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On the spatio-temporal dynamics of soil moisture at the field scale

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SUMMARY

In this paper, we review the state of the art of characterizing and analyzing spatio-temporal dynamics of soil moisture content at the field scale. We discuss measurement techniques that have become available in recent years and that provide unique opportunities to characterize field scale soil moisture variability with high spatial and/or temporal resolution. These include soil moisture sensor networks, hydrogeophysical measurement techniques, novel remote sensing platforms, and cosmic ray probes. Techniques and methods to analyze soil moisture fields are briefly discussed and include temporal stability analysis, wavelet analysis and empirical orthogonal functions. We revisit local and non-local controls on field scale soil moisture dynamics and discuss approaches to model these dynamics at the field scale. Finally, we address the topic of optimal measurement design and provide an outlook and future research perspectives.

1. Introduction

Soil moisture is a key state variable in the terrestrial system as it controls the exchange of water and energy between the land surface and the atmosphere. These exchange processes are characterized by a high nonlinearity and complex feedback mechanisms. Soil moisture is highly variable in space and time with characteristic length scales ranging from a few centimeters up to several kilometers and characteristic time scales ranging from minutes up to years. In recent years, soil moisture has been the subject of several review papers. In particular, these review papers focused on different measurement technologies available at the field to catchment scale with a focus on hydrogeophysical methods, sensor technologies and distributed sensor networks (Fares et al., 2013; Robinson et al., 2008a,b), the importance of soil moisture for describing and understanding vadose zone processes (Vereecken et al., 2008a), the role of soil moisture in climate and atmospheric processes (Seneviratne et al., 2010), and the role that soil properties can play in soil moisture estimation (Zhu et al., 2012).

Many studies analyzed spatial variability of soil moisture at a range of scales, including the field scale (Bell et al., 1980; Nielsen et al., 1973), the catchment scale (Rosenbaum et al., 2012; Western et al., 2004), the regional scale (Romshoo, 2004; Zhao et al., 2013) and the continental scale (Entin et al., 2000; Li and Rodell, 2013). Western et al. (2002) reviewed the various scaling techniques that are available to link soil moisture variability across scales and made a distinction between behavioral techniques and process-based techniques with an emphasis on statistical distribution properties and spatial correlation. Recently, Vanderlinden et al. (2012) analyzed the temporal stability of soil moisture across a range of scales using data retrieved from literature. This analysis showed that there is a set of intertwined factors and effects such as measurement design, soil, vegetation, topography and climate that play together to determine the temporal stability of soil moisture.

Different quantitative methods are available to analyze spatio-temporal dynamics and patterns of soil properties across a broad range of scales. These methods include among others geostatistics, spectral and wavelet analysis, multi-fractal analysis, state-space analysis and fuzzy-set analysis (Si, 2008). In this review, we will present and discuss techniques and methods that are currently in use to map and characterize spatio-temporal soil moisture variability at the field scale. Accurate knowledge of field scale variability of soil moisture is important for the management of agricultural fields in terms of maximizing crop growth and reducing negative impacts of fertilizer applications and pesticides on groundwater resources. Understanding the controls on soil moisture variability is the key to improving irrigation management strategies with respect to crop production and optimal use of available water resources. Local scale knowledge of soil moisture dynamics and its spatial variability is also crucial to improve our understanding of biogeochemical processes and lateral surface and subsurface flow processes. This review is organized in seven sections. In Section 2, we will discuss available measurement techniques to characterize field scale variability of soil moisture. In Section 3, we

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will briefly discuss approaches to analyze spatio-temporal patterns in soil moisture. Section 4 reviews and classifies spatio-temporal properties of soil moisture fields at the field scale. Sections 5 and 6 provide an overview of modeling activities addressing field scale soil moisture variability and the optimal design of monitoring strategies, respectively. Finally, we provide conclusions and an outlook in Section 7.

2. Measuring spatial variability of soil moisture at the field scale

Since the first attempts to characterize field scale soil moisture variability (Nielsen et al., 1973), tremendous progress has been made with respect to measuring soil moisture. In the following, we review the most commonly used techniques to measure soil moisture at the field scale, including point measurements with electromagnetic soil moisture sensors, hydrogeophysical methods, and active and passive microwave remote sensing. We also highlight cosmic-ray probes as an emerging technology to monitor field-average soil moisture content.

2.1. Point measurements with electromagnetic soil moisture sensors

2.1.1. Time domain reflectometry

Time domain reflectometry (TDR) was introduced by Topp et al. (1980) and has developed into a standard method to measure soil moisture. TDR measures the dielectric permittivity of the soil, which is known to be strongly related to soil moisture content because of the strong contrast between the dielectric permittivity of water and that of the other soil constituents. Empirical and semi-theoretical models are available to relate dielectric permittivity and soil moisture content (Roth et al., 1990; Topp et al., 1980). In the case of TDR, the dielectric permittivity is determined from the velocity of an electromagnetic wave that is emitted by a pulse generator ('cable tester') and passed along the waveguides of the TDR probe. The propagation velocity is determined from the measured travel time along a TDR probe with a known length. For more information on the principles of TDR, the reader is referred to the comprehensive review of Robinson et al. (2003). Several TDR probes can be combined in a network configuration using multiplexing systems (Heimovaara and Bouten, 1990; Weihermuller et al., 2013). However, such networks of probes are still restricted to local applications (e.g. trenches or small field plots) because of the limitations on cable length (<20 m) for accurate TDR measurements.

At larger scales, many studies on field-scale variability of soil moisture have used TDR for manual sampling campaigns. For instance, a detailed investigation on soil moisture pattern dynamics and connectivity in spatial patterns has been undertaken at the Tarrawarra catchment (Australia), which involved the spatial characterization of soil moisture in the top 0.30 m at 520 sampling locations (Grayson et al., 1997; Western et al., 2001).

2.1.2. Capacitance and TDT sensors

In the last decade, cost-effective alternatives to TDR have emerged. In particular, capacitance sensors are relatively inexpensive and easy to operate. The basic principle of the capacitance method is to incorporate soil medium that surrounds the sensor prong as part of the dielectric of the sensor capacitor. The permittivity of the soil is then determined by measuring the charge time from a starting voltage to a voltage with an applied capacitor voltage. Typically, capacitance sensors operate at a measurement frequency between 50 and 100 MHz. Therefore, sensor output is to some extent influenced by the electrical conductivity and imaginary dielectric permittivity of the soil (Kelleners et al., 2005; Kizito et al., 2008; Robinson et al., 2005), which affects the accuracy of soil moisture measurements with capacitance sensors.

Another cost-effective electromagnetic sensor type is the time domain transmission (TDT) sensor, which measures the propagation velocity of an electromagnetic wave along a closed transmission line. Currently, there are different TDT approaches available. For instance, Blonquist et al. (2005) reported on the Acclima TDT sensor (McCready et al., 2009), which uses a waveform interpretation process similar to conventional TDR systems. According to Blonquist et al. (2005), the Acclima TDT sensor produced very similar measurement accuracy compared to reference TDR systems (within ±3 permittivity units within a permittivity range of 9–80). Unfortunately, the Acclima TDT sensor does not (yet) allow direct insertion in natural soils. Other TDT sensors use the oscillation frequency of a ring oscillator on a printed circuit board track to approximate propagation velocity, and such design can easily be inserted in undisturbed soils. Since these TDT sensors operate at higher frequencies than capacitance methods, they are expected to provide a higher measurement quality (Blonquist et al., 2005). One example of such a TDT sensor is the SPADE sensor (sceme.de GmbH i.G., Horn-Bad Meinberg, Germany; Hübner et al. (2009)), which was recently tested by Qu et al. (2013). They found that the SPADE sensor showed good agreement with TDR measurements after consideration of temperature effects on the sensor.

2.1.3. Wireless soil moisture sensor networks

In recent years, wireless soil moisture sensor networks have emerged. They enable the observation of spatio-temporal soil moisture variability in near real-time and allow to bridge the gap between local and regional scale measurements (e.g. remote sensing) (Robinson et al., 2008a). Sensor networks ideally consist of hundreds of soil moisture sensors that transmit information to a main server with wireless communication technology. Because of the multitude of soil moisture measurements within the sensor network, the interpretation of the sensor signal should be straightforward and unambiguous. In order to maximize the number of sensor nodes, the soil moisture sensors have to be as inexpensive as possible without compromising sensor accuracy too strongly. Therefore, capacitance and TDT sensors are currently considered to be most appropriate for wireless soil moisture sensor networks (Bogena et al., 2007; Rosenbaum et al., 2010). The potential of sensor networks to resolve catchment-scale soil moisture patterns with an unprecedented combination of high spatial and temporal resolution has recently been demonstrated (Bogena et al., 2010). Recent applications of wireless sensor networks include monitoring of soil moisture combined with salinity in irrigated fields to optimize irrigation management (Wu and Margulis, 2013; Yu et al., 2013), spatio-temporal observation of soil moisture in forested sites (Rosenbaum et al., 2012), and validation of remote sensing data (Moghaddam et al., 2010).

2.2. Hydrogeophysical methods

Multi-point measurements using electromagnetic soil moisture sensors usually provide a limited spatial resolution because measurements on a large number of locations are labor-intensive in case of manual surveys and cost-intensive in case of network installations. Non-invasive geophysical methods, such as ground penetrating radar (GPR), electromagnetic induction (EMI), and electrical resistivity tomography (ERT) offer potential to overcome this limited spatial resolution (Robinson et al., 2008a,b) and can return information with a spatial resolution down to several meters even for large fields.