Response of ECH$_2$O Soil Moisture Sensor to Temperature Variation

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Introduction

Temperature may affect dielectric moisture sensors through direct effects on sensor circuitry, through effects on the dielectric constant of water, and through effects on water-soil interaction. It is well known that the dielectric permittivity of water (ε_{fw}) decreases approximately 0.7% °C^{-1} for temperatures from 5 to 35 °C. Hence, if bulk soil dielectric permittivity had a temperature dependence related solely to ε_{fw}, measurements of soil dielectric (ε_s) would show a negative correlation with temperature that would increase with water content. Results from Pepin et al. (1995) show this negative correlation, but the overall changes are lower than predicted from a dielectric mixing model that integrated the change in dielectric permittivity of water. In contrast, Wraith and Or (1999) show a positive correlation between temperature and ε_s for a silt loam at all water contents, and a positive correlation for another silt loam and oxisol at low water content, changing to a negative correlation at higher water contents. Thus, it appears that there is a need for additional explanation for the change in ε_s with temperature.

Or and Wraith (1999) provide a theory that suggests ε_s may change with the amount of bound and free water in a system. The objective of their analysis was to understand why ε_s is different from ε_{fw} in some soils and provide a hypothesis for the positive correlation of temperature with ε_s. The dielectric permittivity of water is frequency dependent. ε_{fw} decreases drastically at 18 GHz, well above the frequency of dielectric soil moisture sensors. When water is bound to soil surfaces, this relaxation frequency decreases to frequencies that are in the dielectric sensor range. Since the relaxation frequency is temperature dependent, the dielectric permittivity measured by these sensors changes with temperature. The relationship between temperature and relaxation frequency is positive, which would account for observations of increases in apparent water content with increased temperature. A corollary to this theory is that soil with lower water content should be more influenced by this phenomenon because the majority of the water is in close proximity to the solid surface.

This hypothesis is further supported by observation of es in different soil textures. Or and Wraith (1999) show ε_s vs T to be negative for a low surface area soils with varying water content, but positive for high surface area soils with low water content. Soils with high surface area and high water content gave differing results, with the highest surface area showing a positive correlation and the rest showing a negative one. Experimentation with a transmission line oscillator (Seyfried and Murdock, 2001) gave similar results, with silt and clay loam soils exhibiting a positive correlation at all water contents, and sand and sandy loam showing a slightly negative correlation. The objective of this note is to demonstrate the temperature dependence of the ECH$_2$O Soil Moisture Probe output in several different media, and compare it to results shown in literature. In addition, we suggest a possible correction factor to remove changes in apparent water content due to temperature fluctuations.

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Methods

A small thermally isolated chamber (43 cm x 37 cm x 20 cm) was constructed to use opposing heating and cooling sources to control temperature. A CR10X micrologger (Campbell Scientific, Logan, UT) was employed to read all sensors and thermocouples as well as control air temperature in the chamber from +5° to 45° C. Three ECH_2O soil moisture probes were placed in various media in the chamber along with a CS615 soil moisture probe (model CS615, Campbell Scientific, Logan, UT). Air and soil temperature was monitored by copper-constantan thermocouples placed at four locations (2 in air, 2 in soil). The thermocouples in the soil were used to determine temperature at the media surface, and at the approximate location of the probes. ECH_2O probes were supplied with a 10 ms excitation of 2500 mV and read using a single ended measurement. A 24 h sinusoidal cycle of temperature variation was programmed into the micrologger to mimic diurnal temperature change under field conditions. Because the CR10X controlled air temperature in the range of +5° to 45° C, peak-to-peak media temperature varied depending on its thermal properties, but was typically in the range of ± 15 °C.

Probes were tested in air, water, and five different soils: sand, loamy sand, Prior sandy loam, Palouse silt loam, and Houston Black clay loam. Each soil was tested with at least two water contents to show how temperature dependence changed with soil water content.
Results were compared to show temperature dependence of the probe in air and water. In addition, the change in apparent water content (calibrated probe output) per unit change in temperature was found for several water contents and soil types. Temperature dependence of the CS615 was evaluated concurrently in all tests except the Houston Black clay loam. All data collected has been transformed to volumetric water content ($m^3\ m^{-3}$), determined from standard calibration equations used by the ECH_2O probe and CS615. Using the correlation between ECH_2O output and temperature, a correction equation was derived and implemented to smooth temperature-related fluctuations.

Results and Discussion

To understand the effect of temperature on dielectric water content measurement, it is important consider results from a variety of media. Testing probes in air can help determine how the sensor circuitry itself is susceptible to changes in temperature, while testing submersed in water can determine temperature effects under maximum load. Soil tests using different textures and water contents can provide further understanding of temperature effects, as they will show how other factors, such as the bound and free water effects, influence probe readings.

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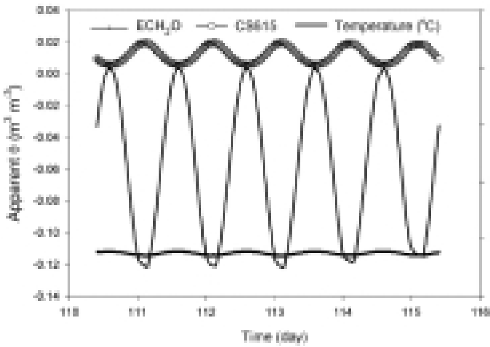

Fig. 1. Calibrated ECH$_2$O and CS615 output in air duringl cycles of air temperature in a controlled environment. Apparent water content values were calculated from standard calibration equations for each probe.

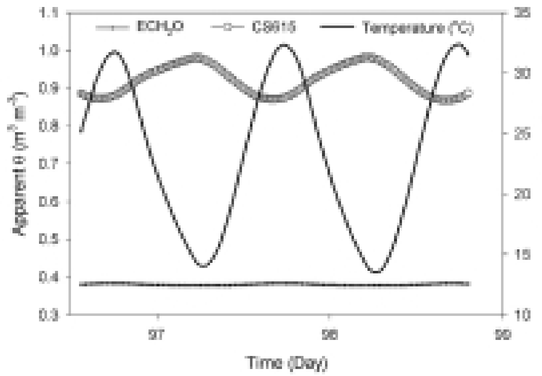

Fig. 2. Apparent water content measured by ECH$_2$O and CS615 probes while submerged in water inside a controlled-temperature chamber. The ECH2O output of ~38% VWC when submerged in water is typical, and reflects the saturation of probe output in pure water.

Air tests showed that the ECH$_2$O circuitry itself has an extremely low sensitive to temperature change (Fig. 1). Change in apparent measured volumetric water content (θ_m) were 0.000116 m^3 m^{-3} °C^{-1} and -0.000391 m^3 m^{-3} °C^{-1} for the ECH$_2$O and CS615, respectively. These results suggest that any changes in ECH$_2$O sensor output due to temperature are not due to electronics. Temperature tests submerged in water showed more sensitivity to temperature changes (Fig. 2), 0.000369 m^3 m^{-3} °C^{-1} and -0.00605 m^3 m^{-3} °C^{-1} for the ECH$_2$O and CS615, respectively. The negative correlation of temperature with probe output for the CS615 agrees with the expected result from the change in ε_{fw} with temperature. The positive correlation of the ECH$_2$O output with temperature requires additional explanation. Under maximum load, much of the electric field of the ECH$_2$O probe is contained within the sensor board (FR4) (hence the underestimate of water content), and sensor output may therefore be influenced by the temperature sensitivity of FR4 dielectric permittivity as well as ε_{fw}.

Response to soil temperature fluctuation was variable. Overall, changes in temperature had little effect on θ_m in soils with low actual volumetric water content (θ_a), but increased considerably with increasing θ_a (Fig. 3).

In both low surface area soils, the sand and loamy sand, the ECH$_2$O and CS615 showed little

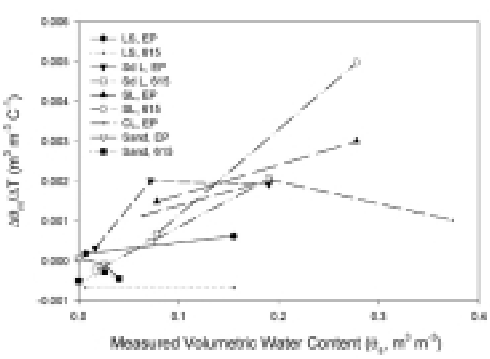

Fig. 3. Change in measured water content per unit change in temperature with respect to actual soil water content for the ECH$_2$O (EP) and CS615 (615) moisture probes.

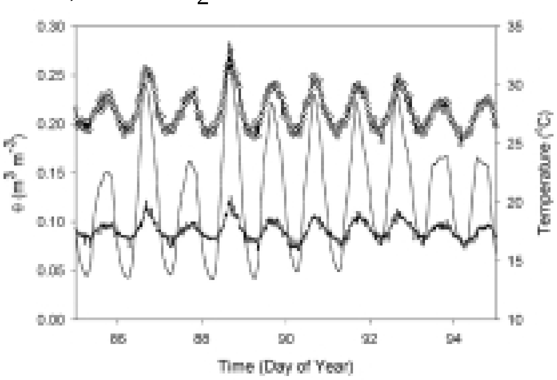

Fig. 4. TDR measured volumetric water content (line and symbols) and temperature (solid line) for a Brocko silt loam under greenhouse conditions (Wraith et al., 1995).

response to changing temperatures. The finer textured soils showed moderate temperature sensitivity, with the highest being 0.003 and 0.005 m^3 m^{-3} °C^{-1} for the ECH$_2$O and CS615 sensors,

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respectively. Experimental evidence shows these changes in water content are not out of the ordinary for TDR based dielectric measurement in soils (Fig. 4, 0.00423 $m^3\ m^{-3}\ °C^{-1}$) (Wraith et al., 1995; Or and Wraith, 1999; Wraith and Or, 1999). Generally, sensitivity was at or below 0.002 % $°C^{-1}$ for both sensors, with the CS615 less sensitive to temperature fluctuations at moderate θ_a.

To illustrate sensor response to temperature fluctuations over time, ECH_2O and CS615 sensor output for a sandy loam is shown in Figs. 5a. and 5b. The magnitude of temperature dependence for both sensors increases with increasing θ_a, but while ECH_2O θ_m correlation with temperature is positive for all θ_a, the CS615 correlation is negative at low θ_a, near neutral at medium θ_a, and positive for high θ_a. Although temperature response from both probes appears to be significant, it is important to note several things. First, temperature variation is +/- 15° C, a temperature range that is only seen in field soils under extreme conditions. Typical diurnal temperature range in medium to wet soils with plants growing on the surface are considerably smaller than those in the figure. Second, since changes in θ_m with temperature are small for both sandy (coarse grained) soils, it supports the theory of Or and Wraith (1999) that temperature effects may be due to bound and free water on soil surfaces.

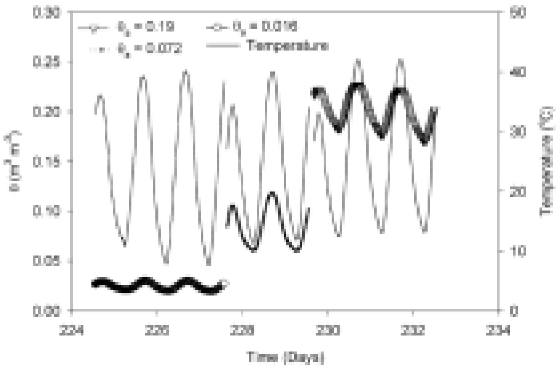

Fig. 5.a. Temperature and apparent water content of a Prior sandy loam. Water content was measured with an ECH_2O probe buried in the soil; actual values of water content are shown in the legend.

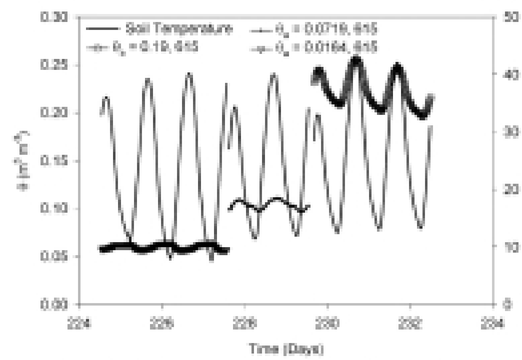

Fig. 5.b. Water content output from the CS615 probe in the same Prior sandy loam soil. Soil temperature and actual water contents shown are the same as Fig. 4.a.

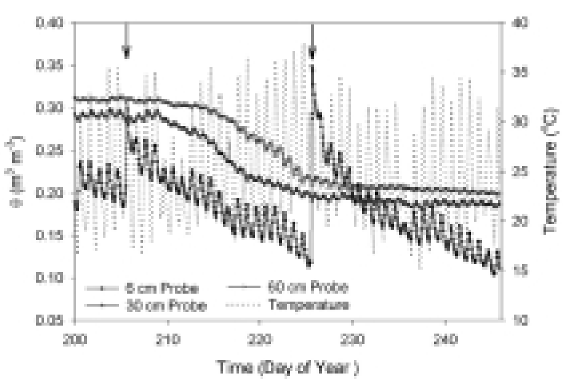

Fig. 6. Water content at 6, 30 and 60 cm and soil temperature at 6 cm in a Palouse silt loam. The bare soil surface was planted with tomato plants at 35 cm spacing. Arrows indicate irrigation events.

Because ECH2O probes are primary in situ field instrumentation, it may be useful to briefly consider some data from two field installations. In a silt loam, with sparse ground cover and infrequent irrigation, temperature-dependent output fluctuations can be seen in surface (6 cm) and, to a much smaller degree, subsurface (30 cm and 60 cm) probes (Fig. 6). These data contrast with output in a Prior sandy loam. Probes were buried in a potato field below a mature canopy at 12 to 24 cm depths with 27 h center-pivot irrigation. While air temperatures varied from 10 to 37°C (not shown), no temperature sensitivity can be seen in the output of the probe (Fig. 7). Combining the information from these field installations, it appears that temperature fluctuations are most

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problematic when the probes are shallow and the soil surface is bare, while deeper installation and canopy shading will remove the majority of temperature effects.

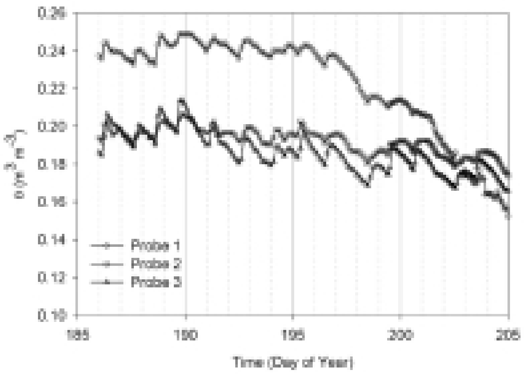

Fig. 7. Dynamic changes in water content of an center-pivot irrigated potato field. Probes were buried diagonally from 12 to 24 cm in a sandy loam soil. The field was irrigated on a 27 h cycle, with occasion stoppage for field maintainence. Difference in water content are primarily due to the location of ECH_2O probes with respect to potato roots and tubers. Although air temperature varied considerably, no temperature-dependent fluctuations can be seen in probe output.

From the several soils and water contents tested, it appears the probe output and temperature are linearly related, so a simple multiplier for probe output should provide an appropriate temperature correction. The temperature corrected water content (θ_t) is given by

$$\theta_t = \left[\frac{T_r + C}{T_i + C}\right]\theta_m \qquad [1]$$

where T_i is the temperature at which the measurement was made, T_r is the temperature of ECH_2O probe calibration, and C is a constant. Using the same sandy loam data from Fig. 4.a., Eq. 2

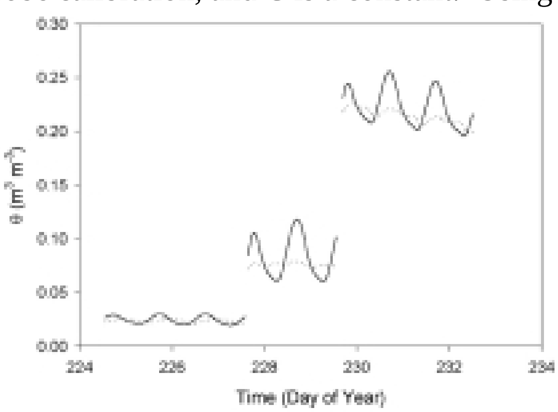

Fig. 8. ECH_2O water content data from Fig. 4.a. (solid line) with temperature corrected water content (dotted line).

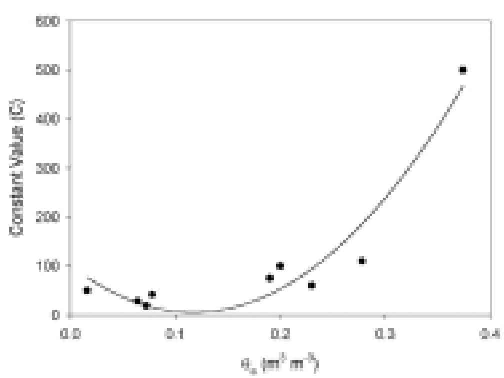

Fig. 9. Relationship between the contant C from the temperature correction function (Eq. 1), and the actual soil water content. Data are from three soils: Houston black clay loam, Palouse silt loam, and Prior sandy loam. A quadratic function was used to fit the data ($C = 101.4 - 1636.4\theta_a + 6889\theta_a^2$, $R^2 = 0.929$).

reduced temperature-dependent fluctuations considerably (Fig. 8). Although temperature-dependent fluctuation in ECH_2O output was greatly reduced, some variability remains. We hypothesize more variability could be removed if temperature were measured directly at the probe surface. Optimal C values for several soils and water contents were determined visually, and compared to θ_a (Fig. 9). A quadratic function fit to the points

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$$C = 101.4 - 1636.4{*}\theta_a + 6989{*}\theta_a^{\,2} \qquad [2]$$

indicates C can be predicted from a probe measurement of water content at (or near) the reference temperature (R^2 = 0.929).

Summary

ECH_2O probe sensors and circuitry show extremely low sensitivity to temperature fluctuations. However, buried in water or soil, changes in temperature did result in changes in probe output. Temperature dependence in coarse-textured soils (and water) was low, regardless of water content. In soils with fine texture, temperature dependence increased, indicating a relationship between the binding of water molecules to soil surfaces and temperature. In most field applications, temperature dependence plays a minor role in probe output change because temperature changes decrease with soil depth and increasing plant cover. Using a simple multiplier for temperature at the probe surface, temperature-dependent variability can be reduced considerably.

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