A data-driven method to remove temperature effects in TDR-measured soil water content at a Mongolian site

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Abstract:

As a convenient, easy-to-use tool, time-domain reflectometry (TDR) is becoming extensively used to measure soil water content. Used not only in hydrological applications, the measurements are also used as ground truth for satellite remote sensing of soil moisture. However, TDR measurements usually include diurnal fluctuation caused by diurnal change of temperature. Though this is an old problem, there is not a general solution. The purpose of this study is to develop an algorithm to remove temperature effects of TDR measurements by analyzing its relationship with meteorological variables. From data observed at a Mongolian site, it is found that impact of soil temperature on soil water content is nearly proportional to soil temperature itself and soil water content. An algorithm is developed and applied to the Mongolian data set. The temperature effects can be effectively removed under dry and wet conditions.

KEYWORDS soil water content; temperature effect; time-domain reflectometry; correction; Mongolia

INTRODUCTION

Soil moisture is one of most important hydrological variables. It controls infiltration, evapotranspiration and groundwater recharge, and plays an essential role in most environmental processes (Seneviratne et al., 2002). Recently, its impacts on climate systems have been widely recognized (Climate Research Committee, National Research Council, 1994). It has long been recognized that reliable, robust and automated techniques for soil moisture measuring can be extremely useful in hydrological, environmental, agricultural and socioeconomic perspectives (Walker et al., 2004).

Soil moisture measurement, in situ and/or from space, makes it possible to improve the accuracy of hydrological model outputs and the reliability of weather and climate model predictions. Walker et al. (2004) reported that time-domain reflectometry (TDR) is accurate among all the point soil-water dielectrics methods. It has become extensively used due to its simplicity of operation, high accuracy, non-destructive measurements, and moreover due to its automatability (Topp et al., 1980; Dirksen and Dasberg, 1993; Malicki et al., 1996).

TDR is a relatively new method for measurement of volumetric soil water content (hereinafter referred to as soil water content or SWC). Its first application to soil water measurements was reported by Topp et al. (1980). During the early development of TDR for the determination of soil moisture, it was assumed that the effect of temperature on TDR measurements was negligible (Topp et al., 1980). As availability of information on the performance of TDR increased, uncertainties arose regarding some of the early observations (Dirksen and Dasberg, 1993; Whalley, 1993; Pepin et al., 1995; Skierucha, 2009). TDR measures the bulk dielectric permittivity ($\varepsilon$) of the soil from which soil water content can be inferred. The change in soil water content will directly affect dielectric permittivity of the soil.

Pepin et al. (1995) showed a reduction of TDR-measured soil moisture with increased soil temperature. Meanwhile Or and Wraith (1999) reported from literature an increase in measured soil moisture with increased temperature. All these puzzling observations are reproducible and coexist within the range of media properties, water content and temperature encountered in common practice (Or and Wraith, 1999). Many researchers (e.g., Gong et al., 2003; Malicki et al., 1996; De Loor, 1968; Karkkainen et al., 2000; Or and Wraith, 1999) have been continuing to model the soil as a mixture of solid particles, water and air to take into account their contribution to $\varepsilon$. In some studies, the water is divided into free water and bound water which is near to the surface of solid particles to consider the difference between their dielectrical behaviors (e.g., Or and Wraith, 1999). Gong et al. (2003) reported that, as soil texture becomes finer (surface area per unit mass becomes larger) the effect of bound water becomes significant and therefore Topp’s calibration equation (Topp et al., 1980) needs to be adjusted. Accordingly the temperature effect on all four phases (solid, gas, free water, bound water) of the soil column needs to be assessed for the total evaluation of the temperature effect. Skierucha (2009) proposed a new concept of equilibrium water content at which the increase and decrease of $\varepsilon$ with temperature due to the effect of bound water compensate each other.

Or and Wraith (1999) reported that TDR-measured near surface soil water content may exhibit anomalous behavior in the presence of diurnal temperature fluctuations. Further they have proposed a method to correct $\varepsilon$ in order to compute the temperature-corrected soil moisture. Gong et al. (2003) used direct TDR-measured soil water content to add the temperature correction. Skierucha (2009) also suggested two temperature corrections depending on the value of equilibrium water content and TDR-measured soil moisture.

Although aforementioned studies tried to determine the total temperature effect on soil water content, the effect of
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diurnal variations of soil temperature on TDR-measured soil moisture values are not fully eliminated. Kahimba and Ranjan (2007) reported that, in order to figure out the temperature dependency of bulk dielectric permittivity $\varepsilon$ of the soil, the TDR-measured $\varepsilon$ needs to be adjusted to reference temperature. They explained further that the normal practice as reported in literature is to adjust the measured $\varepsilon$ to the reference temperature (e.g., 25°C) used to calibrate the TDR probe. Calibrating the TDR probe at reference temperature will consequently cause an inherent error when the soil water content measurements are made at different soil temperatures.

The purpose of this study is to develop an algorithm to remove temperature effects in TDR measurements by analyzing its relationship with meteorological variables. The data observed at a Mongolian site is used to develop and test our method. By applying Or and Wraith’s model to the data measured at this site, Yamanaka et al. (2003) succeeded in correction of temperature effects under dry conditions. The results of our data analysis elucidated that the impact of soil temperature on soil water content is nearly proportional to soil temperature itself and soil water content. Based on this observation, an algorithm is developed and applied to the Mongolian data set. The temperature effects are effectively removed under both dry and wet conditions.

THE OBSERVATION SITE AND DATA ANALYSIS

Site description

The observation site includes three automatic weather stations (AWSs) and 10 automatic stations for soil hydrology (ASSHs) located in the Mongolian Plateau. Spatial distribution of these stations are shown in Figure 1. As reported in Kaihotsu et al. (2013) and Yamanaka et al. (2007), the site primarily consists of flat terrain covered with pasture grass and shrubs with an elevation between 1200 m and 1600 m above mean sea level. The annual precipitation is about 100–150 mm, mostly comprising summertime rainfall caused by thermal convection and frontal systems. The soil types at all stations are sandy loam or sandy silt loam with abundant gravel where the specific surface area per unit mass is less than 100 m$^2$ g$^{-1}$. At all AWS and ASSH stations, a platinum resistance thermometer (C-PTWP-5, Climetcx Inc., Japan) and TDR sensor (Trime-IT IMKO-Micromodultechnik, Germany) were inserted horizontally at four depths of 0.03 m, 0.1 m, 0.4 m, 1 m and two depths (0.03 m, 0.1 m) respectively. Precipitation is observed by a tipping bucket raingauge (7856M, Davis Instruments, USA). Half hour AWS data and bi-hourly ASSH data are recorded automatically.

Data description

In this study, soil water content and soil temperature from ASSH813 and precipitation data from Daren station (DRS) are used. Though soil water content is also measured at DRS, ASSH813 is selected due to its data quality and continuity. The application of this method to other ASSH stations is also a factor in the data selection. The study period is from September 14, 2008 to December 31, 2011. In order to investigate the temperature effects, data at a depth of 3 cm from the ground surface is selected because of the large variability of soil temperature. The data analysis was carried out at a common temporal resolution of two hours. The 30 minute precipitation data are simply summed up to make bi-hourly precipitation data.

Figure 2 shows the daily soil water content, temperature and precipitation. It is very clear that the summertime rainfall events cause an increase of the soil water content. To avoid the effects of precipitation, in this case rainfall, the days having a daily rainfall amount larger than 0.1 mm are excluded from our data analysis. Also the days with negative soil temperature are excluded because the TDR calibration equation is not applicable to frozen soils. From Figure 2, a soil water content larger than the antecedent one can be observed every winter. Considering the difference in dielectric properties between water and ice, these data should be excluded. After these exclusions, a total of 776 days were excluded, and 428 days remained for further analysis.

Over the whole data period, the diurnal change of soil water content can be observed. Figure 3 shows soil water content over four periods extracted from the above selected

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Figure 1. Spatial distribution of AWSs (DRS and the others) and ASSHs (ASSH813 and the others) at the Mongolian Plateau

Figure 2. Daily soil water content, soil temperature and precipitation
Besides the existence and strength of the diurnal change, one can also confirm that the high values of soil water content appear in daytime. In TDR-measured soil water content, this diurnal change is a result of superimposition of some physical diurnal changes (e.g., Jackson, 1973) and the apparent diurnal change caused by a diurnal change of soil temperature. Previous works (Gong et al., 2003; Kahimba and Ranjan, 2007; Or and Wraith, 1999; Pepin et al., 1995; Skierucha, 2009; Western and Seyfried, 2005; Yamanaka et al., 2003) showed that the diurnal change of soil temperature is the most dominant cause for the diurnal change of TDR-measured soil water content. However, it is very difficult to separate the apparent diurnal change from the physical diurnal changes without additional information. Both physical and apparent diurnal changes will be removed by the data-driven method developed in this study. Therefore, it is important to identify the dominance of the diurnal change caused by soil temperature.

Evaporation is a well known cause for physical diurnal change of soil water content. It tends to decrease the soil water content near the ground surface during the daytime (Jackson, 1973). Meanwhile, higher soil temperature tends to apparently increase TDR-measured soil water content during the daytime. At this Mongolian site, higher TDR-measured soil water content during the daytime is observed. This indicates the dominance of the apparent diurnal change caused by soil temperature.

Data analysis

The data analysis focuses on the relationship between amplitude of soil water content and soil temperature. For 428 selected days, the amplitudes are calculated as follows:

\[ A_{\theta j} = \max(\theta_{ij}, ..., \theta_{i12}) - \min(\theta_{ij}, ..., \theta_{i12}) \]  
\[ A_{T j} = \max(T_{ij}, ..., T_{i12}) - \min(T_{ij}, ..., T_{i12}) \]

where \( \theta_{ij} \) and \( T_{ij} \) are \( j \)-th soil water content (m\(^3\) m\(^{-3}\)) and soil temperature (°C) data in \( i \)-th day respectively; and \( A_{\theta j} \) and \( A_{T j} \) are daily amplitude of soil water content and temperature of \( i \)-th day, respectively. Figure 4 shows \( A_{\theta j} \) and \( A_{T j} \) of the selected days together with daily soil water content of all days. To investigate the relationship among them in the selected 428 days, \( A_{\theta j} \) is plotted against \( A_{T j} \), daily soil tem-

![Figure 3. Bi-hourly soil water content over four continuous periods used in data analysis](image3.png)

![Figure 4. Daily soil water content and amplitudes of soil water content and soil temperature](image4.png)

![Figure 5. Scattergram of amplitude of soil water content against (a) amplitude of soil temperature, (b) daily soil temperature and (c) daily soil water content](image5.png)
perature and daily soil water content in Figure 5. It appears that \( A_t \) is probably proportional to both \( A_t \) and daily soil water content, and is not correlated with daily soil temperature. Only one point with \( A_t = 0.12 \) is far from the data cloud. By checking the data of this day and the previous day, no rainfall was recorded before the rise of the soil water content. Only 1.4 mm of rainfall was recorded early during the following day. Considering the distance of 13 km between DRS and ASSH813, this may be caused by a small scale rainfall system such as a thunderstorm. This day is also excluded in the following analysis.

Based on the relationships revealed in Figure 5, the following formula form is accepted to model the amplitude of soil water content after comparing several forms.

\[
A_t = \alpha \theta \sigma T
\]

(3)

where \( \theta \) is daily soil water content and \( \alpha \) is a coefficient. Using linear regression, \( \alpha \) is determined to be 0.0081°C⁻¹. The correlation coefficient is 0.79. This formula implies the fluctuation of soil moisture is not only affected by soil temperature, but also soil water content itself. The average daily soil temperature amplitude of 20°C at this site may cause a 16% relative change of soil water content.

**ALGORITHM DEVELOPMENT AND RESULTS**

In TDR measurement, the soil water content \( (\theta) \) is usually calculated from the bulk dielectric permittivity \( (\varepsilon) \) by using a calibration curve or equation as follows:

\[
\theta = f(\varepsilon)
\]

(4)

In most cases, this equation is prepared for reference temperature. Topp et al. (1980) proposed

\[
\theta = 4.3 \left( \frac{\varepsilon}{10^{12}} \right)^3 - 5.5 \left( \frac{\varepsilon}{10^{12}} \right)^2 + 2.92 \left( \frac{\varepsilon}{10^{12}} \right) \frac{5.3}{10^{12}}
\]

(5)

to derive soil water content from TDR-measured bulk dielectric permittivity. The reference temperature was 20°C. As pointed out by Kahimba and Ranjan (2007), in order to obtain expected soil water content, the TDR-measured \( \varepsilon \) needs to be adjusted to reference temperature. However, the TDR-measured \( \varepsilon \) is directly used to infer soil moisture in most practices. This may be the main cause of diurnal fluctuation in soil water content.

Based on the mean value theorem, Equation (4) can be re-written as

\[
\theta = f(\varepsilon) + \frac{df(\varepsilon)}{d\varepsilon} \frac{d\varepsilon(T)}{dT} (T - T_{ref})
\]

(6)

where \( \varepsilon \) and \( \varepsilon_r \) are bulk dielectric permittivity at reference temperature \( T_{ref} \) and \( T_r \), a temperature between \( T \) and \( T_{ref} \). Obviously, \( f(\varepsilon) \) is the expected value when the calibration equation is properly used. Hereafter, it is referred to as \( \theta_{ref} \).

Equation (6) becomes

\[
\theta - \theta_{ref} = \frac{df(\varepsilon)}{d\varepsilon} \frac{d\varepsilon(T)}{dT} (T - T_{ref})
\]

(7)

When \( T_r = T_{ref} \), Equation (7) reduces to

\[
\theta - \theta_{ref} = \theta_{ref} \left( \frac{d(\varepsilon)}{d\varepsilon} \frac{d\varepsilon(T_{ref})}{dT} \right) (T - T_{ref})
\]

(8)

a Taylor series omitting terms of degree higher than 2. Though the use of Equation (8) may introduce truncation error theoretically, Figure 5a and Equation (3) suggest that significant higher-degree terms do not exist so that Equation (8) may be still a good approximation.

By assuming the relationship between \( \theta \) and \( (\theta - \theta_{ref})/(T - T_{ref}) \) is the same as that between \( \theta \) and \( A_t/\sigma_T \), \( \theta_{ref} \) can be modeled as \( \alpha \theta \) where \( \alpha \) is a value corresponding to \( \theta \) in Equation (3). Considering the fact that \( \theta \) is a daily average of soil water content, \( \alpha \) can be expected to take a value between \( \theta \) and \( \theta_{ref} \), probably close to \( (\theta + \theta_{ref})/2 \). Based on these observations, Equation (9) is designed to remove temperature effects in soil water content

\[
\theta - \theta_{ref} = \alpha \theta (T - T_{ref})
\]

(9)

For generality, \( \theta \) equal to \( \theta_{ref}, (\theta_{ref} + \theta)/2 \) and \( \theta \) are tested. Correspondingly, the following three correction equations can be derived.

Method A : \( \theta_{ref} = \theta \frac{1}{1 + \alpha(T - T_{ref})} \)

(10)

Method B : \( \theta_{ref} = \theta \frac{1 - \alpha(T - T_{ref})}{2} \)

(11)

Method C : \( \theta_{ref} = \theta (1 - \alpha(T - T_{ref})) \)

(12)

All these three equations are tested using \( \alpha = 0.0081°C^{-1} \) and \( T_{ref} = 20°C \).

Figure 6 shows the autocorrelation coefficients of observed and corrected soil water content over the four periods shown in Figure 3. The corrected soil water content data are calculated by applying Method A, B and C respectively. And the autocorrelation coefficient \( \rho \) is calculated by using

\[
\rho(\tau) = \frac{1}{n - \tau} \sum_{i=1}^{n-\tau} x_i - \mu_1 \frac{x_{i+\tau} - \mu_2}{\sigma_1} \frac{\sigma_2}{\sigma_2}
\]

(13)

where \( \mu_1 = \frac{1}{n - \tau} \sum_{i=1}^{n-\tau} x_i \)

\( \mu_2 = \frac{1}{n - \tau} \sum_{i=1}^{n-\tau} x_{i+\tau} \)

\( \sigma_1 = \sqrt{\frac{1}{n - \tau} \sum_{i=1}^{n-\tau} (x_i - \mu_1)^2} \)

\( \sigma_2 = \sqrt{\frac{1}{n - \tau} \sum_{i=1}^{n-\tau} (x_{i+\tau} - \mu_2)^2} \)
where $x$ is the variable to be processed, $i$ indicates time, $t$ is time lag, $n$ is the number of data points, and $\mu$ and $\sigma$ represent mean value and standard deviation respectively. From Figure 6, the diurnal changes shown in Figure 3 also can be identified. Comparing the autocorrelation coefficient of observed soil water content with those of the corrected soil water content, it is clear that all three methods are capable of removing the diurnal fluctuation in observed soil water content. The small difference between the autocorrelation coefficients of the corrected soil water content suggest that all three methods are nearly equivalent.

Figure 7 shows the corrected and observed soil water content from October 14, 2008 to November 13, 2008. The corrected values are results of Method C applied to all data with positive temperature. Before the rainfall event, the soil water content is about 5%. The diurnal fluctuation is almost removed under this dry condition. After the rainfall event, the soil became relatively wet, and the corrected soil water content shows a relatively reasonable recession after removing the temperature effects. Also the correction not only removes the fluctuation, but also changes the daily average.

Figure 8 shows a histogram of $(q_{ref} - q)$. $q_{ref}$ is the same as those in Figure 7. The maximum, minimum and mean of the difference are 0.0332, -0.0250 and 0.0027. Though the mean value is quite small, the difference is systematic. In cold seasons it takes positive values, and in warm seasons negative values.

**CONCLUSIONS**

The effect of soil temperature on the TDR-measured soil water content has been discussed. The data analysis shows that the change in soil water content is nearly proportional to the change of soil temperature and soil water content itself. However, the soil temperature does not seem to have a significant impact on the change of soil water content at this Mongolian site.

Based on the results of data analysis, the correction methods are proposed and tested. It is found that all three methods are capable of removing the diurnal fluctuation in soil water content, and are equivalent. The correction works for both dry and wet conditions. One noteworthy point is that the soil water content is probably overestimated in warm seasons, and underestimated in cold seasons.

The methodology developed in this study is data driven. No information about soil properties are required because they are considered to be reflected by the data. The longer the data record, the better the site condition will be reflected, and the better the correction will work.
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