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Temporal persistence and stability of surface soil moisture in a semi-arid watershed

Michael H. Cosh [a,*], Thomas J. Jackson [a], Susan Moran [b], Rajat Bindlish [c]

[a] USDA-ARS Hydrology and Remote Laboratory, Beltsville, MD 20705, United States
[b] USDA-ARS Southwest Watershed Research Center, Tucson, AZ 85719, United States
[c] SSAI, Lanham, MD 20706, United States

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Abstract

Satellite soil moisture products, such as those from Advanced Microwave Scanning Radiometer (AMSR), require diverse landscapes for validation. Semi-arid landscapes present a particular challenge to satellite remote sensing validation using traditional techniques because of the high spatial variability and potentially rapid rates of temporal change in moisture conditions. In this study, temporal stability analysis and spatial sampling techniques are used to investigate the representativeness of ground observations at satellite scale soil moisture in a semi-arid watershed for a long study period (March 1, 2002 to September 13, 2005). The watershed utilized, the Walnut Gulch Experimental Watershed, has a dense network of 19 soil moisture sensors, distributed over a 150 km^2 study region. In conjunction with this monitoring network, intensive gravimetric soil moisture sampling conducted as part of the Soil Moisture Experiment in 2004 (SMEX04), contributed to the calibration of the network for large-scale estimation during the North American Monsoon System (NAMS). The sensor network is shown to be an excellent estimator of the watershed average with an accuracy of approximately 0.01 m^3/m^3 soil moisture. However, temporal stability analysis indicated that while much of the network is stable, the soil moisture spatial pattern, as represented by mean relative difference, is not replicated by the network mean relative difference pattern. Rather, the network is composed of statistical samples. Geophysical aspects of the watershed, including topography and soil type are also examined for their influence on the soil moisture variability and stability. Soil type, as characterized by bulk density, clay and sand content, was responsible for nearly 50% of the temporal stability. Topographic effects were less important in defining representativeness and stability.

Keywords: Soil moisture; Temporal stability; Satellite remote sensing; Dielectric measurements; Rock fraction

1. Introduction

Soil moisture research has accelerated in recent years with the launch of several satellite instruments, which measure the surface layer of the soil. These instrument's include Aqua's Advanced Microwave Scanning Radiometer (AMSR-E) (Njoku et al., 2003) and the Tropical Rainfall Measuring Mission's (TRMM) Microwave Imager (Bindlish et al., 2003) as well as the upcoming Soil Moisture and Ocean Salinity (SMOS) (Kerr et al., 2001) mission. As a part of the calibration and validation protocols for these instruments, ground data and modeling are necessary to insure accurate measurements. Field campaigns and in situ networks are two methods of providing such data, however, the expense and limited conditions observed by field campaigns necessitate the construction of in situ networks to provide more robust calibration and validation. Installing large-scale networks in a variety of landscapes will aid in the development of a satellite soil moisture program.

Determining soil moisture at large scales is difficult because of the variability at the surface. Famiglietti et al. (1999) showed how soil moisture varies significantly from small scales (<10 m) to field scale and larger (>1 km). Warrick et al. (1977) concluded that accurate estimates of large-scale soil moisture could be obtained using point observations. Point observations are expensive, since it demands extensive sampling over long time periods (Kachanoski & De Jong, 1988; Martinez-Fernandez & Ceballos, 2003; Vinnikov et al., 1999). Any reduction in the number of sampling points while still accurately estimating the large scale average would be beneficial. Geostatistics could be the

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[*] Corresponding author.
E-mail address: Michael.Cosh@ars.usda.gov (M.H. Cosh).

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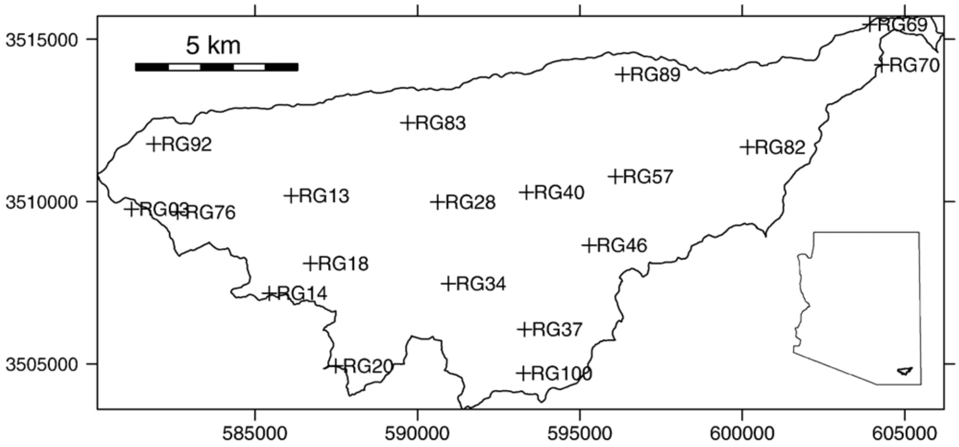

Fig. 1. The Walnut Gulch Experimental Watershed, which contains 19 surface soil moisture sensors.

basis of one strategy. For example, the spatial correlation can be incorporated by kriging (Delhomme, 1979) or semivariogram analysis (Cosh & Brutsaert, 1999), but this also requires a dense sampling network to adequately portray the correlation patterns within the study region. The sampling locations also need to be distributed across different land surface, soils and metrological domains to capture different functional relationships.

Vachaud et al. (1985) developed the concept of temporal stability as a tool in efficiently sampling a sparsely instrumented region. This method identifies stable measurement sites that predict the large-scale average over long time scales. They studied a 2000 m^2 grass field in Grenoble France for a 3-year period. Kachanoski and de Jong (1988) considered the scale dependency of 720-m transect. Cosh et al. (2004a) extended this idea to a larger network (~25 km) in the Walnut Creek agricultural watershed in central Iowa.

Cosh et al. (2004a) was for only a few months in duration, and it was concluded that a longer study period was necessary to capture possible changes in the spatial pattern due to seasonality and remove the influence of short-term weather patterns. In another investigation in Chickasha, Oklahoma, Cosh et al. (2006) extended the period of study for a soil moisture network and coupled it with a local field experiment that would provide an accurate snapshot of the overall soil moisture field. Unfortunately, the time of study was during an unusually dry summer resulting in a narrow range of values for validation. Each of these studies also addressed soil moisture stability in arable land with significant amounts of precipitation. Semi-arid and arid regions are yet to be studied and often these studies are for short durations and do not consider a long-term network. Soil moisture temporal stability in a semi-arid watershed holds key differences from previous studies because of the low average soil moistures and seasonality of precipitation.

This study extends the length of time used in a temporal stability study for a soil moisture network and couples the analysis with an intense field experiment to validate the network soil moisture measurements during the rainy season in a semi-arid watershed. Temporal stability analysis and correlation analysis will be used to examine a 3.5-year study period (March 1, 2002 to September 13, 2005) of the Walnut Gulch Experimental Watershed (WGEW) in southeastern Arizona. The dramatic variations in temporal and spatial variability of surface soil moisture make semi-arid regions difficult to quantify with traditional short-term investigations. In addition, regression analysis will be used to estimate the contribution of various land surface parameters such as soil type, rock fraction, and topography to the temporal stability and representative character of the network in an effort to identify time stability indicators. Lastly, the network average will be compared to satellite data to determine if there are relationships between space-borne sensors and in situ data.

2. Study region

Walnut Gulch watershed is a semi-arid region in southeastern Arizona that has been hydrologically monitored since 1954. The watershed is located around the historic town of Tombstone featuring an ephemeral tributary of the San Pedro River. The soil moisture sensor network is distributed uniformly across the 150 km^2 watershed (Fig. 1). The dominant land use is rangeland with vegetation varying from shrubs to grasses. In addition to numerous flumes and raingages, 21 soil moisture sensors (Stevens Hydra Probes[1]) have been recording surface soil moisture and soil temperature since 2002 as part of a program to calibrate and validate satellite estimated soil moisture. Of these 21 sensors (identified as RG## for the raingage that they are located near), 19 are located within the watershed, while two are in the outlying region and are not considered in the remainder of the study. These sensors are installed horizontally at 5 cm with a sensing range of 3–7 cm from the surface and record hourly instantaneous data. The period of study available for the current investigation is from March 1, 2002 to September 13, 2005. The majority of the precipitation in this watershed occurs during the late summer months, during the North American Monsoon season. The study also includes the Walnut Gulch Soil Climate Analysis Network (SCAN) station. This station (Water Climate Center Staff, 2005) has a variety of meteorological and hydrological sensors including a Hydra probe soil moisture sensor at 5 cm. Because

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[1] Mention of this product does not constitute an endorsement.

of the close proximity of the SCAN station to RG83, the SCAN data are not used in the calculation of any averages or statistics, but is included to provide some comparison.

In August of 2004, the Soil Moisture Experiment (SMEX04) was conducted in cooperation with the North American Monsoon Experiment (NAME) (Gutzler et al., 2005). NAME was organized to study the North American Monsoon System (NAMS) that controls the precipitation cycle for much of the interior and southwestern United States (Gochis et al., 2003). Intensive aircraft surveys and ground truth sampling was organized and executed throughout the summer of 2004 to measure the hydrologic state at a high temporal resolution. In order to explore the contributions of the land surface interactions in NAMS, intensive soil moisture investigations were conducted in southeastern Arizona (USA) and northern Sonora (Mexico). These included an aircraft campaign was organized to study the spatial distribution of surface soil moisture using the Polarimetric Scanning Radiometer (PSR) operated by the NOAA Environmental Technology Laboratory and a large-scale ground validation campaign in the Walnut Gulch Experimental Watershed (WGEW). Point samples of surface soil moisture, both gravimetric and dielectric, were collected at the watershed scale (64 samples over 25 km by 10 km) and the regional scale (40 samples over 50 km by 75 km) between 11am and 3pm (MST) each day to coincide with aircraft overflights and satellite overpasses. These samples are considered 'transient' because they do not sample the exact same soil volume from one day to the next day as is the case with in situ sensors. These will be subject to small-scale variability (Famiglietti et al., 1999). This data provides a basis for evaluating both the quality of the in situ network calibration and its spatial representation. Five dielectric probe samples were also taken at each of the 64 sites. In a manner similar to Cosh et al. (2005), the dielectric probes were calibrated using the co-located gravimetric samples to create a site-specific calibration equation for volumetric soil moisture (VSM). From the Gravimetric Soil Moisture, in g/g, the (Gravimetrically-based) Volumetric Soil Moisture of the Sample ($\mathrm{GVSM_{SAMP}}$) is calculated with

$$\mathrm{GVSM_{SAMP}} = \mathrm{GSM}{*}\mathrm{BD_{SAMP}} \tag{1}$$

where $\mathrm{BD_{SAMP}}$ is the bulk density of the sample volume. Volumetric soil moisture is the most common form of soil moisture used in modeling and remote sensing because it is the most easily measured using aircraft and satellite sensors. Field samples of bulk density and volumetric rock fraction, $\mathrm{RF_{SAMP}}$, were taken independently near the raingages and soil moisture sampling sites while making sure not to disturb the installations. One of the 5 dielectric soil moisture samples, θ, was taken at the exact same location as the gravimetric sample. This concurrent observation was used to calibrate other dielectric observations using the following equation

$$\theta = \frac{[1.07 + 6.4V - 6.4V^2 + 4.7V^3] - a_0}{a_1} \tag{2}$$

where V is the voltage reading from the probe, and a_0 and a_1 are calibration constants, the root mean square error between the $\mathrm{GVSM_{SAMP}}$ and θ is minimized by changing a_0 and a_1 (Delta-T Devices Ltd., 1999). The overall root mean square error (RMSE) associated with the calibration for the WGEW dielectric probe sampling as compared to the gravimetric sampling was 0.024 $\mathrm{m^3/m^3}$. The WGEW presents a new challenge, because of the large amount of surface rock in the study region and throughout southeastern Arizona. To address this a new method of rock fraction correction will be introduced.

3. Rock fraction

There is a degree of bias in the location of ground sampling, because of the presence of a large amount of rock at the surface. Samples were generally taken at locations with fewer surface rocks. This sample represents the soil (plus small rocks) rock fraction. However, for remote sensing and grid based modeling, the volumetric moisture of the surface layer is required. A procedure was developed for converting the point observations, which is referred to as the Rock Fraction Correction (RFC).

The bulk density (and volumetric rock fraction) samples were approximately 300 $\mathrm{cm^3}$ in volume, which is comparable to the ground sampling protocols for soil moisture (100 $\mathrm{cm^3}$). During SMEX04, surface volumetric rock fraction was measured for each sampling location in the study, defined as percentage volume not passing a no. 10 sieve (2 mm). There is a need to 'correct' this ground sample to a large-scale estimate, which would incorporate a more accurate rock fraction. The first step in this correction is to calculate the volumetric soil moisture of the soil only, $\mathrm{GVSM_{SOIL}}$. This is accomplished by using the volumetric rock fraction of the sample at the surface, $\mathrm{RF_{SAMP}}$, with

$$\mathrm{GVSM_{SAMP}} = \mathrm{GVSM_{SOIL}}{*}(1 - \mathrm{RF_{SAMP}}). \tag{3}$$

The $\mathrm{GVSM_{SAMP}}$ is an aggregate soil moisture composed of soil moisture and rock and Eq. (3) demonstrates how these two variables can be separated. In order to provide a more area representative estimate of volumetric rock fraction, we used the data provided in the Soil Survey Geographic Database (Soil Survey Staff, 2004). Using the $\mathrm{VSM_{SOIL}}$ and the rock fraction estimate from the SSURGO database, the rock fraction corrected volumetric soil moisture, $\mathrm{VSM_{RFC}}$, is calculated by

$$\mathrm{GVSM_{RFC}} = \mathrm{GVSM_{SOIL}}{*}(1 - \mathrm{RF_{SSURGO}}). \tag{4}$$

More simply, this equation can be rewritten as

$$\mathrm{GVSM_{RFC}} = \mathrm{GVSM_{SAMP}}{*}\left(\frac{1 - \mathrm{RF_{SSURGO}}}{1 - \mathrm{RF_{SAMP}}}\right) \tag{5}$$

which clearly shows how the rock fraction correction is a scaling value, referred to as the Rock Fraction Correction. This correction should also be applied to the dielectric probe samples, because the dielectric probes are inserted in the ground with the same bias of sampling location (more soil than rock). The $\mathrm{GVSM_{SAMP}}$ can be replaced with $\overline{\theta}$, which is the average volumetric soil moisture from the site specific calibrated dielectric probes. This is based on

Table 1
Rock fractions and the rock fraction correction

Site	Sample rock fraction	SSURGO rock fraction	RF correction	RMSE, $\bar{\theta}$ m^3/m^3	RMSE, $\bar{\theta}_{\mathrm{RFC}}$ m^3/m^3	R^2
RG003	0.11	0.1400	0.96629	0.017	0.017	0.695
RG013	0.23	0.1600	1.09091	0.130	0.155	0.446
RG014	0.24	0.3713	0.82730	0.018	0.016	0.599
RG018	0.20	0.1600	1.05000	0.024	0.024	0.680
RG020	0.42	0.3713	1.08405	0.082	0.073	0.626
RG028	0.23	0.5175	0.62662	0.046	0.012	0.643
RG034	*	0.4163	0.71429	*	*	*
RG037	*	0.5313	0.67958	*	*	*
RG040	0.08	0.3825	0.67120	0.054	0.018	0.701
RG046	0.15	0.5175	0.56765	0.126	0.072	0.000
RG057	0.29	0.5625	0.61620	0.062	0.024	0.060
RG069	0.17	0.5438	0.54970	0.093	0.024	0.600
RG070	0.31	0.5438	0.66123	0.038	0.013	0.345
RG076	0.18	0.2413	0.92530	0.112	0.102	0.006
RG082	0.13	0.5850	0.47701	0.080	0.022	0.763
RG083	0.21	0.5175	0.62076	0.046	0.009	0.707
RG089	0.41	0.3825	1.04661	0.091	0.090	0.122
RG092	0.07	0.5175	0.51882	0.053	0.017	0.430
RG100	0.34	0.4163	0.88447	0.045	0.033	0.662

'*' indicates no sampled rock fraction and the Rock Fraction Correction is estimated from nearby similar $\mathrm{RF}_{\mathrm{SSURGO}}$ site. RMSE values and R^2 were calculated between the dielectric probe soil moisture ($\bar{\theta}$ or $\bar{\theta}_{\mathrm{RFC}}$) and $\mathrm{SMSN}_{\mathrm{RFC}}$.

the average of five sampling points compared to the single gravimetric sample.

$$\bar{\theta}_{\mathrm{RFC}} = \bar{\theta}*\left(\frac{1-\mathrm{RF}_{\mathrm{SSURGO}}}{1-\mathrm{RF}_{\mathrm{SAMP}}}\right). \tag{6}$$

It is also necessary to apply a correction to the 19 WGEW soil moisture sensor network (SMSN) data sets. Since the SMSN sensors were installed in the same soil (locally) that was sampled during SMEX04, it is logically to apply the same RFC to the sensor data per site, resulting in an $\mathrm{SMSN}_{\mathrm{RFC}}$ for each sensor.

Table 1 shows the rock fractions and the correction constants. This also lists the RMSE values for comparison of the $\mathrm{SMSN}_{\mathrm{RFC}}$ with ($\bar{\theta}$) and ($\bar{\theta}_{\mathrm{RFC}}$) as well as the R^2 values (this value is the same for both comparisons because one is a linear combination of the other). RMSE values decreased from 0.064 to 0.42 m^3/m^3 error on average. R^2 values were often high indicating a moderate to strong relationship between the ground sampling and the local soil moisture sensor though some sensors had poor performance to local measurements. The RMSE of the $\mathrm{SMSN}_{\mathrm{RFC}}$ average to the $\bar{\theta}_{\mathrm{RFC}}$ (which is based on 64 sampling points) is approximately 0.01 m^3/m^3 for the SMEX04 time period. For two of the locations (RG34 and RG37), there were no local rock fraction samples taken, so the rock fraction correction for the nearest sample (<1 km away) site was used.

Fig. 2 is a plot of the two SMSN time series (uncorrected and corrected) during the SMEX04 experiment. Using the RFC on the soil moisture sensor network lowers the estimated soil moisture for the WGEW by approximately 0.023 m^3/m^3. This correction is sensor location dependent and not uniform for all sensors. Also plotted are the uncorrected ($\bar{\theta}$) and corrected ($\bar{\theta}_{\mathrm{RFC}}$) soil moisture averages from the dielectric probe sampling during SMEX04. The average difference between these measurements is 0.02 m^3/m^3. Fig. 3 is a plot of the entire period of study with an inset of the SMEX04 time period for reference. This study uses the RFC soil moisture data.

4. Temporal stability methods

The main tool for temporal stability analysis is the mean relative difference plot. This plot compares a particular soil moisture sensor location to the sensor network average computed from all sensors. Introduced by Vachaud et al. (1985), the mean relative difference (MRD) is defined as

$$\bar{\delta}_i = \frac{1}{t}\sum_{j=1}^{t}\frac{S_{i,j}-\bar{S}_j}{\bar{S}_j} \tag{7}$$

where $S_{i,j}$ is the jth sample at the ith site of n sites within the study region. $\bar{S}_j$ is the computed average among all sites for a given date

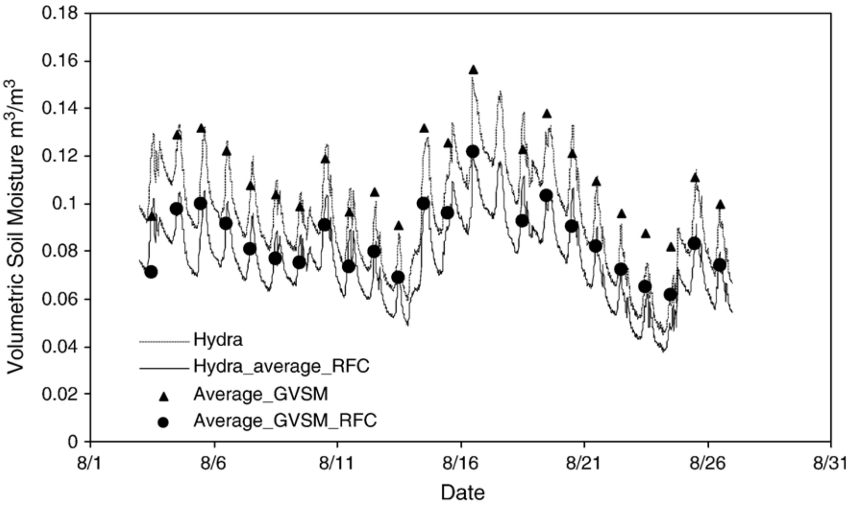

Fig. 2. Time series of soil moisture network average and the SMEX04 GVSM average with and without the Rock Fraction Correction.

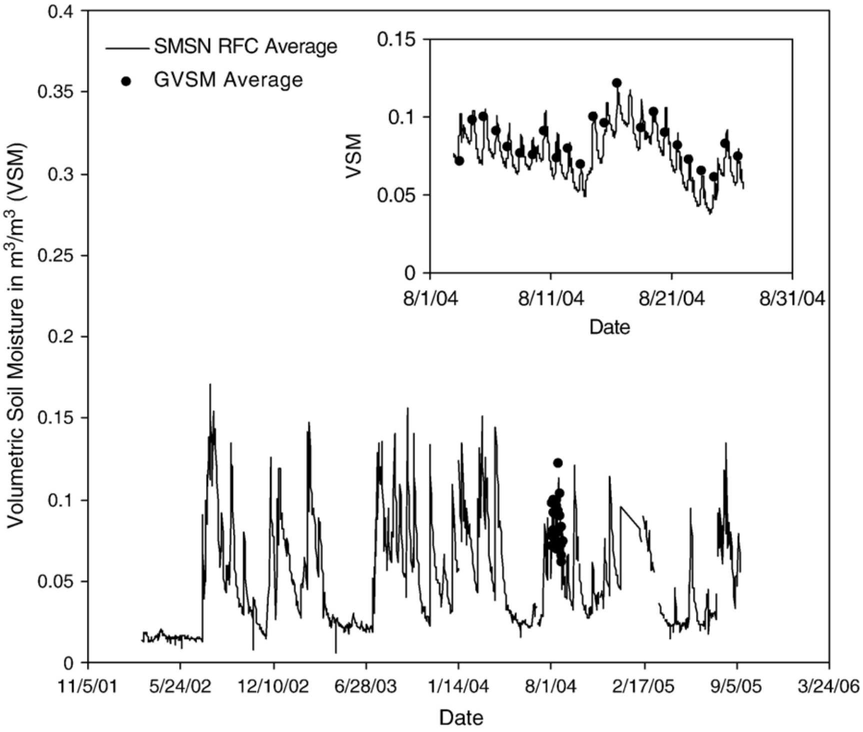

Fig. 3. A time series plot of the SMSN average for the entire study period. The inset plot details the SMEX04 study period and the associated $\mathrm{GVSM}_{\mathrm{RFC}}$ average.

and time j ($j=1$ to t). The sensors in this study record hourly data (instantaneous in situ measurement) and the gravimetric samples were collected each day between 11am and 3pm. It is assumed that results of this analysis are applicable to any time of day because samples are only compared at the same time period. The mean relative difference compares the value at a particular site to the average over the area of study. It determines if it is consistently greater or less than the mean and how variable that relationship is

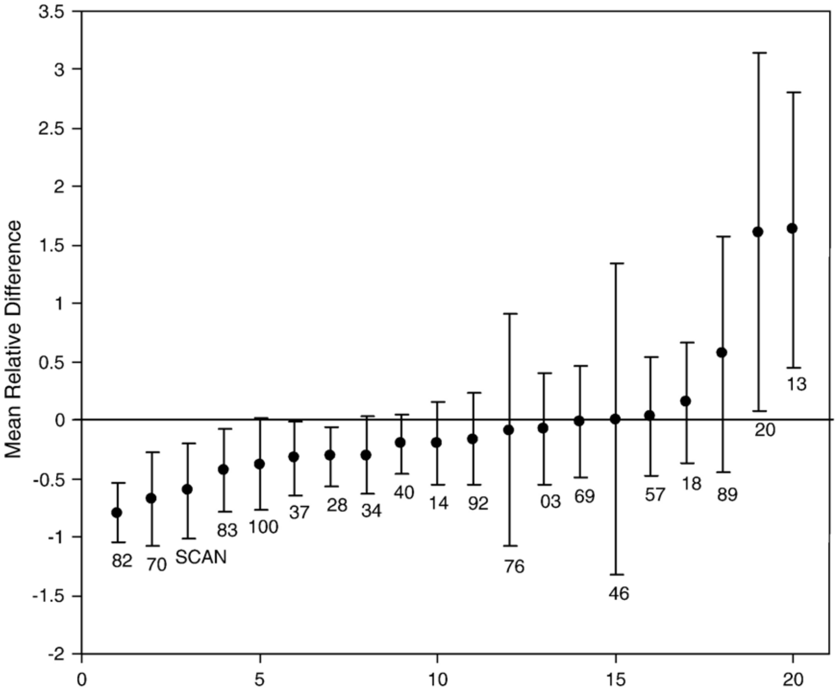

Fig. 4. Mean relative difference plot for the Walnut Gulch Experimental Watershed. The time period is June 2002 to September 2005. Error bars are one standard deviation of the relative differences. Labels refer to the raingage location number.

Table 2
Statistics for the soil moisture sensor network

Raingage	MRD	MRD, S.D.	Bias	RMSE
82	−0.792	0.256	−0.032	0.038
70	−0.678	0.403	−0.032	0.042
SCAN	−0.604	0.403	−0.021	0.027
83	−0.426	0.353	−0.017	0.024
100	−0.375	0.399	−0.011	0.017
37	−0.328	0.316	−0.012	0.018
28	−0.309	0.254	−0.012	0.016
34	−0.303	0.331	−0.009	0.015
40	−0.202	0.255	−0.009	0.014
14	−0.200	0.357	−0.004	0.014
92	−0.161	0.394	−0.008	0.015
76	−0.083	0.997	−0.008	0.046
3	−0.077	0.480	0.003	0.021
69	−0.012	0.478	0.000	0.021
46	0.009	1.331	−0.001	0.052
57	0.036	0.511	−0.004	0.017
18	0.149	0.512	0.014	0.027
89	0.566	1.006	0.026	0.060
20	1.611	1.530	0.059	0.077
13	1.628	1.179	0.060	0.074

Shown are the MRD (mean relative difference) and its standard deviation, and also the bias and root mean square error for each sensor as compared to the watershed average for the entire time period. Units are in m^3/m^3.

as determined by the standard deviation of the relative differences (SDRD), defined as

$$\sigma(\delta)_i^2 = \frac{1}{t-1}\sum_{j=1}^{t}\left(\frac{S_{i,j}-\bar{S}_j}{\bar{S}_j}-\delta_i\right). \tag{8}$$

A sensor is considered to be temporally stable if it has a low SDRD (for this study, approximately less than 0.60 m^3/m^3), such that there is a consistent, though potentially biased relationship between the site and the overall average. A site is considered representative of the large-scale average if its MRD is near zero. A large MRD (positive or negative) is a potentially correctable problem, whereas a large standard deviation is not. A large standard deviation is an indication that the soil moisture at the site is not linearly related to the watershed average; therefore, it is simply a poor predictor.

The correlation coefficient is another method of assessing temporal stability of spatial patterns (Chen et al., 1997; Cosh et al., 2004a). A correlation coefficient measures the relationship between two samples and is defined for these purposes by

$$r_{i,i'} = \frac{\sum_j (S_{i,j}-\bar{S}_{\bullet,j})(S_{i',j}-\bar{S}_{\bullet,j})}{\sqrt{\sum_j (S_{i,j}-\bar{S}_{\bullet,j})^2}\sqrt{\sum_j (S_{i',j}-\bar{S}_{\bullet,j})^2}} \tag{9}$$

where $S_{i,j}$ and $S_{i',j}$ are the volumetric soil moisture values for two sampling sites, i and i', for a given time, j. The average soil moisture for that time including sampling points is $\bar{S}_{\bullet,j}$. Closely correlated sites should have an $r_{i,i'}$ near 1, while uncorrelated sites have $r_{i,i'}$ values near 0. Vachaud et al. (1985) used a similar measure, the rank correlation coefficient, but the tendency of soil moisture sensors to occasionally report erroneous data values, including dropped values, negatively impacts the value of this coefficient. The correlation coefficient is less sensitive to this problem, because the total number of sites reporting doesn't affect this statistic in the same manner that it affects the rank correlation coefficient.

Temporal stability has also been shown to be related to soil type, topography, and land cover (Jacobs et al., 2004; Mohanty & Skaggs, 2001). However, we do not yet have a full understanding of the interaction and impact of all factors on temporal stability. To study these relationships, a simple multivariate regression analysis or general linear model (GLM) is used to quantify the dependence of temporal stability on associated land surface parameters.

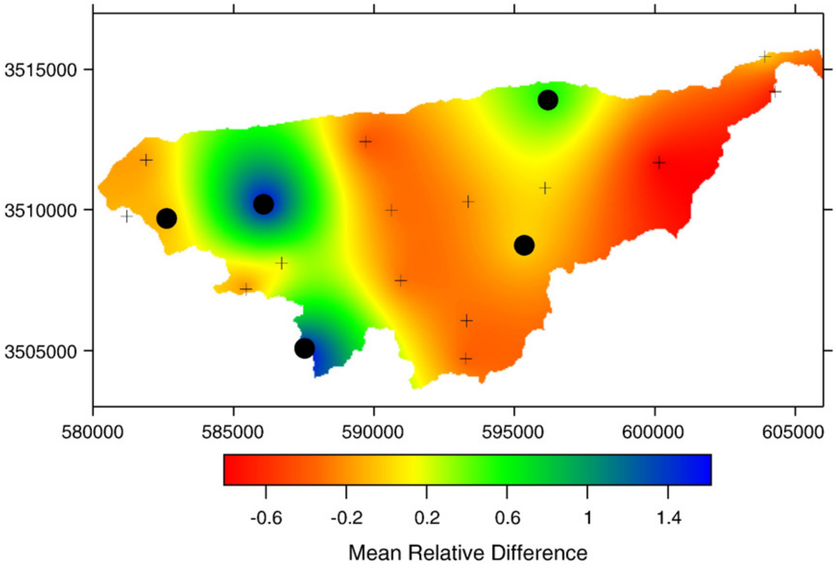

Fig. 5. Map of the mean relative differences for the Walnut Gulch Experimental Watershed for 19 soil moisture probes identified by a '+'. Locations with high mean relative difference standard deviations are also represented by a circle. The period of study is March 1, 2002 to September 2005.

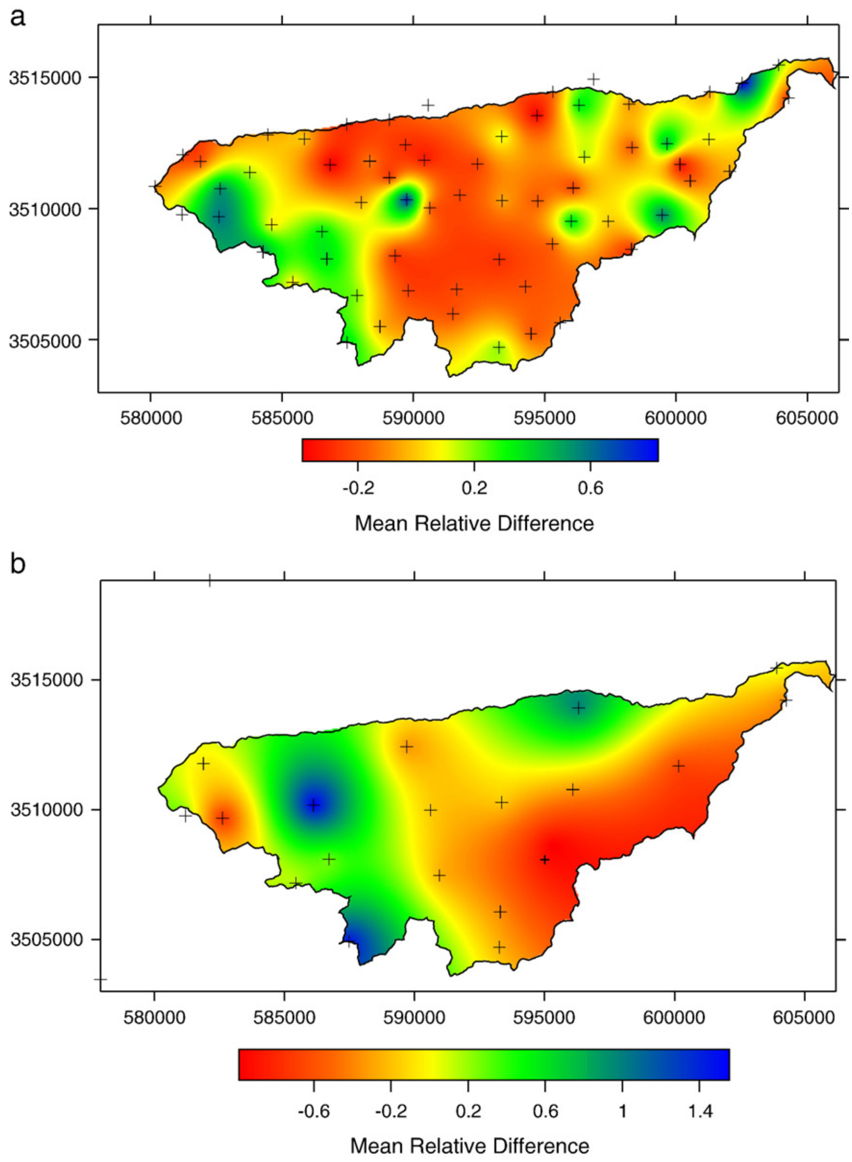

Fig. 6. (a) Map of the MRD for the 64 GVSM sampling points during SMEX04 (August 3–26, 2004). (b) Map of the MRD for the soil moisture sensor network during the SMEX04 study period (August 3–26, 2004).

Cosh et al. (2004b) demonstrated how a modified GLM can be used to compute R^2 values which quantify how much of the variability of a parameter can be attributed to other land surface characteristics. The characteristics of interest in this study include bulk densities, sand and clay content, rock fraction, slope, aspect, and elevation, and they were assumed to be linear covariates. More complex models are not considered in the present study. From the model, the sequential sum of squares (SeqSS) for each parameter and the total sum of squares (TSS) can compute the coefficient of determination, R^2, by

$$R^2 = \frac{\mathrm{SeqSS(parameter)}}{\mathrm{TSS}}. \tag{10}$$

The total of these R^2 values also provides an estimate of the total model quality. The method used in this study will not consider covariate interactions and will only focus on the linear relationships.

5. Results

A 3.5-year time period was available for study, March 1st, 2002 to September 13th, 2005. Fig. 4 contains the results of the temporal stability analysis for the 19 sensor locations within the watershed. Five of these locations (RG76, RG46, RG89, RG20, and RG13) are observed to have a greater SDRD than the other sensors. Other sensors are much better at estimating the watershed average, such as RG03 and RG69. Table 2 lists the statistics for comparing the watershed average to each sensor. It is shown that many sensors have an RMSE of approximately 0.02 m^3/m^3 when estimating the watershed average, which is good for a relatively sparse network. Fig. 5 is an interpolated color map of the MRD that illustrates the soil moisture pattern of the wet and dry areas for the same time period. Sensors that had large SDRD are circled. There is a tendency for less stable sites to have positive mean relative differences. In a semi-arid watershed in a region such as Arizona, a majority of the time the watershed average is expected to be less than 0.10 m^3/m^3 volumetric soil moisture. Because soil moisture varies between 0.0 m^3/m^3 and ~0.50 m^3/m^3, most often instability will occur at high moisture values, whereas, erroneously low moistures will appear accurate and stable. However, one location with a negative mean relative difference is identified as unstable as well. It is necessary to closely examine the rainy, or wet periods, or a semi-arid watershed to identify unstable sensors, which may be masked by this low moisture stability. SMEX04 was an opportune rainy period to more closely examine the network to detect these unstable sensors.

The comparison of the averages is one method of determining accuracy, another is to consider the spatial patterns of soil moisture. Fig. 6a is an MRD plot for the SMEX04 GVSM sampling (August 3–26, 2004). This spatial pattern is quite different from the MRD plot for the soil moisture sensor network, shown in Fig. 5. Part of this difference will be related to the greater density of the GVSM data set. In addition, these are for different time periods, therefore the sensor network pattern must be reexamined for the shorter SMEX04 time period. Fig. 6b is the MRD plot for the soil moisture network for only the SMEX04 time period (August 3–26, 2004). The patterns are still different, while the pattern for the network over the shorter period remains qualitatively consistent with the 3.5-year time frame. Therefore, while the soil moisture pattern indicated by the moisture network does not coincide with the GVSM estimation of the soil moisture pattern, the network still is able to estimate large-scale soil moisture means. Due to the local-scale variability at the surface, the exact location of the sensor largely determines the mean relative difference. Therefore, the network does not record an accurate map of the surface soil moisture, but it is an accurate set of sample points that predict a large-scale average. In order to accurately record soil moisture patterns, higher density sampling or aircraft surveys are more appropriate.

Correlation analysis revealed that there is little to no relationship between the MRD and the correlation coefficients for the sensor locations. Table 3 shows the correlation coefficients between the soil moisture sensors in order of increasing MRD for the entire study period (March 1, 2002–September 13, 2005). There are a wide range of values from weak correlation ($-0.3 < r_{i,i'} < 0.3$) to strong negative ($r_{i,i'} < -0.7$) and strong positive ($r_{i,i'} > 0.7$) with no trend or relationship to MRD. This may indicate that moisture within the water is distributed at small scales and is not spatially correlated. Future work will analyze in greater detail how the spatial correlation lengths of soil moisture affect stability and estimation.

Using a GLM, the relationship between various topographic parameters and soil properties was quantified for both the sensor network and the GVSM sampling sites from SMEX04, in a manner similar to Cosh et al. (2004b). Table 4 contains the R^2 values for GLM analyses conducted on three data sets: SMSN (3.5 year), SMSN (SMEX04 only), and SMEX04 Gravimetric Sampling. For the SMSN 3.5 year study, the results show that the leading soil parameters of importance for MRD are sample bulk density ($R^2 = .318$), sand ($R^2 = .125$), and clay percentages ($R^2 = .062$). These parameters account for approximately 50% of the variability of MRD and can be considered a proxy for the soil type. It can be concluded that soil type not only influences MRD, but stability as well, where stability is represented by SDRD. Almost 60% of the SDRD variability can be credited to the soil type parameters listed in Table 4. These findings are in agreement with the previous studies by Mohanty and Skaggs (2001) and Jacobs et al. (2004), where it was demonstrated that soil type and topography influence MRD and SDRD.

For the SMSN SMEX04 only data set indicates a greater reliance on sample bulk density, while other soil parameters

Table 3
Correlation coefficients between soil moisture sensors for March 1, 2002 to September 13, 2005

	82	70	SCAN	83	100	37	28	34	40	14	92	76	3	69	46	57	18	89	20	13
82	1.00	0.12	0.91	0.85	0.26	0.33	0.48	0.31	0.73	0.13	0.36	0.07	−0.10	0.10	−0.07	0.33	−0.37	−0.02	−0.23	−0.07
70		1.00	0.11	0.08	0.03	0.02	0.04	0.04	0.09	0.02	0.05	0.02	−0.02	0.01	0.06	−0.01	−0.03	0.01	−0.12	0.00
SCAN			1.00	0.79	0.22	0.30	0.46	0.25	0.63	0.10	0.34	0.18	−0.11	0.01	0.06	0.36	−0.40	0.01	−0.25	−0.07
83				1.00	0.24	0.32	0.46	0.30	0.69	0.19	0.37	0.00	−0.06	0.06	−0.22	0.40	−0.31	−0.02	−0.21	−0.06
100					1.00	0.12	0.14	0.12	0.24	0.05	0.11	−0.02	−0.01	0.05	−0.05	0.08	−0.7	0.03	0.04	0.00
37						1.00	0.17	0.59	0.27	0.08	0.76	0.23	−0.02	0.06	−0.09	0.56	−0.09	−0.02	−0.05	0.00
28							1.00	0.21	0.42	0.09	0.20	0.01	−0.02	0.02	−0.08	0.15	−0.15	−0.01	−0.10	−0.04
34								1.00	0.32	0.09	0.11	0.32	0.00	0.06	−0.15	0.07	−0.02	−0.04	−0.04	−0.03
40									1.00	0.13	0.34	0.00	−0.06	0.15	−0.14	0.26	−.20	−0.04	−0.16	−0.09
14										1.00	0.10	−0.08	0.03	0.07	−0.23	0.06	0.02	−0.05	−0.02	0.01
92											1.00	0.02	0.01	0.07	−0.08	0.60	−0.11	−0.04	−0.10	−0.01
76												1.00	−0.06	−0.14	0.40	0.02	−0.14	0.05	−0.07	−0.04
3													1.00	0.33	−0.09	−0.06	0.08	−0.03	0.07	0.02
69														1.00	−0.22	0.05	0.03	−0.01	0.04	0.04
46															1.00	−0.05	−0.14	0.06	−0.11	−0.06
57																1.00	−0.18	−0.01	−0.03	0.04
18																	1.00	−0.04	0.11	0.04
89																		1.00	−0.01	−0.01
20																			1.00	0.05
13																				1.00

Table 4
R^2 values from General Linear Model for mean relative difference the WGEW sensor network and the watershed sampling during SMEX04

	SMSN, 3.5-year		SMSN during SMEX04		SMEX04 sampling	
	MRD	SDRD	MRD	SDRD	MRD	SDRD
Soil characteristics						
Sample bulk density	0.318	0.080	0.465	0.489	0.005	0.022
Soil bulk density	0.003	0.000	0.049	0.061	0.002	0.012
Rock fraction	0.021	0.232	0.013	0.023	0.007	0.003
Clay Percentage	0.062	0.154	0.008	0.009	0.000	0.002
Sand percentage	0.125	0.125	0.118	0.076	0.110	0.069
Topographic						
Elevation	0.019	0.015	0.032	0.102	0.000	0.018
Slope	0.077	0.003	0.042	0.071	0.048	0.123
Aspect	0.143	0.053	0.031	0.000	0.015	0.010
Total model	0.774	0.662	0.757	0.830	0.187	0.200

MRD is the Mean Relative Difference and SDRD is the Standard Deviation of the Relative Differences.

decrease in importance ($R^2 < 0.010$). This indicates that for short periods of time (such as the month long SMEX04), the relationships between these soil parameters and stability can change. Topographic parameters have minimal relationships to MRD or stability, as most of the R^2 values are less than 0.10. The exception is aspect, which has some influence on the MRD for the sensor network. Slope is shown to have little to no effect on stability; however, given the large spatial scale of the study, in comparison to that of Jacobs et al. (2004), it is reasonable to conclude that slope cannot be included in this study. All sampling locations are positioned in a flat land surface, though nearby topography may be varied. Topographic information for the GLM analysis is derived from larger scale (30 m DEM data) maps, which can be misrepresentative of the small-scale point measurements that compose this sensor network. Analysis of the SMEX04 sampling was less conclusive, as both GLM results had R^2 values equal to or less than 0.20, which is not significant. Clearly, future work is necessary to evaluate which parameters play crucial roles in the temporal stability of the WGEW.

Lastly, the primary purpose of the soil moisture sensor network in the WGEW is to support the calibration and validation of the AMSR-E satellite instrument. Temperature brightness data has been collected over the globe and soil moisture products have been produced for many different vegetation covers. However, a simple comparison of network soil moisture to satellite emissivity indicates that there exists a subtle relationship for this watershed network. Fig. 7 is a plot of the ascending ($R^2 = 0.29$) (overpass at 13:30 MST) and descending ($R^2 = 0.22$) (overpass at 1:30 MST) emissivities for WGEW compared to the coincident WGEW soil moisture average for the shorter time period of January 1–September 30, 2004. Using AMSR-E data, emissivity, *e*, as defined by

$$e = \frac{\mathrm{TB}_{10.7\mathrm{GHz}}}{0.861 * \mathrm{TB}_{37\mathrm{GHz}} + 52.55} \tag{11}$$

where $\mathrm{TB}_{10.7\ \mathrm{GHz}}$ is the temperature brightness at 10.7 H GHz in K and $\mathrm{TB}_{37\ \mathrm{GHz}}$ is the temperature brightness at 37 V GHz in K (De Jeu, 2003). There is a weak, but evident relationship between the observed soil moisture and satellite emissivity, as shown by the R^2 values, which shows the potential of estimating soil moisture from remote sensing observations. This weak relationship can be attributed to the spatial variability and the size of the AMSR-E foot-print (60 × 60 km).

6. Conclusions

It has been shown that the WGEW SMSN is an accurate and stable estimator of the watershed average. However, the surface

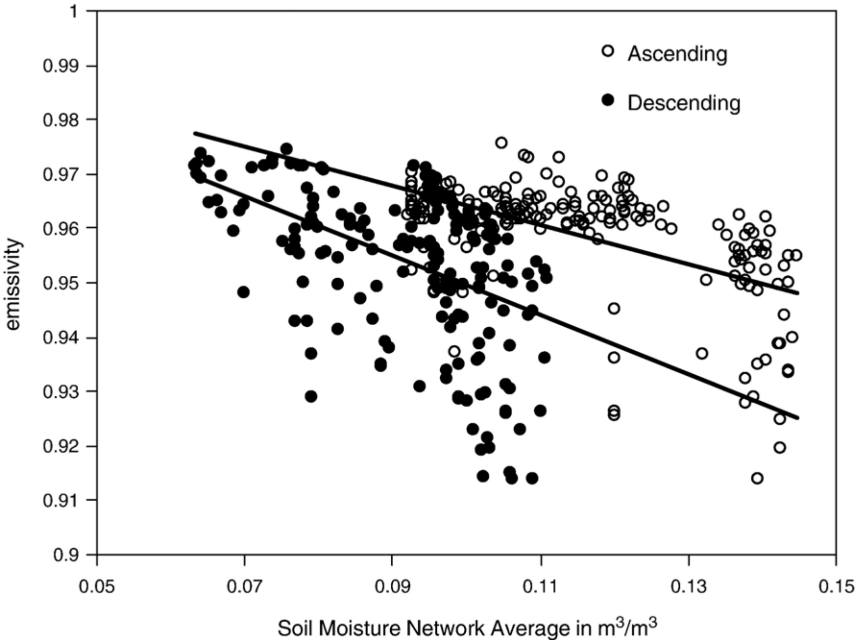

Fig. 7. Comparison of the soil moisture average from the WG network and the emissivities derived from Ascending and Descending scenes of AMSR-E.

pattern of soil moisture was not consistent as determined by comparing the MRD pattern between a dense (64 sampling points) ground sampling effort and the in situ soil moisture network (19 sites). If one of the more representative sites were to be used as a surrogate for the watershed average, the RMSE would be approximately 0.01 m^3/m^3 for a long study period. In semi-arid watersheds, unstable sensors have a tendency to have a higher MRD, because most of the time the entire network has very low moisture. Variability can therefore only occur as high moisture values. Since volumetric soil moisture must be non-negative and soil moisture is low in a semi-arid region, the soil moisture distribution is non-normal and skewed negatively. MRD variance is greater for sites, which have a greater MRD, because these locations are biased toward higher soil moisture values and therefore have a greater dynamic range. Previous studies have shown unstable sensors in both high and low MRD, and the SDRD values are generally larger than those found in Martinez-Fernandez and Ceballos (2003) and Vachaud et al. (1985) which are based on similar types of measurements (in situ sensors). The SDRD values are comparable however to those found by Jacobs et al. (2004) which used transient (non-in situ) sensors. This is most likely a result of the differences in sampling method, in situ versus transient sampling and time interval of sampling. Relationships between temporal stability and land surface parameters were investigated with a GLM. Soil characteristics, including bulk density and sand and clay content, was shown to be responsible for 50% of the temporal stability, but less influence (~20%) on the representative character. Topographic parameters, such as slope, aspect, and elevation, had little effect ($R^2 < 0.20$) on stability or representative character. Lastly, comparisons of the sensor network average to the emissivities from the AMSR-E instrument demonstrated that there is a good relationship.

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