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Temperature Effects on Soil Dielectric Properties Measured at 50 MHz

Mark S. Seyfried* and Laura E. Grant

In recent years a number of soil water monitoring instruments have been developed and made commercially available. These instruments generally respond to the complex soil dielectric permittivity and operate at frequencies between 10 and 150 MHz. Although there is some evidence that these instruments are sensitive to temperature change in certain soils, little empirical data exists describing the degree of this sensitivity. We quantified temperature effects on both the real and imaginary components of the complex permittivity for 19 soils collected around the United States using the Hydra Probe soil water sensor, which operates at 50 MHz. We found that the real component response ranged from positive to negative such that the effect of a 40°C temperature change resulted in a maximum apparent water content change of $\pm 0.028 \text{ m}^3 \text{ m}^{-3}$ among soils. The effect of temperature on the imaginary component was as much as six times greater than on the real component, changing about $2\% \text{ }^\circ\text{C}^{-1}$, which is similar to that observed for electrical conductivity. The high imaginary component sensitivity to temperature is probably responsible for the high temperature sensitivity noted for commercial soil water sensors because they generally respond to a composite of both components. In addition, there was a strong linear correlation ($R^2 = 0.81$) between the effect of temperature on the calculated soil water content and the magnitude of the imaginary component. While this relationship suggests the possibility of calculating temperature effects on Hydra Probe-calculated soil water content in the field, it applies only to saturated soil conditions at present.

ABBREVIATIONS: TDR, time domain reflectometry.

Soil water content (θ , $\text{m}^3 \text{ m}^{-3}$) is a basic hydrologic parameter that affects groundwater recharge, surface water flow, transpiration, and carbon fixation. Electronic monitoring of θ facilitates the study of those processes by providing detailed temporal data. Most instruments currently in use measure soil dielectric permittivity, directly or indirectly, and then calculate θ with an equation relating permittivity to θ (e.g., Topp et al., 1980). Unfortunately, the relationship between permittivity and θ is not unique but is affected by the measurement frequency, soil properties (e.g., electrical conductivity, clay mineralogy, clay content), and temperature (Or and Wraith, 1999; Jones and Friedman, 2000; Friedman and Robinson, 2002). We focus on temperature because, although temperature effects on time domain reflectometry (TDR) have received some attention (e.g., Persson and Berndtsson, 1998; Or and Wraith, 1999; Evett et

al., 2005; Logsdon, 2005b), temperature effects on other commercial instruments are relatively unknown even though these instruments are widely used and evidence suggests that they may experience dramatic temperature effects (Baumhardt et al., 2000; Seyfried and Murdock, 2001; Blonquist et al., 2005).

Issues related to the use of soil dielectric properties to determine θ result, at least in part, from the fact that permittivity (ϵ^*) is a complex number. Thus,

$$\epsilon_r^* = \epsilon_r' - j\epsilon_r'' \quad [1]$$

where

$$\epsilon_r^* = \epsilon^* / \epsilon_0 \quad [2]$$

and ϵ_r^* is the relative complex permittivity, ϵ_r' is the real component of ϵ_r^* , ϵ_r'' is the imaginary component of ϵ_r^* , ϵ_0 is the free space permittivity ($8.854 \times 10^{-12} \text{ F m}^{-1}$), and $j = \sqrt{-1}$. The real component is related to the amount of energy stored in a material as molecules shift alignment in an alternating electric field, and the imaginary component, sometimes called the loss factor, is related to the energy lost in that applied field. The imaginary component is the result of two processes, electrical conduction and molecular relaxation (Topp et al., 2000; Robinson et al., 2003). These are related to ϵ_r'' as follows:

$$\epsilon_r'' = \epsilon_{r,mr}'' + (\sigma / 2\pi f \epsilon_0) \quad [3]$$

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where $\epsilon''_{r,mr}$ is the relative permittivity due to molecular relaxation, σ is the low frequency (dc) electrical conductivity, and f is the measurement frequency. Soil water instruments make use of the strong correlation between ϵ'_r and θ observed in soils. In nondispersive, nonlossy soils, where $\epsilon'_r \gg \epsilon''_r$, the $\epsilon'_r(\theta)$ relationship is robust and temperature effects can be estimated with reasonable accuracy for both TDR (Pepin et al., 1995) and other commercial instruments (Seyfried and Murdock, 2001, 2004), assuming that soil water has the known dielectric properties of pure water. Complications arise as ϵ''_r increases.

High ϵ''_r values affect θ estimation in two ways. First, while θ calculations are based on the $\epsilon'_r(\theta)$ relationship, most instruments respond to both ϵ'_r and ϵ''_r . For example, the apparent permittivity (ϵ_a) is generally used to calculate θ from TDR data. It is determined for a sinusoidal plane wave propagating along a transmission line (assumed analogous to TDR signal propagation) and is related to both ϵ'_r and ϵ''_r as follows:

$$\epsilon_a = \epsilon'_r/2 \left\{ 1 + \left[1 + \left(\epsilon''_r/\epsilon'_r \right)^2 \right]^{0.5} \right\} \quad [4]$$

Clearly, high values of ϵ''_r elevate ϵ_a and confound θ estimation. With other instruments the relationship may be different, but the problem remains that both components affect the measured variable. The second way is the less widely recognized but well documented dispersion of ϵ'_r . That is, soil ϵ'_r itself may be elevated above that expected, assuming that soils have the same dielectric properties as independent mixtures of soil particles and free water (Campbell, 1990; Saarenketo, 1998; Robinson et al., 2005; Chen and Or, 2006). Chen and Or (2006) have shown that these effects may be attributed to interfacial polarization (or the Maxwell–Wagner effect).

The issue of high ϵ''_r is especially important when working with the commercial (non-TDR) soil water sensors mentioned above because ϵ''_r is strongly dependent on the measurement frequency (see Eq. [3]). It turns out that ϵ''_r tends to decline, in some soils dramatically, as f increases from the KHz to the MHz region (Saarenketo, 1998; Robinson et al., 2005; Chen and Or, 2006). Because the commercial instruments generally operate at relatively low frequencies (10–150 MHz), the ϵ''_r term will tend to be greater for those instruments than for TDR, which operates at frequencies between 600 and 1000 MHz (Robinson et al., 2005).

The effects of temperature on θ estimation are strongly related to ϵ''_r . Both $\epsilon''_{r,mr}$ and σ are temperature dependent. The effect of increasing temperature on $\epsilon''_{r,mr}$ is to shift the $\epsilon''_r(f)$ relationship (which is declining under the conditions of interest) to the right, resulting in elevated ϵ''_r (Tinga, 1992). The effect of temperature on σ is well established and results in an increase with temperature of about 2% °C⁻¹ (Or and Wraith, 1999). Thus, both processes cause an increase in ϵ''_r with temperature, which will tend to result in an apparent increase in θ . This trend is opposed to that predicted from the dielectric properties of pure water (Weast, 1986).

Although a general understanding of these issues has emerged in recent years, few experimental data have documented the sensitivity of ϵ'_r or ϵ''_r to soil type or to temperature change. Similarly, few data have described the linkage of ϵ'_r and ϵ''_r , particularly with respect to temperature effects. The direct

effect of these processes on θ estimation, as well as the potential for improved measurement accuracy, has led others to recommend that greater attention be devoted to the separation of ϵ'_r and ϵ''_r in future research (Blonquist et al., 2005; Robinson et al., 2003). Consistent with that recommendation, we previously described how the $\epsilon'_r(\theta)$ relationship for different soils is affected by ϵ''_r (Seyfried et al., 2005). In this paper we extend that analysis to consider temperature effects. The objectives of this work are (i) to quantify the effect of temperature on ϵ'_r and ϵ''_r for a wide variety of soils and (ii) to examine the relationship between $\epsilon'_r(T)$ and ϵ''_r to evaluate the potential for predicting temperature effects from ϵ''_r information. Our data were collected only at 50 MHz, using Hydra Probe soil water sensor (Stevens Water Monitoring Systems, Portland, OR), and therefore have direct implications for commercial instruments that operate near that frequency. The results should also provide useful insights into the dielectric properties of soils in general.

Materials and Methods

Hydra Probe Description

The design and measurement approaches behind the Hydra Probe soil water sensor used in our analysis are based on the work of Campbell (1988, 1990) and described in greater detail in Seyfried et al. (2005). When a voltage is applied to a coaxial probe, the reflected signal is related to the probe impedance (Z_p) such that

$$\frac{Z_p}{Z_c} = \frac{1 + \Gamma}{1 - \Gamma} \quad [5]$$

where Z_c is the characteristic impedance of the coaxial cable (determined independently) and Γ is the complex ratio of the reflected voltage to the incident voltage. Under these conditions, the probe impedance is determined by the electrical properties of the probe itself (Z_0) and the ϵ_r^* of the media in the sensing volume (e.g., soil). These are related by

$$Z_p = \frac{Z_0}{\sqrt{\epsilon_r^*}} \cot \operatorname{anh} \frac{\omega L \sqrt{\epsilon_r^*}}{c} j \quad [6]$$

where L is the electric length of the probe and c is the speed of light (Campbell, 1990). By inverting Eq. [6], ϵ_r^* (and therefore ϵ'_r and ϵ''_r) can be solved for given the measured reflected voltages (Campbell, 1990). Note that the value of ϵ''_r obtained in this way does not distinguish between $\epsilon''_{r,mr}$ and σ .

The Hydra Probe consists of a 4-cm diameter cylindrical head that has four 0.3-cm diameter tines that protrude 5.8 cm. These are arranged such that a centrally located tine is surrounded by the other three tines in an equilateral triangle with 2.2-cm sides. A 50-MHz signal is generated in the head and transmitted via planar waveguides to the tines, which constitute a coaxial transmission line. In addition, the Hydra Probe has a thermistor embedded in the sensor head to measure temperature. The raw signal output is four analog dc voltages that are transmitted to a data logger (or other voltage measuring device). Manufacturer-supplied software uses the first three voltages to calculate ϵ'_r and ϵ''_r (using Eq. [6]) and the fourth to calculate temperature.

Experimental Procedures

The soil temperature data were collected in conjunction with a previously published study of soil water calibration (Seyfried et al., 2005). The soils used were selected to represent a wide range of textures and mineralogy and have been described in Seyfried et al. (2005). A table summarizing the soil properties is included here (Table 1).

The temperature sensitivity of each soil was determined at two different water contents: oven-dry and effective saturation. Triplicate samples of oven-dry soil were packed uniformly into plexiglas Tempe cells as described by Seyfried et al. (2005).

The surface was covered with parafilm to prevent evaporation, and the sensor was placed vertically (tines inserted downward from the top) into the cell. The three replicates were run simultaneously. All data were collected and stored on a data logger. In addition, a fourth “dummy” cell also packed with oven-dry soil and instrumented with a thermistor, was prepared.

The four cells were then placed in a controlled-temperature incubator. Temperature was varied from 45 to 5°C in 10°C increments. Thermal equilibrium was assumed when the air temperature in the chamber and the dummy cell temperature were within 0.5°C. Each soil-temperature combination was measured a minimum of 20 times. Following the oven-dry readings, distilled, deionized water was added slowly from below until glistening at the surface indicated effective soil saturation. Temperature sensitivity data were then collected in the same manner as for the oven-dry soil with the dummy cell saturated. Water content at effective saturation was determined gravimetrically.

In addition, we were concerned that there may be some instrument response to temperature independent of soil conditions, for example, due to the electronic components of the instruments. To evaluate the instrument response we placed the same Hydra Probe sensors in the incubation chamber suspended in air and applied temperatures ranging from 45°C to 0°C.

Results and Discussion

Instrument Response

When the instruments were suspended in air, there was a small positive effect of temperature on ϵ_r' , while the effect on ϵ_r'' was negligible. Ideally, the measured ϵ_r' would be 1 for all temperatures because the ϵ_r' of air is 1 and is not affected by temperature. The response of all three sensors was similar and well described ($R^2 = 0.99$) by the equation

$$\epsilon_r' = 1.205 + 0.00456T + 0.0001908T^2 \quad [7]$$

where T is the air temperature in °C.

If we assume that this response is a result only of the instrument components and therefore applicable to all measurements, the impact of the instrument temperature effect on calculated θ can be estimated from the $\epsilon_r'(\theta)$ relationship. Because the $\epsilon_r'(\theta)$ relationship is nonlinear, the impact of this effect varies with θ . We illustrate this for a 40°C temperature change (from 5 to 45°C) in Fig. 1 using the general $\epsilon_r'(\theta)$ calibration equation from Seyfried et al. (2005). We found that, with this fairly extreme change, the instrument effect is greater than 0.01 m³ m⁻³ in dry soil. At higher water contents instrument temperature effects

TABLE 1. Properties of soils tested.

NRCS ID no.†	State	Site	Depth cm	Clay %		Mineral‡	Horizon
				—	—		
2030	AR	Lonoke Farm	20	15.1	7.6	ND	A
2026		Walnut Gulch	10	11.7	70	ND	A
			25	22.4	48.2	ND	Bk1
			50	21	40.4	ND	Bk2
2013	GA	Watkinsville	5	10.8	73.8	KK	Ap1
			50	63.2	25.4	GI, KK	Bt1
	ID	Breaks	30	17	59	ND	A3
2010	MS	Newton (21)	10	6.3	45.5	KK, VR	Ap
			20	6.4	49.6	ND	E
2033	MS	Onward (25)	5	27.8	6.2	MT	Ap
			20	35.8	3.8	ND	Bg
			50	10.9	21.7	ND	Bw
	MS	Tunica (26)	20	30.8	27.4	MT	A1
			50	42.7	1.5	MT	BgB1
			50	20.4	26.4	ND	ND
2041	VT	Mt. Mansfield	0–3			organic	Oi
2027	GA	Little River	5	2.8	88.1	ND	Ap
	OK	Fort Reno	10	15	67	ND	Ap
			50	35	47	ND	Bt
2031	IA	Ames	5	36	17.6	MT	A

† NRCS, Natural Resource Conservation Service.

‡ Dominant clay mineral, ND = not determined, KK = kaolinite, GI = gibbsite, VR = vermiculite, MT = montmorillonite.

were much lower. For a 20°C change the effects are less than 0.01 m³ m⁻³ for all water contents.

Oven-Dry Soil

In all oven-dry soils we observed a small, nonlinear positive ϵ_r' temperature response. Although this was a consistent trend, on 10 of the 60 soil- replicate combinations there was a discontinuous, unexplained ϵ_r' drop at the highest temperature recorded (45°C). Disregarding those readings, the magnitude and direction of the temperature response was practically equivalent to that observed in air, so that when the oven-dry data were corrected to account for the instrument temperature sensitivity using Eq. [7], no temperature response was observed (Fig. 2).

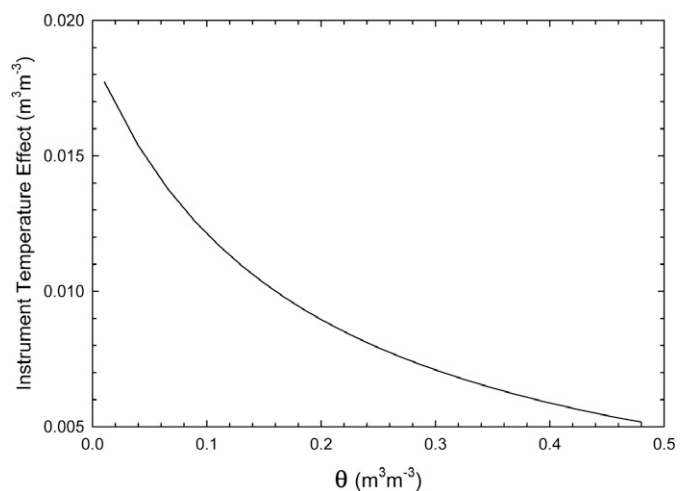


FIG. 1. Instrument temperature effect, defined here as the apparent change in soil water content (θ) due to Hydra Probe electrical components when subjected to a 40°C temperature change, plotted as a function of the actual water content. For example, if soil at 0.30 m³ m⁻³ experiences a temperature change of 5 to 45°C, the instrument effect will cause an apparent water content rise of about 0.007 to 0.307 m³ m⁻³.

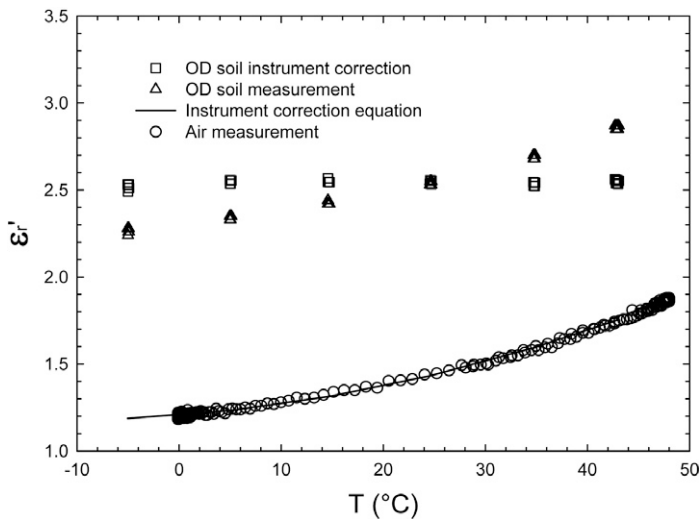


FIG. 2. Oven-dry (OD) soil corrected for instrument effects. The instrument correction equation (Eq. [7]) was fitted to the air data. After correcting for instrument effects to 25°C, ϵ_r' , the real component of relative complex permittivity, is essentially independent of temperature and slightly greater than 2.5.

This result indicates that oven-dry soils are insensitive to temperature change, which is expected for the air and solid constituents. The instrument-corrected oven-dry ϵ_r' values for the 19 mineral soils ranged from 2.47 to 2.99, with a mean of 2.70 and standard deviation of 0.130, which is consistent with TDR data reported in the literature (Hook and Livingston, 1995). The temperature effect on measured ϵ'' was an order of magnitude less than that observed for ϵ_r' and was therefore ignored.

Effective Saturation

Real Component

We used eight soils to represent the ϵ_r' temperature response at effective saturation for the 19 soils examined (Fig. 3). In all cases the ϵ_r' value plotted is corrected for instrument temperature sensitivity using Eq. [7]. Values among soils are displaced vertically due to variations in the effective saturation, which is largely a function of clay content. For each soil, the average value of three sensors is plotted. Twenty values for each soil-temperature combination are plotted, but individual values are practically indistinguishable because of the low degree of variability among averaged values.

The response of all soils was roughly linear, with slopes ranging from slightly positive to slightly negative and some soils essentially insensitive to temperature. For the measured temperature range of 5 to 45°C, the largest positive ϵ_r' change was 3.7, and the largest negative change was -2.0 among all soils. The lower value is in close agreement with what is calculated using the mixing model equation as suggested by Roth et al. (1990) and used by Seyfried and Murdock (2001) to describe temperature effects in sand. That equation can be written as

$$\sqrt{\epsilon_r'} = \theta \sqrt{\epsilon_{r,w}'(T)} + \theta_s \sqrt{\epsilon_{r,s}'} + \theta_g \sqrt{\epsilon_{r,g}'} \quad [8]$$

where θ ($\text{m}^3 \text{m}^{-3}$) is the volumetric fraction and ϵ_r' the relative real permittivity of soil constituents denoted by the subscripts w

for water, g for gas, and s for solids. (θ , without subscript, is used to denote soil water content, consistent with the text). The $\epsilon_{r,w}'(T)$ term represents the temperature effect on pure water and was calculated as (Weast, 1986):

$$\epsilon_{r,w}' = 78.54[1 - 4.58 \times 10^{-3}(T - 25) + 1.19 \times 10^{-5}(T - 25)^2 - 2.8 \times 10^{-8}(T - 25)^3] \quad [9]$$

If we use the measured values of $\theta = 0.28 \text{ m}^3 \text{m}^{-3}$ and $\theta_a = 0.05$, and assume $\epsilon_{r,s}' = 5$ for the Tifton soil, we calculate an ϵ_r' change of -1.8 when temperature increases from 5 to 45°C, which is close to the -2.0 observed. The neutral to positive changes in other soils indicate that the soil water system does not behave as if it were composed of pure water and inert soil.

When ϵ_r' values were converted to θ using previously developed calibrations (Seyfried et al., 2005), the effects of temperature were reasonably well described as a linear function of temperature, with R^2 values greater than 0.80 apart from four soils for which the slope $d\theta/dT$ was essentially 0. This linear temperature dependence is consistent with what others have reported for TDR (Persson, and Berndtsson, 1998; Logsdon, 2000, 2005b). The slope $d\theta/dT$ ranged from 0.0007 to -0.0007 $\text{m}^3 \text{m}^{-3} \text{°C}^{-1}$. This corresponds to a calculated θ change of 0.028 $\text{m}^3 \text{m}^{-3}$ for a 40°C temperature change.

There is no equation analogous to Eq. [8] to calculate the upper limit for positive temperature effects. However, the $d\theta/dT$ slopes we calculate for these soils are within the range of values reported for TDR in high clay-content, smectitic soils (Persson, and Berndtsson, 1998; Logsdon, 2000). Previous research (Seyfried and Murdock, 2001) indicates that the $d\theta/dT$ slopes are greatest (in absolute value) when the soil is saturated. This indicates that for many field conditions, temperature effects on θ values calculated from Hydra Probe measurements, although observable, will not be substantial. That is, for most soils, the absolute value of $d\theta/dT$ will be less than 0.0007 $\text{m}^3 \text{m}^{-3} \text{°C}^{-1}$,

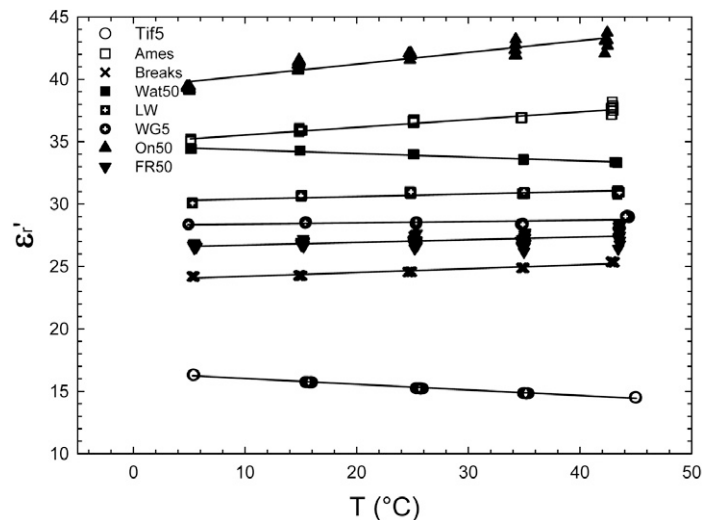


FIG. 3. Effect of temperature on ϵ_r' (real component of relative complex permittivity) for eight representative soils (Tif5 = Little River, 5 cm; Ames = Ames, 5 cm; Breaks = Breaks, 30 cm; Wat50 = Watkinsonville, 50 cm; LW = Little Washita, 50 cm; WG5 = Walnut Gulch, 5 cm; On50 = Onward, 50 cm; and FR50 = Fort Reno, 50 cm; see Table 1). Each point is the average of data from three individual sensors. Twenty measurements were made at each temperature. Lines represent the linear temperature effect for each soil.

the temperature range experienced will often be less than 40°C, and the soil will probably not be saturated much of the year. All of these conditions will tend to reduce the temperature effect range to less than 0.028 m³ m⁻³.

Imaginary Component

For all soils and all sensors, the effect of temperature on ϵ_r'' was remarkably linear and always positive. For 16 of the 19 soils investigated, linear regression of ϵ_r'' on temperature resulted in R^2 values greater than 0.99; for the remaining three soils, the R^2 values were greater than 0.93. The soils represented in Fig. 4, which are the same as those in Fig. 3, exemplify the linearity and range of slopes observed among soils. Slopes ($d\epsilon_r''/dT$) calculated from regression analysis ranged from 0.10 to 1.11, almost six times greater than that obtained for $d\epsilon_r'/dT$. Also note that ϵ_r'' values, at any temperature, are correlated with the $d\epsilon_r''/dT$ slope (the R^2 between the slope and y intercept is 0.97).

We noted previously (Seyfried et al., 2005) that ϵ_r'' varies more among soils than ϵ_r' . Here we found that it also varies much more with temperature. From these data, it is clear that soil dielectric moisture sensors operating at frequencies near 50 MHz that respond to a composite of ϵ_r' and ϵ_r'' (e.g., Eq. [3]) have a great potential for positive temperature sensitivity. We illustrate this with data from the Ames soil, which has a strong ϵ_r'' temperature response relative to ϵ_r' (Fig. 5). The ϵ_a calculated from Eq. [3] varies from 41 to 57 as temperature changes from 5 to 43°C. Using a previously developed calibration equation (Seyfried et al., 2005), this corresponds to an apparent θ change of 0.117 m³ m⁻³ or a $d\theta/dT$ of 0.0031 m³ m⁻³ °C⁻¹, considerably more than the apparent θ change of 0.021 m³ m⁻³ or a $d\theta/dT$ of 0.00056 m³ m⁻³ °C⁻¹ calculated from ϵ_r' . These dramatic temperature effects on ϵ_a are consistent with data reported by Seyfried and Murdock (2001) in which the $d\theta/dT$ for an unsaturated sample was 0.0039 m³ m⁻³ °C⁻¹, and more recently by Evett et al. (2006), who reported even greater tem-

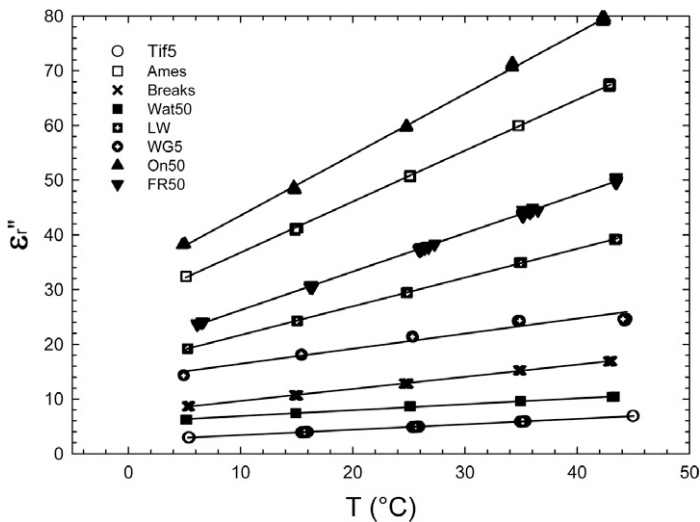


FIG. 4. Effect of temperature on ϵ_r'' (imaginary component of relative complex permittivity) for eight representative soils (Tif5 = Little River, 5 cm; Ames = Ames, 5 cm; Breaks = Breaks, 30 cm; Wat50 = Watkinsonville, 50 cm; LW = Little Washita, 50 cm; WG5 = Walnut Gulch, 5 cm; On50 = Onward, 50 cm; and FR50 = Fort Reno, 50 cm; see Table 1). Each temperature- ϵ_r'' combination is represented by 12 to 15 measurements.

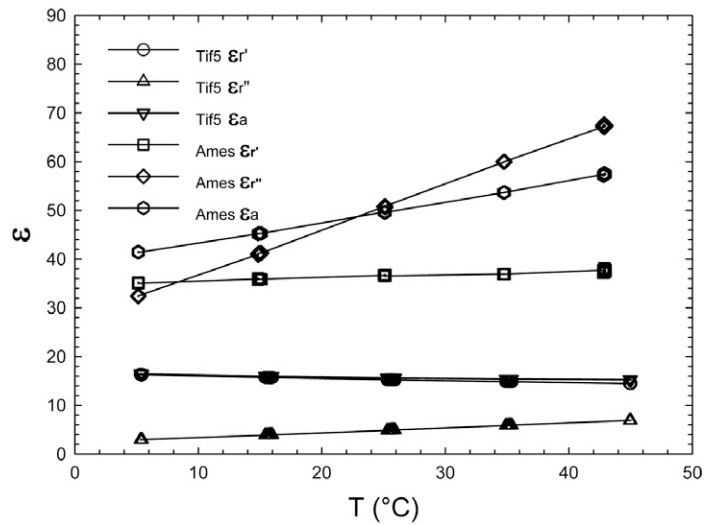


FIG. 5. Comparison of the measured ϵ_r' (real component of relative complex permittivity) and ϵ_r'' (imaginary component of relative complex permittivity) temperature (T) response with apparent permittivity, ϵ_a , calculated using Eq. [3]. The Ames soil is representative of high ϵ_r'' soils, and the Tif5 soil is representative of low ϵ_r'' soils. Where ϵ_r'' is low, there is little impact on ϵ_a , and sensor type is not critical.

perature sensitivity. In contrast, similar ϵ_a calculations for the Tifton soil, which has a negative temperature response, indicate that sensor type is not critical for low ϵ_r'' soils because ϵ_r' and ϵ_a are practically indistinguishable.

We cannot determine from Hydra Probe data alone the relative contribution of $\epsilon_r''_{r,mr}$ or σ to ϵ_r'' . One can express ϵ_r'' as either purely relaxation or purely conductivity using Eq. [4]. For example, following von Hippel (1995), ϵ_r'' can be described as the *dielectric conductivity* (σ_d), with units of dS m⁻¹, as

$$\sigma_d = \epsilon_0 \epsilon_r'' f 2\pi \quad [10]$$

If the contribution of $\epsilon_r''_{r,mr}$ is very small, σ_d calculated in this way should be equivalent to the electrical conductivity. We have shown this to be true for Hydra Probe measurements in aqueous salt solutions for σ values up to ~ 3.5 dS m⁻¹ (Seyfried and Murdock, 2004).

The advantage of considering ϵ_r'' in terms of σ_d is that the temperature response of electrical conductivity is fairly well documented (Sheets and Hendrickx, 1995; Or and Wraith, 1999), thus enabling the estimation of temperature effects. Some evidence in the literature indicates that σ dominates the ϵ_r'' signal at 50 MHz (Robinson et al., 2005; Campbell, 1990; Hasted, 1973). If this is the case for soils in general, then the slope $d\sigma_d/dT$ determined from Hydra Probe measurements and Eq. [10] should be approximately equal to $d\sigma/dT$ calculated with standard relationships used for soils.

We tested this approach using the temperature correction equation of Sheets and Hendrickx (1995). They calculate σ_{25} , the electrical conductivity corrected to 25°C, with a correction factor C_T , such that

$$\sigma_{25} = C_T \sigma, \quad C_T = 0.447 + 1.4034 e^{(-T/26.815)} \quad [11]$$

The slope $d\sigma/dT$ predicted with this approach is highly linear, with a value of $0.019 \text{ S m}^{-1} \text{ C}^{-1}$, which is very similar to that used by others (Kelleners et al., 2005; Or and Wraith, 1999). After converting ϵ_r'' measurements to σ_d , we found that temperature effects were strongly linear with an average $d\sigma_d/dT$ for all soils of $0.018 \text{ S m}^{-1} \text{ C}^{-1}$. Soils with a relatively high σ_{25} tended to agree with Eq. [11] most closely (Fig. 6). Deviation from slopes of $0.019 \text{ S m}^{-1} \text{ C}^{-1}$ implies that mechanisms other than electrical conductivity contribute to ϵ_r'' in those soils, which is consistent with observations of Kelleners et al. (2005) and Logsdon (2005a). Recent research by Chen and Or (2006) has shown that electrical conductivity and molecular relaxation are intimately linked through the process of interfacial polarization, so that ultimately, temperature effects may be very difficult to predict. As a practical matter, however, predictions of σ_{25} based on Eq. [11] did not generate large errors for any of the soils tested and so may provide a reasonable basis for estimating temperature effects. Although our data are only for effective saturation, it is reasonable to expect that it would hold for other water contents as well.

Water Content Temperature Effects and ϵ_r''

The data plotted in Fig. 7 relate the slope of the apparent water content response to temperature ($d\theta/dT$) for all 19 mineral soils to the ϵ_r'' measured at 25°C (ϵ_{r25}''). The choice of x axis is somewhat arbitrary in that we could use other measures of ϵ_r'' such as the y -intercept or slope and achieve approximately the same result due to the high correlation among those variables. The relationship is roughly linear over the whole range ($R^2 = 0.81$), although the correlation is much better for the relatively high ϵ_r'' (>10) soils.

Negative slopes in Fig. 7 characteristic of the low ϵ_{r25}'' soils are consistent with previous research in sands (Pepin et al., 1995) and the assumption that bulk soil dielectric properties can be approximated assuming that soil particles are inert and the soil solution has dielectric properties of pure water (e.g., Eq. [8]). Different mechanisms have been proposed to explain observed temperature effects on θ (Persson and Berndtsson, 1998; Or and Wraith, 1999; Robinson et al., 2005; Chen and Or, 2006). For Hydra Probe measurements, these effects are not directly related to ϵ_r'' as they are with instruments that respond to both components (e.g., Eq. [3]), which explains why the Hydra Probe is insensitive to temperature relative to other, low-frequency instruments. The connection rather appears to be the result of interfacial polarization, as recently described by Chen and Or (2006). Basically, an increasing temperature causes the electrical conductivity to increase (as described previously), which then enhances interfacial polarization, increasing ϵ_r' . Thus temperature, ϵ_r'' , ϵ_r' , and θ calculations are linked in a complex manner that is sensitive to soil properties.

Given the relationship shown in Fig. 7 and the fact that the Hydra Probe provides measurements of ϵ_r' , ϵ_r'' , and temperature, it should be possible to use ϵ_r'' values to calculate the temperature response of a given soil at any time in the field. This approach has the great advantage of predicting temperature effects without requiring a detailed understanding of the interactions within the soil solution

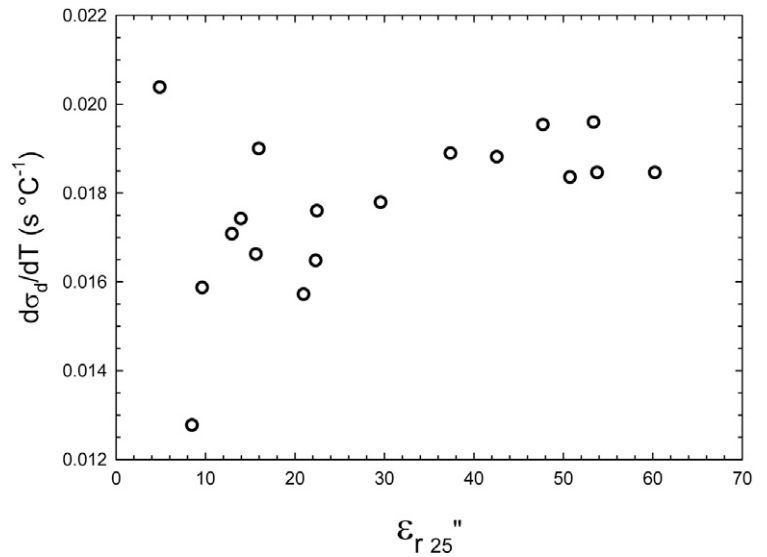


FIG. 6. The temperature (T) response of σ_d (dielectric conductivity) as a function of ϵ_r'' (imaginary component of relative complex permittivity) measured at 25° (ϵ_{r25}''). The soils with relatively high ϵ_r'' respond as if all losses were from σ . Even at lower values, the difference between the $d\sigma_d/dT$ slope and 0.019 is small.

and between clay surfaces that lead to soil-specific responses. Unfortunately, the data presented here apply only to effectively saturated soil. It is well known that electrical conductivity is highly sensitive to changes in θ , and it is not clear how those changes will affect the relationship between $d\theta/dT$ and ϵ_r'' . A more practical application of this information awaits a more comprehensive understanding of ϵ_r'' , θ , and temperature interactions. In the meantime, the relationship illustrated in Fig. 7 can be regarded as qualitative guide to the magnitude of temperature effects that might be expected in soils.

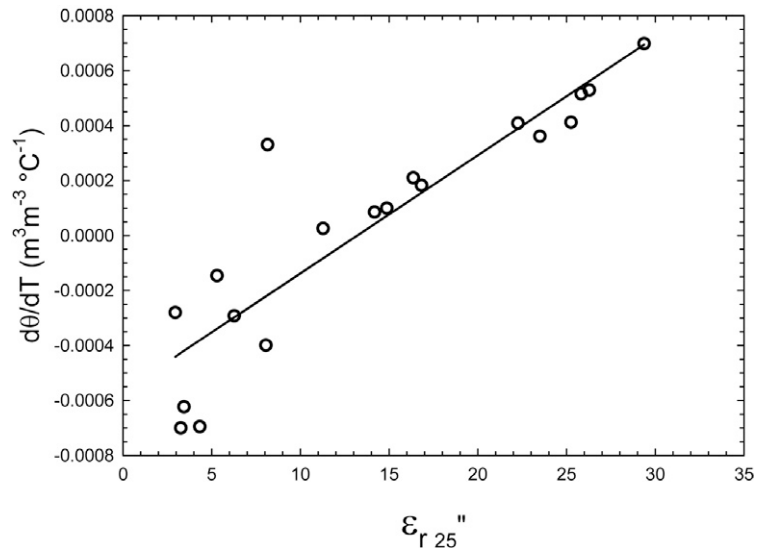


FIG. 7. The effect of temperature (T) on estimated soil water content (θ), quantified by $d\theta/dT$, as a function of ϵ_{r25}'' (imaginary component of relative complex permittivity measured at 25°C). Although there is considerable scatter about this relationship, especially for relatively low values of ϵ_{r25}'' , it is clear that positive temperature effects are associated with high ϵ_{r25}'' values.

Conclusions

We documented the ϵ_r' and ϵ_r'' temperature sensitivity of 19 mineral soil samples representing a wide range of texture and mineralogy when measured at 50 MHz with the Hydra Probe. With respect to ϵ_r' , we found a small, nonlinear temperature response that is apparently a result of the instrument components. This effect is small enough to be ignored for many applications, or can be taken into account. In oven-dry soil, no temperature effect was observed if instrument effects were considered. In saturated soil, temperature responses were both positive and negative for different soils. When converted to water content, the response was linear and fell between -0.028 and $0.028 \text{ m}^3 \text{ m}^{-3}$ for temperatures ranging from 5 to 45°C. The lower (negative) extreme among soils was in close agreement to that predicted assuming the dielectric properties of the soil solution were equivalent to those of pure water. Positive temperature effects were within the range reported for clay soils and TDR.

In all soils investigated, there was a distinct, highly linear relationship between ϵ_r'' and temperature in the saturated samples (negligible in oven-dry samples). The range in magnitude of ϵ_r'' and of temperature effects was much greater than that observed for $\epsilon_r'(T)$ with the same samples. This explains the extreme temperature sensitivity exhibited by some instruments that do not distinguish ϵ_r' from ϵ_r'' but respond to both. It also indicates that those instruments will experience highly variable temperature effects among different soils.

When ϵ_r'' was expressed as σ_d , we found that the temperature response was similar to that predicted for σ in general, implying that σ is largely responsible for the measured ϵ_r'' values. The positive correlation between the magnitude of ϵ_r'' and the θ (and therefore ϵ_r') temperature response is consistent with interfacial polarization as a dispersion mechanism at 50 MHz, which is directly related to σ . This documented relationship between the θ temperature response and ϵ_r'' indicates that there is a potential for estimating temperature response based on ϵ_r'' data. Before this can be accomplished, however, the interactions between θ , ϵ_r' , and ϵ_r'' must be also be considered.

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