the Little River Watershed (LRW) Tifton, Georgia and compared to the Tropical Rainfall Measurement Mission Microwave Imager (TMI) 10.65 GHz vertical and horizontal (V and H) sensors and vegetation density Normalized Difference Vegetation Index (NDVI) from the Moderate Resolution Imaging Spectroradiometer (MODIS) for the period from 1999 through 2002. The *in situ* soil moisture probes exist in conjunction with rain gauge stations throughout the sampling region. It was found that the TMI was able to observe soil moisture conditions when vegetation levels were low. However, during several months each year high vegetation levels mask the soil moisture signal from the TMI. When the monthly averaged observation from the TMI, MODIS, and *in situ* probes were subjected to a multivariable comparison the correlation value increased slightly, improving the accuracy of the TMI—soil moisture correlation. Our results show that the TMI estimate would not result in an adequate monitoring of large land areas but when used in conjunction with other satellite sensors and *in situ* networks and model output can constitute an effective means of monitoring soil moisture of the land surface.

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Keywords: Soil moisture; Microwave remote sensing; Hydrological processes; Vegetation index

1. Introduction

Soil moisture is an important variable in land surface hydrology. The amount of moisture in the soil

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has a direct effect on the hydraulic conductivity. Accurate measurement of volumetric soil moisture helps hydrologists predict amount of runoff, recharge rate, evaporation and other important variables (Jackson and Schmugge, 1996). Precise assessment of these variables will aid in the development of meteorological forecasting, flood management schemes, impact assessments, wetland delineation and hydrological models. Unfortunately, *in situ* measurements of soil moisture are often time-consuming and require a large work force to adequately sample even small watersheds (Rawls et al., 1982). Permanently automated sampling sites are able to cover specific areas, but it is not feasible to have such sites located everywhere. Satellites offer a solution to these problems as they can observe large areas and are not restricted by rough terrain and/or adverse weather conditions (Jackson, 1993).

Thermal emissions from soils in the microwave region are sensitive to variations of the moisture in the soil (Guha and Lakshmi, 2002). It has been shown that microwave radiation in lower frequencies can penetrate several centimeters into most soils (Jackson and Schmugge, 1989; Zhan et al., 2002). Any moisture that is present in the top 5 cm of soil can affect the amount of microwave radiation that is emitted at low frequencies (Schmugge et al., 2002). Longer wavelengths penetrate deeper into the soil and are less likely to be affected by cloud cover or vegetation. The amount of microwave energy that is emitted to space is primarily dependent on the amount of water in the soil. Surfaces covered with water will emit low amounts of microwave radiation, whereas dry soils emit much more radiation in the microwave frequencies (Wang and Schmugge, 1980). It is impossible to separate the effects of surface roughness and vegetation unless one of the variables is known a priori (Schmugge, 1985; Bindlish et al., 2003).

In this study the effectiveness of the TMI to observe soil moisture in the southern coastal plain region of Georgia is evaluated. Specifically, the affects of vegetation on the TMI soil moisture observations will be investigated. If the observations from a passive microwave remote sensing system can be calibrated to the conditions in this watershed then vast areas of the land surface can also be mapped and studied. As our ability to map soil moisture improves so will our understanding of the hydrological cycle.

2. Background

There have been several attempts to assess the feasibility of using passive microwave remote sensing technology to measure soil moisture. Studies have been conducted on ground based, airborne, and satellite based sensors. The remotely measured soil moisture values have been compared to *in situ* soil moisture observations and predicted soil moisture values generated using hydrological and climate models. Numerous studies involving several spaceborne sensors have been performed at many frequencies in various locations around the globe.

Data gathered from Skylab's 1.4 GHz radiometer were compared to Scanning Multichannel Microwave Radiometer (SMMR) brightness temperatures (Wang, 1985). In 1988 6.6 GHz brightness temperatures recorded by the SMMR were correlated with soil moisture values (Choudhury and Golus, 1988). L band microwave (1.4 GHz) data gathered by the Pushbroom Microwave Radiometer (PBMR) have been used to make soil moisture maps (Wang, 1985). Soil moisture observations were collected over Southeastern Botswana using the 6.6 GHz channel on the SMMR (Owe et al., 1992). The sensitivity of the Special Sensor Microwave/Imager (SSM/I) channels to soil moisture, vegetation, and surface temperature has also been explored (Lakshmi, 1998; Choudhury et al., 1994). In 1995 the relationship between Antecedent Precipitation Index (API) and 6.6 GHz SMMR observed brightness temperatures was analyzed. The evidence showed that at 6.6 GHz, nighttime observations were more accurate and that vertical polarized microwave energy is less affected by vegetation (Ahmed, 1995). It was observed that at 19 GHz there is a nearly linear relationship between brightness temperatures and the soil moisture (Lakshmi et al., 1997). The hydraulic properties of the Little Washita watershed in Oklahoma were studied using the Electronically Scanned Thinned Array Radiometer (ESTAR) at 1.4 GHz (Mattikalli et al., 1998). Microwave observations from 6 to 18 GHz obtained by SMMR were used to observe land surface parameters over West Africa (Njoku and Li, 1999). Dual polarization passive microwave and multi-frequency (5–90 GHz) sensors were used to study vegetation and soil moisture in West

Africa (Magagi et al., 2000). TMI 10.65 GHz channel observations are being recorded with the long-term goal of developing a daily 4-year soil moisture pathfinder data set. This effort to utilize a remote sensing satellite platform to observe soil moisture conditions over an extensive period of time is the first of its kind (Bindlish et al., 2003).

3. Data and methods

3.1. Field site

The Little River Watershed is located in the Southern Coastal Plain region of Georgia with primarily loamy sand soil. The watershed encompasses 334 km² and the topography is generally flat with meandering streams (Fig. 1). The major land use is agricultural (36%) with forested land surrounding the riparian zones. The bulk of agricultural land is used for cotton, peanuts, and vegetables. Woodlands occupy 40% of the watershed and are dominated by pines interspersed with a few hardwoods (Bosch et al.,

1999). The USDA (United States Department of Agriculture) chose this site to represent the coastal plains regions of the North American East Coast (Sheridan, 1997).

3.2. Soil climate analysis network (SCAN) site

The National Weather and Climate Center (NWCC) have installed a weather station, known as a Soil Climate Analysis Network (SCAN) site, in Tifton (Paetzold and Schaefer, 2000). This site measures the air temperature, humidity, incoming radiation, rainfall, wind speed and barometric pressure, and also has soil moisture probes buried in the subsurface that can measure soil temperature, conductivity, salinity, and soil moisture. The probes are placed at depths of 5, 10, 20, 50, and 102 cm. Observations at the SCAN site are taken every half an hour and are available on the internet (<http://www.wcc.nrcs.usda.gov/scan/site.pl?sitenum=2027andstate=ga>).

3.3. Rain gauge probe sites

Beginning in the summer of 2001, placement of a series of stationary soil moisture probes began throughout the Little River Watershed in Tifton, Georgia. These probes were installed at 5, 20 and 30 cm depths at existing automated rain gauge sites with radio transmitter towers. Observations are taken every half an hour, and each observation contains data for soil moisture (buried capacitance probes), temperature, and conductance (Stevens Soil moisture Company, 1994: Please note that product names are provided for completeness in descriptions only and do not suggest endorsement by University of South Carolina or the United States Department of Agriculture). By the end of 2002, there were 11 fixed soil probe sites that were operational. There are plans to expand the network of probes throughout the watershed. The current probes have been placed in pastures, tilled soils, brush, and grassy fields with soil types including Tifton loamy sand, Dothan loamy sand, Fuquay loamy sand and Sunsweet loamy sand (Table 1). A complete listing of all the monthly averaged data gathered from the soil moisture probes, TMI 10.65 GHz sensors, MODIS 16-day average 500 m resolution normalized difference vegetation index (NDVI), SCAN soil moisture site, and rainfall

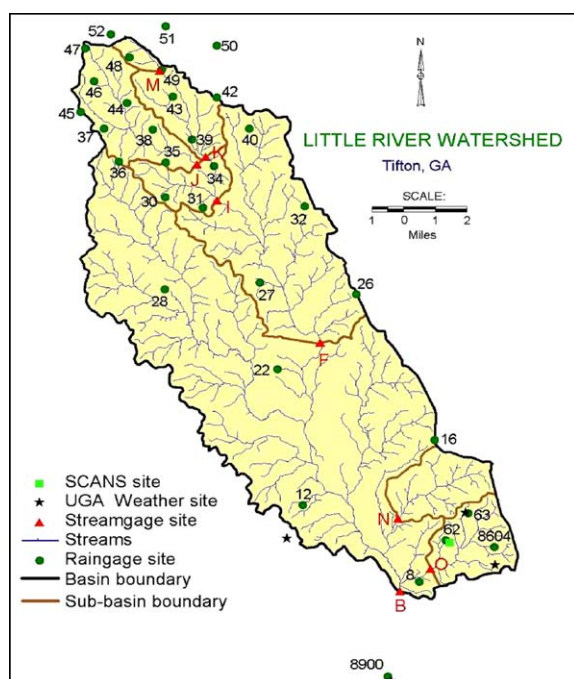


Fig. 1. Little River Watershed Tifton, Georgia.

Table 1
Rain gauge site numbers, activation dates, land use, and soil types

Site	Activation date	Land use	Soil type
SCAN Site	19-May-99	Grass	Dothan LS
Gibbs Farm	03-Mar-00	Tilled	Tifton LS
Station Z	02-Jul-02	Tilled	Cowarts LS
Bellflower Farm	26-Jun-02	Tilled	Dothan LS
RG 12	19-Oct-01	Pasture	Fuquay LS
RG 16	03-Jan-01	Grass	Tifton LS
RG 22	29-Oct-01	Brush	Tifton LS
RG 26	19-Dec-01	Pasture	Tifton LS
RG 31	12-Dec-01	Pasture	Tifton LS
RG 32	03-Jan-01	Grass	Tifton LS
RG 34	12-Dec-02	Pasture	Fuquay LS
RG 39	29-Jan-02	Pasture	Fuquay LS
RG 43	29-Jan-02	Field border	Tifton LS
RG 50	24-Jan-02	Pasture	Sunsweet GSL
RG 63	17-Oct-01	Grass	Fuquay LS

in the Little River Watershed (LRW) for 2002 is provided in Table 2.

3.4. TMI

The Tropical Rainfall Measurement Mission Microwave Imager (TMI) was launched in 1997. The original orbital altitude was 350 km. However, the TMI was boosted in August 2001 to a higher orbit of 402.5 km, and the original swath width of 780 km was increased by 15% to 897 km. TMI has an orbit that extends from 35°N to 35°S, limiting the amount of land area that is covered. This orbit is designed to keep the TMI over the tropics as much as possible. When the orbit is mapped out in two dimensions it resembles a sinusoidal wave. The sensors on board the TMI have nine channels, with frequencies as follows: 85.5 GHz HV (horizontal and vertical polarizations), 37 GHz HV, 21.3 GHz V, 19.4 GHz HV, and 10.7 GHz HV. These frequencies/channels are horizontally and vertically polarized, with the exception of the 21.3 GHz channel. The effective field of view (EFOV), or surface area that contributes to the remotely sensed data, varies for each wavelength; the EFOV increases as the size of the corresponding wavelength increases. Channels 1 and 2 (10.65 GHz V and H) have an EFOV of 63 km by 37 km; channels 3 and 4 (19.35 GHz V and H) have a EFOV of 30 km

by 18 km; channel 5 (21.3 GHz V) has an EFOV of 23 km by 18 km; channels 6 and 7 (37 GHz V and H) have a EFOV of 16 km by 9 km; and channels 8 and 9 (85.5 GHz V and H) have a EFOV of 7 km by 5 km. Channels 8 and 9 are also set to collect data at double resolution. Any data obtained within the coordinates 31.4°N to 31.7833°N and 83.3667°W to 83.8167°W corresponding to the LRW Tifton, Georgia were used in the calculations. The TMI completes an orbit every 91 min, making 15.7 orbits per day. Thus, the TMI overpasses Tifton at different local times each day, providing one to three overpasses over the LRW. The TRMM repeats its orbital cycle every 42 days, passing over the same spot at the same local time.

In this study, the polarization difference brightness temperature of the 10.65 GHz channels, viz., the difference of the vertical and the horizontal polarization brightness temperatures is used.

We have used monthly average data throughout this study. This is to minimize day-to-day variability. In addition, it is our aim to use results of this study for long-term monitoring in a ‘climate’ sense rather than instantaneous changes associated with daily variations. Monthly averaged data are more stable and hence easier to use.

The Little River Watershed is located in a relatively homogenous region with the area outside the watershed having similar land cover, cropping practices and soil types. Therefore, we were justified in using the TMI to study the variability of soil moisture over the smaller watershed.

4. Results

4.1. Analysis of data

The SCAN site data were downloaded from the NWCC website and then sorted so that only data points within a half an hour of a TMI overpass were retained (<http://www.wcc.nrcs.usda.gov/scan/site.pl?sitenum=2027andstate=ga>). Only the data from the 5 cm depth probe were used here, as any deeper soil moisture would have no effect on the 10.65 GHz polarization difference. Even though we have instantaneous, simultaneous observations from the *in situ* and satellite sensors, we however average up to a monthly time period. Daily/instantaneous data

Table 2

Monthly average data from all rain gauge site soil moisture probes (volumetric soil moisture), TMI (K), and the average rainfall (inches) within the LRW for 2002

Month	TMI (K)	NDVI	SCAN	RG 12	RG 16	RG 22	RG 26
Jan	11.51	0.652	0.097	0.1168	0.109	0.106	0.277
Feb	9.03	0.652	0.077	0.0896	0.136	0.090	0.268
Mar	11.77	0.665	0.091	0.1009	0.110	0.086	0.263
April	10.28	0.657	0.099	0.0866	0.120	0.068	0.277
May	9.13	0.669	0.064	0.0500	0.043	0.032	0.125
June	8.52	0.698	0.030	0.0485	0.046	0.067	0.179
July	6.62	0.755	0.059		0.073	0.068	0.242
Aug	5.47	0.752	0.053	0.0260	0.050	0.047	0.217
Sept	6.40	0.732	0.083	0.0809	0.106	0.084	0.247
Oct	8.29	0.723	0.094	0.0918	0.141	0.106	0.345
Nov	9.01	0.699	0.100	0.1054	0.157	0.102	0.414
Dec	11.96	0.651	0.097	0.1213	0.148	0.122	0.392
Month	Rain (in.)	RG 31	RG 32	RG 34	RG 43	RG 50	RG 63
Jan	0.40	0.074	0.094	0.116			0.184
Feb	0.80	0.086	0.112	0.089	0.011	0.136	0.174
Mar	4.84	0.123	0.098	0.100	0.025	0.149	0.223
April	4.84	0.092	0.085	0.086	0.018	0.118	0.189
May	2.44	0.042	0.035	0.050	0.007	0.060	0.100
June	2.53	0.043	0.046	0.048	0.010	0.059	0.075
July	0.60	0.119	0.079		0.008	0.101	0.090
Aug	2.61	0.039	0.034	0.026	0.009	0.072	0.068
Sept	2.40	0.102	0.054	0.080	0.014	0.109	0.068
Oct	6.46	0.151	0.104	0.091	0.037	0.142	0.227
Nov	5.19	0.162	0.142	0.105	0.028	0.142	0.313
Dec	3.87	0.107	0.142	0.128	0.038	0.146	0.322

exhibits greater range of fluctuations which are not of interest to this study as we attempt to deal with the seasonal/climatic variability. A comparison of the probes at each depth was carried out, the results showed a near constant vertical profile of soil moisture. The SCAN site became operational in 1999; therefore the comparison of the data set starts at that time. Unfortunately, the soil surrounding the soil moisture probes collapsed in late 1999, leaving the probes partly exposed and slanted; in order to function properly the probes need to be completely buried in the soil layer. The SCAN site was not repaired until early 2000. The observations during the time when the probes were exposed varied from very high (nearly 100% water by volume) to absolute zero.

The rain gauge based soil moisture probes became operational in early 2002. Only data from the 5 cm depth probes were used, as with the SCAN site only readings taken within a half an hour of a TMI overpass were retained. (This is to ensure almost simultaneous

observations by the *in situ* probes and the TMI satellite sensor.) All of the volumetric soil moisture values were then averaged together and an average monthly value was calculated. The average monthly soil moisture probe readings were further averaged with the monthly average SCAN site reading to create a new variable labeled SCANall (Figs. 2 and 3). Fig. 2 illustrates in detail the TMI, MODIS, rainfall, and SCANall observations for the LRW in 2002. All of the data sets follow the same seasonal cycle of high at the beginning and end of the year with a decline during the middle, except the NDVI data set which follows an inverted pattern. When a linear regression of the SCAN site verses the soil moisture probes were calculated a high R^2 value of 0.7072 was found, indicating that there is a strong relationship between the observations of the SCAN site and the average observations of the soil moisture probes (Fig. 3). This high correlation validates the use of the SCAN site as a stand alone soil moisture gauge for the entire LRW

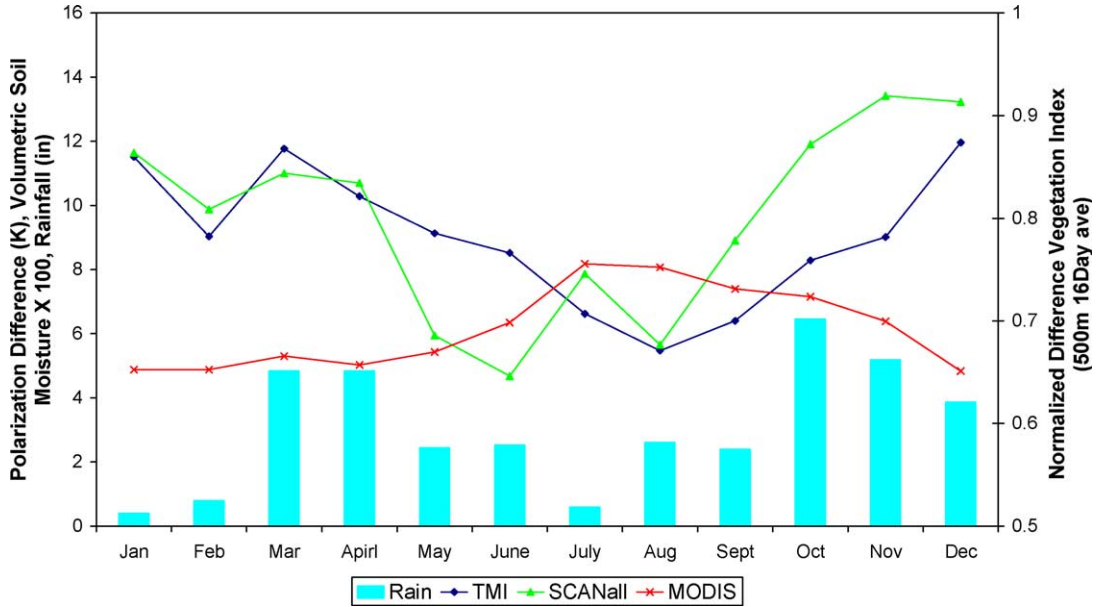


Fig. 2. Comparison of TMI 10.65 GHz polarization difference, average soil moisture based on SCAN site and all soil moisture probes, and the rainfall observed by the SCAN site for the year 2002.

for the years prior to the soil moisture probes installation.

Seasonal variations of the precipitation, vegetation, SCAN site soil moisture, and TMI 10.65 GHz polarization difference for the LRW are illustrated in Fig. 4. The TMI data follows the soil moisture observations, excluding the fall months, with a range of 8K (14–6K). A maximum polarization difference was recorded in the spring of both 2000 and 2001 at 14K. Conversely, a minimum value of 6K can be seen during the fall of every year on record. The faulty soil probe data is marked by the abnormally low soil moisture values starting in the 8th month of 1999 and continuing until the 5th month of 2000. The data points from these months were eliminated from the final analysis. The resulting regression lines for 2000–2002 are shown in Fig. 5. It can be seen that as the soil moisture increases the corresponding polarization differences also increase. There is however an exception for year 2000 wherein the polarization difference decreases with increase in soil moisture. On examination of the time series of soil moisture, precipitation and polarization difference, it is seen that the largest increases in soil moisture correspond to the months with high vegetation cover. As a result

the polarization difference decreases due to attenuation by the vegetation canopy even though the soil moisture has increased. Even though this is generally true in the region for any particular year, i.e. vegetation cover is maximum for the summer months corresponding to high soil moisture, in the other years (viz., 2001, 2002), there is large soil moistures and corresponding large polarization differences for the low vegetation cover (i.e. winter months, i.e. January–March and October–December) as well. A similar relationship can be seen in the latter half of 2001, and to a far lesser extent in the fall months of

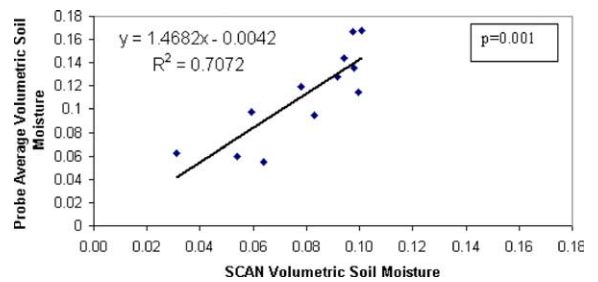


Fig. 3. Regression of the SCAN site and the average of all the soil moisture probes. This graph shows that the monthly average SCAN site is representative of the LRW monthly average soil moisture conditions in 2002.

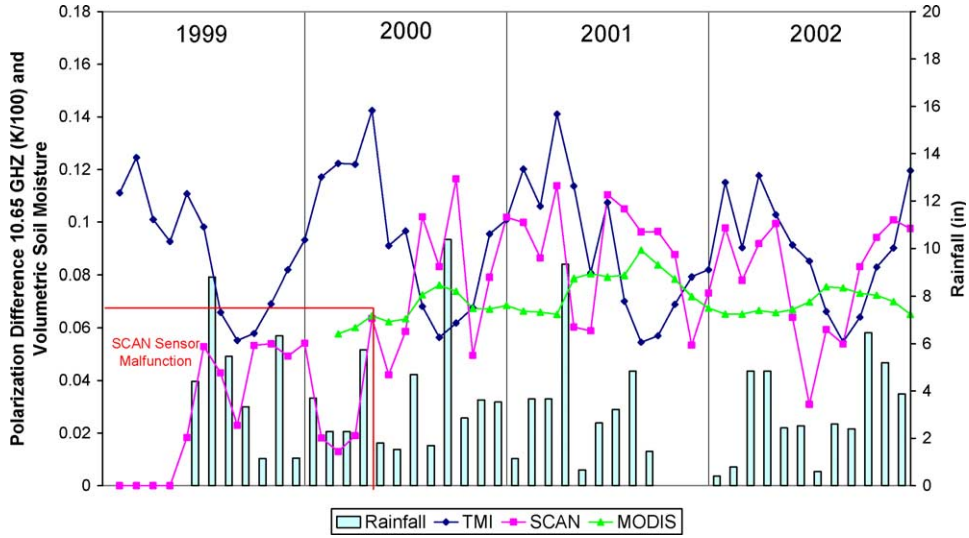


Fig. 4. Monthly average TMI polarization difference, soil moisture, NDVI and precipitation from the LRW in Tifton, GA.

2002. The linear regression for 2000 is by necessity based only on the final months of the year (months that were thrown out due to inaccuracies caused by vegetation) if data for the whole year were available the resulting linear regression might more closely match the results for the subsequent two years.

NDVI vegetation density estimations are based on a simple ratio of red and infrared light (Tucker, 1979). The NDVI data used in this paper were obtained from

the MODIS and are 16-day average 500 m resolution product (<http://edcimswww.cr.usgs.gov/pub/imswelcome/>). These NDVI observations were averaged over an area based on the TMI sampling box, which contains the entire Little River watershed and some of the area immediately surrounding it. Fig. 6 is a linear regression of volumetric soil moisture vs. NDVI; the low R^2 value of 0.125 indicates that there is little or no relationship between vegetation levels and the soil

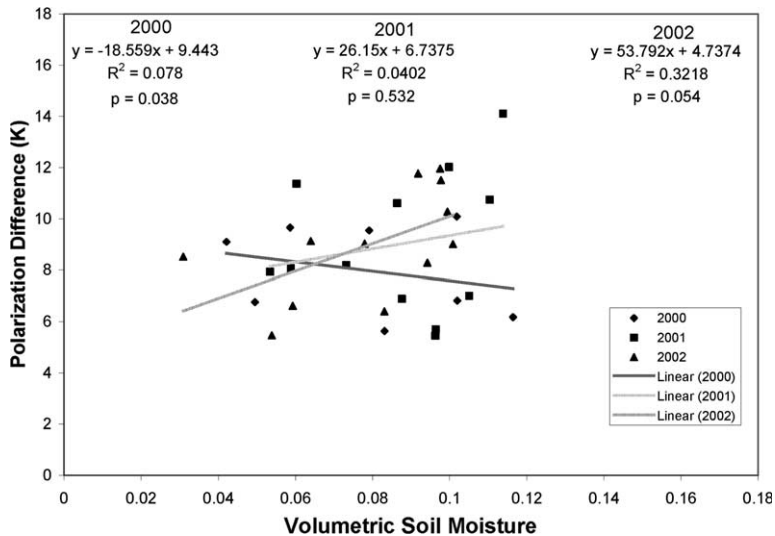


Fig. 5. Regression between monthly average polarization difference and *in situ* soil moisture for the years 2000, 2001, and 2002.

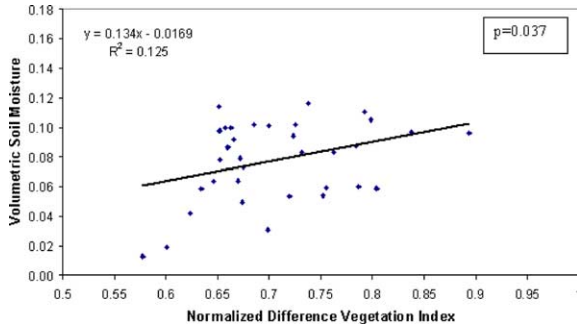


Fig. 6. The low correlation between the SCAN site VSM observation and MODIS NDVI show that there is no significant relationship between vegetation and soil moisture.

moisture in this region. Fig. 7 is a plot of the linear regression of polarization difference vs. NDVI. This function has an R^2 value of 0.4333, indicating that there is a strong relationship between the level of vegetation and the corresponding TMI polarization difference observation. The lower NDVI values observed during the winter months were assumed to represent mostly fallow fields surrounded by pine forests. The mild winter conditions and high abundance of evergreens in the watershed implies that there should be a background amount of green vegetation throughout the year. The rise in NDVI values in the spring and summer months are thus attributed to agriculture.

4.2. Interpretation of time series

The observed monthly values of the 10.65 GHz polarization difference brightness temperature and

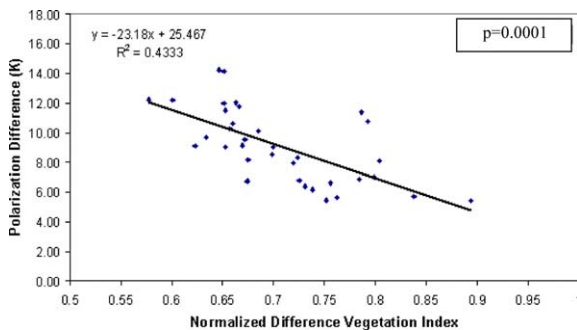


Fig. 7. The high correlation between NDVI and the TMI observed polarization difference shows that there is an inverse relationship between vegetation density and polarization difference.

soil moisture display a seasonal cycle. The polarization difference typically peaks early in the year and drops off during the summer months, only to rise once more in the winter. Whereas the soil moisture observations follow a similar but more dynamic pattern that varies especially in the fall of every recorded year. Overall the seasonal patterns match up for most of the year. However, as the level of vegetation increases; as indicated by the NDVI values; the TMI readings begin to show less correlation to the soil moisture. When the NDVI values were compared to the corresponding polarization difference and soil moisture values it was found that higher levels of NDVI lowered the resulting TMI readings (Figs. 6 and 7). In essence the vegetative canopy shielded the soil moisture observations from the TMI, lowering the accuracy of the soil moisture prediction. This phenomenon is expected based upon microwave radiative transfer theory. Thus, during several months of each year, the TMI polarization difference is almost exclusively the product of vegetation and not soil moisture.

In 2002 a relatively higher correlation between the remotely sensed TMI data and the observed *in situ* volumetric soil moisture was found (Fig. 5). The other two years showed little relationship between the variables and in 2000 the slope of the line was negative. When the months with high vegetation levels were removed (July through October) the regression line R^2 values increased to 0.4454 (Fig. 8a). Examination of the high vegetation density months of July–October (Fig. 8b) shows a greatly reduced sensitivity (slope of the line is 4.9 versus 50.1 in Fig. 8a) as well as little correlation (0.161 vs. 0.45). Fig. 7 shows the linear relationship between the TMI polarization difference and the MODIS NDVI readings had an R^2 value of 0.4333. To further investigate the affect of vegetation on the TMI observations, correlations between the TMI and NDVI observations were made when vegetation was high (NDVI of more than 0.7) and when vegetation was low (Fig. 9). The relatively higher level of correlation between TMI polarization difference and the NDVI when vegetation levels were low compared to high shows that as the level of vegetation increased the TMI soil moisture observations are increasingly inaccurate. Furthermore, Fig. 6 shows that there is little correlation between NDVI and the soil moisture.

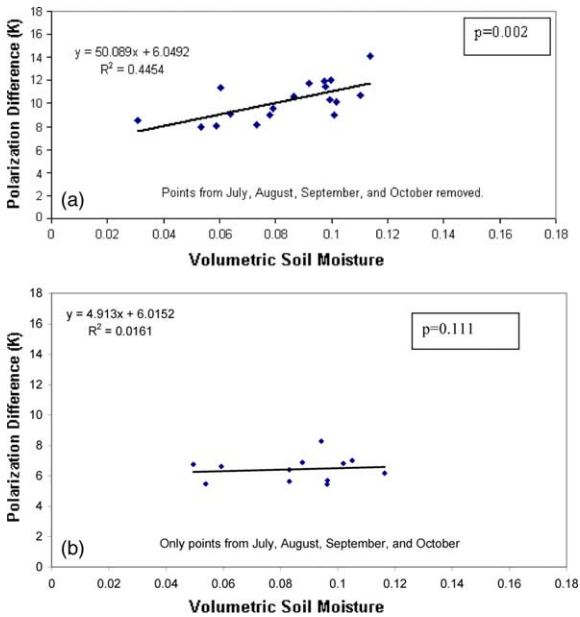


Fig. 8. (a) Regression of monthly average polarization differences and *in situ* soil moisture minus data from the months of July, August, September, and October. (b) Regression of monthly average polarization differences and *in situ* soil moisture for the months of July, August, September, and October.

It was found that the TMI tended to overestimate soil moisture at the beginning and end of the year, and underestimate soil moisture during the middle of the year. In order to explain this pattern of error and

reduce its affects, an NDVI dataset was compiled (Table 3). The multi-linear regression of the average monthly soil moisture, polarization difference, and NDVI had an R^2 value of 0.337 with a p value of 0.158 (Table 3). Thus, when vegetation levels were high the TMI observations are based primarily on vegetation water content, where as when there was less vegetation the TMI was able to observe the soil moisture signal. Ultimately, the best fit line was found by normalizing the TMI signal against the NDVI values (Eq. (1))

$$VSM = -0.102 + 0.00849 \times TMI + 0.151 \times NDVI \quad (1)$$

where VSM is the SCAN site volumetric soil moisture (expressed as percent), TMI is 10.65 GHz polarization difference, and NDVI is the MODIS 16 day 500 m average (R^2 equal to 0.337, $p=0.158$).

The data used to generate Eq. (1) can be found in Table 3. The level of correlation between polarization difference and soil moisture increased slightly when vegetation conditions were taken into account, but the confidence level was reduced. This equation describes the dependence of polarization difference brightness temperature on vegetation index and volumetric soil moisture. This is used in a purely diagnostic mode without any attempt for predictive purposes.

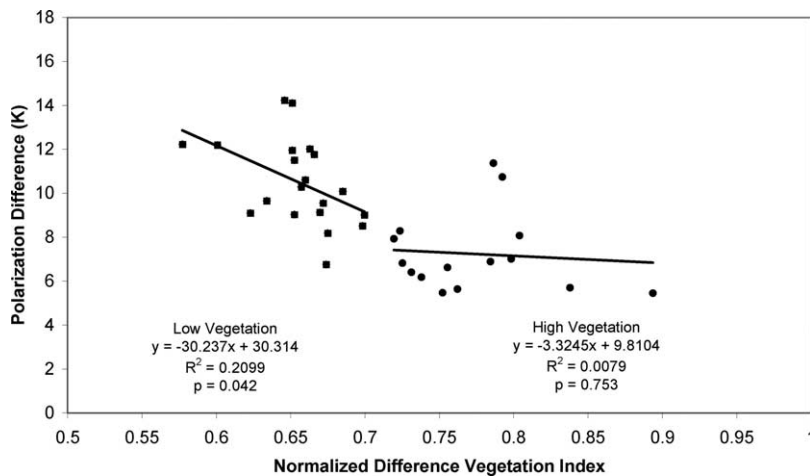


Fig. 9. The regression line labeled low vegetation was calculated using only months that had NDVI values of less than 0.7. The regression line labeled high vegetation was calculated based only on months that had an NDVI value of greater than 0.7. It can be seen that as the NDVI values increase the polarization difference starts to level off at around 7K.

Table 3

Monthly average multi-linear regression data relating the polarization difference from TMI (K), SCAN site and other rain gauge site volumetric soil moistures (percentage) to the MODIS NDVI

Polarization difference (K)	Volumetric soil moisture (%)	NDVI
TMI	SCANall	MODIS
11.51	11.645	0.652
9.03	9.877	0.652
11.77	11.004	0.665
10.28	10.695	0.657
9.13	5.941	0.669
8.52	4.679	0.698
6.62	7.864	0.755
5.46	5.655	0.752
6.40	8.906	0.731
8.28	11.906	0.723
9.01	13.415	0.699
11.96	13.229	0.651

5. Conclusions and discussions

It was shown in the previous section that there is a relation between polarization difference and volumetric soil moisture. However, during months of high vegetation (NDVI value of over 0.7), the TMI was not sensitive to the soil moisture conditions. When data points from July through October were removed, the R^2 value of a linear relationship increased to 0.4454 (Figs. 5 and 8). This exercise emphasizes two main issues, first the TMI polarization difference responds to variations in soil moisture and secondly that vegetation can mask this response. There appears to be an NDVI threshold of 0.7, over which the soil moisture signal is masked from the TMI 10.65 GHz channel.

In the past rain gauge and stream gauge readings were the only constant source of hydrologic data that could be used to predict soil moisture. When a comparison of the correlation between monthly rainfall and the monthly average soil moisture was carried out, it was found that there was virtually no relationship. This implies that the remotely sensed data is a better indicator of the near surface soil moisture conditions than the monthly *in situ* rainfall measurements (Figs. 2 and 4). However, the LRW, unlike most watersheds, has a well-established network of rain gauges that provide updated rainfall information every half an hour. In areas that are observed with this level of rainfall data it should be

possible to predict the resulting soil moisture using a model. In ungauged watersheds the TMI can provide an additional source of soil moisture observations.

The high conductivity of the sandy soils in the research area must be taken into account. With the 5 cm soil moisture probe measurements only taken every half an hour, rain events could be missed, or only captured in a few data points. Additionally, much of the cropland in Tifton is irrigated. Water from irrigation systems is not accounted for by either the rain gauges or soil moisture probes. The TMI sensor observing the watershed as a whole is affected by water from irrigation systems. In this soil type more frequent sampling both by the *in situ* probes and the satellite system is needed to better understand the dynamics of the hydrologic cycle within the LRW. However, the strength of the TMI is its ability to observe vast land areas around the globe on a monthly basis. Most importantly, the results show that it is feasible to use a satellite system to detect the soil moisture changes in Tifton, Georgia during most of the year.

The equation of the line generated from the multi-linear regression of NDVI, TMI 10.65 GHz polarization difference, and soil moisture is expressed in Eq. (1). It is hoped that with additional data an equation of this type can be developed that can be used to improve the TMI's ability to estimate the soil moisture signature through vegetation. Attempts to improve the accuracy of the TMI soil moisture observations using Eq. (1) yielded only a slight improvement in accuracy. The combined data set from the SCAN site, TMI, and MODIS show that there is a relationship between soil moisture, vegetation, and polarization brightness temperature. The affects of vegetation on the polarization brightness temperature are evident when the values are compared to the NDVI values. The vegetation acts as a mask that prevents the TMI 10.65 GHz channel from sensing the soil moisture conditions on the ground. Herein lies the primary difficulty with current passive microwave remote sensing technology; large amounts of ground data are needed to accurately calibrate the measurements. Measurements taken by the satellite without ground based data and/or remotely sensed NDVI values cannot be considered highly accurate. Currently, a four-year daily record of TMI soil moisture observations is being compiled, all of the data used within this paper were based on monthly averages (Bindlish et al., 2003).

The resulting relationships between soil moisture, NDVI, and observed microwave brightness temperature reinforce those findings. The relatively high levels of vegetation in the LRW present both a challenge and an opportunity to explore the ability of this technology to function in the south-eastern region of the United States of America. It is hoped that this paper will help support future work done in the field of passive microwave remote sensing.

The use of TMI alone would not result in an adequate product for soil monitoring in vast land areas. However, a combination of TMI and the AMSR (Advanced Microwave Scanning Radiometer) current in orbit onboard the AQUA satellite and the vegetation data from MODIS (Moderate Resolution Imaging Spectroradiometer) may accomplish this task. The 6.6 GHz (C-band channel) of the AMSR suffers from radio frequency interference (RFI) and the use of TMI data (in the tropics) to supplement the AMSR 10 GHz X band with temporally frequent observations would help in (a) RFI mitigation and (b) greater temporal frequency of observations. It is our hope that the algorithms developed by using the 4-years and more of the TMI X-band data set will establish a basis for utilization of AMSR data which will lead to L-band sensors (HYDROS, SMOS) in the future.

The use of remotely sensed data to predict soil moisture is an emerging technology that shows promise. This technology is still in its infancy and has several hurdles still to overcome. The bulk of the data currently being used is from systems that were not originally designed to detect soil moisture. The promising results of many of these projects should help provide support and funding for new satellite systems. The addition of new satellite platforms with better resolution and lower gigahertz frequency channels should help to improve the quality and resolution of the data. The recently launched AMSR has a 6 GHz channel that is hoped will provide better quality soil moisture measurements to date.

References

- Ahmed, N.U., 1995. Estimating soil moisture from 6.6 GHz dual polarization, and/or satellite derived vegetation index. *Int. J. Remote Sensing* 16, 687–708.
- Bindlish, R., Jackson, T.J., Wood, E., Huilin, G., Starks, P., Bosch, D., Lakshmi, V., 2003. Soil moisture estimates from TRMM Microwave Imager observations over the Southern United States. *Remote Sensing Environ.* 85, 507–515.
- Bosch, D.D., Davis, F.M., Sheridan, J.M., 1999. Rainfall characteristics and special correlation for the Georgia coastal plain. *Trans. ASAE* 42 (6), 1637–1644.
- Choudhury, B.J., Golus, R.E., 1988. Estimating soil wetness using satellite data. *Int. J. Remote Sensing* 9, 1251–1257.
- Choudhury, B.J., Tucker, C.J., Golus, R.E., Newcombe, W.W., 1994. Monitoring vegetation using Nimbus-7 scanning multi-channel microwave radiometer's data. *Int. J. Remote Sensing* 8, 225–239.
- Earth Observing System Data Gateway (n.d.). Retrieved from <http://edcimswww.cr.usgs.gov/pub/imswelcome/>
- Guha, A., Lakshmi, L., 2002. Sensitivity, spatial heterogeneity, and scaling of C-Band microwave brightness temperatures for land hydrology studies. *IEEE Trans. Geosci. Remote Sensing* 40 (12), 2626–2635.
- Jackson, T.J., 1993. Measuring surface soil moisture using passive microwave remote sensing. *Hydrol. Process.* 7, 139–152.
- Jackson, T.J., Schmugge, T.J., 1989. Passive microwave remote sensing system for soil moisture: some supporting research. *IEEE Trans. Geosci. Remote Sensing* 27, 225–235.
- Jackson, T.J., Schmugge, T.J., 1996. Remote sensing applications to hydrology: soil moisture. *Hydrolog. Sci.* 41, 517–530.
- Lakshmi, V., 1998. Special sensor microwave imager data in field experiments: FIFE-1987. *Int. J. Remote Sensing* 19, 481–505.
- Lakshmi, V., Wood, E.F., Choudhury, B.J., 1997. Evaluation of special sensor microwave/imager satellite data for regional soil moisture estimation over the Red river basin. *J. Appl. Meteorol.* 36, 1309–1328.
- Magagi, R.D., Kerr, Y.H., Meunier, J.C., 2000. Results of combining L and C band passive microwave airborne data over Sabelian area. *IEEE Trans. Geosci. Remote Sensing* 38, 1997–2008.
- Mattikalli, N., Enman, E.T., Ahuja, L., Jackson, T.J., 1998. Microwave remote sensing of soil moisture for estimation of profile soil property. *Int. J. Remote Sensing* 19, 1751–1767.
- Njoku, E.G., Li, Li, 1999. Retrieval of land surface parameters using passive microwave measurements at 6–18 GHz. *IEEE Trans. Geosci. Remote Sensing* 37, 79–93.
- Owe, M., Van de Griend, A.A., Chang, A.T.C., 1992. Surface soil moisture and satellite passive microwave observations in semi-arid Southern Africa. *Water Resour. Res.* 28 (3), 829–839.
- Paetzold, R.F., Schaefer, G.L., SNOTEL (SNOWpack TELEmetry) and SCAN (Soil Climate Analysis Network) automated weather stations for applications in agriculture and water resources management: current use and future perspectives, Lincoln, Nebraska (March 2000). Retrieved from <ftp://ftp.wcc.nrcs.usda.gov/downloads/factpub/SNOTEL-SCAN.pdf>
- Rawls, W.J., Barkensiek, D.L., Saxton, K.E., 1982. Estimation of soil properties. *Trans. ASAE* 25 (5), 1316–1320.

- SCAN site Information for Little River in the state of Georgia. (n.d.) Retrieved 2-Sept-2003 from <http://www.wcc.nrcs.usda.gov/scan/site.pl?sitenum=2027andstate=ga>
- Schmugge, T., 1985. Remote sensing of soil moisture. In: Anderson, M.G., Burt, T.P. (Eds.), *Hydrological Forecasting*. Wiley, New York, pp. 101–124.
- Schmugge, T.J., Kustas, M.P., Ritchie, J.C., Jackson, T.J., Rango, A., 2002. Remote sensing in hydrology. *Adv. Water Resour.* 25, 1367–1385.
- Sheridan, J.M., 1997. Rainfall-streamflow relations for coastal plain watersheds. *Am. Soc. Agri. Engrn* 13 (3), 333–334.
- Stevens Soil moisture Company. *Hydra Soil Moisture Probe User's Manual*. Version 1.2P/N92915REV A. Chantilly, VA, June 1994.
- Tucker, C.J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing Environ.* 8, 127–150.
- Wang, J.R., 1985. Effect of vegetation on soil moisture sensing observed from orbiting microwave radiometers. *Remote Sensing Environ.* 17, 141–151.
- Wang, J.R., Schmugge, T.J., 1980. An empirical model for the complex dielectric permittivity of soils as a function of water content. *IEEE Trans. Geosci. Remote Sensing GE-18* (4), 288–295.
- Wang, J.R., Shiue, J.C., Schmugge, T.J., Engman, E.T., 1990. The L-band PBMR measurements of surface soil moisture in FIRE. *IEEE Trans. Geosci. Remote Sensing GE-28*, 906–914.
- Zhan, X., Miller, S., Chauhan, N., Di, L., Ardanuy, P., 2002. *Soil moisture: visible/infrared imager/radiometer suite algorithm theoretical basis document*. Raytheon Systems Company, Maryland, Version 5, March 2002.