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Automated general temperature correction method for dielectric soil moisture sensors

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ABSTRACT

An effective temperature correction method for dielectric sensors is important to ensure the accuracy of soil water content (SWC) measurements of local to regional-scale soil moisture monitoring networks. These networks are extensively using highly temperature sensitive dielectric sensors due to their low cost, ease of use and less power consumption. Yet there is no general temperature correction method for dielectric sensors, instead sensor or site dependent correction algorithms are employed. Such methods become ineffective at soil moisture monitoring networks with different sensor setups and those that cover diverse climatic conditions and soil types. This study attempted to develop a general temperature correction method for dielectric sensors which can be commonly used regardless of the differences in sensor type, climatic conditions and soil type without rainfall data.

In this work an automated general temperature correction method was developed by adopting previously developed temperature correction algorithms using time domain reflectometry (TDR) measurements to ThetaProbe ML2X, Stevens Hydra probe II and Decagon Devices EC-TM sensor measurements. The rainy day effects removal procedure from SWC data was automated by incorporating a statistical inference technique with temperature correction algorithms. The temperature correction method was evaluated using 34 stations from the International Soil Moisture Monitoring Network and another nine stations from a local soil moisture monitoring network in Mongolia. Soil moisture monitoring networks used in this study cover four major climates and six major soil types. Results indicated that the automated temperature correction algorithms developed in this study can eliminate temperature effects from dielectric sensor measurements successfully even without on-site rainfall data. Furthermore, it has been found that actual daily average of SWC has been changed due to temperature effects of dielectric sensors with a significant error factor comparable to ±1% manufacturer's accuracy.

1. Introduction

Soil moisture is a key variable controlling the exchange of energy and water fluxes between the land surface and atmosphere (Bandara et al., 2013). Due to its high interactions with atmosphere it makes a significant impact on the development of weather patterns including heat waves (Seneviratne et al., 2006) and precipitation (Koster et al., 2004). As extreme weather and climate events have become more frequent during the past decade, there was an urgent need in all branches of earth science to develop techniques for continuous measurements of soil moisture on a global scale. During the last decade advances in soil moisture measuring techniques both *in situ* and from space have been made. With the launching of two dedicated satellite missions, Soil Moisture and Ocean Salinity (SMOS) (Kerr et al., 2010), and Soil Moisture Active Passive (SMAP) (Entekhabi et al., 2010), a number of new ground-based soil moisture observational networks were established and added to the existing moisture monitoring for the calibration and validation of remotely sensed soil moisture (Rüdiger et al., 2007; Jackson et al., 2010). These newly developed and existing long-term networks have been recently collected and harmonized as the International Soil Moisture Monitoring Network (ISMN) (Dorigo et al., 2011; Dorigo et al., 2013; Robock et al., 2000).

Electromagnetic sensors have been widely used to establish continuous *in situ* moisture networks (Mittelbach et al., 2012). These sensors measure the bulk dielectric permittivity (ε) of soil from which the soil water content (SWC) can be inferred. The main techniques used by these sensors can be classified as time domain

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reflectometry (TDR) and frequency domain reflectometry (FDR) or capacitance. Of these the TDR sensors are the costliest but the most accurate under field conditions due to their lower sensitivity for variations in soil properties and temperature (Western and Seyfried, 2005). Thus, TDR sensors are often used as reference sensors (Western and Seyfried, 2005; Baumhardt et al., 2000) in moisture monitoring networks (e.g. OzNet in Australia) (Rüdiger et al., 2007). In contrast, non-TDR sensors are often criticized due to their high sensitivity to soil properties and temperature, in particular FDR sensors for their high temperature sensitivity. Though they are less accurate, non-TDR sensors are extensively used in soil moisture networks for long-term monitoring due to their low cost, ease of use and low power consumption (Rosenbaum et al., 2011). Dorigo et al. (2011) specifically emphasized the necessity of a temperature correction method for soil moisture data sets available in ISMN since most of those data sets were measured with highly temperature sensitive non-TDR sensors. Over the past decade, studies (e.g. Lu et al., 2015; Yamanaka et al., 2003) have found that not only non-TDR but TDR sensor measurements also have significant errors associated with temperature fluctuations.

Several analyses (e.g. Gong et al., 2003; Hanson and Peters, 2000; Or and Wraith, 1999; Schanz et al., 2011; Skierucha, 2009; Saito et al., 2012; Yamanaka et al., 2003) have already discussed dielectric sensors' temperature effects and proposed correction algorithms. Moreover, for some FDR sensors (e.g. Stevens Hydraprobe), manufacturers are providing a temperature calibration due to their high temperature sensitivity (Bellingham, 2007). However, it is observable that as yet there is no adequate or if not effective temperature correction method for dielectric sensors. As a consequence, Dorigo et al. (2013) have again pointed out in their study the issue of temperature-related errors in dielectrically measured *in situ* soil moisture data sets hosted by ISMN on global automated quality control of *in situ* soil moisture data from the ISMN. Moreover, in this study we found that some of the moisture monitoring networks (e.g. TERENO (Terrestrial Environmental Observatories) in Germany (Zacharias et al., 2011), USCRN (United States Climate Reference Network) in the US (Bell et al., 2013)) of ISMN which used the temperature calibrated Stevens Hydraprobe sensors also exhibited temperature-related fluctuations exceeding the specifications of the manufacturer's accuracy. Therefore, moisture monitoring networks such as ISMN must urgently devise a more effective temperature correction method, in order to ensure the accuracy of their soil moisture data sets. These are widely used as primary data sources for remote sensing-based soil moisture and the land surface model (LSM).

Although it is found to be substantial, there is no criterion in the automated quality control system of ISMN for removing temperature-related inaccuracies (e.g. Dorigo et al., 2013). This is perhaps due to limitations in the applicability of existing temperature correction algorithms and lack of on-site rainfall data. In general, existing temperature corrections were developed for some selected soil moisture ranges (e.g. Saito et al., 2012) and are comprised of sensor or site dependent constants (e.g. Ledieu et al., 1986; Skierucha, 2009; Verhoef et al., 2006; Western and Seyfried, 2005). That makes it difficult to use those temperature corrections in a centralized data portal such as ISMN which contains soil moisture data which were measured from various sensor setups under diverse climatological and site conditions. Additionally, most of the soil moisture monitoring networks do not measure the rainfall data which is one of the commonly used data sources either for the development or validation of temperature correction algorithms (e.g. Verhoef et al., 2006; Saito et al., 2012; Lu et al., 2015). According to Dorigo et al. (2013), 60% of ISMN's soil moisture monitoring networks do not provide rainfall data. This makes it difficult to evaluate the performance of existing temperature correction algorithms or develop new correction methods for such monitoring networks.

This study proposes a methodology to overcome aforementioned limitations with existing methods by developing a general temperature correction method for dielectric sensors. The method is data-driven and requires neither sensor (or site) dependent constants nor on-site rainfall data. Compared to the authors' previous temperature correction method, there are two distinct differences: (i) soil moisture data sets used in this study were observed with different dielectric sensors and under diverse climatological conditions as well as soil types; and (ii) a new approach has been incorporated to lift the requirement of on-site rainfall data.

1.1. Background

Studies regarding the temperature effects of dielectric sensors have generally concluded that the temperature effect varies with the sensor's measurement frequency (Western and Seyfried, 2005; Verhoef et al., 2006), soil moisture level and temperature variabilities, namely the climatic condition (Halbertsma et al., 1996; Chanzy et al., 2012; Saito et al., 2012) and soil type (Or and Wraith, 1999; Malicki et al., 1996; Skierucha, 2009). The existing temperature correction methods can be mainly categorized into two groups. One consists of mixture model-based approaches (e.g. Halbertsma et al., 1996; Or and Wraith, 1999; Dirksen and Dasberg, 1993; Roth et al., 1990). The other group comprises empirical correction methods (e.g. Gong et al., 2003; Ledieu et al., 1986; Skierucha, 2009; Verhoef et al., 2006; Western and Seyfried, 2005). However, both groups have limitations. In addition to the question about their correctness, mixture model-based approaches require laborious soil property information (e.g. Or and Wraith, 1999) which are not readily available. Moreover, several mixture model-based correction algorithms (e.g. Or and Wraith, 1999; Yamanaka et al., 2003) failed to remove the temperature effects at high SWC levels. Conversely, empirical methods consist of sensor and/or site (soil) dependent constants (e.g. Skierucha, 2009) and some of the methods were tested in laboratory conditions and did not reduce temperature effects at field conditions (Saito et al., 2012).

In contrast, authors have developed a simple, effective data-driven approach which successfully removed the temperature effects in both wet and dry conditions. This method requires only soil moisture, temperature and on-site rainfall data. No soil property information is required as all information including the soil property is implicitly reflected in the SWC data. In that study, Eq. (1) expressed the temperature effects on TDR measured SWC by analysing SWC and temperature data.

$$A_\theta = \alpha\theta_d A_T \tag{1}$$

where α represents temperature correction coefficient, θ_d stands for daily mean SWC, A_θ and A_T are daily amplitudes of SWC and soil temperature, respectively. The amplitudes of SWC and temperature were considered to be half the difference between the maximum and minimum of the SWC and temperature diurnal cycles, respectively.

Authors showed that a similar form of equation can be derived through a Taylor expansion of the calibration curves such as Topp's equation (Topp et al., 1980). By assuming apparent diurnal fluctuations of dielectrically measured SWC caused by the change in temperature from reference temperature, it can be expressed by Eq. (1). A general form (Eq. (2)) was developed to represent actual and measured SWC as a function of actual and reference temperature.

$$\theta - \theta_{ref} = \alpha\theta_c(T - T_{ref}) \tag{2}$$

In Eq. (2), θ, θ_{ref} stand for measured and reference SWC at T and T_{ref}, respectively. T is actual soil temperature and T_{ref} is a temperature at which the calibration curve was created. Usually θ is the SWC reading from the sensor which is converted from measured dielectric permittivity of soil with the calibration curve. θ_c is the