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Journal of Hydrology 323 (2006) 168–177
Journal of Hydrology
www.elsevier.com/locate/jhydrol

Temporal stability of surface soil moisture in the Little Washita River watershed and its applications in satellite soil moisture product validation

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Received 27 September 2004; revised 22 August 2005; accepted 23 August 2005

Abstract

The concept of temporal stability can be used to identify persistent soil moisture patterns and estimate the large scale average from select representative sensor locations. Accurate and efficient estimation of large-scale surface soil moisture is a primary component of soil moisture satellite validation programs. However, monitoring the soil surface at large grid scales is difficult. As part of the aqua satellite advanced microwave scanning radiometer (AMSR) Validation Program, a soil moisture sensor network was installed in the little Washita river watershed in Oklahoma, USA in 2002. Along with data from the soil moisture experiment 2003 (SMEX03), this network will provide a valuable dataset for satellite soil moisture product validation. Analysis shows that most of the network sensors are temporally stable at multiple scales and four sites are identified as representative with negligible bias and small standard deviation to the watershed mean. As part of this analysis, the protocols established for large-scale soil moisture sampling campaigns such as in the soil moisture experiments (SMEX) are validated. This analysis showed that basing grid scale estimates on six sampling points is reasonable and accurate. Temporal stability is shown to be a valuable tool for soil moisture network analysis and can provide an efficient means to large-scale satellite validation.

Keywords: Temporal stability analysis; Time series analysis; Surface soil moisture; Soil Moisture experiment 2003 (SMEX03); Little Washita river watershed

1. Introduction

Estimating spatial soil moisture has long been a challenge using conventional technologies. New options are emerging that utilize remote sensing and modeling (Njoku et al., 2003; Robock et al., 2003). However, these techniques still require validation using conventional methods. Here, the primary interest is in the validation of passive microwave observations, such as those provided by the advanced microwave scanning radiometer (AMSR) for estimation of surface soil moisture. These measurements are made over large footprints or pixels (the area on

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0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2005.08.020

the ground that the sensor measures) on the order of 10–50 km in diameter. Few current monitoring networks are either dense or extensive enough to estimate the footprint scale surface soil moisture with a good degree of accuracy. The mismatch in scale between satellite footprints (>10 km) and ground sampling (∼5 cm) makes most attempts at statistical sampling difficult.

Warrick et al. (1977) and Russo and Bresler (1980) demonstrated that by using soil moisture scaling theory, moisture field averages could be accurately estimated using only point observations. Some recent studies have focused on approaches to scaling at large resolutions, including geostatistical analysis (Western and Bloschl, 1999), probability density function analysis (Avissar and Pielke, 1989), and fractal analysis (Rodriguez-Iturbe et al., 1995). Each of these approaches assumes some knowledge of the surface soil moisture distribution at finer resolutions, as a result of intensive sampling campaigns over long periods of time (Chen et al., 1995; Kachanoski and De Jong, 1988; Yoo, 2002). Other geostatistical analyses, such as kriging (Delhomme, 1979; Burgess and Webster, 1980) and semivariogram analysis (Cosh and Brutsaert, 1999) require a dense sampling network to capture the spatial character of the soil moisture field. Vinnikov et al. (1999) studied the impact of increasing the number of point samples in a study region, to identify the threshold number of sites for accurate (low error) estimation. This point theory approach carries the burden of bias. Random selection within a domain can result in the selection of a point with high bias, which can significantly alter the large-scale estimate.

As a solution to this dilemma, Vachaud et al. (1985) proposed the method of temporal stability to determine representative locations within a field, thus improving sampling efficiency while maintaining accuracy. Their study estimated large-scale soil moisture in a 2000 m^2 grass field by determining which sampling locations within the study region maintain a low bias relationship to the spatial average and also have low variability. By extending this concept to a temporally stable soil moisture sensor network, it may be possible to create a dataset of considerable quality for validation of large-scale estimates.

Grayson and Western (1998) extended the work of Vachaud et al. (1985) by examining small watersheds with significant relief ranging in size from 0.1 to 27 km^2. These included the Tarrawarra catchment (Australia), mostly dryland grazing, Chickasha, OK, USA, mostly pastures and winter wheat, and Lockyersleigh (Australia), mixed grazingland and woodland. The limitation of these watersheds was the small scale. Kachanoski and De Jong (1988) argued that spatial scales must be considered in temporal stability analysis. These scales could include the correlation length scale, which they applied to a small grassland field in Canada. Mohanty and Skaggs (2001) expanded this work by studying how various surface parameters, such as soil type, slope, and vegetation cover, affected the spatio-temporal stability of grassland and winter wheat near Chickasha (OK, USA). In another investigation, Cosh et al. (2004) studied a temporary network of surface soil moisture sensors near Ames, Iowa as part of the Soil Moisture Experiment 2002 (SMEX02). These sensors were located throughout a small agricultural watershed dominated by corn and soybean fields. Temporally stable sites were identified and moisture patterns were shown to be persistent for a short time period, though they concluded a longer time period is necessary.

As these studies demonstrate, large-scale estimation of surface soil moisture can present a difficult task for hydrologists and climatologists. The process requires a dense network of moisture probes located throughout a region, which is difficult to install and maintain. One approach to this problem is to utilize temporal stability in hopes of identifying representative as well as anomalous sites. If a site is temporally stable with regard to surface soil moisture, it has a persistent relationship with the well-defined large-scale average for a long period of time. Using this information, sampling schemes can be made more efficient by reducing the number of monitoring sites, while maintaining the accuracy of the network based estimate. In this investigation, the following concepts are explored. First, the integrity of a large-scale network of soil moisture sensors located near Chickasha, OK is analyzed through temporal stability analysis for a 21-month study period. This analysis identifies sites that are not representative of the footprint scale. In addition, the network representativeness is assessed using the SMEX03 Field Experiment data from the summer of 2003. Also, the impact of two different time scales, seasonal and time of day is isolated by temporal stability results. Finally, the sampling schemes used in snapshot field campaigns, such as the SMEX experiments, are addressed to determine how few points are necessary to adequately represent this particular watershed.

2. Study region

Intensive field campaigns have been conducted to give snapshot imagery of spatial soil moisture patterns for short periods of interest. Many of these campaigns involved the Little Washita Watershed (Jackson et al., 1995, 1999, 2002; Famiglietti et al., 1999). This 610 km^2 watershed is located in southwestern Oklahoma and is classified as moist and sub-humid with the land cover dominated by rangeland and cropland, mostly winter wheat, but including some corn and grasses. The topography is considered rolling with few hills or outcrops. Soils range from sands and silts to clays. Allen and Naney (1991) give a thorough description of the watershed and its features.

The Grazinglands Research Laboratory (USDA-ARS) operates an intensive network of surface monitoring sites in and around the watershed (www.grl.ars.usda.gov/micronet/). This network, referred to as the Micronet, records many hydrologic variables, including air temperature, relative humidity, rainfall, solar radiation, and profile soil temperature. These stations were distributed throughout the watershed area approximately every 5 mile in an attempt to record information on a semi-uniform grid. The instruments are installed at the edges of agricultural fields and their monitoring footprint is maintained as a short grass. The topography at each location is flat, though some fields contain low relief (less than 20 m). As part of the Aqua AMSR Validation Program (Njoku et al., 2003), Vitel Hydra Probe[1] soil moisture sensors were installed at 13 of these sites. Their locations are shown in Fig. 1. Soil moisture and temperature readings are recorded at a depth of 5 cm (sensing range is between 3 and 7 cm), with a measurement interval of 30 min. Within the same

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

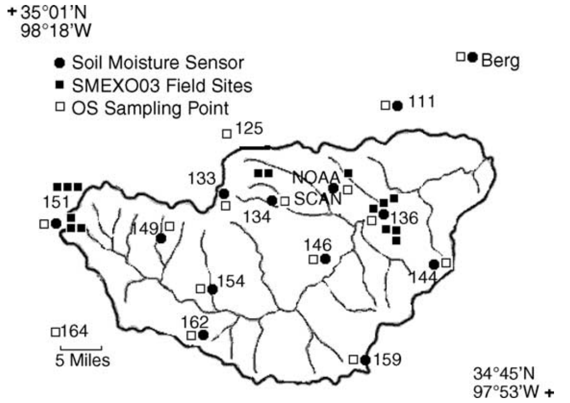

Fig. 1. The Little Washita River Watershed Micronet. Micronet sites are marked with empty squares and Micronet sites with soil moisture sensors are marked with full circles. Sampling fields are marked with full squares.

field as the NOAA Micronet site, the Natural Resources Conservation Service (NRCS) operates a Soil Climate Analysis Network (SCAN) station. This SCAN station includes soil moisture measurements using the same type of sensors, but at depths of 5, 10, 15, 20, and 40 cm. These instruments are located approximately 100 m apart along the edge of the field. Due to the spatial correlation of these sites, only the Micronet site will be used in calculating the watershed means, however, occasionally the SCAN site is included to demonstrate the quality of the station.

Another data set used here is from the Soil Moisture Experiment 2003 (SMEX03) conducted in July 2003 in and around the Little Washita Watershed. Intensive watershed field scale sampling as well as grid-scale (∼25 km) regional sampling was conducted once a day using both gravimetric sampling and impedance probes. In the watershed, 15 fields (approximately 800 by 800 m) were sampled at 14 points within each watershed field. Over 600 impedance probe measurements were taken each day during the experiment. These probe measurements were calibrated with coincident gravimetric samples, developing individual calibrations for each of the 15 fields in the study (each calibration had an root mean square error, RMSE, less than 0.05 m^3/m^3). These watershed fields are shown in Fig. 1. This intensive sampling was designed to support the calibration of low-altitude aircraft passive microwave remote sensing efforts, which flew at mid-day. In addition, 15 Micronets in and around the watershed were sampled at one point within the field each afternoon at approximately 1:30 pm local time as part of regional sampling. These fields are identified in Fig. 1. It is assumed that this regional sampling and the intensive watershed sampling are synchronized at noon local time because there is little change in mean soil moisture over a few hours. In the long term, this study will also help to identify critical sites, which should continue to operate should network reduction become necessary.

3. Temporal stability analysis

The principal tool employed for summarizing and assessing the statistics used in the 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 is defined as

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

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 and time j ($j=1$–t). The mean relative difference measures how a particular site compares to the average over the area of study, i.e. determines if it is consistently greater or less than the mean and how variable that relationship is as determined by the standard deviation of the relative differences. Temporal stability is defined simply as having a low standard deviation of the relative differences (for this study, approximately less than 3 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 characteristic of the large-scale average if its mean relative difference is near zero and there is a small standard deviation. Bias is a potentially correctable problem, whereas a large standard deviation is not. One aspect of temporal stability not discussed in this work is the temporal correlation of the data series. At this long time scale, the temporal trend of soil moisture can be assumed to be negligible and the variance is not affected.

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

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

where $S_{i,j}$ and $S_{i',j}$ are soil moistures for two sampling sites, i and i', for a given time, j. The average soil moisture for that time across all sampling points is $\bar{S}_{\cdot,j}$. It is expected that closely correlated sites will have a $r_{i,i'}$ 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 negatively impacts the value of this coefficient. The correlation coefficient is less sensitive to this problem, because the total number of sites does not affect this statistic as it affects the rank correlation coefficient.

4. Micronet results and discussion

The mean relative difference plot is shown in Fig. 2 for 30-min 5 cm depth Micronet data from July 12,

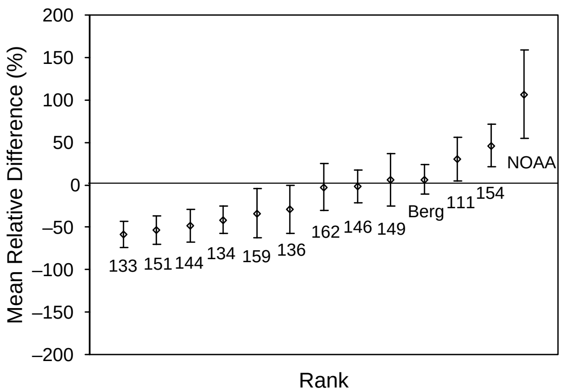

Fig. 2. The mean relative difference plot for the Little Washita Micronet for the time period of study, July 2002–April 2004. Error bars correspond to one standard deviation of mean relative differences.

Table 1
Sample statistics for the Micronet sites

Micronet site	MRD	Std Dev.	Bias	RMSE	R^2
133	−58.9	15.4	−0.078	0.083	0.780
151	−53.0	16.9	−0.073	0.076	0.811
144	−48.2	19.6	−0.067	0.071	0.764
134	−41.3	15.9	−0.057	0.062	0.792
159	−33.6	29.2	−0.037	0.045	0.785
136	−28.7	28.0	−0.033	0.044	0.831
162	−3.1	27.7	0.005	0.038	0.840
146	−2.1	19.0	0.000	0.020	0.900
149	5.4	30.7	0.010	0.036	0.750
Berg	5.9	17.4	0.007	0.024	0.859
111	30.3	26.0	0.040	0.054	0.767
154	45.9	25.2	0.061	0.072	0.807
NOAA	106.6	51.8	0.124	0.127	0.620
SCAN	218.7	123.4	0.239	0.243	0.449

Mean relative difference (MRD), and the standard deviation (Std Dev.) are in % and Bias and RMSE are in m^3/m^3.

2002 to April 29th, 2004. Only time increments that had seven or more sensors reporting were used in this analysis, which is greater than 95% of the time. The standard deviations were low (<30%) for many of the sites, indicating temporal stability for the network. Four sites, Micronets 146, 149, 162, and Berg had small mean relative difference values and standard deviations when compared to the watershed average as shown in Table 1. These sites are considered the most representative sites, which could be used on long time scales as accurate estimators of the watershed average. Only one of these sites is centrally located within the watershed, as shown in Fig. 1, though not all centrally located sites are representative. These sites have a variety of soils from sands to clays and their topography is similar, rolling hills. There appears to be no distinctive characteristic that would indicate soil moisture temporal stability. Fig. 3 contains a plot of each of these four representative points versus the watershed average for the entire data series. Micronet 162 seems to deviate from the average more than the other representative Micronet sites, especially for dry conditions. This is most likely due to the response of the watershed average to rain events, whereas, Micronet 162 responds slower. The SCAN site was not used to calculate the watershed average, because Micronet NOAA is located in the same field.

The results of this watershed temporal stability analysis are similar in magnitude to results from previous temporal stability experiments. Martinez-Fernandez and Ceballos (2003) found similar results in their study of the REMEDHUS stations in central Spain. Mean relative differences between ±50% and small standard deviations (usually less than 20%). The longer time scale of their study (3 years) is the most likely cause of their lower standard deviations. Jacobs et al. (2004) showed mean relative differences for a watershed in Iowa to range between −50 and +50% with standard deviations less than 30% for most sites in their study. In contrast, Vachaud et al. (1985) had much smaller mean relative differences and standard deviations for their study in France. However, this study had a smaller spatial domain and a 2.5-year study period.

Similar conclusions are drawn from an analysis of the coefficients of correlation. Table 2 shows the strength of the correlations for the Micronet and SCAN sites. SCAN is included in this analysis because it is located within the same domain and is a similar configuration to the Micronet sites. Again, it is not included in the remainder of the analysis because it is in the same field as the NOAA Micronet site and it would be inappropriate to include. A majority of the correlations are strong (>0.75) with only two anomalous sites. This indicates a persistent spatial pattern of surface soil moisture that strengthens the application of temporal stability analysis. Without a persistent pattern, there would not be temporally stable sites. The NOAA and SCAN sites have a weak correlation with respect to each other as well as the other Micronet sites.

By comparing results of temporal stability analysis, seasonal and hourly stability was also examined. The 21-month study period was split into four seasons and a temporal stability analysis was conducted for the 13 Micronet sites. Fig. 4 contains a temporal stability analysis by season. Overall rank for the plot was determined by the rank for the sites in Fig. 2. It is shown that the mean relative difference is consistent for each site with low variability among seasons. The NOAA Micronet still has the greatest mean relative difference and the greatest variability among seasons. Fig. 5(a) contains the mean relative difference plot for each hour of the day (Central Standard Time). Fig. 5(b) shows the same plot, but scaled by

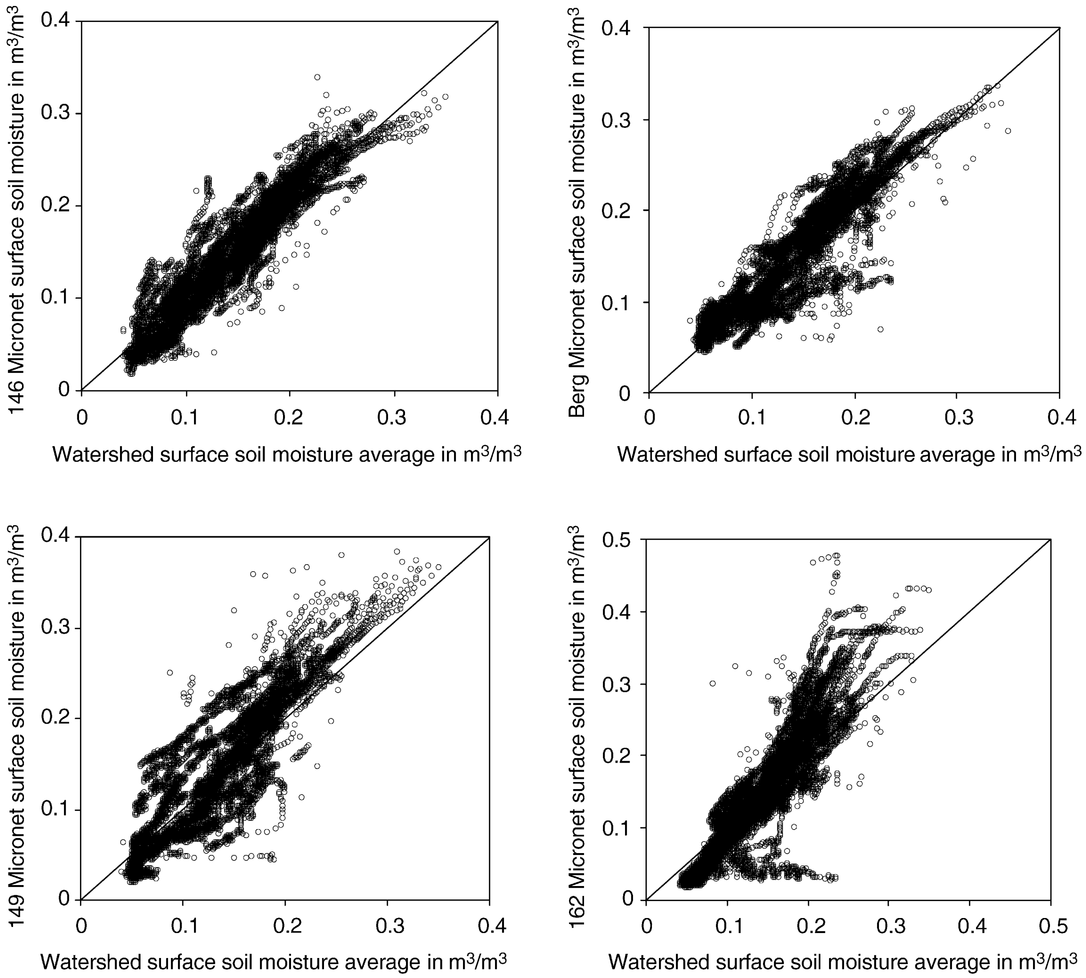

Fig. 3. Micronet volumetric soil moisture values for the four temporally stable Micronets versus the watershed average volumetric soil moisture of the entire network.

subtracting the daily mean relative difference from each hour. There is almost no change in the mean relative difference between hours of the day, demonstrating that surface soil moisture experiences no diurnal effect in comparison to the changes in moisture at longer time scales. It is concluded that the network is temporally stable at each of these time scales.

Each of the above analyses result in the conclusion that the NOAA site is biased higher than the watershed average and has considerable variability. To investigate this anomaly further, gravimetric soil moisture data were collected in the LW02 field adjacent to the NOAA Micronet station during SMEX03. For LW02 (the field adjacent to the NOAA and SCAN sites), this shorter duration data set was analyzed using temporal stability analysis for the 14 sampled points in the field along with the Micronet (NOAA) and the SCAN site. Although of shorter duration and with a limited range of conditions, the mean relative difference plot shown in Fig. 6 indicates that the NOAA and SCAN sites have higher soil moisture values than the remainder of the field sampling points. Only one other sampling site (ranked 13th in Fig. 6) had a large mean relative difference standard deviation. This is the result of natural variability within the field. Closer examination of field LW02 revealed topography and diverse soil

Table 2
Correlation coefficients between sites for the entire study period

	133	134	136	144	146	149	151	154	159	162	Berg	NOAA	SCAN
111	0.87	0.78	0.77	0.73	0.86	0.64	0.83	0.75	0.82	0.80	0.85	0.66	0.75
133		0.89	0.79	0.73	0.87	0.76	0.86	0.82	0.79	0.81	0.84	0.45	0.68
134			0.76	0.75	0.85	0.76	0.90	0.81	0.67	0.77	0.75	0.41	0.54
136				0.85	0.88	0.69	0.75	0.65	0.70	0.79	0.83	0.42	0.47
144					0.89	0.60	0.72	0.60	0.73	0.72	0.79	0.25	0.43
146						0.77	0.87	0.75	0.82	0.83	0.85	0.54	0.65
149							0.81	0.80	0.72	0.81	0.77	0.42	0.47
151								0.77	0.66	0.78	0.78	0.52	0.37
154									0.83	0.91	0.75	0.50	0.64
159										0.84	0.83	0.36	0.61
162											0.76	0.45	0.63
Berg												0.60	0.60
NOAA													0.37

taxonomy influence it is stability as compared to the NOAA and SCAN sites. Both the Micronet NOAA and SCAN sites are along ridgeline at the edge of the field. The sites also contain a more compact soil than the rest of the field. It is recommended that these locations be investigated for installation location errors.

To determine if the Micronet as a whole accurately estimates the watershed average, field sampled gravimetric/impedance soil moisture data were compared to the Micronet average. Fig. 7 shows how these compare for the SMEX03 study period. There is a negligible difference (RMSE <0.01 m^3/m^3)

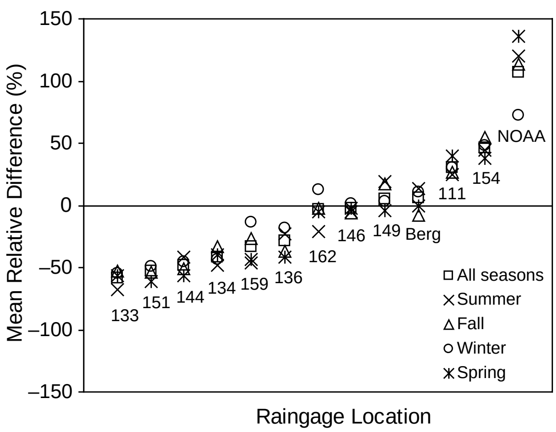

Fig. 4. Mean relative difference plot for each of the four seasons during the study period. Site rank is based on the overall rank.

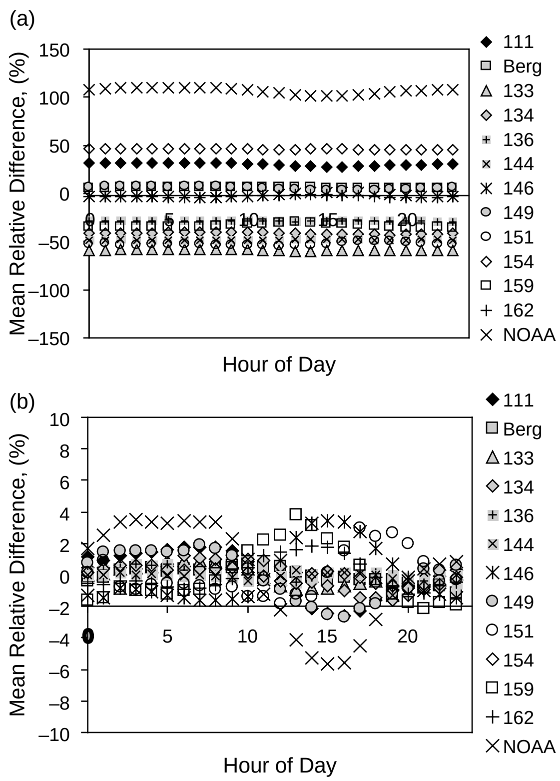

Fig. 5. (a) Mean relative difference values for each site for each hour of the day during the study period. (b) The average mean relative difference subtracted from the plot in (a). There are some sites with minor temporal changes, but most are less than 3% change. All times are in Central Standard Time.

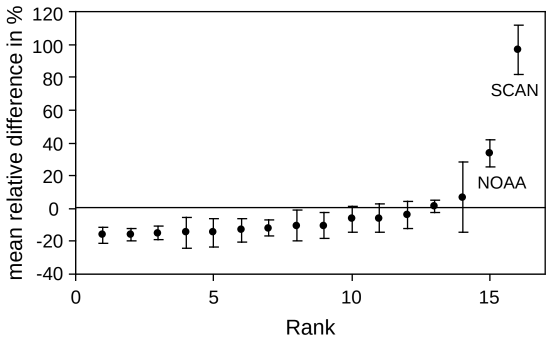

Fig. 6. A mean relative difference plot for field LW02 which contains both Micronet NOAA and SCAN soil moisture sensors. Fourteen points were sampled during the SMEX03 experiment, throughout 400 by 800 m field.

between the Little Washita Sampling average and Micronet average. The observed difference between the two estimates is less than 0.01 m^3/m^3 and a paired *t*-test indicates they are equal at a 99% confidence level. This indicates that the Micronet on average is a good representation of the watershed with respect to surface soil moisture during the SMEX03 experiment.

5. Sampling protocol validation

The SMEX experiments collected large-scale soil moisture estimates for the purposes of satellite validation. These sites were sampled daily at the time of satellite overpass to provide a snapshot estimate. Logistically, only a few locations could be sampled within a single satellite footprint, therefore a minimum number of sites had to be established as a representative sample. As part of the experimental design of SMEX03, six sampling points were selected to represent an area of 625 km^2 (the scale of the Little Washita Watershed), which is also the scale of EASE grid satellite products. Spacing between sites was nominally 8–10 km. To validate this general method of sampling, the watershed average as determined by intensive watershed sampling (LW-avg) was compared to a six-point Micronet sampled average over the same area, as shown in Fig. 8. The mean estimate of six randomly chosen Micronet sampling points (6-point avg) within the Little Washita study region was estimated by the bootstrap method. Using the bootstrap method, six sites were randomly selected and a watershed average computed per day. This process was repeated 1000 times. The results were sorted and the 25th and 975th values represent the 95% confidence interval for the prediction of the watershed average based on only six points. The average root mean square error was 0.02 m^3/m^3 volumetric soil moisture. For all but one day, the LW-avg is within the 95% confidence interval for the 6-point sample.

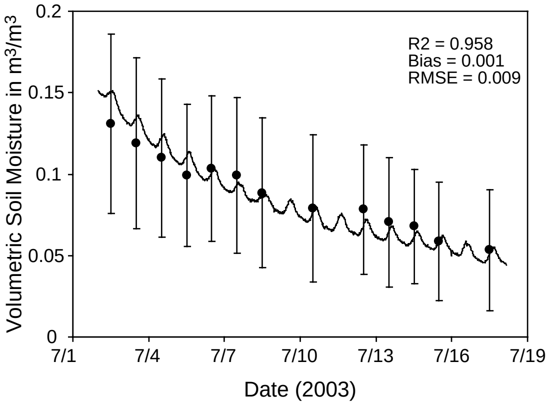

Fig. 7. Average soil moisture value from the Little Washita Micronet (line) versus the Watershed sampling estimated average soil moisture with one standard deviation error bars.

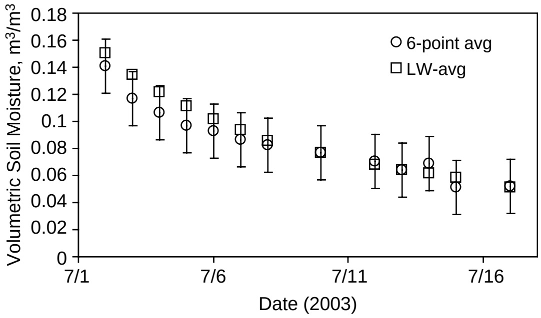

Fig. 8. Comparison of the Little Washita average based on all regional sampling points (avg) and an average based on the intensive gravimetric field sampling (LW-avg). Error bars for the sampling are a bootstrap estimate 95% confidence interval for six randomly sampled sites.

6. Conclusions

At the watershed scale, the Little Washita Watershed Micronet soil moisture network was shown to be useful in future monitoring and satellite validation programs as well as modeling. All of the sensors but one were temporally stable while only one field site among those sampled demonstrated instability. It is suggested that this site not be used in future analyses. Four sites are also shown to be representative of the network average, namely Micronets 162, 146, 149, and Berg. These sites could be used to accurately estimate the watershed surface soil moisture mean for long-term studies in lieu of operating the entire Micronet. Also, the intensive sampling mean during SMEX03 closely agreed with the average based on the Micronet sensors. Incorporating this knowledge of the temporal stability of the sensor network provides an improvement to the standard point sampling theory, which does not consider the representative character of the individual sampling locations, allowing for high bias sites to be included in an estimate. This single point sampling theory proves inefficient when considering the results of the temporal stability analysis, which reveals that four of thirteen Micronet sites provide an accurate approximation of the watershed average. Future soil moisture satellite products will benefit from the utilization of temporal stability analysis because it has the ability to verify stable soil moisture networks as well as identify representative and anomalous sites, thus improving any ground validation programs.

Extrapolation of this temporal stability technique to similarly sized watersheds should be conducted with caution. Topography is rolling, but does not play a significant role in the distribution of soil moisture. Also, the vegetation cover is dominated by winter wheat and pastures. Different land cover types should be addressed separately to verify the stability. All Micronet sites are installed in short grass; therefore, their moisture condition is similar to the adjacent field, since the land cover is dominated by grasses and grains. Future studies are needed to assess how diverse vegetation affects the seasonality of stability.

Finally, the sampling scheme used in the Soil Moisture Experiments (SMEX02, SMEX03, and SMEX04) was tested for its ability to estimate grid scale surface soil moisture contents. Logistics and economics require that a minimal amount of points be sampled for such large-scale estimation while statistics support a larger number. As a compromise, six-point sampling for an EASE-grid scale area was demonstrated to be an accurate method of estimation. The RMSE between intensive sampling and the six-point sampling scheme was less than 0.02 m^3/m^3 soil moisture. It is therefore reasonable to continue this sampling protocol for future large-scale soil moisture experiments.

Future work centering around this type of analysis should include a more detailed analysis of the seasonal and temporal character of stability. Specifically, areas with changing land cover, such as agricultural land, which develops from seed, through the growth cycle and ending with harvest might have a strikingly different stability pattern. Also, areas with different climate and topography would be of interest.

Acknowledgements

The authors would like to thank the Soil Moisture Experiment 2003 Science Team and the USDA-ARS Grazinglands Research Laboratory for their assistance in the collection of this data set. We would also like to thank the National Aeronautics and Space Administration for their generous contributions to the study. This work was supported by the NASA Aqua AMSR, Terrestrial Hydrology and Global Water Cycle Programs.

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