Initial soil moisture retrievals from AMSR-E: Multiscale comparison using in situ data and rainfall patterns over Iowa

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Coupled with information from the North American Land Data Assimilation System (NLDAS), standard soil datasets and vegetation and land surface parameters, a land surface microwave emission model (LSMEM) is employed using AMSR-E brightness temperatures at X-band (10.7 GHz) to determine soil moisture over Iowa for June and July 2002. Comparisons of calculated soil moisture with in situ validation data collected from a densely monitored watershed as part of the SMEX02 campaign, indicate that accuracies in the order of 3% vol./vol. are achievable, even where agricultural surfaces such as corn and soybean dominate. Additionally, to qualitatively evaluate the derived product and identify the level of coherence between related hydrometeorological data, a comparison of soil moisture retrievals with precipitation patterns is undertaken. Consistent spatial correlation is observed between these two fields, illustrating not only that remotely sensed soil moisture has potential to provide improved characterisation of large scale precipitation patterns, but that such patterns may also offer a pathway towards enhanced assessment of soil moisture retrievals.


1. Introduction

The distribution of soil moisture patterns throughout a catchment plays a critical role in a variety of hydrological processes. Accurately characterizing the spatial distribution and temporal evolution of soil moisture would provide insight into larger scale processes and contribute to developments towards improved distributed modeling of terrestrial hydrologic processes. Observing the spatial distribution of soil moisture at the catchment scale is a difficult task requiring intensive field instrumentation for accurate spatial representation. At regional or continental scales, point scale measurement techniques are infeasible, limiting the ability to describe the spatial variability to meso-scale modeling or remote sensing approaches. As a consequence, much recent effort has been directed towards microwave remote sensing techniques, particularly with the advancement of assimilation approaches that combine land surface modeling with satellite retrieval options [Walker and Houser, 2001; Crow and Wood, 2003].

The launch of the Advanced Microwave Scanning Radiometer (AMSR-E) offers an opportunity to determine global soil moisture patterns at scales suitable for inclusion in land surface and general circulation models. While microwave techniques offer some advantages over instrumented networks, their utility is hampered by issues associated with retrieval depth, the coarse scale of current passive radiometric measurements and robust algorithm development. Radio frequency interference (RFI) [Li et al., 2004] at C-band and atmospheric and vegetation effects at higher frequencies also complicate accurate retrieval. With the development of various soil moisture algorithms [Njoku and Li, 1999; Owe et al., 2001; Gao et al., 2004] comes the need for rigorous assessment against available field data. A number of recent field experiments (see SMEX02 http://hydrolab.arsusda.gov) and data from in situ installations such as the Oklahoma Mesonet (http://www.mesonet.org), currently offer the best available means for evaluation, providing a critical link between algorithm assessment and product development. However, there are inherent disparities in comparing remotely sensed soil moistures with largely point scale measurements that limit a thorough assessment of spatial characterisation. There is a need for increased levels of spatially (and temporally) equivalent data sets. Unfortunately these are rarely, if at all, available.

In this study, soil moisture is estimated using the Land Surface Microwave Emission Model (LSMEM) of Driesch et al. [2004] and Gao et al. [2004], and evaluated with in situ data collected over a watershed in central Iowa, at a scale comparable with an AMSR-E footprint. Additionally, soil moisture patterns are compared with daily state-wide precipitation patterns, obtained from the North American Land Data Assimilation System (NLDAS) (http://ldas.gsfc.nasa.gov), to characterize the level of accord between these distinct hydrological variables. The results of this study demonstrate the capacity to estimate the near surface soil moisture over a variety of surface and hydrometeorological conditions, while obtaining accuracies suitable for use in land surface modeling applications. Furthermore, a strong correspondence between soil moisture fields and precipitation data was observed, giving confidence in the performance of the retrieval algorithm and offering a pathway towards improving the consistency in meteorological forcings and model output.

2. Modeling Framework

LSMEM was employed to estimate soil moisture values from AMSR-E brightness temperatures for the summer growing period over Iowa. Using an inverted numerical framework, soil moistures were determined from observed microwave brightness temperatures and ancillary data. LSMEM employs an iterative technique to estimate the soil moisture from an initial value, based on antecedent
moisture condition. Using radiative transfer theory, a brightness temperature is calculated corresponding to estimated moisture, surface temperature and land cover conditions, from which the emissivity value is also determined. Successive iterations are performed, based on varying the estimated soil moisture, until the computed and measured horizontal brightness temperature match to within acceptable bounds. The reader is directed to Gao et al. [2004] and McCabe et al. [2005] for further information on model implementation and a detailed description of LSMEM and its required parameter values.

3. Data Sources and Preprocessing

AMS-E 10.7 GHz (X band) horizontally polarized brightness temperatures were processed over Iowa for the period June through July 2002, coinciding with SMEX02. Brightness temperature data with a processed resolution of 25 km, were interpolated onto a 0.125 degree grid (approx. 14 km) using a combination of nearest neighbour and weighted average (2 pixels) approaches. These techniques minimize data smoothing. Interpolation was deemed necessary to maintain spatial consistency with precipitation, surface temperature and ancillary data such as vegetation and soil information, derived primarily from the NLDAS. While the quantitative analysis of soil moisture retrievals presented here focus on the Walnut Creek watershed due to the density of available field measurements, state-wide estimates of soil moisture were also produced for comparison with precipitation records. Two data sets were created from the processed ascending and descending orbits. Early morning overpasses (approx. 2 a.m.) were used in producing estimates of the diurnal change in soil moisture to ensure that rainfall events, particularly afternoon convective storms, are captured before significant evaporative and infiltration effects diminish their characterization. For the watershed analysis, a daily average of the morning and afternoon overpasses was calculated for comparison with in situ measurements.

4. Results and Discussion

4.1. Watershed Sampling in Walnut Creek, Iowa

SMEX02 provided a comprehensive watershed sampling, collecting some 4,500 theta probe measurements over 11 days between June 25 and July 12. Nineteen sampling sites (from a total of 33) were discriminated within a single resampled AMSR-E pixel over the Walnut Creek catchment, offering a spatially representative in situ soil moisture sample. AMSR-E early morning and afternoon retrievals were averaged and compared with the areally averaged in situ soil moisture. These data were sampled to coincide within a few hours of the afternoon AMSR-E overpasses. The Walnut Creek watershed comprises approximately 65% of the resampled AMSR-E pixel, offering excellent scale equivalence. The standard deviation both between and within the sample sites was not generally greater than 3%, indicating a high degree of spatial consistency across the watershed.

Figure 1 illustrates the comparison between measured and observed soil moisture, identifying the AMSR-E
retrievals coincident with theta probe samples and the ±1 standard deviations of in situ measures. Although only eight sample days were available for comparison, consistent agreement between the two measurements is evident. Considering both the scale disparity and the issue of differing sampling depths, there is a significant level of equivalence. A mean absolute error of 2.64% vol./vol. was calculated, having a correlation coefficient of 0.87. The RMS error of 4.1% vol./vol. was highly affected by a single ‘outlier’, attributed to soil moisture estimation immediately following an intense precipitation event after an extended dry period (July 6). The incidence of a saturated or close to saturation near surface storage can bias both remote sensing observations and in situ measurements. Exclusion of this data point reduces the RMS error by a factor of 2. While this level of accuracy exceeds expectations given the variety of scale, sensor and measurement issues, the SMEX02 watershed sampling represents the most equivalent form of comparison available for assessing remote measures. Further work is required to corroborate these results over longer time periods and with increased data length, particularly given that previous sensitivity studies indicate accuracy constraints on soil moisture retrievals for vegetation water contents exceeding 1.5 kg.m$^{-2}$ [Njoku and Li, 1999].

4.2. Correlation in Precipitation and Soil Moisture Patterns

While obtaining a quantitative equivalence between satellite retrieved soil moistures and in situ measures is a necessary task, there are clear obstacles in achieving a robust evaluation strategy based on traditional assessment techniques alone. Given that; 1) retrieved and measured soil moisture values use physically different estimation techniques; 2) scale disparities exist between the point measurement and satellite footprint; and 3) near surface soil moisture retrievals are not the same as depth averaged in situ techniques, it is critical to develop a variety of means to evaluate retrieved soil moisture. One approach is through the identification of expected responses in related hydrological process or proxy data streams.

To examine this concept further, soil moisture maps containing periods of wetting and drying dynamics were identified from two months of LSMEM based retrievals. Significant rainfall events were identified from the NLDAS data archive, which offers a combined gauge-radar rainfall estimate [see Cosgrove et al., 2003], allowing comparison between these different data streams. Some confidence in the soil moisture retrievals was gained through examination of drying periods subsequent to rainfall events, with retrieved imagery correctly distinguishing the recession of moist areas over this time. Of particular interest however, is the concurrence between increases in soil moisture and daily rainfall patterns. Some correlation between these variables should be expected, despite variations in soil properties, vegetation structure and antecedent conditions. In identifying suitable imagery to illustrate the hydrological response, it was important to ensure that; 1) a relatively dry period prior to the rain event to maximise the hydrological effect and 2) the rainfall occur in the afternoon or evening closest to the second AMSR-E overpass so as to maximize the preservation of moisture patterns and minimize the influence of evaporation and sub-surface drainage.

Three examples of rainfall-soil moisture coherence are presented in Figure 2, identifying changes in soil moisture between two AMSR-E overpasses separated by a precipitation event. Calculated differences are based on early morning overpasses of the day following the precipitation event, subtracted from the day before. Examining the rainfall distribution over Iowa, one can clearly delineate areas of correspondence in changes of the soil moisture storage. As expected, this is particularly so for heavier

Figure 2. Calculated soil moisture differences (% vol./vol.) for early morning AMSR-E overpasses (top) between days interceded by the precipitation event (mm) (bottom). See color version of this figure in the HTML.
precipitation, as is the case for July 19, but is still evident for less intense rainfall on June 26 and July 5. Interestingly, for the image around July 19, evidence of concentrated moisture loss is apparent in central-northern Iowa, possibly a sustained response to significant storm events there during July 10–11. A similar drying region is present in the difference map around July 5 (Figure 2b). However, no explanation for this is immediately apparent, since NLDAS records indicate no significant rainfall amounts in the previous 10 days.

[15] Comparing meteorology from products independent of the NLDAS, for instance the Iowa Environmental Mesonet (IEM) (http://mesonet.agron.iastate.edu/browser/), offers an increased level of assessment. While there are some mismatches both in spatial distribution and quantities, the precipitation sources generally agree quite well. However, soil moisture difference maps for all dates indicate regions which are not directly explained by either of the rainfall distributions. Such anomalies result from one (or all) of three possibilities: 1) soil moisture retrievals sometimes provide erroneous results; 2) NLDAS and similar products do not fully capture or describe precipitation events due to network sparsity; or 3) there is a spatial mismatch between incident rainfall and the observable soil moisture patterns. While both 1) and 2) certainly occur, 3) is apparent in all the examples shown here. Although rainfall patterns are well correlated with soil moisture distributions, there is a geographical inconsistency routinely observed in the surface moisture response. These spatial disparities have clear implications for distributed land surface modelling, where precipitation forcing is the primary control on surface flux development.

5. Conclusion

[16] Remote sensing approaches have potential to offer increased insight into large scale hydrological patterns and responses. However, efforts towards this task have been complicated by the difficulty in deriving, and then evaluating, robust interpretive models. Included amongst these problems is the vexing issue of how to assess remote sensing predictions. In evaluating remotely sensed soil moisture, the physical and intuitive link with patterns of precipitation has not been effectively exploited, with traditional quantitative analysis preferred to such qualitative approaches. As the availability of data increases through current and future satellite missions, so to will the need to validate these products over varied regions of the Earth; including regions where little if any in situ measurements exist. With improvements in the ability to remotely monitor precipitation, capturing the spatial patterns may provide an appropriate means of assessing soil moisture products, even where absolute accuracy remains an issue.

[17] In determining soil moisture from satellite platforms, the LSMEM algorithm provides robust and accurate estimates, consistent with observed hydro-meteorological conditions. The use of precipitation patterns derived from NLDAS illustrates the value of such proxy measurements in monitoring the performance of retrieval algorithms. Overall, there is a clear coherence of spatial patterns observed between these data sets. However, the converse of this approach raises an interesting possibility i.e. that soil moisture patterns might be able to improve the representation of precipitation patterns in operational data sets. Continued investigation utilising high resolution radar rainfall data, evaluating a more extensive period of records and encompassing a variety of land surface types, should further illustrate the capability and limitations of these alternative assessment techniques.

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References


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