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Using remotely-sensed estimates of soil moisture to infer soil texture and hydraulic properties across a semi-arid watershed

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Abstract

Near-surface soil moisture is a critical component of land surface energy and water balance studies encompassing a wide range of disciplines. However, the processes of infiltration, runoff, and evapotranspiration in the vadose zone of the soil are not easy to quantify or predict because of the difficulty in accurately representing soil texture and hydraulic properties in land surface models. This study approaches the problem of parameterizing soil properties from a unique perspective based on components originally developed for operational estimation of soil moisture for mobility assessments. Estimates of near-surface soil moisture derived from passive (L-band) microwave remote sensing were acquired on six dates during the Monsoon '90 experiment in southeastern Arizona, and used to calibrate hydraulic properties in an offline land surface model and infer information on the soil conditions of the region. Specifically, a robust parameter estimation tool (PEST) was used to calibrate the Noah land surface model and run at very high spatial resolution across the Walnut Gulch Experimental Watershed. Errors in simulated versus observed soil moisture were minimized by adjusting the soil texture, which in turn controls the hydraulic properties through the use of pedotransfer functions. By estimating within a continuous range of widely applicable soil properties such as sand, silt, and clay percentages rather than applying rigid soil texture classes, lookup tables, or large parameter sets as in previous studies, the physical accuracy and consistency of the resulting soils could then be assessed.

In addition, the sensitivity of this calibration method to the number and timing of microwave retrievals is determined in relation to the temporal patterns in precipitation and soil drying. The resultant soil properties were applied to an extended time period demonstrating the improvement in simulated soil moisture over that using default or county-level soil parameters. The methodology is also applied to an independent case at Walnut Gulch using a new soil moisture product from active (C-band) radar imagery with much lower spatial and temporal resolution. Overall, results demonstrate the potential to gain physically meaningful soil information using simple parameter estimation with few but appropriately timed remote sensing retrievals.

Keywords: Parameter estimation; Soil moisture; Active microwave; Passive microwave; PBMR; Land surface modeling; Model calibration; Soil hydraulic properties; Temporal sampling; Watershed modeling; Soil type; Pedotransfer functions

1. Introduction

Soil moisture remains an essential yet elusive component of Earth system science research across a wide range of scales and applications. In addition to impacting agriculture, water resource management, and extreme events such as flooding and drought, the day-to-day variability in soil moisture on field

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to global scales is an important quantity for atmospheric modeling and prediction. In fact, the accuracies of climate, mesoscale, boundary layer, land surface, and hydrologic models are ultimately dependent on proper treatment and simulation of the state and transfer of water and heat at the land surface (Betts, 2000; Betts et al., 2003; Berbery et al., 2003; Findell & Eltahir, 2003; Koster, 2004).

Unfortunately, soil moisture is not as easily measured or observed as atmospheric properties such as temperature, humidity, and wind speed. For example, in-situ or remotely-sensed observations of soil moisture for initialization, update, and validation purposes are not yet available on the scales of most models. Observations are generally confined to short-term field experiments, many of which have highlighted the heterogeneous nature of soils in terms of water content and texture (Mohanty et al., 2002). Indirect estimates of soil moisture can be obtained using thermal infrared measurements (Carlson et al., 1995), but require a priori information on the surface characteristics. As an alternative, passive and active microwave remote sensing methods have had the greatest success in estimating soil moisture in a temporally and spatially consistent manner (Hollenbeck et al., 1996; Moran et al., 2004; Thoma et al., 2006).

Recent studies have noted that the most successful and promising approach to estimating soil moisture continuously over time and space must include a combination of remote sensing and modeling (Entekhabi et al., 1999; Houser et al., 1998). The majority of land surface models (LSMs) require soil hydraulic parameters to solve for the transport of moisture within the soil using Richards' (1931) formulations. These parameters are often derived from soil texture information, but due to the heterogeneous nature of soils and lack of detailed maps of soil properties, soil parameterization schemes are often crude, inflexible, or inappropriate. Further, LSM simulation of soil moisture can be more dependent upon the specification of hydraulic parameters than atmospheric forcing or surface conditions (Gutmann & Small, 2005; Pitman, 2003; Santanello & Carlson, 2001).

Because of these difficulties, numerous attempts have been made to optimize LSM parameters using observations of state variables such as soil moisture and surface temperature as constraints (Gupta et al., 1999; Hess, 2001; Hogue et al., 2005; Liu et al., 2004, 2005). While these studies highlight the potential for parameter estimation techniques to derive large sets of 'effective' parameters and diagnose specific model weaknesses, little has been gained in terms of acquiring physically meaningful or hydraulically consistent estimates of individual parameters. Because of the complexity and number of estimation techniques and parameter sets employed in these studies, it remains difficult to infer or derive any parameter information that could be applied to other independent studies or models.

With these issues in mind, this paper examines the potential use of passive and active microwave retrievals of near-surface soil moisture to calibrate an LSM and infer a physically meaningful and consistent set of soil hydraulic parameters, using a combination of high-resolution land surface modeling and parameter estimation. The experimental design of this work was originally developed for the purpose of estimating troop and vehicle mobility for the United States Army based on operational soil moisture prediction from a very limited set of input data (Army Remote Moisture System; ARMS; Tischler et al., 2007). Here, we have tested and extended ARMS to assess the ability of parameter estimation techniques to minimize inherent model error, yet still provide information on difficult to obtain soil properties over the Walnut Gulch Experimental Watershed in Arizona.

Accordingly, Section 2 summarizes the current state of knowledge of the many components of the ARMS project including soil parameterizations in LSMs, microwave remote sensing of soil moisture, and parameter estimation. In Section 3, the models, site, and remote sensing data employed in this study are described. Results of the calibration experiments are presented in Section 4, including an evaluation of the optimized parameters and sensitivity to temporal sampling of remote sensing. Finally, Section 5 discusses the limitations and applicability of the results, including suggestions for the future utility of physically meaningful parameters in LSMs.

6. Conclusions

This paper has examined a straightforward method of using microwave remote sensing of near-surface soil moisture to calibrate an offline land surface model, and in the process infer soil texture and hydraulic properties at high spatial resolutions. This approach expands and improves upon a wide body of previous work by incorporating pedotransfer functions into the LSM to ensure consistent and physically meaningful soil parameters, and by addressing the temporal sampling of remote sensing imagery needed for successful calibration. As a testbed for the ARMS project, this research was able to retrieve soil texture and property estimates that correspond well with observed soils over the WGEW. Once estimated for this region, these parameters were also used to simulate soil moisture over seasonal time scales with a great deal of accuracy compared to simulations with default soils and soil properties based on lookup tables.

Specific results of this study include the following:

1) Limited microwave retrievals of near-surface soil moisture can be used to calibrate an LSM to within .02 $m^3\ m^{-3}$ accuracy at high temporal and spatial resolutions.
2) Optimizing soil hydraulic properties using PTFs gives better and more physically meaningful results than a one-at-a-time parameter estimation approach.
3) Errors in the calibration process are minimized when there are at least 3 images included that represent the typical range of moisture exhibited by the soil type during a drydown period.
4) Independent tests indicate that this methodology can be successful in calibrating LSMs over seasonal and longer timescales for use in specialized prediction systems.