Different Rates of Soil Drying after Rainfall Are Observed by the SMOS Satellite and the South Fork in situ Soil Moisture Network

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(Manuscript received 15 July 2014, in final form 31 October 2014)

ABSTRACT

Soil moisture affects the spatial variation of land–atmosphere interactions through its influence on the balance of latent and sensible heat fluxes. Wetter soils are more prone to flooding because a smaller fraction of rainfall can infiltrate into the soil. The Soil Moisture Ocean Salinity (SMOS) satellite carries a remote sensing instrument able to make estimates of near-surface soil moisture on a global scale. One way to validate satellite observations is by comparing them with observations made with sparse networks of in situ soil moisture sensors that match the extent of satellite footprints. The rate of soil drying after significant rainfall observed by SMOS is found to be higher than the rate observed by a U.S. Department of Agriculture (USDA) soil moisture network in the watershed of the South Fork Iowa River. This leads to the conclusion that SMOS and the network observe different layers of the soil: SMOS observes a layer of soil at the soil surface that is a few centimeters thick, while the network observes a deeper soil layer centered at the depth at which the in situ soil moisture sensors are buried. It is also found that SMOS near-surface soil moisture is drier than the South Fork network soil moisture, on average. The conclusion that SMOS and the network observe different layers of the soil, and therefore different soil moisture dynamics, cannot explain the dry bias. However, it can account for some of the root-mean-square error in the relationship. In addition, SMOS observations are noisier than the network observations.

1. Introduction

Soil water content is arguably the most important factor in determining the spatial variation in land–atmosphere interactions, the exchange of mass and energy that occurs when energy from the sun is absorbed by Earth’s surface (e.g., Campbell and Norman 1998). Consider the following. The albedo of bare soil depends strongly on its water content. The Bowen ratio (the ratio of sensible heat flux to latent heat flux) will be much smaller for bare soil when it is wet than when it is dry because much of the absorbed solar radiation will be consumed by the latent heat of vaporization as soil water evaporates and water moves from the surface to the atmosphere. Adequate soil water will support vegetation, and when vegetation is present, a soil water potential in the root zone greater than the wilting point will result in transpiring plants and the Bowen ratio will
again be small. When plants are stressed, they close their stomata to conserve water, the Bowen ratio increases, and the color of the vegetation lightens, which increases the albedo of the canopy (Jacobs and van Pul 1990). It is therefore not surprising that soil moisture has been found to play an important role in the weather and climate of Earth’s atmosphere (e.g., Findell and Eltahir 2003; Koster et al. 2003; Gutowski et al. 2004).

Soil moisture also plays an important role in land surface hydrology, and specifically in the occurrence and severity of flooding (e.g., Hillel 2003). The soil receives and stores the water brought by precipitation. When soil has a good structure (large aggregates and pores), water from precipitation can more easily infiltrate and the soil can store larger amounts of water. Soils that are at or close to saturation will not be able to receive more water from subsequent precipitation, which leads to runoff and flooding. Besides the destructive power of flood water, runoff and flooding degrade soil structure through erosion and carry with it eroded soil and other chemicals that pollute rivers, lakes, and streams. Foreknowledge of the water stored in soil may enable improved forecasts of the location, timing, and severity of flooding (Komma et al. 2008; Wanders et al. 2014).

The European Space Agency’s Soil Moisture Ocean Salinity (SMOS) satellite was launched in 2009 in order to make observations of near-surface soil moisture, which is the water content of the first few centimeters of the soil at the soil surface (Kerr et al. 2010). The SMOS satellite carries an L-band (frequency of 1.4 GHz, corresponding wavelength of 21 cm) radiometer, or passive microwave remote sensing instrument. This instrument measures the electromagnetic radiation in the microwave portion of the spectrum that is naturally emitted by Earth’s surface. Terrestrial microwave emission depends on soil water content because the emissivity of soil is nearly directly proportional to its moisture content because of the high dielectric constant of liquid water at microwave wavelengths and the relatively low dielectric constant of air and vegetation (e.g., Ulaby and Long 2013). At L band the atmosphere is essentially transparent, emits negligible radiation, and there is little extraterrestrial radiation. Hence, the brightness temperature of the radiation captured by SMOS is directly proportional to the temperature of Earth’s surface and its emissivity. As the soil water content increases, the terrestrial emissivity decreases and less microwave radiation and lower brightness temperatures are observed by SMOS.

It is near-surface soil moisture that is the source of evaporating water and the soil water content that determines the balance between infiltration and runoff. Frequent observations of near-surface soil moisture can also be used to estimate soil moisture at greater depths, such as the water accessible to plants (Calvet and Noilhan 2000), and thus, the entire reservoir of water that can be exchanged between the soil and the atmosphere. To most effectively use satellite observations of near-surface soil moisture in weather, climate, and land surface hydrology models, the observations must be quantitatively assessed in comparison to a standard so that the statistical properties of the observations can be found. This process is called validation.

One of the current approaches to validate satellite observations is to use measurements of near-surface soil moisture made with a limited number of in situ sensors arranged in a sparse network to properly account for the spatial variability of near-surface soil moisture across large satellite footprints on the order of tens of kilometers (Cosh et al. 2004, 2006; Crow et al. 2012). However, we hypothesize that the reservoir of soil water observed by an in situ soil moisture network is fundamentally different than the reservoir of soil water observed by SMOS. If this hypothesis is true, wetting events will result in satellites and in situ networks observing different values of near-surface soil moisture and could therefore lead to inaccurate validation statistics.

We make this hypothesis because the L-band emission from land surfaces originates within the first few centimeters of the soil surface. The water content of this layer of soil at the surface may wet and dry at a different rate than the soil that is measured by an in situ soil moisture network, whose sensors are typically located at a fixed depth below the soil surface and are therefore sensitive to the water content of a different layer of soil, a layer centered at the depth of the sensor, farther away from the soil surface. The geometry of this situation is shown in Fig. 1. This circumstance is unavoidable: for practical reasons, in situ sensors must be buried below the surface because the physical geometry of many, if not all, in situ sensors requires burial at a deeper depth for the sensor to remain in place for long periods of time.

In this work, we compare observations of near-surface soil moisture made by SMOS to observations of near-surface soil moisture made by a U.S. Department of Agriculture (USDA) in situ soil moisture network located in the watershed of the South Fork Iowa River during and after the period of the Iowa Flood Studies (IFloodS) experiment in the state of Iowa. Again, we hypothesize that these near-surface soil moisture observations are fundamentally different and therefore exhibit different soil moisture dynamics. We will test our hypothesis by investigating how these two observations change after precipitation events.
2. SMOS versus in situ sensor near-surface soil moisture

A variety of sensors are available to measure in situ soil moisture, but all have one thing in common: they are sensitive to soil moisture (and more strictly, the electrical properties) of a finite volume of soil with nonzero thickness because of the specific measurement technique that they employ and resulting physical geometry of the sensor. This point is especially relevant when measuring near-surface soil moisture because gradients of soil moisture can exist near the soil surface. The South Fork network soil moisture sensors are Hydra Probes (Stevens Water Monitoring Systems, Inc.). According to the manufacturer, these sensors have a sensing volume that is a cylinder of diameter 3.0 cm and length 5.7 cm. In the South Fork watershed, these sensors are installed at 5 cm below the soil surface for both practical and theoretical reasons. First, in order to avoid potential influence from changes in water content that may occur above the soil, the centerline of the probe must be installed at least 1.5 cm below the soil surface. In reality, the sensor must be installed at least 2–3 cm below the surface because nearly all soil surfaces are not perfectly flat. Second, the farther into the soil any sensor is buried, the more likely it will stay in place for a long period of time. It is usually not practical to continually monitor whether a soil moisture sensor is still in place. Third, both SMOS and NASA’s Soil Moisture Active Passive (SMAP) mission (another L-band satellite instrument for which the South Fork network was installed) have an objective to measure the soil moisture of the 0–5-cm layer to within a 0.04 m³ m⁻³ root-mean-square error (RMSE; Kerr et al. 2010; Entekhabi et al. 2010). However, when installed at 5 cm, the sensor is technically sensitive to the moisture content of the 3.5–6.5-cm layer of soil.

In contrast, the near-surface soil moisture observed by satellite passive microwave remote sensors corresponds to a layer of soil immediately at the soil surface. Schmugge et al. (1974) were one of the first to report in the scientific literature that passive microwave remote sensing could be used to monitor near-surface soil moisture. They found a linear relationship between the L-band brightness temperature observed by an airborne radiometer and the 0–15-cm gravimetric soil moisture in bare fields. Wilheit (1978) created a model of coherent electromagnetic fields to predict the reflectivity (and thus emissivity) of a layered surface such as a soil. The model indicated that L-band radiometry would be sensitive to changes in soil moisture over a depth of between \( \frac{1}{8} \) and \( \frac{1}{10} \) of a wavelength (2–3 cm). Schmugge and Choudhury (1981), while investigating both coherent and noncoherent (power but not phase) radiative transfer models, used measured soil moisture and temperature profiles to estimate that the L-band emitting depth is approximately 2 cm.

Newton et al. (1982) conducted experiments with a ground-based L-band radiometer that supported the prediction of a 2-cm emitting depth. Njoku and O’Neill (1982) also conducted experiments and found that the L-band brightness temperature best correlates to 0–2 cm despite also measuring the soil moisture of the 0–5-cm layer. Wang et al. (1983) reported on the relationship of L-band brightness temperature and 0–2.5-cm soil moisture despite also measuring soil moisture at deeper depths, including 0–5 cm. However, Schmugge et al. (1986) reviewed passive microwave remote sensing research and focused on 0–5 cm as the emitting layer at L band. Meanwhile, Wang (1987) reported on the relationship between L-band brightness temperature and 0–2.5-cm soil moisture despite also measuring soil moisture at deeper depths. Jackson and Schmugge (1989) stated that at L band a 5-cm emitting depth has been shown to be appropriate by “experimental studies,” but no data or references to these studies were provided.

Pampaloni et al. (1990) used an airborne L-band radiometer to observe bare and vegetated agricultural fields in Italy. The lowest correlation between brightness temperature and soil moisture was observed for 0–1-cm soil moisture and the highest correlation was observed for 0–20-cm soil moisture. However, the authors noted...
that the soil moisture profiles they measured were fairly uniform, and therefore, there was a high correlation between soil moisture at shallower and deeper depths.

Jackson et al. (1997) critically examined the current research on the emitting depth at L band. Using a truck-mounted radiometer system, they compared observations of horizontally polarized emissivity to the emissivity predicted with a model that assumed a layer of soil with uniform properties and soil moisture. For bare soil, the best estimates of emissivity were made when they used soil moisture observations from the 0–3- or 0–5-cm layers. For a maize canopy, the best estimates were made with soil moisture from the 0–5-cm layer.

Laymon et al. (2001) used a truck-mounted radiometer system and found that both 0–3 and 0–5 cm appeared to be appropriate at L band and that the emitting depth varies with soil water content, being shallower for higher water contents. Schneeberger et al. (2004) used a ground-based radiometer to demonstrate that soil drying starts at the surface and progresses into the soil. Thin layers near the surface can have a great effect on the L-band brightness temperature, particularly during wetting events. Escorihuela et al. (2010) analyzed data from a tower-mounted radiometer and also found that the sampling depth depends on soil moisture conditions.

When considering the entire dataset (both a dry period when soil moisture was less than 0.20 m$^{-3}$ and the complementary wet period), the emitting depth appeared to be 2 cm. For the wet period, the emitting depth was shallower (about 1 cm) and for the dry period, the emitting depth was larger (about 3 cm) for horizontally polarized brightness temperature.

Jackson et al. (2012) analyzed near-surface soil moisture from SMOS and from the USDA Agricultural Research Service (ARS) in situ networks in Arizona, Oklahoma, Georgia, and Idaho. Each network employs the same sensors at the same depth as the South Fork network. They found that the observations compared favorably and that SMOS was close to accomplishing its goal of a 0.04 m$^{-3}$ RMSE accuracy. Al Bitar et al. (2012) compared SMOS observations with in situ soil moisture measurements at a depth of 5 cm at USDA Soil Climate Analysis Network (SCAN) sites. They found that, in general, SMOS observations exhibited a larger dynamic range, which they hypothesized could be caused by the satellite instrument observing a layer of soil closer to the surface that wets and dries more quickly than a deeper soil layer monitored by the SCAN sites. However, these SCAN sites are single points (and not a network of in situ measurements), and thus, there is a large scale mismatch with satellite observations.

Recent theoretical modeling conducted by Goodberlet and Mead (2012) indicated that the soil moisture sampling depth at L band may be less than 1 cm. Finally, Dimitrov et al. (2014) found in an experiment with a tower-mounted radiometer observing bare soil that a model performed better compared to observations when it used 0–2-cm soil moisture than 0–5-cm soil moisture.

This summary of research on the topic of the L-band soil moisture sampling depth is not exhaustive, but it is a good example of the variety of conclusions that have been made. It is important to note that not all of these experiments used direct (gravimetric sampling) measurements of near-surface soil moisture through the emitting depth. Some employed models of heat and moisture transport in soil to infer the water content of thinner soil layers that were not directly measured from other layers of soil that were directly measured. There are three things to keep in mind. First, in situ and remote sensors observe quantities of soil water that are significantly different: in situ sensors measure a layer of soil below the soil surface, and remote sensors observe a layer of soil at the soil surface. (And, in fact, both observe electrical properties that are related to soil moisture via models.) Second, it is not clear how thick this layer observed by L-band radiometers is, and it may vary with moisture content. Third, both SMOS and SMAP have directives from their respective space agencies to measure the 0–5-cm soil moisture to within a 0.04 m$^{-3}$ RMSE. The question remains as to whether an actual difference in soil moisture between the layer of soil observed by a remote sensor (at the soil surface) and the layer of soil measured by an in situ sensor (at a depth below the surface) exists at the satellite scale, and whether this difference is important or not.

3. Experiment

We tested our hypothesis concerning the soil moisture dynamics observed by satellites versus in situ networks with observations from SMOS and satellite-scale near-surface soil moisture observed by a network of in situ sensors that has been developed in the watershed of the South Fork Iowa River in central Iowa. Many of the observations were collected during the IFloodS experiment. The goal of IFloodS was to provide data for the assessment of the strengths and weaknesses of precipitation retrievals from space in the context of land surface hydrology. Accordingly, ground-based observations of precipitation were made with both remote sensing instruments and in situ gauges along with measurements of other hydrologic variables such as streamflow and soil moisture in the South Fork Iowa River basin and the Turkey River basin.

The South Fork watershed is dominated by row crop agriculture, primarily maize (corn) and soybean. In
2012, 82% of the watershed was planted in row crops (59% of the land area in maize, 23% in soybean). There has been a slight decrease in the coverage of row crops over the last several years, and the fraction of land area in soybean has slowly decreased due to maize being more profitable (in 2003, 87% of the land area was row crop and 35% of the land area was in soybean). The locations of the nodes that compose the network are shown in Fig. 2. At each station, Hydra Probe sensors were installed to measure volumetric soil moisture and soil temperature at 5, 10, 20, and 50 cm. Two tipping-bucket precipitation gauges were also installed at each station. Installation was completed in April 2013 before the beginning of IFloodS and to prepare for SMAP validation activities. The soil moisture sensors have been calibrated to the specific soil found at each node. More information about the watershed and the network can be found in Coopersmith et al. (2015).

Figure 2 also contains the locations of the three SMOS pixel centers that are nearest to and therefore relevant to the watershed. SMOS uses the Icosahedral Snyder Equal Area (ISEA) 4H9 grid. Each point of this grid has a fixed latitude and longitude and is referenced by a discrete global grid (DGG) identifier. While the grid resolution is 15 km, the actual footprint or area of ground that contributes to the signal measured by SMOS is at least 40 km in diameter. Hence, SMOS data are oversampled and the SMOS pixels defined by DGG’s 200056, 200057, and 200569 each cover large fractions of the watershed. We used version 5.51 of the SMOS Level 2 Soil Moisture product, which employs the Mironov et al. (2009) soil dielectric model.

We identified nine periods of dry weather after significant rainfall between day of year 115 and 330 in 2013. These periods are shown in Fig. 3. Vegetation attenuates microwave emission from the soil, and at high column densities completely masks the soil moisture signal. The period of time we examined encompasses the full growing season of maize and soybean. However, it has been shown that L-band radiometry is sensitive to near-surface soil moisture throughout the growing season for maize (Hornbuckle and England 2004), and since soybean does not accumulate as much biomass, we are able to use SMOS observations throughout the year in the South Fork watershed.

4. Results

We fit an exponential model to SMOS and in situ network near-surface soil moisture observations for the nine periods of dry weather defined in Fig. 3:

\[
\theta_v = Ae^{Bt} + C, \quad (1)
\]

where \(\theta_v\) is the volumetric soil moisture; \(A\), \(B\), and \(C\) are real numbers unique to SMOS and network soil moisture for each case; and \(t\) represents time. The rate of soil drying \(D(t)\) is equal to the absolute value of the time derivative of (1):

\[
D(t) = \text{rate of soil drying} = \left| \frac{\partial \theta_v}{\partial t} \right| = |ABe^{Bt}|. \quad (2)
\]

We define \(D_i\), the initial rate of soil drying, as (2) evaluated at \(t = 0\):

\[
D_i = \text{initial rate of soil drying} = D(t = 0) = |AB|. \quad (3)
\]

An example of our procedure is shown in Fig. 4. This is case 3 in Fig. 3, which includes day of year 180. Soil moisture observations from the network and from SMOS pixel 200056 along with the appropriate fits using (1) are shown in Fig. 4 (top). A significant rainfall resulted in an increase in soil moisture and a subsequent decrease in near-surface soil moisture over a period of 15 days. This period of time after rainfall is often called a drydown. We will refer to it simply as soil drying. The difference (residuals) between the observations and each fit are shown in Fig. 4 (middle). Note that the SMOS observations are more variable over time.
The rate of soil drying over the 15-day period is shown in Fig. 4 (bottom). The rate of soil drying is greater for SMOS than for the network over the first 5 days.

The initial rate of soil drying and the RMSE of the observations compared to the fits for all nine cases are compiled in Table 1. The values of $D_i$ for each SMOS pixel are greater than the network (often much greater) for all cases except for cases 5 and 7, where $D_i$ for two of the three SMOS pixels is $0.02 \text{m}^3 \text{m}^{-3} \text{day}^{-1}$, the other SMOS pixel is $0.01 \text{m}^3 \text{m}^{-3} \text{day}^{-1}$, and the network is $0.01 \text{m}^3 \text{m}^{-3} \text{day}^{-1}$. The largest network value among the nine cases is $0.03 \text{m}^3 \text{m}^{-3} \text{day}^{-1}$ (for cases 2 and 3), while there are four cases when one or more SMOS pixels have $D_i \geq 0.10 \text{m}^3 \text{m}^{-3} \text{day}^{-1}$. The value of $D_i$ will depend on the distance from the soil surface at which the soil water content is measured, soil hydraulic properties, the size and duration of the preceding rain event, the antecedent soil moisture conditions, and weather conditions such as solar radiation, wind speed, and the relative humidity of the boundary layer (e.g., Campbell and Norman 1998). Larger values of $D_i$ for the SMOS pixels are consistent with SMOS observing a layer of soil at the soil surface, which can more readily lose water via evaporation and infiltration than the layer of soil observed by the network, which is farther away from the surface and underneath the surface layer and hence dries less quickly. Also note that the SMOS observations are noisier (have a higher RMSE) than the network observation in each case.

5. Analysis

To analyze the rates of soil drying found for SMOS and the South Fork network, we pursue three objectives in this section. First, we verify that (1) can be used to model soil drying. Second, we show that different rates of soil drying indicate that different soil layers are being observed. We do this by using both an agroecosystem model appropriate for changes in soil moisture that occur at a single point and a small network of in situ soil moisture sensors distributed within a $1 \text{ km} \times 1 \text{ km}$ field of maize that more closely replicates changes in soil moisture that occur over larger spatial scales. Finally, we investigate how the use of near-surface soil moisture from in situ networks may impact the validation of satellite observations.

a. Verification of the simple model of soil drying

To verify that (1) is appropriate for changes in near-surface soil moisture following a rainfall event, we used an agroecosystem model [the agricultural version of the Integrated Biosphere Simulator with variably saturated flow component (Agro-IBIS VSF; Soylu et al. 2014)] to simulate soil drying. This model is similar to other land surface models in that it estimates the exchange of energy and water between Earth’s surface and atmosphere. It is different from many models in two main ways. First, the properties of the vegetation canopy, such as height and leaf area index, are prognostic, which means that the vegetation develops in response to actual
weather conditions instead of being prescribed. Second, it simulates coupled energy and moisture transport in the soil in response to gradients in soil water potential such that capillary rise from a water table can occur. We ran the model for the 2011 growing season using in situ measurements of precipitation, solar radiation, air temperature, relative humidity, and wind speed observed in a 1 km × 1 km field of maize near Ames, Iowa, and validated the model using soil moisture observed by a calibrated cosmic-ray neutron detector (Irvin 2013; Carr 2014). This field is approximately 50 km from the center of the South Fork watershed and has the same general characteristics as agricultural fields within the watershed in terms of soil type and topography. The vertical resolution of the model in the soil was 1 cm for the first 10 cm, and then increased steadily until reaching 1.5 cm at the bottom of the soil column, 5 m below the soil surface. Normal annual precipitation for central Iowa is close to 840 mm. The previous year, 2010, was characterized by much higher than normal precipitation, with a total of 1273 mm recorded at the field site. The 2011 growing season began with more typical weather conditions. Precipitation was below average near the end of the growing season, such that the total amount of precipitation for 2011 was 814 mm.

An example of soil drying after rainfall that occurred shortly before the maize was harvested in October is shown in Fig. 5. We chose to average the top three soil layers of the model to produce a 0–3-cm soil moisture value in order to represent the quantity of soil water that is sensed by SMOS in view of the summary presented in section 2. A fit for the 0–5-cm soil moisture was similar. To represent the network observations, we chose to average the 4–5- and 5–6-cm layers to produce a 4–6-cm layer that closely matches the theoretical 3.5–6.5-cm layer of soil observed by an in situ sensor buried at 5 cm. It is obvious that (1) is an appropriate model, and, if anything, may underestimate the actual initial rate of soil drying. Note that the 0–3-cm layer is initially wetter than the 4–6-cm layer by 0.06 m³ m⁻³ and then, after about a day and a half, is slightly drier (≤0.01 m³ m⁻³) than the deeper layer. Also note that diurnal variations in the water...
content of the 0–3-cm layer are stronger than for the 4–6-cm layer. These phenomena are expected because the 0–3-cm layer is closer than the 4–6-cm layer to the soil surface at which water from precipitation is received by the soil, and closer to the imaginary plane at which solar radiation is effectively intercepted by Earth’s surface.

b. Different rates of soil drying indicate different layers of soil

The rate of soil drying in the agroecosystem model for three rain events in 2011 is shown in Fig. 6. We considered events in the early part of the growing season when the soil surface was essentially bare, shortly after planting (May–June); during the middle of the growing season (July–August); and the same event as shown in Fig. 5. The initial rate of soil drying for each case and for each soil layer, as well as for the 0–5-cm soil layer, is listed in Table 2. In each event, the rate of soil drying for the 0–3-cm layer is initially higher than for the 4–6-cm layer. The values of $D_i$ for the 0–3 and 0–5 cm are nearly the same. These values of $D_i$ are similar to what we report in Table 1.

The agroecosystem model that we used to create Figs. 5 and 6 is similar to other land surface process models that have been validated using point measurements, that is, measurements of soil moisture observed at a single point, and not necessarily representative of the variety of soil textures, slopes, and aspects relative to the sun that are found in an agricultural field, let alone an entire watershed, that affect soil drying. To better approximate the variety of soil types and topography that would be integrated by the South Fork network, we analyzed soil moisture measured by in situ sensors at eight points arranged in a sparse network within the same 1 km $\times$ 1 km field in which we collected the data to drive the agroecosystem model. The eight points were chosen to represent the variety of soil textures and topography within the field.

The sensors were CS-616 water content reflectometers (Campbell Scientific, Inc.). At each of the eight points, there were two sensors installed at 1.5 cm below the soil surface (one near a row of plants and one between the rows) and two sensors at 4.5 cm below the soil surface (also one near a row and one between the rows). This type of installation, for this particular sensor, results in measurements of the water content of the 0–3- and 3–6-cm soil layers (Hornbuckle and England 2004). The sensors were calibrated to the soil at each point and a temperature correction was applied (Rowlandson et al. 2012).

The rate of soil drying observed by these in situ sensors for the same three events in 2011 that we used with the agroecosystem model is shown in Fig. 7. Both the mean and plus/minus one standard deviation for the $2 \times 8 = 16$ sensors installed at 1.5 cm and for the 16 sensors installed at 4.5 cm are shown. Although a variety of rates of soil drying are observed by sensors at both depths over time, the mean value of the rate of soil drying is almost always significantly different at 1.5 cm compared to 4.5 cm for each of the three events, and usually largest for the sensors at 1.5 cm. The initial rate of soil drying for each event and each layer is listed in Table 2. Again, these rates of soil drying are consistent with those listed in Table 1.

It is clear from Figs. 5–7 and Table 2 that both the agroecosystem model and the sensor data from the 1 km $\times$ 1 km field indicate that soil layers closer to the soil surface initially dry at a higher rate following significant rainfall than layers of soil farther from the soil surface. Since $D_i$ obtained with the agroecosystem model and with the in situ field measurements are consistent with $D_o$ observed by SMOS, we can say with confidence that the rate of soil drying observed by SMOS is indeed different than the rate observed by the South Fork network. Furthermore, because the initial rates of soil drying observed by SMOS are larger (except for two cases in which one of the three SMOS pixels was similar) than the rates observed by the network, we can also say that SMOS observes a layer of soil closer to the soil surface than the layer of soil observed by the network, and that the difference in the soil moisture dynamics of these two layers are significant at the satellite scale, because we have shown that both a model and in situ measurements indicate the soil layers at the surface initially dry faster than layers away from the soil surface. On a side note, our investigation illustrates why many investigators have come to different conclusions regarding the emitting depth for L-band radiometry since...
the soil moisture dynamics of the 0–3- and 0–5-cm layers (as illustrated by $D_i$ in Table 2) are so similar.

c. Impact on satellite validation

What is the impact of our conclusion that SMOS and the South Fork network observe different layers of soil with different soil moisture dynamics? The direct comparison of SMOS near-surface soil moisture observations with the observations made by the South Fork network during the period we examined in Fig. 3 is shown in Fig. 8. The correlation coefficient varies between 0.64 and 0.68. However, RMSEs are higher than desired (between 0.079 and 0.082 m$^3$ m$^{-3}$ for the three SMOS pixels) and SMOS near-surface soil moisture is drier than the South Fork (by at least 0.05 m$^3$ m$^{-3}$). Dry biases in retrieved SMOS soil moisture have been observed in other validation studies in agricultural landscapes of North America (Al Bitar et al. 2012; Gherboudj et al. 2012; Collow et al. 2012; Magagi et al. 2013). Besides drying at a faster rate, the layer of soil at the soil surface observed by SMOS may also wet faster during rain events. Therefore, a wet bias during and immediately after rainfall may mask a dry bias seen over longer periods (Jackson et al. 2012). One common hypothesis for the existence of this dry bias is differences in sensing depths and volumes between SMOS and in situ measurements (Al Bitar et al. 2012; Jackson et al. 2012).

Besides a dry bias, the conclusion that SMOS and the South Fork network observe different layers of soil may also contribute to the noise (RMSE) observed in Fig. 8. To investigate, we compared the 0–3- and 4–6-cm soil moisture produced by the agroecosystem model over the 2011 growing season. The result is shown in Fig. 9 (top). Each data point corresponds to a 15-min time step in the model. The three events considered in Fig. 6 are highlighted. Note that a dry bias between 0–3 and 4–6 cm is not present as it is in the SMOS and South Fork comparison in Fig. 8. On the other hand, there are several times that the 0–3-cm soil moisture is higher than 4–6-cm soil moisture, and by examining the July–August and September–October events, it is clear that this occurs during precipitation events. Initially the 0–3-cm soil moisture is greater,
Table 2. Initial rate of soil drying (m$^3$ m$^{-3}$ day$^{-1}$) for different layers of soil according to the agroecosystem model (representative of the point scale) for the events in Fig. 6 and the in situ sensors (in the 1 km × 1 km field) for the events in Fig. 7.

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<th>Agroecosystem model</th>
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<tr>
<td></td>
<td>0–3 cm</td>
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<td>May–June</td>
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then as drying occurs, the 0–3-cm soil moisture comes back to the 1:1 line and steadily decreases over time at approximately the same rate as the 4–6-cm soil moisture.

SMOS observations do not occur every 15 min, but rather at 0600 or 1800 local solar time (LST) about once a day at the latitude of the South Fork network. We reduced the model observations to match SMOS overpasses for the field in which the data for the model were collected for the year 2011. The result is shown in Fig. 9 (bottom). Note that a significant number of the wetting events remain. The RMSE for the 0–3- and 4–6-cm soil moisture comparison with the 15-min data is 0.015 m$^3$ m$^{-3}$ and increases to 0.043 m$^3$ m$^{-3}$ when only considering SMOS overpass times. The RMSE for a 0–5- and 4–6-cm soil moisture comparison (not shown) with the 15-min data is 0.011 m$^3$ m$^{-3}$ and increases to 0.031 m$^3$ m$^{-3}$ when only considering SMOS overpass times. This increase in the RMSE for only SMOS overpass times is consistent with the large portion of summertime precipitation that occurs at night in Iowa and the rest of the U.S. Midwest as opposed to the late afternoon or early evening in most of the rest of the country. Both the frequency of storms and total precipitation peak after midnight but before 0800 CST (Takle 1995). SMOS observations at 0600 LST are likely to catch the changes in near-surface soil moisture that result from these overnight rains.

Recall that the model is appropriate for point-scale observations. We did the same analysis for the 16 in situ sensors installed at 1.5 cm and the 16 in situ sensors installed at 4.5 cm in the 1 km × 1 km field, which more closely simulates what would be observed by the South Fork network. The comparison between the mean soil moisture observed by sensors installed at 1.5 cm below the soil surface and sensors installed at 4.5 cm below the surface for all sample times is shown in Fig. 10 (top). The three events considered in Fig. 6 are highlighted along with an additional event, from 30 May to 9 June. We believe the unusual behavior of this additional event is associated with the initial installation of the sensors since the behavior ends after the first significant rain on 9 June that occurred after sensor installation. When in situ sensors are installed, the soil surrounding the sensors is disturbed and the soil bulk density is likely lower than the surrounding soil. Significant rainfall may allow loosened soil to come back in contact with the sensors. Excluding the period from 30 May to 9 June, the behavior after rainfall is similar to what we observed in Fig. 9, especially for the September–October event. There is also no dry bias associated with the sensors at 1.5 cm. The RMSE for the 0–3- and 3–6-cm soil moisture comparison with the 15-min data is 0.019 m$^3$ m$^{-3}$ (excluding the period from 30 May to 9 June because of its unusual behavior related to instrument installation). When only SMOS overpass times are considered (Fig. 10, bottom), and again eliminating the period from 30 May to 9 June, the RMSE remains the same, 0.019 m$^3$ m$^{-3}$.

The data in Figs. 9 and 10 indicate that there should not be a dry bias between the soil layer observed by SMOS and the layer observed by the South Fork network over the growing season. On the other hand, the data in Figs. 9 and 10 do indicate that some of the 0.08 m$^3$ m$^{-3}$ RMSE in the relationship between SMOS and the South Fork network in Fig. 8 can be attributed to our conclusion that SMOS and the South Fork network observe different layers of soil because each soil layer exhibits different soil moisture dynamics that are readily apparent after significant rainfall and, to a lesser extent, after long periods of dry weather. However, our analysis is not able to quantify the amount of the RMSE due solely to the difference in the soil moisture dynamics of the two soil layers observed by SMOS and the South Fork network. The 0.03–0.04 m$^3$ m$^{-3}$ RMSE of the agroecosystem model results at SMOS overpass times is an extreme case as it only represents what we might expect at a single point. The comparison between in situ sensors installed at 1.5 and 4.5 cm is closer to what would be observed at the satellite scale as the RMSE of 0.02 m$^3$ m$^{-3}$ is for a total of 16 sensors at 1.5 cm and 16 sensors 4.5 cm (similar to the number of nodes in the South Fork network). On the other hand, the spatial variability of precipitation will be much larger over the South Fork network, which spans an entire watershed with an extent of close to 40 km, as compared to a 1-km field.

6. Conclusions

The rate of soil drying after rainfall observed by SMOS is higher than the rate observed by the South Fork in situ soil moisture network. We used both an agroecosystem model that accounts for heat and moisture transport in soil and in situ sensors arranged in a sparse network within an agricultural field to show that the rate of soil drying is higher for the layer of soil at the soil surface as compared to a layer farther way from the

surface. As a result, we can conclude that SMOS observes the soil water content of a shallow layer of soil at the soil surface a few centimeters in depth, while the South Fork network observes a layer of soil centered at the depth at which its soil moisture sensors are installed (approximately 5 cm). This layer observed by the South Fork network does not extend to the soil surface. Consequently, SMOS and the South Fork network observe the water content of different layers of the soil, and these layers have different soil moisture dynamics that are significant at the satellite scale.

Several investigators have reported a dry bias in SMOS near-surface soil moisture observations as compared to in situ soil moisture networks. We also found a dry bias, and our conclusion that SMOS and the South Fork network observe different layers of soil may at first appear to explain this dry bias. However, our analysis using the agroecosystem model and a 1-km scale sparse network does not show a dry bias between these two layers over a growing season. On the other hand, our analysis did show that the RMSE of the relationship between these two layers is significant as compared to the 0.04 m$^3$ m$^{-3}$ RMSE goal for the SMOS mission. For the agroecosystem model, the RMSE in the relationship between a soil layer similar to what is observed by SMOS and the soil layer observed by an in situ network was between 0.03 and 0.04 m$^3$ m$^{-3}$. For the 1-km scale network, the RMSE in the relationship between sensors installed at 1.5 and 4.5 cm was 0.02 m$^3$ m$^{-3}$. Differences in the two layers primarily arise from precipitation events, when the water content of the layer at the surface is greater than the water content measured by the network. The surface layer water content also tends to be less than the network water content near the end of longer periods of dry weather. In addition, we found that SMOS near-surface soil moisture observations are inherently noisier than the soil moisture observed by the South Fork network.

Consequently, our findings cannot explain the observed dry bias in SMOS observations, but they may explain some of the RMSE associated with the
comparison between SMOS observations and in situ network observations. It is important to note that our analysis applies directly only to the South Fork network, and it is possible different conclusions could be drawn for other geographic regions. The terrestrial L-band brightness temperature can also be affected by the magnitude and shape of vertical gradients in soil moisture and temperature within the emitting depth (Raju et al. 1995; Schneeberger et al. 2004; Hornbuckle and England 2005), but we did not consider these effects in our analysis, and they may not be relevant at the satellite scale.

There are other possible explanations for the dry bias in SMOS near-surface soil moisture. A dry bias means that the terrestrial L-band brightness temperature measured by SMOS is higher than expected according to the model used to produce retrievals of near-surface soil moisture. To compensate, the soil water content of the model must be decreased in order to increase the emissivity of the soil and thus increase the brightness temperature. This could happen if the model underestimated the amount of vegetation covering the soil or underestimated soil surface roughness. Since SMOS simultaneously retrieves both near-surface soil moisture and the amount of vegetation, and since soil roughness has a similar effect as vegetation on the brightness temperature (Patton and Hornbuckle 2013), a wrong estimate of vegetation would mean that the retrieval model is deficient. It is also possible that the modeled soil dielectric properties may not be appropriate. A dry bias would also occur if the surface temperature used by the model to represent the temperature of the soil and vegetation is too low. Low-level radio frequency interference that is not detected by SMOS may also add enough power to the signal to cause the estimate of soil moisture to be too low.

In view of our conclusions, we recommend that validation of L-band satellite observations of near-surface soil moisture include the characterization of three distinct quantities: the water content of the surface soil layer observed by satellites; the water content of the deeper soil layer observed by networks; and the water content of the 0–5-cm soil layer, which is used as the validation standard. A special focus should be made on the characterization of these three quantities during the period of soil drying immediately after significant rainfall, in a manner similar

![Fig. 8. A comparison of the near-surface soil moisture observations from the South Fork network and the three closest SMOS pixels (DGGs 200056, 200057, and 200569) from day of year 115 to 330 in 2013. The black solid line is the 1:1 line. The other solid lines are regressions for each SMOS pixel vs the South Fork network.](image-url)
to that which has been done for periods of more stable soil water content (Adams et al. 2013), using both measurements and models. Such work may reduce the RMSE between satellite and in situ network observations and thus show that satellite missions are in fact meeting their accuracy requirements.

Acknowledgments. The authors received support from the NASA Terrestrial Hydrology Program, a NASA Earth and Space Sciences graduate fellowship, a grant from the USGS/Iowa Water Center, the Department of Agronomy at Iowa State University, and the USDA Agricultural Research Service. The authors also appreciate the constructive comments made by the reviewers. This research was performed as part of Iowa Agriculture and Home Economics Experiment Station project IOW05387.

FIG. 9. A comparison of the volumetric water content of the 4–6- and 0–3-cm soil layers as predicted by an agroecosystem model. (top) All data points (15-min time steps). (bottom) Only data points that coincide with a SMOS overpass.

FIG. 10. A comparison of the average value of 16 in situ soil moisture sensors buried at 1.5 cm and the average value of 16 in situ soil moisture sensors buried at 4.5 cm within a 1 km × 1 km field of maize. (top) All data points (15-min time steps). (bottom) Only data points that coincide with a SMOS overpass.


