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Upscaling of field-scale soil moisture measurements using distributed land surface modeling

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Abstract

Accurate coarse-scale soil moisture information is required for robust validation of current- and next-generation soil moisture products derived from spaceborne radiometers. Due to large amounts of land surface and rainfall heterogeneity, such information is difficult to obtain from existing ground-based networks of soil moisture sensors. Using ground-based field data collected during the Soil Moisture Experiment in 2002 (SMEX02), the potential for using distributed modeling predictions of the land surface as an upscaling tool for field-scale soil moisture observations is examined. Results demonstrate that distributed models are capable of accurately capturing a significant level of field-scale soil moisture heterogeneity observed during SMEX02. A simple soil moisture upscaling strategy based on the merger of ground-based observations with modeling predictions is developed and shown to be more robust during SMEX02 than upscaling approaches that utilize either field-scale ground observations or model predictions in isolation.

Keywords: Distributed land surface modeling; Microwave remote sensing; Surface soil moisture

1. Introduction

No passive spaceborne soil moisture sensor in the foreseeable future will have a ground spatial resolution finer than 30-km. Current soil moisture observations from the advanced microwave scanning radiometer (AMSR) sensor aboard the NASA AQUA satellite, for instance, are derived from radiometer observations with a -3 dB resolution of $\sim$60 km. Given the magnitude of heterogeneity typically observed in surface soil moisture fields [1,36,15,16], ambiguities associated with upscaling point-scale observations to spaceborne radiometer footprint scales have emerged as a major challenge in attempts to validate remote sensing soil moisture retrievals [18,10].

Even extensive soil moisture networks like the Oklahoma Mesonet, the Illinois Water Survey, and the Southern Great Plains ARM-CART system have an average site spacing greater than 30 km and will provide, at best, a single observation within a given footprint. Networks with denser soil moisture sampling locations typically cover only a fraction of a radiometer footprint and will be vulnerable to extrapolation error in the presence of heterogeneous rainfall. Some of these difficulties can be mitigated through optimized interpolation and site selection approaches. Block-kriging techniques, for instance, allow for the optimal interpolation of point-scale measurements based on a spatial field's auto-correlation structure. This possibility has spawned interest in accurately measuring and/or generalizing the spatial structure of soil moisture fields under various hydrologic

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conditions [12,40,38,25]. There is also growing evidence that surface soil moisture fields, due to the static influence of soil, vegetation, and topography, exhibit temporally persistent spatial patterns at local scales (<5 km) [37,18,26,22]. Such persistence, or time stability, can be exploited by selecting measurement sites which consistently reflect soil moisture conditions over a wider geographic area. However, the upscaling skill of time-stability methodologies is reduced by the impact of spatially heterogeneous rainfall [10] which may reduce it's effectiveness when applied within coarser footprint scales (>10 km).

In addition to ground-based networks, an alternative source of surface soil moisture is distributed land surface modeling. Such models can synthesize spatially distributed rainfall, land use, soil, and topographic maps to produce surface soil moisture predictions over large-spatial areas. Because they are distributed in nature, these predictions do not suffer from the same spatial support and sampling density inadequacies as ground-based networks. However, the use of unconstrained model output as a source of validation data is likely to be problematic. Reasons for skepticism include well-known errors in spatial patterns of observed rainfall [34] and soil texture fields [44] typically used to force models, difficulties surrounding proper model calibration and parameter identification [4,20,21], and the inability of current observing systems to measure some key model inputs (e.g. wind speed and relative humidity) at fine spatial scales (<10 km). In addition, absolute levels of modeled soil moisture have been shown to be highly model dependent [24,13]. This implies that model representation of relative space/time patterns may be more meaningful than predictions of absolute soil moisture magnitudes. However, to date, relatively few validation studies have focused explicitly on evaluating spatially distributed predictions from land surface models [19].

A third possibility are approaches based on a combination of distributed modeling and local soil moisture observations. A range of possible strategies exist including data assimilation and model calibration strategies. But the basis of each is the presumption that model output, at the very least, contains basic spatial information about the relative relationship between soil moisture at a given measurement location and spatially averaged soil moisture within some larger regional area. If this is true, the relative spatial patterns predicted by the model can be integrated with sparse ground-based observations to improve estimates of footprint-scale soil moisture averages. Such integrated estimates will be more accurate than unconstrained model predictions if the relative patterns of soil moisture predicted by models prove more robust to modeling uncertainty than predictions of absolute soil moisture.

Intensive soil moisture sampling conducted during the Soil Moisture Experiment in 2002 (SMEX02) between June 25 and July 12, 2002 in central Iowa provides an unique opportunity to test aspects of this hypothesis and examine the potential role of land surface modeling in upscaling local soil moisture observations. Specifically, this analysis will evaluate the degree to which a land surface hydrology model can accurately reproduce surface (0–6 cm) soil moisture heterogeneity and spatial patterns observed in extensive ground-based soil moisture observations made during SMEX02. Basic upscaling strategies that use TOPLATS simulations to upscale local-scale observations to footprint-scale (>30 km) soil moisture means will be evaluated based on their potential as validation strategies for coarse-scale spaceborne soil moisture retrievals. As a first step, this analysis will focus primarily on upscaling field-scale (800 m) soil moisture observations. However, prospects for upscaling point-scale observations will also be discussed.

2. Land surface modeling

Land surface modeling was based on TOPmodel-based Land Atmosphere Transfer Scheme (TOPLATS) [14,28] predictions over the 6378 km^2 regional domain displayed in Fig. 1. A model grid size of 90-m, requiring approximately 800,000 individual pixels, was used for all simulations. Several modifications were made to the model relative to the baseline version described in [28]. Most critically, the two-layer soil water balance was expanded to four layers. Calculations of diffusive and gravity drainage fluxes retain the same numerical form. However, these fluxes are now calculated for each of four soil layers and simultaneously balanced using a semi-implicit numerical scheme. The modification requires new user inputs of depths for the top three soil layers (the fourth soil layer is bounded at the bottom by a dynamic water table depth) and the specification of areal rooting fractions in all four layers. Results for the new four-layer version of TOPLATS are also reported in [11].

A second modification was made to allow for the calculation of separate soil and canopy contributions to evapotranspiration within TOPLATS grid elements. Previous versions of TOPLATS required that grid elements be characterized as either solely bare soil or solely vegetated with direct soil evaporation neglected in vegetated pixels. In reality, soil evaporation plays a significant role in determining surface soil moisture under sparse canopies and between crop rows. To capture this, total grid cell evapotranspiration (E_T) was calculated as:

$$E_T = f_v T + (1 - f_v)E, \quad (1)$$

where f_v is the vegetated fraction of the grid cell, T is the transpiration calculated from the vegetated fraction of grid cell, and E is direct soil evaporation from the bare