Evaluation of AMSR-E-Derived Soil Moisture Retrievals Using Ground-Based and PSR Airborne Data during SMEX02

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ABSTRACT

A Land Surface Microwave Emission Model (LSMEM) is used to derive soil moisture estimates over Iowa during the Soil Moisture Experiment 2002 (SMEX02) field campaign, using brightness temperature data from the Advanced Microwave Sounding Radiometer (AMSR)-E satellite. Spatial distributions of the near-surface soil moisture are produced using the LSMEM, with data from the North American Land Data Assimilation System (NLDAS), vegetation and land surface parameters estimated through recent Moderate Imaging Spectroradiometer (MODIS) land surface products, and standard soil datasets. To assess the value of soil moisture estimates from the 10.7-GHz X-band sensor on the AMSR-E instrument, retrievals are evaluated against ground-based sampling and soil moisture estimates from the airborne Polarimetric Scanning Radiometer (PSR) operating at C band. The PSR offers high-resolution detail of the soil moisture distribution, which can be used to analyze heterogeneity within the scale of the AMSR-E pixel. Preliminary analysis indicates that retrievals from the AMSR-E instrument at 10.7 GHz using the LSMEM are surprisingly robust, with accuracies within 3% vol/vol compared with in situ samples. Results from these AMSR-E comparisons also indicate potential in determining soil moisture patterns over regional scales, even in the presence of vegetation. Assessment of soil moisture determined through local-scale sampling within the larger-scale AMSR-E footprint reveals a consistent level of agreement over a range of meteorological and surface conditions, offering promise for improved land surface hydrometeorological characterization.

1. Introduction

Soil moisture and its spatial distribution play a critical role in agricultural, hydrological, and meteorological applications. The soil moisture content assumes significant control on hydrological responses across many spatial and temporal scales, influencing runoff generation through antecedent conditions, modulating interactions between the land surface and the atmosphere, and comprising a component of the feedback systems present in the land–atmosphere interface. The distribution of soil moisture patterns throughout a catchment influences a variety of hydrological processes. Knowledge of this state variable offers insights into percolation, infiltration, and runoff mechanisms, and is a controlling factor in the evaporative process, reflecting the prevailing water and energy balance conditions at any particular time by influencing the partitioning between latent and sensible heat fluxes. Identifying the spatial distribution and temporal evolution of the soil moisture would provide significant insight into larger-scale processes, and would undoubtedly see a corresponding development in improved modeling attempts to describe these processes.

Understanding the spatial variation of soil moisture is a perplexing problem, and much research has been directed toward this task (Entekhabi and Rodriguez-Iturbe 1994; Famiglietti and Wood 1995; Grayson and Blöschl 2000; Western et al. 2001; Wilson et al. 2004). Accurate representation of soil moisture at the catchment scale is difficult, and intensive field instrumentation is required if spatial patterns are desired (e.g., Western et al. 1999). Microwave remote sensing offers some advantages over instrumented networks, but also suffers from issues associated with the depth of the retrieval, which is generally claimed to be less than 5 cm of soil depth at 1.4 GHz (and shallower at higher frequencies) (Jackson et al. 1995), the coarse scale of spa-
ceborne passive radiometric measurements (>25 km), and the development of robust retrieval algorithms. The issue of the radio frequency interference (RFI) (Li et al. 2004) at C-band frequency, and the atmospheric and vegetation influences at higher frequencies, further complicates accurate estimation over large areas.

A number of recent studies have compared higher-resolution soil moisture retrievals from airborne microwave radiometers, such as the L-band Electronically Scanned Thinned Array Radiometer (ESTAR) (Jackson et al. 1995; Le Vine et al. 2001; Gao et al. 2004) and the C-band Polarmetric Scanning Radiometer (PSR) (Jackson et al. 2002). These sensors offer excellent detail of the surface soil moisture state at subkilometer resolutions, offering an opportunity to examine the scaling characteristics of soil moisture (Crow and Wood 1999; Kim and Barros 2002). While the heterogeneous nature of soil moisture is recognized in a theoretical sense (Entekhabi and Rodriguez-Iturbe 1994; Grayson and Blöschl 2000), few practical techniques exist to adequately or efficiently characterize this property at large scales. The insight that is accessible through remote sensors should facilitate a greater understanding of the broader-scale patterns that are available from current platforms, such as the Advanced Microwave Scanning Radiometer (AMSR)-E (Njoku et al. 2003), and future satellite missions such as those of the Soil Moisture and Ocean Salinity (SMOS) (Kerr et al. 2001) and Hydrosphere State (HYDROS). However, this task has been complicated by the difficulty in deriving, and then evaluating, robust interpretive models.

The launch of the AMSR-E sensor on the National Aeronautics and Space Administration’s (NASA’s) Earth Observing System (EOS) platform *Aqua* offers an opportunity to determine global soil moisture patterns at scales that are suitable for inclusion in land surface and general circulation models. While there are numerous assimilation studies attending to this task (Reichle et al. 2001; Walker and Houser 2001; Crosson et al. 2002; Crow and Wood 2003) there is perhaps a more pressing need for increased evaluation of the retrieved products to assess the worth of soil moisture information derived from this sensor (see, e.g., Crow et al. 2001). Algorithm assessment and intercomparison are required before confidence in the planned global products can be ascertained. A number of field experiments undertaken over the last few years (see information online at http://hydrolab.arsusda.gov) provide an excellent source of detailed information for product evaluation. Such multifaceted hydrological experiments offer a level of assessment that is not normally available for remote sensing studies and facilitate the critical link between algorithm assessment and product development.

In this paper, an evaluation of soil moisture predictions using a microwave emission model against field data, collected concurrently with the Soil Moisture Experiment 2002 (SMEX02) campaign (see Cosh et al. 2004), is presented. Using information from the North American Land Data Assimilation System (NLDAS) and ancillary data, brightness temperatures from AMSR-E 10.7 GHz (X band) are incorporated into a land surface microwave emission model to produce a soil moisture product equivalent to the 0.125° (~14 km) resolution of the NLDAS product. A comparison with the dense network of ground-based measurements and airborne information that were collected during the SMEX02 field campaign in Iowa is undertaken and an assessment of the derived soil moisture retrieval is offered.

2. Land Surface Microwave Emission Model

In the determination of soil moisture from retrieved AMSR-E brightness temperatures, the Land Surface Microwave Emission Model (LSMEM) (Drusch et al. 2004; Gao et al. 2004) was utilized. LSMEM makes a number of important assumptions in estimating the soil moisture that have been shown to hold true over sparse vegetation (Jackson et al. 1995; Jackson et al. 1999), but have not been rigorously tested over denser vegetation, as is characteristic of the Walnut Creek catchment in Iowa. It is generally accepted that determining the soil moisture in areas with dense vegetation is problematic (Ferrazzoli et al. 2002; Schmugge et al. 2002), and the work presented here represents a first attempt at retrieving soil moisture values from AMSR-E over this particular land surface coverage.

Following its description in Gao et al. (2004), LSMEM is based on a solution of the radiative transfer equation as derived in Kerr and Njoku (1990), describing the brightness temperature of soil covered by a layer of vegetation ($T_{b, v, p}$) as

$$T_{b, v, p} = T_{au} + e^{-\tau_{at}}(T_{ad} + T_{sky}e^{-\tau_{at}})(1 - \varepsilon_p) e^{-\tau_{rv}} + e^{-\tau_{at}}(\varepsilon_p T_s e^{-\tau_{rv}} + T_v (1 - \omega_s) (1 - e^{-\tau_{rv}})) \times [1 + (1 - \varepsilon_p) e^{-\tau_{rv}}],$$

(1)

where $T_{au}$ and $T_{ad}$ are the upward and downward contributions from the atmosphere, $T_v$ the effective soil temperature, $T_v$ the vegetation temperature, $T_{sky}$ the cosmic radiation, $\tau_{at}$ the optical depth of the atmosphere, and $\varepsilon_p$ the rough soil emissivity. For vegetation having cylindrical structure, $\omega_s$ is the single scattering
albedo and \( \tau^* \) is the optical depth of the vegetation (Chang et al. 1980). In the literature, vegetation single scattering albedo varies from 0.04 to 0.1 (Ulaby et al. 1983; Pampaloni and Paloscia 1986). Because there is no robust database for this value over a large area, an average of 0.07 is used in this analysis, following that from similar investigations (Kerr and Njoku 1990). In the case of bare soil, the brightness temperature \( (T_{bs,p}) \) can be calculated using a simplified form of (1):

\[
T_{bs,p} = T_{au} + e^{-\tau^*}(T_{ad} + T_{sky}e^{-\tau^*})(1 - e_p) + e^{-\tau^*} e_p T_s.
\]

In determining the soil moisture, LSMEM calculates a weighted composite brightness temperature based on the relative fraction of bare and vegetated cover at the pixel scale.

In this analysis, LSMEM is used in an inverted numerical framework to solve for the soil moisture, given knowledge of the brightness temperature (observed from AMSR-E). An iterative technique is employed to identify the soil moisture, starting from an initial estimate of the antecedent moisture condition. The brightness temperature corresponding to the specified moisture and emissivity conditions can then be calculated and compared to the measured brightness temperature. Successive iterations are performed on the soil moisture until convergence with the observed horizontal brightness temperature is reached. Further details on the model and parameter requirements can be found in Gao et al. (2004).

3. Methodology and data description

Issues associated with RFI (Li et al. 2004) have diminished the utility of C-band measurements in determining the soil moisture states over large areas of the globe, particularly across the continental United States. As such, renewed focus on X-band measurements is required to further assess its suitability for soil moisture estimation. Until the launch of L-band missions (SMOS and HYDROS), information from the 10.7-GHz sensors on board *Aqua* (AMSR-E) and the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) offer the best alternative for moisture retrieval.

To examine this, AMSR-E 10.7-GHz (X band) horizontally polarized brightness temperature records were processed from 19 June through to the end of July 2002, encompassing the SMEX02 observation program (see experimental description and design in Jackson and Cosh 2003). Analysis of the available data focuses primarily on the Walnut Creek watershed because of the density of available measurements and the existence of a nearby Soil Climate Analysis Network (SCAN) site (see Fig. 1), which provides long-term measurements of profile soil moisture over a variety of depths. The following sections present an overview of the procedures employed in this analysis, and also a description of the data sources utilized to determine the near-surface soil moisture predictions.

Data sources

1) AMSR-E microwave brightness temperature

In order that microwave brightness temperatures could be integrated into the existing NLDAS and LSMEM framework, AMSR-E data were regridded onto the regularized 0.125° NLDAS lattice (see Fig. 1). Transferring the gridded 25-km product to 0.125° inevitably requires some form of data interpolation. To retain the information content of the original data, the regridding procedure was chosen so as to minimize any smoothing of the data. Where the NLDAS grid points coincide with AMSR-E grid centers, or within a user-defined search distance, the regridded brightness temperature is assigned the original value. Otherwise, an average of the two nearest AMSR-E brightness temperatures is calculated, weighting each value by the inverse of the distance between the AMSR-E and NLDAS grid centers (i.e., the AMSR-E value closest to the NLDAS grid center will have the most weight). Alternatively, data from the NLDAS could have been scaled to the AMSR-E resolution. In doing this, however, the information content present in the high-resolution vegetation data would have been degraded, as would the surface temperature information and State Soil Geographic Data Base (STATSGO) soil property data. The chosen techniques represent a compromise between the variety of resolutions, sources, and scaling characteristics of the data used in this analysis.

2) PSR C-band soil moisture

The PSR is an airborne microwave radiometer operated by the National Oceanic and Atmospheric Administration (NOAA) Environmental Technology Laboratory (Piepmeier and Gasiewski 2001), which was flown aboard the NASA P-3 aircraft for the purpose of obtaining polarimetric microwave emission during SMEX02. It has been successfully used in previous field experiments, including the 1999 Southern Great Plains Experiment (SGP99) (Jackson et al. 2002). The PSR data provide an excellent intermediary source of validation information between the scales of the AMSR-E
Fig. 1. (top) Regridded 0.125° AMSR-E-derived soil moistures over Iowa, with the boxed region identifying the extent of the PSR aircraft measurements. (bottom left) Regional sampling locations, an example of a resampled PSR image, and (bottom right) the location of the Walnut Creek watershed, encompassed by two AMSR-E pixels. The background image at the lower right is the original PSR resolution. The dotted parallel points represent watershed sampling transects, while the single points identify regional sampling locations. Nineteen sample sites within the catchment boundaries were used in determining the catchment averages for comparison with the AMSR-E retrievals.
pixel and ground-based measurements and offer the only feasible means of comparing predictions with a reasonable spatial equivalence and similar measurement characteristics to AMSR-E. Data from the PSR at C band were supplied in an irregularly spaced grid at a nominal resolution of 800 m, with soil moisture predictions calculated independently by U.S. Department of Agriculture (USDA) scientists (R. Bindlish 2004, personal communication). The PSR measurements supplied 10 complete moisture maps of the region, encompassing an area of approximately $0.7^\circ \times 1.0^\circ$ (78 km $\times$ 111 km). Given the scale differences between the AMSR-E and PSR measurements, it is anticipated that various surface physical and hydrological influences, which are only observable at higher resolutions, might contribute to soil moisture differences between the sensors.

The PSR retrievals (Bindlish 2004) derive soil moisture values centered around 7 GHz (C band). Apart from the defined scale disparities, comparison with AMSR-E 10.7-GHz values are not expected to exhibit major differences, although there will be some effects from the different water dielectric properties at the two frequencies, as well as surface vegetation and roughness influences (Jackson et al. 2002). Jackson et al. (2002) indicate that for low soil moistures (high brightness temperatures) both sensors should exhibit similar results. The level of agreement might be expected to be lower as the soil moisture increases, particularly given the vegetation characteristics of the study area. To examine the scale effects and to facilitate a spatially equivalent comparison with the derived AMSR-E values, the PSR soil moisture measurements were resampled to a number of resolutions between 1 and 25 km to assess the level of statistical variation in the soil moisture field. In this reanalysis, a bilinear interpolation scheme was employed to make use of the high-resolution data, as opposed to the downscaling of the AMSR-E information. The results indicated a preservation of the major statistical features across scales, while also retaining many of the visual characteristics that are evident at the native sub-1-km resolution. This provides some confidence in upscaling the original 800-m PSR measurements to the resampled AMSR-E resolution ($0.125^\circ$) for the intercomparison between the sensors.

### 3) Land Surface Temperature

The North American Land Data Assimilation System (Cosgrove et al. 2003) offers a variety of forcing data for use in land surface and other model simulations. This data system offers an excellent opportunity to explore regional-scale processes, particularly where extensive ground-based records do not exist. Land surface temperatures were derived from the variable infiltration capacity (VIC) model (Liang et al. 1994), nested within NLDAS, to facilitate the estimation of soil moisture. Surface temperature measurement is an integral step in predicting soil moistures in LSMEM. While efforts to utilize coincident microwave-based temperature measurements show promise (e.g., Owe et al. 2001), remotely sensed infrared techniques provide a more accurate source of available data at a variety of resolutions (e.g., Wan et al. 2002).

The NLDAS temperatures have recently been evaluated against geostationary satellite data and in situ measurements over the Atmospheric Radiation Measurement (ARM) Cloud and Radiation Test Bed (CART) region for a select period, with accuracies on the order of 3–4 K (Mitchell et al. 2004). While this level of retrieval accuracy is not ideal for land surface flux retrieval, estimation of soil moisture is less sensitive to uncertainties in the surface temperature, making these suitable for use within LSMEM. It is expected that this level of accuracy will affect uncertainties in emissivity by approximately 0.01, not unduly influencing the desired 4% volumetric soil moisture retrieval accuracy. The surface temperature, representing both sparsely and vegetated surfaces, is determined coincident with the AMSR-E overpass time using NLDAS sources, and is defined as an “effective temperature” here because the penetration depth at X band is less than 1 cm. Deeper-layer soil temperatures are unlikely to influence the microwave brightness temperature.

### 4) Vegetation Water Content

Given the influence of vegetation growth during the SMEX02 experiment and the distinct distributions of corn and soybean throughout the Walnut Creek watershed, determining the vegetation water content (VWC) plays an important role in characterizing soil moisture estimates. Vegetation water content was derived using a combination of MODIS land cover classifications and leaf area index (LAI) (Myneni et al. 2002), employing general relationships between LAI, foliar and stem biomass, and relative water content estimates for these biomass components (Rodell et al. 2005). While some in situ measurements of the VWC are available for the SMEX02 period (Jackson et al. 2004), a focus on using operationally derivable products was preferred, hence the decision to employ available monthly data rather than locally based vegetation information.

Inevitably, this will introduce some error into model
predictions, especially because vegetation growth during the growing season can be dramatic for the cornfields, which comprise approximately 45% of the Walnut Creek catchment area (soybean make up a similar proportion). Jackson et al. (2004), using an empirical approach linking VWC with Landsat reflectance data, determined that the VWC for corn increased in mean values from 0 to 5 kg m\(^{-2}\) over the course of the campaign, while soybean had a much smaller range of 0–1 kg m\(^{-2}\). However, even in situ measurements are not without uncertainty (see Anderson et al. 2004), with results displaying increased variability across the catchment as the growing season progressed. The operational remotely sensed data used here to derive the VWC, display reduced dynamics relative to the high-resolution study of Jackson et al. (2004). Indeed, after rescaling the original 1-km data to 0.125°, just two pixels represent much of the Walnut Creek watershed. VWC values for these pixels ranged from 0.98 to 2.16 and from 1.11 to 1.85 for June and July, respectively, accurately reflecting the increase in vegetation growth and content over this period.

5) Ancillary data and model parameters

One of the key differences to previous applications of the LSMEM is the consideration of vegetation cover using a semiempirical formulation of the Normalized Differential Vegetation Index (NDVI) (see Baret et al. 1995). Data from the MODIS NDVI vegetation product (Huete et al. 1994) was reprocessed to provide coverage at 0.125°, consistent with data from the NLDAS database, offering an improved assessment of vegetation cover. Among other model inputs, some parameters are assigned constant values, such as the sensor frequency (10.7 GHz), atmospheric contribution (determined from a radiative transfer model following Drusch et al. 2001), vegetation structure parameter (determined from Table 1 in Jackson and Schnugge 1991), soil roughness (0.3 from Choudhury et al. 1979), and the single scattering albedo (0.07, based on studies by Ulaby et al. 1983; Pampaloni and Paloscia 1986). The rough soil emissivity is a function of soil moisture, soil texture, and surface roughness, and is calculated by determining the reflectivity of a smooth surface (using the Fresnel equation) and then applying the approach of Choudhury et al. (1979) to get the rough soil reflectivity, from which the emissivity can be calculated.

Other parameters maintain temporal stability but have spatial variability, such as the soil texture (STATSGO) and soil bulk density (NLDAS), which are all determined at 0.125° resolution. Parameters that vary both spatially and temporally include the vegetation fractional coverage and vegetation water content, which are both included as monthly averages.

4. Results

Assessments of the LSMEM-determined AMSR-E soil moisture product were undertaken against field and PSR-based aerial measurements during the SMEX02 observation period. The following section presents an analysis to examine the retrieval accuracy and capability of AMSR-E to capture the local-scale dynamics that are present in the evaluation data.

a. AMSR-E comparisons with ground-based networks

1) Soil Climate Analysis Network site

The SCAN installation offers a continuous and complimentary dataset to the in situ measurements determined during the SMEX02 campaign. The Ames, Iowa, SCAN site (see Fig. 1) has been in operation since September 2001 and provides continuous hourly data measured over a number of depths by a Stevens Vitel Hydra Probe. Data from the SCAN site were extracted and compared with a collocated AMSR-E pixel (the same pixel used in the following watershed analysis).

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Although clearly representing a scale mismatch, the temporal dynamics of the in situ measurements are expected to offer some insight into the ability of AMSR-E to reproduce local-scale observations. It should be noted that the SCAN site is located in a fallow portion of a grassed field, representing a different vegetation structure to the predominant types within Walnut Creek. Furthermore, Cosh et al. (2004) observed a significant bias (~20%) in the SCAN data compared to the regional soil moisture average. While the site possibly represents a “wetter” estimate of soil moisture, the temporal dynamics of the response should still be useful.

Figure 2 illustrates the resulting SCAN response at 2 in. (~50 mm), along with the measured precipitation at the site and the retrieved AMSR-E soil moisture. There is a strong correlation between the data for the period of 20 June–4 July, with observations reflecting the drying down after the rain events earlier in the month. A relatively constant offset during this period of approximately 10% vol/vol is also evident, which is likely a result of the relative depths of measurement (AMSR-E at 10.7 GHz approximates a 0.5-cm near-surface soil measure) or the wet bias of the SCAN site described above. The onset of the rain events on 4, 6, and 10 July incite a marked spike in both responses, gradually drying down again toward the end of the month and re-
suming a positive bias. There is no obvious explanation for the AMSR-E afternoon prediction on 2 July, which describes a typical response to a rainfall event, because no precipitation was recorded over watershed sites on this day. Interesting diurnal effects are also evident in the AMSR-E response, with afternoon values (1400 LST) being generally greater than the early morning (0200 LST) estimates over the daily cycle. Afternoon overpasses also exhibit a greater degree of variation, perhaps in response to increased uncertainties in the land surface temperature during the daytime. These diurnal differences might also be related to geometrical variations associated with ascending and descending orbits, but are beyond the scope of this paper to examine further. Overall, the AMSR-E retrievals, although obviously influenced by pixel-to-point-scale and measurement disparities, reflect the trends observed in the SCAN response.

2) Sub-pixel-scale sampling in Walnut Creek

The primary source of soil moisture estimation during SMEX02 was the use of theta probes to measure the 0–6-cm volumetric soil moisture. These devices measure the dielectric constant of the medium and convert this to a moisture measurement using calibration equations, which are determined from standard functions or uniquely calibrated to soil property data. During the watershed sampling, over 4500 unique theta-probe samples were collected, allowing a detailed accounting of the soil moisture variability within the study catchment. Of these, 19 sampling sites (from a total of 33 sites) were within the resampled AMSR-E footprint (Fig. 1), allowing a spatially representative in situ soil moisture average to be computed and compared with the AMSR-E grid value.

AMSR-E morning and afternoon retrievals were averaged and compared with the area-averaged soil moisture recorded from each watershed sampling location within Walnut Creek. Table 1 details the statistical properties of the in situ distribution and the coincident AMSR-E pixel, and Fig. 3 compares the collocated retrievals from both the airborne C-band PSR and the X-band AMSR-E. As can be seen, there is a gradual increase in the catchment-averaged soil moisture as the field campaign progresses, consistent with the record of precipitation over the campaign. Also, both individual field site– and the catchment-averaged standard deviation (across all field sites) was not generally greater than 3%, indicating a level of spatial consistency in the moisture range across the watershed over all days (see ±1 std dev). Figure 3b indicates a strong equivalence with the AMSR-E pixel, especially considering both the scale disparity between the two approaches and the different sampling depths of the techniques. Although only eight sample days were available for comparison, consistent agreement between the two measurements is shown. The mean absolute error between the samples is 2.64% vol/vol with a $r^2$ value of 0.75. A root-mean-square error (rmse) of 4.1% vol/vol belies the goodness of fit, because half of this error is attributed to the single offset value that is evident in Fig. 3, which, upon removal, reduces the retrieval rms to 2.17% vol/vol. The data point that is responsible for this overestimate coincides with a significant rainfall event, indicating that the AMSR-E retrieval is likely overestimating the

**Table 1.** Statistics for the in situ watershed sampling of Walnut Creek. The average soil moisture and standard deviations are derived from the supplied means at each sample site. AMSR-E values indicate the resampled pixel that encompasses the greater portion (~65%) of the Walnut Creek catchment (see Fig. 1) and represent the average of morning and afternoon overpasses.

<table>
<thead>
<tr>
<th>Date</th>
<th>Samples</th>
<th>Avg soil moisture</th>
<th>Avg std dev</th>
<th>AMSR-E</th>
</tr>
</thead>
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<tr>
<td>25 Jun 2002</td>
<td>272</td>
<td>12.784</td>
<td>2.626</td>
<td>9.5</td>
</tr>
<tr>
<td>26 Jun 2002</td>
<td>273</td>
<td>12.079</td>
<td>2.805</td>
<td>X</td>
</tr>
<tr>
<td>27 Jun 2002</td>
<td>273</td>
<td>11.253</td>
<td>2.331</td>
<td>7.0</td>
</tr>
<tr>
<td>1 Jul 2002</td>
<td>103</td>
<td>9.511</td>
<td>1.626</td>
<td>6.5</td>
</tr>
<tr>
<td>5 Jul 2002</td>
<td>271</td>
<td>14.837</td>
<td>2.458</td>
<td>X</td>
</tr>
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<td>2.079</td>
<td>X</td>
</tr>
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</table>
soil moisture response because of near-surface saturation.

3) REGIONAL SAMPLING OVER THE SMEX02 DOMAIN

A concurrent regional-scale sampling strategy, conducted during the campaign, was designed to capture the broader-scale soil moisture patterns at the resolution of the satellite footprint, incorporating 46 unique sites distributed across the SMEX02 domain. At the NASA-processed resolution of 25 km, it was anticipated that approximately four sites would fall within an AMSR-E footprint. The grid of individual sample sites covers a domain of approximately 50 km × 100 km. Both ground-based and PSR airborne measurements were collected between 1200 and 1500 local time to coincide with the afternoon AMSR-E overpass. Of the sample locations, sites 8 and 9 correspond to positions within Walnut Creek and the resampled AMSR-E pixel analyzed above (see Fig. 1 for the location of the catchment and grid structure over the region). For this analysis, both morning and afternoon AMSR-E overpasses were used, including those days affected by precipitation events (i.e., 4, 6, and 10 July).

In undertaking regional sampling, three theta-probe measurements and a single gravimetric sample (separating the 0–1- and 1–6-cm soil profiles) were collected at each of the sites. Results of the regional analysis are shown in Fig. 4, which illustrates the average volumetric soil moisture content measured at sites 8 and 9, along with the regional mean of all of the sites, measured using hand-held theta probes that were calibrated to the independently evaluated gravimetric moisture contents. Included in each image are the retrieved AMSR-E soil moisture values over the corresponding areas. The bars for each sample day in the regional analysis (Fig. 4b) identifying the ±1 std dev over all the sites were generally in the range of 2–3% vol/vol. Data points represent regional averages of the theta-probe moisture readings and standard deviations at each site, for all of the 46 samples locations. Overall the trends, if not the actual values, are well represented across the regional scale. However, the trends for sites 8 and 9 (average of the two sites) are less well reflected, highlighting the difficulty in resolving the pixel-point-scale disparity. While areal-averaged values are able to retain dominant trends (Fig. 4b), local-scale responses are more difficult to capture (Fig. 4a).

Overall, the AMSR-E estimates describe a more rapid dry-down than do corresponding in situ measurements, which is likely a result of the different measurement sampling depths (1 versus 6 cm). The spatial homogeneity during the drier periods before 4 July is clearly featured in the AMSR-E estimates. A significant amount of variability is observed in the regional AMSR-E responses during the period of 7–14 July, corresponding to a number of precipitation events occurring across the region. Interestingly, this seems to be in contradiction to the theta-probe samples, which show reduced daily variations in the standard deviations over these wetter periods. Given the spatial distributions of soil moisture that is evident in the PSR imagery during this time (see below), it would be expected that more variation should be present than is observed in the

![Figure 3](image-url)
in situ measurements. While this is potentially a sampling depth issue, it could also be an artifact of averaging out the individual site standard deviations across the region. Still, in examining the individual standard deviations for all sites over the 16 days of measurement, 90% of the data had a standard deviation less than 4% vol/vol and 50% less than 2% vol/vol, indicating the reduced variation of in situ measurements compared to AMSR-E retrievals.

b. AMSR-E comparison with the PSR

PSR-derived soil moisture values, resampled to 0.125°, were compared to the single-pixel AMSR-E-retrieved values over the Walnut Creek catchment for all available PSR flights (see Fig. 5). While there appears to be a consistent bias between the PSR and AMSR-E values, with PSR estimates generally being higher than the corresponding AMSR-E predictions, the general trend is well reflected. AMSR-E values respond sharply to precipitation events occurring across the catchment on 4 and 6 July, but a lack of coincident PSR flights at this time limit a similar comparison for this sensor. Even with the limited samples, the consistent bias and dynamic response of the AMSR-E retrievals is reflected in the statistics, with a correlation coefficient of 0.72, a mean absolute error of 6.85% vol/vol, and an rms error of 7.47% vol/vol.

The relatively poor statistical comparison misrepresents the level of spatial coherence that is manifest in
the areal imagery. Regional-scale responses derived from both the resampled PSR and AMSR-E soil moisture retrievals are shown in Fig. 6. Although reflecting different sensor (C and X band) and scale characteristics (aggregated 800 m and disaggregated 25 km), these images illustrate a significant level of visual agreement, indicating that some confidence can be placed in the remotely sensed AMSR-E retrievals. The period preceding the rainfall event of 4 July (23 mm at the SCAN site) displays relatively homogeneous regional estimates across all scales of the PSR and in the 0.125° AMSR-E retrievals, although AMSR-E estimates are drier than the corresponding PSR values (consistent with Fig. 5). Although a significant amount of precipitation occurred on 4 July, the majority fell after the PSR flight and AMSR-E overpass, so its influence is not well represented. Where rain events are significant across the region (see Fig. 2), the identification of rain-affected areas is captured and displays consistency between the PSR and AMSR-E instruments (see 10–11 July in Fig. 6).

For the limited imagery that is available for the intercomparison, it would seem that AMSR-E retrievals are more sensitive to moist conditions than are the corresponding PSR estimates. These responses can, perhaps, be attributed to scale effects in the AMSR-E measurements, given that the coarse PSR imagery is originally determined from a much more spatially dense dataset, which more accurately captures the heterogeneity. As mentioned previously, there are also frequency differences between the two sensors, which are likely to influence the level of agreement between the retrievals. The sensing depth of PSR is about 1.5 times that of AMSR-E, and, as a result, AMSR-E may show a larger dynamic range in moisture responses, tending to be drier during dry conditions and wetter after rainfall. The coincidence of a number of smaller precipitation events (throughout June and July) that are timed in close proximity to the AMSR-E overpass tended to exaggerate the retrieval values, although these are not shown here. Overall, the AMSR-E retrievals illustrate a considerable level of agreement with the dynamic trends and statistical structure that is evident in the PSR imagery, correctly identify the transition from dry to wet states and the subsequent dry down and wetting up that occurs throughout the region.

5. Summary and conclusions

Considerable agreement was observed between watershed samples of the volumetric soil moisture and AMSR-E retrievals over a variety of surface and atmospheric conditions. The level of accord was reduced somewhat upon comparison with data from the regional values. AMSR-E values exhibited significantly more spatial variability across the region than did the corresponding ground-based samples, which illustrated a surprisingly consistent level of variability throughout the experimental period. It is interesting that more variation was not evident within the in situ measurements, particularly given the changing hydrometeorology over the experimental period. AMSR-E performs well over these varying conditions, reflecting reduced regional variability during dry periods and increased regional variability during periods with precipitation. It is not particularly surprising that in situ watershed measurements represent a more realistic estimate of the catchment-averaged soil moisture observed at the AMSR-E resolution than the comparatively few measurements taken at the regional scale.

These results raise some issues with regards to evaluating remotely sensed predictions. Apart from the fact that AMSR-E values are sensing a near-surface soil moisture response and in situ evaluation measurements are taken over the top 60 mm, few datasets exist that adequately capture the statistical variability over areas that are large enough to encompass the AMSR-E footprint. The PSR and similar airborne instruments represent an excellent compromise, but are limited in their broader and regular application. Although similar spatial patterns were reflected between the PSR and AMSR-E imagery, the soil moisture values from the PSR were derived using a different interpretive model than the emission model used here. It is not known what contribution this makes to the observed differences, with a consistent bias being observed between AMSR-E comparisons and also with the average watershed measurements. These disparities, however, are more likely a result of different model parameterizations, scales of measurement, and sensing depth, rather than algorithm differences.

While it is recognized that soil moisture exhibits levels of variability that are dependant on the scale at which it is observed, the relative importance of different controls on soil moisture in space and time is poorly understood (Wilson et al. 2004). Small-scale influences on the soil moisture, such as soil properties and vegetation, are difficult to distinguish from larger-scale controls, such as topography and atmospheric forcing (see Vinnikov et al. 1996; Entin et al. 2000). Given these factors, and the difficulty that exists in assessing remotely sensed products at large scales and over various domains using traditional techniques, some effort should be directed toward developing techniques that would offer a commensurate level of information against which comparisons could be made. Jackson et
Fig. 6. Resampled (left) PSR and (right) AMSR-E soil moisture retrievals at 0.125° throughout the SMEX02 campaign. Images are not strictly collocated because of geometric and projection differences (see Fig. 1). The dashed box represents the footprint of the aggregated PSR measurements. Both morning and afternoon AMSR-E overpasses were used depending on data availability. An outline of the Walnut Creek catchment is included for comparison.
al. (1993) explored such an approach, illustrating the relationship between microwave brightness temperatures and precipitation patterns over the Walnut Gulch catchment in southern Arizona. Similar hydrological pattern-based approaches offer an intuitive technique with which to assess soil moisture distributions and allow an excellent qualitative analysis to be attempted (e.g., McCabe et al. 2005).

More quantitative-based approaches might include the use of land surface models, such as comparing model output with remote sensing data at desired scales. The NLDAS determines soil moisture within a modeling framework, using observed and modeled atmospheric information to drive a number of land surface schemes, which, in turn, provide predictions of a variety of hydrological functions, such as surface fluxes, surface temperature, and soil moisture. However, soil moisture determination from these systems has been shown to be variable in both intercomparisons with the individual land surface models that comprise the NLDAS and against in situ records (see Robock et al. 2003; Mitchell et al. 2004; Schaake et al. 2004). While there is the potential for assessing the NLDAS predictions against remotely sensed retrievals, there is also an opportunity for assimilating these values back into the system to improve the spatial representation and predictive performance.

One of the key issues concerning the AMSR-E program is whether soil moisture retrievals can be reliably determined in the presence of agricultural biomass. The work presented here offers some progress toward this task, addressing the issue of soil moisture retrieval over landscapes where vegetation cover has a significant seasonal influence. Results from the AMSR-E analysis indicate that there is potential in determining soil moisture patterns over regional scales and larger, even where vegetation may prove to be an issue. There are, however, important issues of the within-pixel vegetation heterogeneity, scaling of vegetation indices, capture of vegetation surface dynamics, and techniques used to operationally determine these variables that remain unresolved and require further assessment.

Comparison of the soil moisture determined through local-scale sampling with larger-scale AMSR-E retrievals reveals a consistent level of agreement over a wide range of hydrometeorological conditions. Further examination of the scale influences on remotely sensed retrievals and the interactions between precipitation, varying vegetation dynamics, and also the distribution of surface fluxes are the focus of current work and will further assist in improving our understanding of these interrelated processes.

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REFERENCES


