Soil moisture monitoring for climate research: Evaluation of a low-cost sensor in the framework of the Swiss Soil Moisture Experiment (SwissSMEX) campaign

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[1] Soil moisture measurements are essential to understand land surface–atmosphere interactions. In this paper we evaluate the performance of the low-cost 10HS capacitance sensor (Decagon Devices, United States) using laboratory and field measurements. Measurements with 10HS sensors of volumetric water content (VWC, Vol.%), integrated absolute soil moisture (millimeters) over the measured soil column, and the loss of soil moisture (millimeters) for rainless days are compared with corresponding measurements from gravimetric samples and time domain reflectometry (TDR) sensors. The field measurements were performed at two sites with different soil texture in Switzerland, and they cover more than a year of parallel measurements in several depths down to 120 cm. For low VWC, both sensor types present good agreement for laboratory and field measurements. Nevertheless, the measurement accuracy of the 10HS sensor reading (millivolts) considerably decreases with increasing VWC: the 10HS sensors tend to become insensitive to variations of VWC above 40 Vol.%. The field measurements reveal a soil type dependency of the 10HS sensor performance, and thus limited applicability of laboratory calibrations. However, with site-specific exponential calibration functions derived from parallel 10HS and TDR measurements, the error of the 10HS compared to the TDR measurements can be decreased for soil moisture contents up to 30 Vol.%, and the day-to-day variability of soil moisture is captured. We conclude that the 10HS sensor is appropriate for setting up dense soil moisture networks when focusing on medium to low VWC and using an established site-specific calibration function. This measurement range is appropriate for several applications in climate research, but the identified performance limitations should be considered in investigations focusing on humid conditions and absolute soil moisture.

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1. Introduction

[2] Soil moisture is a key variable of the climate system. It affects surface fluxes and can subsequently impact air temperature, boundary layer stability, and precipitation (see e.g., *Seneviratne et al.* [2010] for a review). Long-term measurement networks of soil moisture have traditionally been scarce [e.g., *Robock et al.*, 2000], due to the associated high costs and delayed recognition of the importance of soil moisture for climate modeling and regional weather prediction. However, the investigation of soil moisture–climate relationships has gained increasing attention in recent years [e.g., *Betts*, 2004; *Koster et al.*, 2004; *Seneviratne et al.*, 2006; *Dirmeyer et al.*, 2006; *Vautard et al.*, 2007; *Teuling et al.*, 2010a; *Hirschi et al.* 2011], and new measurement techniques, such as ground penetrating radar GPS [*Larson et al.*, 2008], the measurement of cosmic ray neutrons [*Zreda et al.*, 2008], distributed temperature sensors [*Steele-Dunne et al.*, 2010] and remote sensing [e.g., *Schmugge et al.*, 2002; *Tapley et al.*, 2004; *Jackson*, 2005; *Wagner et al.*, 2007; *de Jeu et al.*, 2008] have been developed. Remote sensing, in particular, has several limitations: Microwave-based measurements only capture soil moisture from top soil layers (few centimeters), and estimates from the Gravity Recovery and Climate Experiment (GRACE) only provide large-scale estimates (400–500 km resolution

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[e.g., *Ramillien et al.*, 2008]) and do not distinguish between soil moisture, groundwater, snow, and other forms of land water storage.

[3] Hence, ground-truth data remain crucial for the calibration and validation of remote sensing–derived estimates and for the evaluation of land surface and climate models. Historically, long-term networks were only available in a few regions, for example in Illinois [*Hollinger and Isard*, 1994], the former Soviet Union [*Vinnikov and Yeserkepova*, 1991], as well as in China and Mongolia (see *Robock et al.* [2000] and *Seneviratne et al.* [2010] for an overview). These networks used labor-intensive, noncontinuous and/or destructive measurement techniques, e.g., gravimetric sampling or neutron probe measurements. Continuous measurements of soil moisture, however, may be of key relevance when investigating, e.g., soil moisture persistence patterns or soil moisture–atmosphere interactions and feedbacks. This latter aspect is also relevant for the validation of remote sensing products. Through the increasing interest of soil moisture in different disciplines, in 2010 the International Soil Moisture network (ISMN) was established (http://www.ipf.tuwien.ac.at/insitu). It is operated in cooperation with the Global Soil Moisture Databank [*Robock et al.*, 2000] and involves several noncontinuous and continuous networks in America, Australia, Asia and Europe.

[4] Two of the most common techniques allowing continuous soil moisture measurements make use of the dependency of the permittivity of the soil on volumetric water content [*Robinson et al.*, 2008]. These are either based on time domain reflectometry (TDR) [see, e.g., *Topp and Reynolds*, 1998; *Robinson et al.*, 2003; *Topp*, 2003; *Robinson et al.*, 2008] or soil capacitance techniques [e.g., *Dean et al.*, 1987; *Topp*, 2003; *Bogena et al.*, 2007; *Robinson et al.*, 2008]. TDR sensors operate at higher frequencies and have been shown to be of higher accuracy than the capacitance-based sensors [e.g., *Walker et al.*, 2004; *Robinson et al.*, 2008]. The capacitance sensors, on the other hand, are less accurate but are also of significantly lower cost. This allows the use of a higher number of instruments and thus much denser networks. Given the strong spatial and temporal variability of soil moisture at relatively small scales [e.g., *Teuling and Troch*, 2005], it has been suggested that it would be an advantage for some applications to choose less accurate but cheaper sensors in order to decrease the sampling error due to spatial variability [see, e.g., *Teuling et al.*, 2006; *Bogena et al.*, 2007; *Robinson et al.*, 2008]. Accordingly, several networks have been established recently using capacitance probes. One example is the Soil Climate Analysis Network (SCAN) in the United States (http://www.wcc.nrcs.usda.gov/scan/), where soil moisture is measured since 1991.

[5] Several previous studies have evaluated the performance of low-cost sensors [e.g., *Roth et al.*, 1990; *Veldkamp and O'Brien*, 2000; *Czarnomski et al.*, 2005; *Bogena et al.*, 2007]. The conclusions for the calibration differ and depend on the sensor type. In general, laboratory tests are needed to verify whether the volumetric water content (VWC) can be estimated accurately with a universal calibration equation, often supplied by the manufacturer [*Baumhardt et al.*, 2000; *Veldkamp and O'Brien*, 2000]. *Baumhardt et al.* [2000] stressed the need of a soil-specific calibration for a multisensor capacitance probe especially under conditions of near-saturation. *Bogena et al.* [2007] evaluated a low-cost soil moisture sensor by including laboratory and field experiments with a TDR as reference sensor. They found significant differences between the TDR and the low-cost sensor measurements when a calibration function derived from laboratory experiments was used. *Veldkamp and O'Brien* [2000] solved the limited applicability of the manufacturer's empirical calibration function using a three-phase mixing model to generate a more robust calibration for a sensor based on frequency domain reflectometry.

[6] In the present article, we evaluate the performance of a low-cost soil moisture sensor for climate monitoring under controlled and field conditions, using laboratory measurements and measurements from two different Swiss Soil Moisture EXperiment (SwissSMEX, section 2.3) sites. The main objectives of this study are to derive error estimates associated with these instruments, the possibility to transfer laboratory findings of the performance of the low-cost sensor to field conditions and to evaluate the possibility to represent VWC and absolute soil moisture using the capacitance sensor. These aspects are of key relevance for the validation of land surface and climate models and the possible assimilation of soil moisture observations in these models.

[7] The article is structured as follows. First, data and methods, including instruments, laboratory and field measurements as well as data processing used in this study, are presented in section 2. Results from the laboratory and field measurements are presented and evaluated in section 3. A discussion of the results and their significance for the climate community, as well as the main conclusions are provided in section 4.

2. Data and Methods

2.1. Instruments

[8] The instruments used in this study are the TRIME-EZ and TRIME-IT sensors (IMKO GmbH, Germany) based on the TDR technique, and the 10HS sensor (Decagon Devices, United States) based on the capacitance technique. The used TRIME-IT and TRIME-EZ sensors have rod lengths of 11 and 16 cm, respectively. They measure at a frequency of 1 GHz and are independent of the excitation voltage. The applied 10HS sensor has a rod length of 10 cm and measures with a frequency of 70 MHz. The 10HS is superior to the forerunner and widely used EC-5 sensor (Decagon Devices) because of its independency from the excitation voltage and the larger sampling volume, which results in more robust estimates of average spatial soil moisture conditions. Data are logged with a Campbell Scientific CR1000 data logger. Characteristics of both sensor types as provided by the manufacturers are listed in Table 1.

2.2. Laboratory Measurements

[9] The aim of the laboratory measurements is to estimate the difference in VWC between the 10HS and the TRIME-IT/-EZ sensors and to estimate the sensitivity as well as the variability within the 10HS sensors. Gravimetric samples are taken as reference measurements.

[10] The experiment included five calibration runs (hereafter referred to as CAL1 to CAL5). For each calibration run

Table 1. Characteristics of the Two Investigated Sensor Types Provided by the Manufacturer[a]

Sensor Measurement Technique	Range of VWC[b]	Operating Temperature	Accuracy	Relation mV - VWC
10HS (Decagon Devices, USA) capacitance technique	0 to 57 Vol.%	0° to 50°C	±3 Vol.% using the standard calibration ±2 Vol.% using soil specific calibration	polynomial third order
TRIME-IT, TRIME-EZ (IMKO GmbH, Germany) time domain reflectometry	0 to 100 Vol.%	−15° to 50°C	±1 Vol.% for 0 to 40 Vol.% ± 2 Vol.% for 40 to 70 Vol.%	linear

[a]See *Decagon Devices* [2009] and *IMKO* [2006].
[b]Volumetric water content.

three plastic containers (26.6 cm × 36.6 cm × 23 cm) with different levels of water content were prepared. These water contents were chosen such that the "first-guess" values cover the range of interest: The necessary mass of soil and water was calculated using the known volume of the plastic containers, the density of solid material (quartz was assumed for both soils) and a mean target porosity. The target porosity was chosen by taken the mean porosity from the Swiss field site of Rietholzbach (http://www.iac.ethz.ch/url/research/rietholzbach) [*Weiler*, 2001]. When the measurements with the sensors were completed, three gravimetric samples were taken out of each container in the depth of sensor measurements. These gravimetric samples were then used to correct the first-guess values to a reference VWC for the laboratory experiment.

[11] Two different materials with known soil properties were used for the measurements: (1) Australian sand (AUS-S), which was chosen because of its homogeneous grain size distribution, with a VWC ranging from 5.2 to 30.2 Vol.%, and (2) fine material with grain size <2 mm from the soil of the SwissSMEX field site Oensingen (OEN-S) with three VWCs ranging from 3.2 to 55.4 Vol.%. The measurements with the sensors were conducted one day after preparing the AUS-S/OEN-S soils with the assumed water content in order to obtain equilibrium water content conditions. Each of the three containers entailed four 10HS sensors; one of them was left in the container as reference to ensure that the VWC during one calibration run was steady. In total 107 10HS sensors were tested. Seven TRIME sensors were included in CAL3 and CAL5. These measurements were conducted parallel to the measurements with the 10HS. During the whole experiment the boxes were covered to minimize evaporation. A summary of the single VWC for each calibration run is provided in Table 2. The listed mean VWC and the corresponding standard deviation refer to the three VWC of the gravimetric samples.

2.3. Field Measurements

[12] The SwissSMEX project (Swiss Soil Moisture EXperiment, http://www.iac.ethz.ch/url/research/SwissSMEX) has been initiated by ETH Zurich, Agroscope ART, and MeteoSwiss in June 2008 with the aim to establish a long-term soil moisture measurement network in Switzerland. In 2010 the complementary project SwissSMEX-Veg was established to enhance the coverage of different land covers. At present, the network consists of 19 sites (Figure 1), including the Rietholzbach research catchment site (http://www.iac.ethz.ch/url/research/rietholzbach), several Swiss-Fluxnet sites (http://www.swissfluxnet.ch), and selected SwissMetNet (http://www.meteoswiss.admin.ch) stations. The sites were set up at grassland (14 sites), forest (4 sites) and arable land (1 site) sites. When the holes were dug for installation of the sensors, care was taken to preserve the original sequence of soil horizons. Soil moisture sensors were installed horizontally into the undisturbed soil. After the installation of the sensors, the soil was compacted upon refilling taking care that the soil horizons were arranged in the original order and with the original density.

[13] For the present field evaluation of the 10HS sensors, data from the SwissSMEX sites Oensingen (OEN) and Payerne (PAY) were used. Land use at both sites is managed grassland. For the grain size analysis, the pipette method [*Scott*, 2000] was used after the organic matter was removed by oxidation with hydrogen peroxide. The organic fraction was determined using the dichromate oxidation method [*Margesin and Schinner*, 2005]. Details about the soils properties are listed in Table 3. At both sites soil moisture is measured with parallel profiles of 10HS and TRIME-IT/-EZ at a temporal resolution of 10 min. At OEN, the sensors were installed at depths of 5, 10, 30, 50, 73, and 120 cm. A gravel layer exists between 75 and 95 cm depth. At PAY, the sensors were installed at 5, 10, 30, 50, and 80 cm depth (the deepest sensor could not be installed due to the presence of molasse). This study is based on observations over a 13 month period (1 September 2008 to 1 October 2009).

2.4. Data Processing

[14] For the evaluation of the 10HS sensor four evaluation criteria were taken into account: (1) the accuracy of sensor

Table 2. Material, Mean and Standard Deviation (std) of Volumetric Water Content (VWC), and Bulk Density (ρ_B) of the Gravimetric Samples for the Different Calibration Runs

Calibration Run	Material	Mean VWC (Vol.%)	std VWC (Vol.%)	Mean ρ_B (g/cm^3)	stdv ρ_B (g/cm^3)
CAL1	AUS-S	5.9	1.0	1.51	0.04
		16.3	1.5	1.53	0.01
		28.9	1.1	1.55	0.01
CAL2	AUS-S	5.2	1.0	1.51	0.01
		18.4[a]	-	1.49	-
		30.3	1.7	1.54	0.00
CAL3	AUS-S	6.8	0.47	1.49	0.03
		13.3	0.42	1.51	0.00
		30.1	1.4	1.5	-
CAL4	AUS-S	6.9	0.4	1.46	0.03
		11.4	0.09	1.42	0.03
		29.3	2.9	1.37	0.12
CAL5	OEN-S	3.2[a]	-	1.27	-
		39.0	2.22	1.12	0.05
		55.4	2.47	1.02	0.04

[a]Only one gravimetric sample.

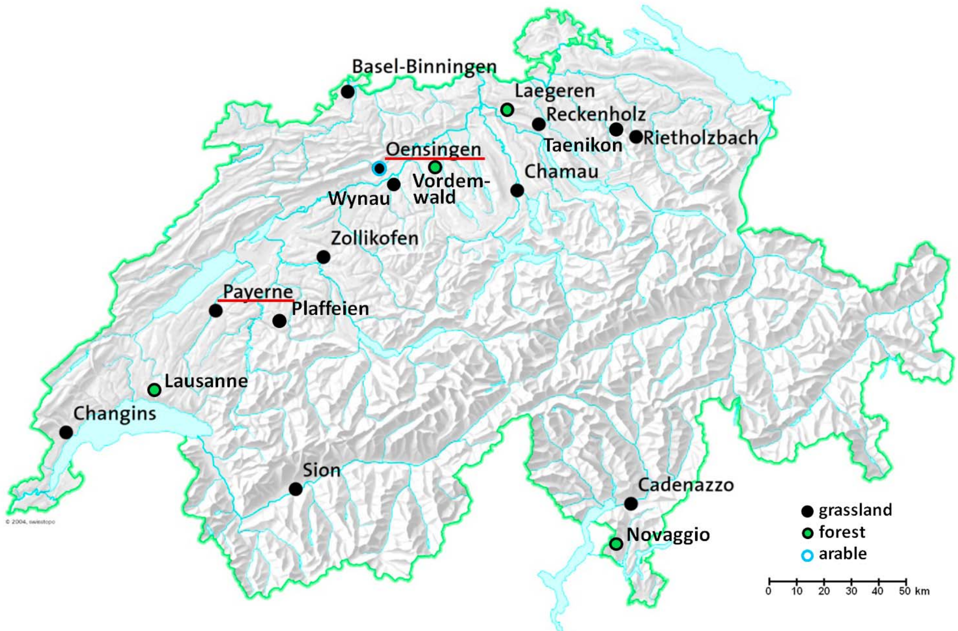

Figure 1. Map of Switzerland showing the location and land use of the SwissSMEX/-Veg soil moisture monitoring sites; highlighted are the sites OEN and PAY involved in this evaluation.

reading (mV), (2) the absolute VWC (Vol.%) for the laboratory and field measurements, (3) the absolute soil moisture (mm), and (4) the daily soil moisture loss (mm). The accuracy of the 10HS sensor reading was assessed with the laboratory measurements, based on the standard deviation between the used 10HS sensor for each VWC and the sensitivity of the sensor reading with increasing VWC. The sensitivity was performed by including the difference in sensor reading (dv_n) per unit of VWC ($dVWC_n$), e.g., *Bogena et al.* [2007]:

$$\frac{dv_n}{dVWC_n} \approx \frac{v_{n+1} - v_{n-1}}{VWC_{n+1} - VWC_{n-1}}. \quad (1)$$

[15] The second evaluation criteria considered the transformation of the 10HS sensor reading (mV) to VWC (Vol.%). This was realized using three different approaches. First, the third-order polynomial function provided by the manufacturer [*Decagon Devices*, 2009] was used. In the second approach, a calibration function was established by relating the sensor reading (mV) to the reference VWC (Vol.%) by a least square exponential fit. For the laboratory measurements the gravimetric samples were used as reference. The resulting function is hereinafter called the "best lab fit." The more reliable TDR sensors [*Robinson et al.*, 2008] that were installed in parallel with the 10HS sensors were used as reference in the field. The resulted function is hereinafter called "best field fit". For the computation of the best field fit, only measurements in 10 cm and 80 cm depths were used, since most other SwissSMEX sites entail TDR measurements in these two depths only. By considering the 10 cm and 80 cm measurements, information about the variability of soil moisture of the 10 cm near-surface layer was implemented directly and information of soil properties of two different depths was implemented indirectly. The TDR and capacitance measurements at the two depths were merged and binned with the accuracy of the 10HS (3 Vol.%) indicated by the manufacturer [*Decagon Devices*, 2009]. The validation of the established function was performed for the measurements in all depths. The third approach to transform the sensor reading into VWC was based on the

Table 3. Basic Soil Properties for OEN and PAY, With Texture According to USDA Soil Taxonomy

		Particle Size Distribution (%)					
Site	Depth (cm)	Clay (<2 μm)	Silt (2–63 μm)	Sand (>63 μm)	Texture	Bulk Density (g/cm^3)	Organic Fraction (%)
OEN	0–25	28.2	57.9	13.9	Silty clay loam	1.39	3.4
	25–75	25.8	56.3	17.9	Silt loam	1.49	2.2
	75–95				Gravel layer		
	95–120	30.2	62.5	7.3	Silty clay loam	1.45	1.4
PAY	0–30	5.9	41.8	52.3	Sandy loam	1.49	1.5
	30–100	19	41.7	39.3	Loam	1.49	0.4

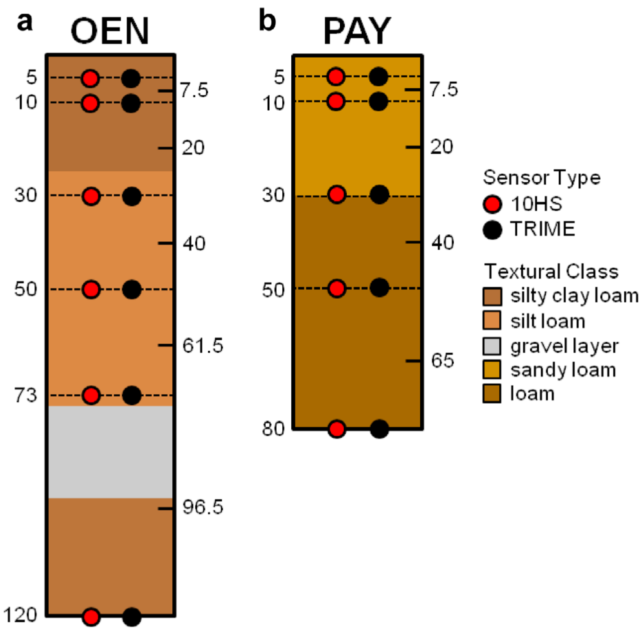

Figure 2. Measurement profile at sites (a) OEN and (b) PAY. The numbers on the left side of the profiles indicate measurement depths of the sensors. The numbers on the right side indicate the integration depth for each sensor used to calculate the absolute soil moisture (millimeters).

concept of the three-phase mixing model [*Veldkamp and O'Brien*, 2000] using

$$\theta = \frac{\left[x^\alpha - (1-\varphi)Per_s^\alpha - \varphi Per_a^\alpha\right]}{\left(Per_w^\alpha - Per_a^\alpha\right)}, \tag{2}$$

where

θ volumetric water content;

x sensor output (mV);

α geometric parameter;

φ porosity;

Per_s specific sensor output for soil matrix (mV);

Per_a specific sensor output for air (mV);

Per_w specific sensor output for water (mV).

[16] The porosity was estimated using the specific weight of quartz of 2.65 g/cm^3 and the mean bulk density for each calibration run for the laboratory measurements (Table 2) and for each soil horizon for the field measurements (Table 3), respectively. The sensor output for air and water included measurements of the sensor in air and water. For the sensor output of the soil matrix, measurements made in oven-dried AUS-S were used. The parameter α, which defines the shape of the calibration function, was fitted.

[17] For the field measurements, the difference in absolute soil moisture S [mm] for the hydrological year 1 October 2008 to 30 September 2009, spring 2009 (MAM) and summer 2009 (JJA) was considered as the third evaluation criteria. S was calculated by integrating the measurements of the TRIME and the 10HS capacitance sensors over the whole soil column. Each measurement is representative for one soil layer. The soil layer thickness is given by the mean distance to the closest upper and lower sensor (Figure 2). As last evaluation criteria the daily soil moisture loss (mm) and its translation in evapotranspiration (mm) and latent heat flux (W m^{-2}) was quantified and included due to its interest in the context of land surface–atmosphere interactions and related climate investigations [e.g., *Seneviratne et al.*, 2010]. To isolate evapotranspiration from other fluxes (i.e., drainage), only recession periods starting at the fourth day after a precipitation event, for the period June to September 2009 were considered.

[18] As goodness of fit the adjusted R^2 and RMSE with regard to the gravimetric ($RMSE_G$) and TDR measurements ($RMSE_T$), respectively, were used. Furthermore, density and frequency plots were considered to highlight the performance of points with higher probability.

3. Results

3.1. Laboratory Measurements

[19] The results of the laboratory measurements for both soils (AUS-S and OEN-S) with VWCs ranging from 3.9 to

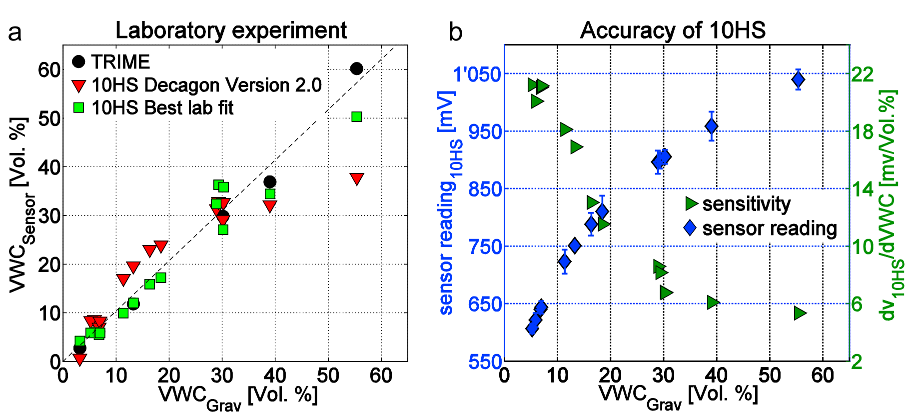

Figure 3. Results of the laboratory measurements with TRIME (TDR) and 10HS (capacitance) sensors as a function of the volumetric water content of the gravimetric samples. (a) VWC from TDR and 10HS. For the 10HS sensor, two calibration functions are displayed (Decagon Version 2.0 function and best lab fit). (b) Measurement accuracy of sensor reading, showing the variability within the 10HS sensor type (blue) and the derivation dv/dVWC of the 10HS sensor (green). Error bars represent the standard deviation within the tested 10HS sensors.

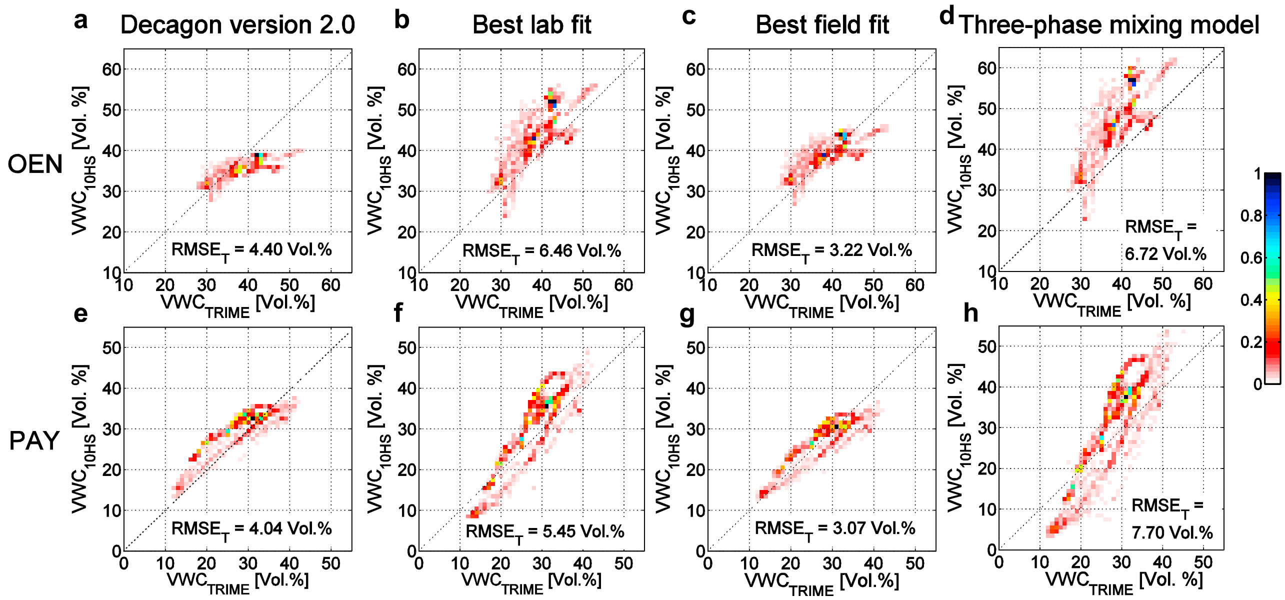

Figure 4. Relations between TRIME (TDR) and 10HS (capacitance) measurements of volumetric water content in the field: (a, b, c, d) OEN and (e, f, g, h) PAY (bottom). Applied functions provided by the manufacturer Decagon version 2.0 (Figures 4a and 4e), the best lab fit (Figures 4b and 4f), the best field fit (Figures 4c and 4g), and three-phase mixing model (Figures 4d and 4h). Panels show the occurrence (relative to maximum) of volumetric water content (Vol.%) for the whole time period 1 September 2008 to 1 October 2009. The $RMSE_T$ is calculated with respect to TRIME (TDR) measurements.

55.4 Vol.% are shown in Figure 3a. The TRIME sensor captured the reference VWC with an overall $RMSE_G$ of 1.5 Vol.%, which corresponds to the specification from the manufacturer (Table 1). By contrast, the 10HS sensor showed considerable biases in the measured VWC, independently of the fitting curve (Decagon Version 2.0 function or best lab fit). The Decagon Version 2.0 calibration function displayed an erroneous relationship, with approximately correct VWC for 10 Vol% and 30 Vol%, but an overestimation in between, and underestimation (plateauing values) above 30–40 Vol%. The overall $RMSE_G$ amounted to 7.1 Vol.%. The plateauing behavior means that the calibration function is not suitable above 30–40 Vol%, a performance considerably lower than the 57 Vol.% suggested by the manufacturer [*Decagon Devices*, 2009]. The best lab fit improved the overall $RMSE_G$ to 3.5 Vol.%. Furthermore, it allowed for a reliable conversion of the sensor reading up to 50 Vol.%. However, application of the best lab fit increased the variability around 30% VWC.

[20] The variation within the 10HS sensor type is shown in Figure 3b and is nearly steady over the whole measurement range. The sensor sensitivity with respect to the dv/dVWC (mV/Vol.%) showed a strong decrease with increasing VWC. For a mean VWC of about 5 Vol.% the sensitivity is about 21 mV/Vol.%. In contrast for a VWC of 50Vol.% the sensitivity is about 4 mV/Vol.%. The decreasing sensitivity is caused by the measurement principle of capacitance sensors, by which the capacitor charges slower at high VWC.

3.2. Field Measurements

[21] As mentioned in section 2.4 and verified by the laboratory results (section 3.1), the TDR sensors can be used as a reliable reference to evaluate the performance of the 10HS capacitance sensors in the field. The validation of the 10HS measurements using the three calibration functions (Decagon Version 2.0, best lab fit, best field fit) for measurements at all depths (6 in OEN and 5 in PAY) is shown as density plots in Figure 4. Similarly to the laboratory experiment, the VWC resulting from the Decagon Version 2.0 calibration leveled off at 30–40 Vol.% (Figures 4a and 4e). This effect had the most impact at the OEN site, which is characterized by high clay content (Table 3) and thus results in a generally higher VWC. Nevertheless, the absolute value of the derived VWC for low water contents (<30–35 Vol%) agreed well for both field sites. Application of the best lab fit (Figures 4b and 4f) resulted in an expansion of VWC estimates to higher values, but also in an enhanced spread of the data over the whole range of measured VWC. The VWCs with highest relative occurrence is overestimated and the lower VWCs are not represented well anymore. Consequently, the $RMSE_T$ increased for the best lab fit compared to the Decagon Version 2.0 function from 4.4 to 6.5 Vol.%, and 4.0 to 5.5 Vol.%, for OEN and PAY, respectively. By contrast, the best field fit (Figures 4c and 4g) led to a marked improvement in the estimation of the VWC values that occurred most frequently. The data

Table 4. Parameters and Statistics of the Best Field Fit for OEN and PAY[a]

Site	Parameters	Adjusted R^2	$RMSE_T$
OEN	a = 1.667; b = 0.003212	0.7643	1.8670
PAY	a = 1.904; b = 0.002936	0.9574	0.6089

[a]Best field fit: exponential function y = aexp(bx).

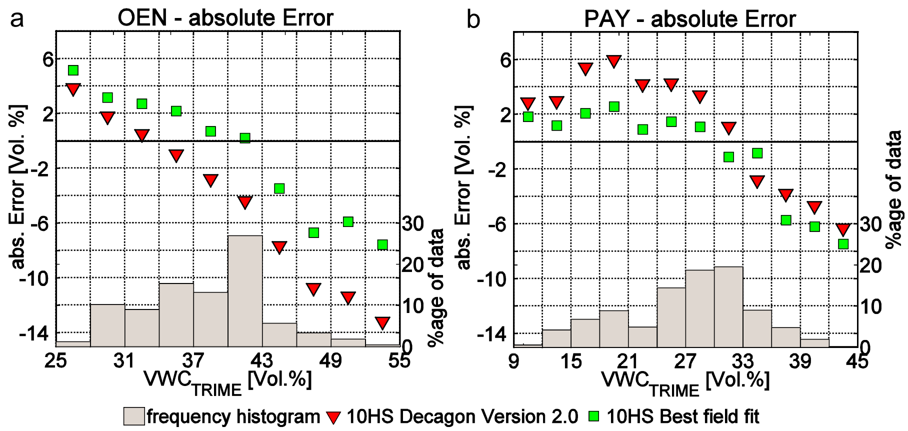

Figure 5. Absolute errors of the 10HS measurements using the manufacturer (Decagon Version 2.0) and best field fit functions with frequency distribution of volumetric water content at the site (a) OEN and (b) PAY sites. The error is calculated as the difference between 10HS and TRIME.

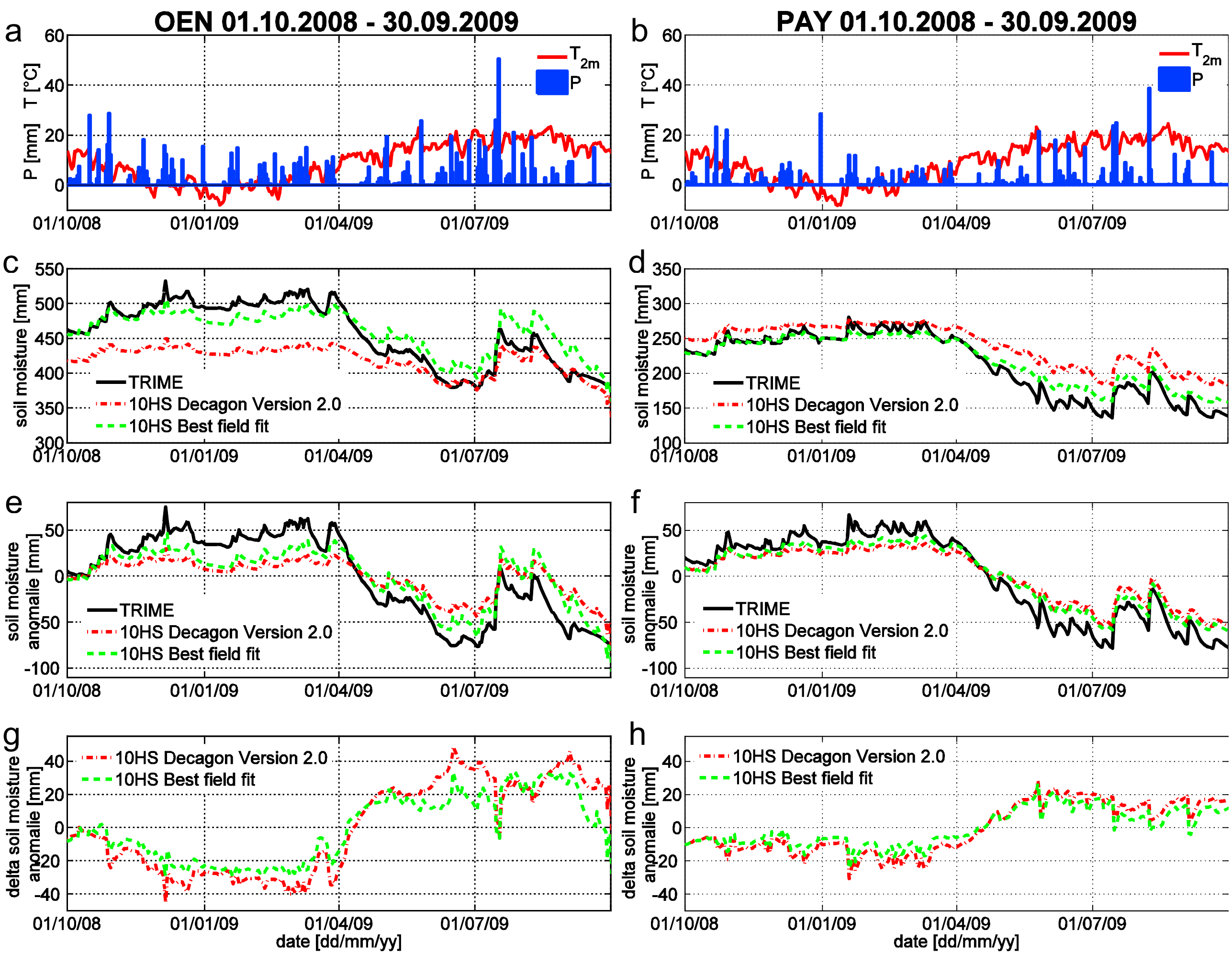

Figure 6. Temporal evolutions of the main climate drivers and soil moisture during the field experiment at the site (a, c, e, g) OEN and (b, d, f, h) PAY. Figures 6a and 6b show daily precipitation (P) and temperature (T), Figures 6c and 6d show soil moisture, Figures 6e and 6f show the soil moisture anomalies (soil moisture relative to the average of available time period), and Figures 6g and 6h show the difference in soil moisture anomalies (10HS-TDR) (mm) over the soil column with different calibration functions during the hydrological year 1 October 2008 to 30 September 2009.

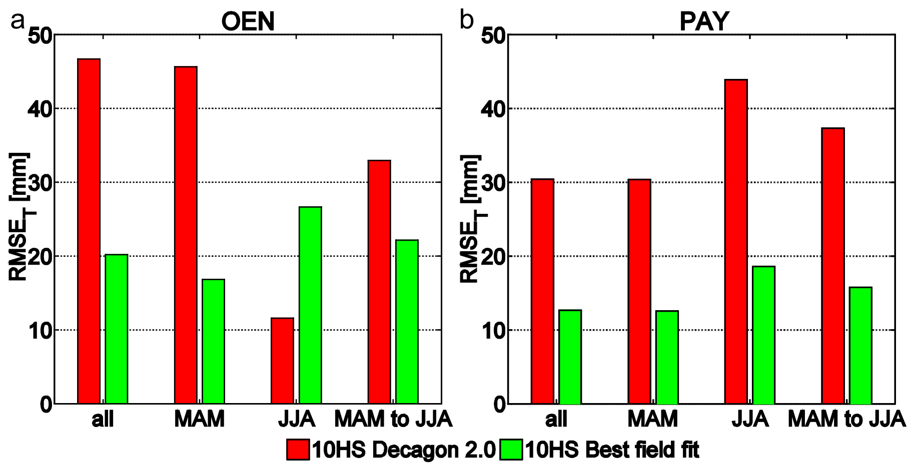

Figure 7. Difference between absolute 10HS measurements derived using two calibration functions and TRIME measurements expressed as $RMSE_T$ (millimeters) for the hydrological year 1 October 2008 to 30 September 2009 (all), spring 2009 (MAM), and summer 2009 (JJA), and over the period spring to summer 2009 (MAM to JJA) at the sites (a) OEN and (b) PAY.

were expanded to higher VWC, while lower VWC were still well represented. This results in a decrease of the $RMSE_T$ compared to the Decagon Version 2.0: from 4.4 to 3.2 Vol.% for OEN and from 4.0 to 3.0 Vol.% for PAY. The parameters and statistics of the best field fit at the two sites are listed in Table 4 (the calibration function for the best lab fit and best field fits are visualized in the auxiliary material).[1] The application of the three-phase mixing model (Figures 4d and 4h) with $RMSE_T$ of 6.7 Vol.% and 7.7 Vol.% for OEN and PAY, respectively, did not lead to improved estimates within this study. Because of the low performance of the best lab fit and the three-phase model within this study, the best field fit was used in subsequent analyses.

[22] The mean absolute error of the VWC of the 10HS sensor at the OEN and PAY sites using the Decagon Version 2.0 and best field fit is shown in Figure 5. Additionally, the frequency histogram for each 3 Vol.% class is displayed Figure 5 (bottom). Consistent with Figure 4, this analysis revealed that the 10HS sensor slightly overestimates the VWC at lower soil moisture contents (<30–35 Vol%) and underestimates it at higher VWC. The best field fit resulted in an absolute error of less than 2 Vol.% for VWC ranges including most measurements (34 to 43 Vol.% for OEN and 24 to 36 Vol.% for PAY). However, the behavior of the sensor was different for the two sites, due to their difference in measured VWC. For the clayey OEN site (Figure 5a), the Decagon Version 2.0 function led to smaller absolute errors than the best field fit at low VWC. On the other hand, for high VWC values the absolute errors were much larger than using the best field fit (13 Vol.% compared to a maximum error of 8 Vol.% using the best field fit). By contrast, at the loamy site PAY (Figure 5b), the best field fit limited the absolute error to around 2 Vol.% starting from low VWC up to 36 Vol.%, while for VWC larger than 36 Vol.% the absolute error increased up to 8 Vol.% and was smaller using the Decagon Version 2.0 function (with a maximal error of 6 Vol.%). This analysis thus reveals the important role of the soil type for the performance of the site-specific calibration.

[23] The temporal evolution of precipitation and 2 m air temperature, together with the absolute soil moisture S (mm) are displayed for both sites in Figures 6a–6d. Both the TRIME and 10HS sensor agreed well regarding the timing of soil moistening and drying, which also matched the meteorological data. Using the best field fit for the 10HS sensor generally improved the derived absolute soil moisture, with the exception of the summer 2009 time period at the OEN site. The corresponding $RMSE_T$ for four time periods (hydrological year 1 October 2008 to 30 September 2009, spring 2009, summer 2009, and spring-summer 2009) are shown in Figure 7. Over the whole hydrological year, the $RMSE_T$ decreased from 47 mm to 20 mm at the OEN site, and from 30 mm to 13 mm for the PAY site. At the PAY site, similar decreases (~60%) in $RMSE_T$ were found for all analyzed time periods. The only case when the best field fit did not reduce the $RMSE_T$ (as also identified in Figure 6) is at the OEN site for the 2009 summer. For this time period and site, one should note that with either estimates (Decagon Version 2.0 function and best field fit), the 10HS sensor measurements erroneously suggest that the summer 2009 absolute soil moisture values are close to winter values (and thus close to saturation), while the TRIME measurements revealed a depleted absolute soil moisture. The reason is the small sensitivity of the 10HS due to the non linearity between the sensor reading and the VWC (see Figure 2b) with increasing VWC. Focusing on soil moisture anomalies (absolute soil moisture relative to the long-term mean, Figures 6e and 6f) and the difference of the soil moisture anomalies (Figures 6g and 6h) between the 10HS and TDR, only a slight improvement using the best field fit compared to the Decagon Version 2.0 was identified. Nevertheless, using the best field fit, the standard error was decreased from 27 mm to 20 mm for the OEN site and from 15 to 11 mm for the PAY site (not shown).

[1]Auxiliary materials are available in the HTML. doi:10.1029/2010JD014907.

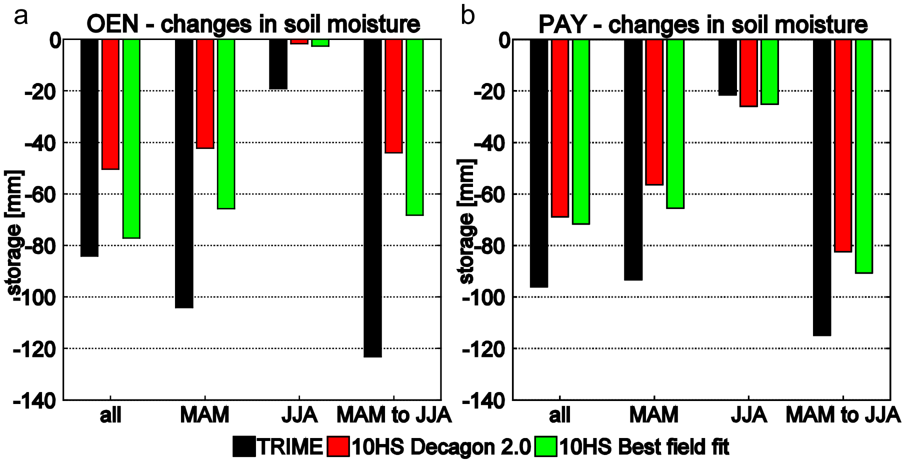

Figure 8. Changes in soil moisture (millimeters) during the hydrological year 1 October 2008 to 30 September 2009 (all), spring 2009 (MAM), and summer 2009 (JJA), and over the period spring to summer 2009 (MAM to JJA) at the sites (a) OEN and (b) PAY.

[24] Taking into account the changes in absolute soil moisture (mm) for the considered time periods, the largest errors for the 10HS sensor measurements were found during the spring dry-downs (Figure 8), with smaller errors when applying the best field fit. For the OEN site the difference in spring compared to TRIME was decreased by 22% using the best field fit. For the site PAY this difference was reduced by 10%.

[25] The daily soil moisture loss, used to estimate the evapotranspiration (mm) or the latent heat flux (W m^{-2}), is shown in Figure 9. For PAY, the TRIME and the 10HS sensors displayed decreasing soil moisture loss with decreasing mean absolute soil moisture (Figure 9b). The limitation of the 10HS sensor readings for high VWC led to a maximum daily soil moisture loss in the order of 4 mm. The 10HS got more comparable to the TRIME with decreasing daily soil moisture. As a consequence, the latent heat flux on a daily time scale under dry conditions was represented satisfactorily using the low-cost sensor. The maximal difference in absolute soil moisture was 1.5 mm (corresponds to a latent heat flux of 42 W m^{-2}) and 1.7 mm (corresponds to a latent heat flux of 48 W m^{-2}) between the Decagon Version 2.0 and best field fit, respectively.

[26] For the OEN site, this effect was neither detectable for the TRIME nor the 10HS sensor (Figure 9a). The response of both sensors scattered and a clear dependency of evapotranspiration on soil moisture was not seen. A possible explanation for the difference between the OEN and PAY site is the impact of groundwater. At the OEN site, a shallow groundwater system combined with clayey soils may result in considerable capillary rise effectively decreasing the estimated evapotranspiration for periods with high ground-

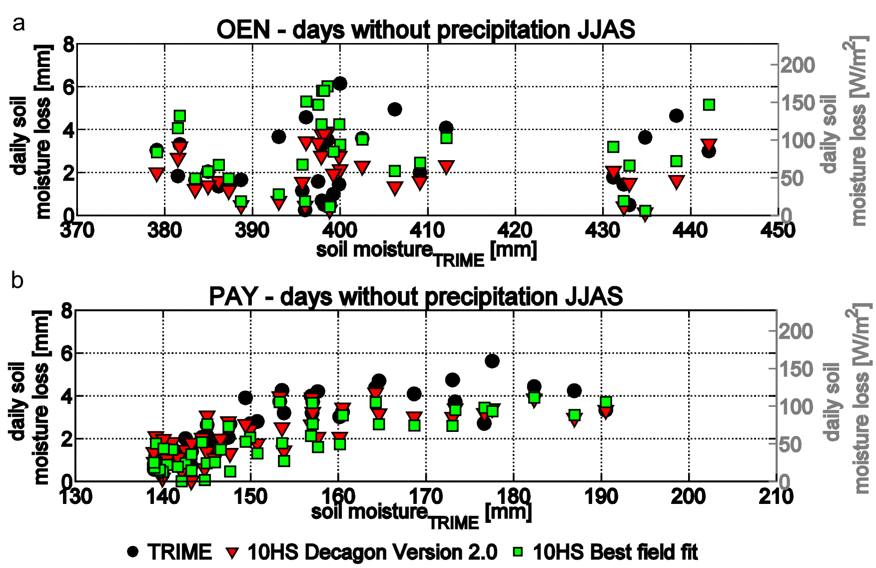

Figure 9. Absolute daily soil moisture loss in millimeters and W/m^2 for the TRIME and 10HS sensors at the sites (a) PAY and (b) OEN for precipitation free periods June to September 2009.

water tables. At the PAY site, which is located on a Molasse plateau, this effect is absent.

4. Discussion and Conclusion

[27] In the current study the capacitance-based soil moisture sensor 10HS was evaluated regarding its accuracy for climate research applications, based both on laboratory and field measurements at two sites with different soil types in Switzerland. We find that the variations between the different 10HS sensors are small. On the other hand, the sensitivity of the 10HS sensor output to VWC decreases with increasing VWC. This effect is caused by the capacitance principle, but is stronger than expected, since the forerunner sensor EC-5 from Decagon Devices was found to react slightly more sensitively at similar higher VWCs [*Bogena et al.*, 2007]. Nevertheless the 10HS is more advantageous due to its independence of the power supply and the larger measurement volume [*Decagon Devices*, 2009]. The standard calibration provided by the manufacturer does not accurately predict the absolute VWC over the whole measurement range, neither under laboratory conditions nor under field conditions. The performance of the 10HS sensor is found to vary as a function of the soil conditions (Figure 2 and Figure 3). Due to this dependency, it was not possible to transfer findings of calibration functions established under laboratory conditions to field conditions. These two aspects conform to different studies, which evaluated other capacitance-based soil moisture sensors [*Veldkamp and O'Brien*, 2000; *Polyakov et al.*, 2005]. The manufacturer's function was found not to be appropriate above 30–40 Vol.%. This result is unexpected since it implies a considerably lower performance than that of about 57 Vol.% indicated by the manufacturer [*Decagon Devices*, 2009]. Good agreement was nonetheless shown for low VWCs (<30–40 Vol.%). In addition, the daily variability for precipitation-free periods was also represented reasonably well, compared to the behavior of the TDR sensor.

[28] Regarding climate applications, extreme soil moisture values are more relevant than medium soil moisture content. Indeed, higher predictability is found for extreme soil moisture contents [*Koster et al.*, 2010], which may in particular apply to extreme events such as heat waves [*Jaeger and Seneviratne*, 2011; *Hirschi et al.*, 2011]. Thus, it may be exactly those VWC conditions that are least well captured (either at the dry or wet end) that are most relevant for climate investigations and applications. With the site-specific calibration function it is possible to reduce the absolute error to about 2 Vol.% for the majority of the measurements including low and moist soil moisture conditions. Nevertheless, larger errors may occur under conditions more extreme than those encountered during the field experiment (despite its length of more than 1 year), such as those that prevailed in the 2003 summer drought heat wave in Europe [e.g., *Andersen et al.*, 2005; *Granier et al.*, 2007; *Loew et al.*, 2009; *Teuling et al.*, 2010a].

[29] In climate research, dry soil moisture conditions are of particular relevance to investigate land-atmosphere interactions. It can be expected that evapotranspiration will decrease at low soil moisture when a soil moisture–limited evapotranspiration regime is reached [e.g., *Seneviratne et al.*, 2010], which is also the regime at which the strongest feedbacks between land and the atmosphere are expected [e.g., *Koster et al.*, 2004; *Hirschi et al.*, 2011]. These medium-to-low soil moisture conditions appeared to be relatively well captured by the 10HS sensor, and represented well for the PAY site. However, the sensor performance at the OEN site is poorer possibly due to higher soil moisture contents during the observed period. This illustrates that soil moisture conditions can strongly vary on relatively small spatial scales (see Figure 1 for the location of the two sites), although the overall dynamics were similar. Beside the representation of dry soil moisture conditions, also accurate measurements during moist conditions are relevant, because it is important to estimate the change in absolute soil moisture (mm) over, for example, a season in an accurate way. Moreover, moist conditions are also highly relevant for runoff generation [e.g., *Koster and Milly*, 1997, *Teuling et al.*, 2010b]. The measurement range of the 10HS sensor can be increased to up to 50 Vol.% with applying a site-specific calibration. The site-specific calibration involved measurements of two TDR sensors (at 10 cm and 80 cm depth), which recorded the VWC parallel to the 10HS sensors. Therewith the calibration is conducted not only using the local soil texture, but also taking into account the actual climate conditions, rise and recession of soil moisture.

[30] The results of our study highlight that the 10HS sensor requires site-specific calibration functions and is mostly appropriate for research investigations related to dry soil moisture conditions. Care has to be taken when measuring at high VWC levels. Our laboratory measurements also confirm the very high accuracy of TDR sensors compared to that of low-cost capacitance sensors. Given the high variability of soil moisture and cost of TDR sensors, we conclude that the most appropriate setup for efficient and accurate soil moisture networks consists of parallel capacitance and TDR measurements, using the latter as reference for the calibration of the low-cost sensors.

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References

Andersen, O. B., S. I. Seneviratne, J. Hinderer, and P. Viterbo (2005), GRACE-derived terrestrial water storage depletion associated with the 2003 European heat wave, *Geophys. Res. Lett.*, *32*, L18405, doi:10.1029/2005GL023574.

Baumhardt, R. L., R. J. Lascano, and S. R. Evett (2000), Soil material, temperature, and salinity effects on calibration of multisensor capacitance probes, *Soil Sci. Soc. Am. J.*, *64*, 1940–1946, doi:10.2136/sssaj2000.6461940x.

Betts, A. K. (2004), Understanding hydrometeorology using global models, *Bull. Am. Meteorol. Soc.*, *85*(11), 1673–1688, doi:10.1175/BAMS-85-11-1673.

Bogena, H. R., J. A. Huisman, C. Oberdörster, and H. Vereecken (2007), Evaluation of a low-cost soil water content sensor for wireless network applications, *J. Hydrol.*, *344*(1–2), 32–42, doi:10.1016/j.jhydrol.2007.06.032.

Czarnomski, N. M., G. W. Moore, T. G. Pypker, J. Licata, and B. J. Bond (2005), Precision and accuracy of three alternative instruments for measuring soil water content in two forest soils of the Pacific Northwest, *Can. J. For. Res.*, *35*(8), 1867–1876, doi:10.1139/x05-121.

Dean, T. J., J. P. Bell, and A. J. B. Baty (1987), Soil-moisture measurement by an improved capacitance technique. 1. Sensor design and performance, *J. Hydrol.*, *93*(1–2), 67–78, doi:10.1016/0022-1694(87)90194-6.

Decagon Devices (2009), *10HS Soil Moisture Sensor Operator's Manual, Version 2.0*, Pullman, Wash.

de Jeu, R., W. Wagner, T. R. H. Holmes, A. J. Dolman, N. C. van de Giesen, and J. Friesen (2008), Global soil moisture patterns observed by space borne microwave radiometers and scatterometers, *Surv. Geophys.*, *29*(4–5), 399–420, doi:10.1007/s10712-008-9044-0.

Dirmeyer, P. A., R. D. Koster, and Z. Guo (2006), Do global models properly represent the feedback between land and atmosphere?, *J. Hydrometeorol.*, *7*(6), 1177–1198, doi:10.1175/JHM532.1.

Granier, A., et al. (2007), Evidence for soil water control on carbon and water dynamics in European forests during the extremely dry year: 2003, *Agric. For. Meteorol.*, *143*(1–2), 123–145, doi:10.1016/j.agrformet.2006.12.004.

Hirschi, M., S. I. Seneviratne, V. Alexandrov, F. Boberg, C. Boroneant, O. B. Christensen, H. Formayer, B. Orlowsky, and P. Stepanek (2011), Observational evidence for soil-moisture impact on hot extremes in southeastern Europe, *Nat. Geosci.*, *4*, 17–21, doi:10.1038/ngeo1032.

Hollinger, S. E., and S. A. Isard (1994), A soil moisture climatology of Illinois, *J. Clim.*, *7*(5), 822–833, doi:10.1175/1520-0442(1994)007<0822:ASMCOI>2.0.CO;2.

IMKO (2006), *TRIME-EZ /-EZC /-IT /-ITC, User Manual*, IMKO Micromodultechnik GmbH, Ettlingen, Germany.

Jackson, T. J. (2005), Estimation of surface soil moisture using microwave sensors, in *Encyclopedia of Hydrological Sciences*, edited by M. G. Anderson, pp. 799–810, John Wiley, Chichester, U. K.

Jaeger, E. B., and S. I. Seneviratne (2011), Impact of soil moisture-atmosphere coupling on European climate extremes and trends in a regional climate model, *Clim. Dyn.*, doi:10.1007/s00382-010-0780-8, in press.

Koster, R. D., and P. C. D. Milly (1997), The interplay between transpiration and runoff formulations in land surface schemes used with atmospheric models, *J. Clim.*, *10*(7), 1578–1591, doi:10.1175/1520-0442(1997)010<1578:TIBTAR>2.0.CO;2.

Koster, R. D., et al. (2004), Regions of strong coupling between soil moisture and precipitation, *Science*, *305*, 1138–1140, doi:10.1126/science.1100217.

Koster, R. D., et al. (2010), The contribution of land initialization to subseasonal forecast skill: First results from the GLACE-2 Project, *Geophys. Res. Lett.*, *37*, L02402, doi:10.1029/2009GL041677.

Larson, K. M., E. E. Small, E. D. Gutmann, A. L. Bilich, J. J. Braun, and V. U. Zavorotny (2008), Use of GPS receivers as a soil moisture network for water cycle studies, *Geophys. Res. Lett.*, *35*, L24405, doi:10.1029/2008GL036013.

Loew, A., T. Holmes, and R. de Jeu (2009), The European heat wave 2003: Early indicators from multisensoral microwave remote sensing? *J. Geophys. Res.*, *114*, D05103, doi:10.1029/2008JD010533.

Margesin, R., and F. Schinner (Eds.) (2005), *Manual for Soil Analysis—Monitoring and Assessing Soil Bioremediation*, 366 pp., Springer, Berlin.

Polyakov, V., A. Fares, and M. H. Ryder (2005), Calibration of a capacitance system for measuring water content of tropical soil, *Vadose Zone J.*, *4*(4), 1004–1010, doi:10.2136/vzj2005.0028.

Ramillien, G., J. S. Famiglietti, and J. Wahr (2008), Detection of continental hydrology and glaciology signals from GRACE: A review, *Surv. Geophys.*, *29*(4–5), 361–374, doi:10.1007/s10712-008-9048-9.

Robinson, D. A., S. B. Jones, J. M. Wraith, D. Or, and S. P. Friedman (2003), A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectometry, *Vadose Zone J.*, *2*(4), 444–475.

Robinson, D. A., C. S. Campbell, J. W. Hopmans, B. K. Hornbuckle, S. B. Jones, R. Knight, F. Ogden, J. Selker, and O. Wendroth (2008), Soil moisture measurements for ecological and hydrological watershed scale observatories: A review, *Vadose Zone J.*, *7*(1), 358–389, doi:10.2136/vzj2007.0143.

Robock, A., K. Y. Vinnikov, G. Srinivasan, J. K. Entin, S. E. Hollinger, N. A. Speranskaya, S. Liu, and A. Namkhai (2000), The global soil moisture data bank, *Bull. Am. Meteorol. Soc.*, *81*(6), 1281–1299, doi:10.1175/1520-0477(2000)081<1281:TGSMDB>2.3.CO;2.

Roth, K., R. Schulin, H. Flühler, and W. Attinger (1990), Calibration of time domain reflectometry for water content measurement using a composite dielectric approach, *Water Resour. Res.*, *26*(10), 2267–2273, doi:10.1029/WR026i010p02267.

Schmugge, T. J., W. P. Kustas, J. C. Ritchie, T. J. Jackson, and A. Rango (2002), Remote sensing in hydrology, *Adv. Water. Resour.*, *25*(8–12), 1367–1385.

Scott, H. D. (2000), *Soil Physics: Agricultural and Environmental Applications*, 421 pp., Iowa State Univ. Press, Ames.

Seneviratne, S. I., D. Lüthi, M. Litschi, and C. Schär (2006), Land-atmosphere coupling and climate change in Europe, *Nature*, *443*, 205–209, doi:10.1038/nature05095.

Seneviratne, S. I., T. Corti, E. L. Davin, M. Hirschi, E. B. Jaeger, I. Lehner, B. Orlowsky, and A. J. Teuling (2010), Investigating soil moisture-climate interactions in a changing climate, *Earth Sci. Rev.*, *99*(3–4), 125–161, doi:10.1016/j.earscirev.2010.02.004.

Steele-Dunne, S. C., M. M. Rutten, D. M. Krzeminska, M. Hausner, S. W. Tyler, J. Selker, T. A. Bogaard, and N. C. van de Giesen (2010), Feasibility of soil moisture estimation using passive distributed temperature sensing, *Water Resour. Res.*, *46*, W03534, doi:10.1029/2009WR008272.

Tapley, B. D., S. Bettadpur, J. C. Ries, P. F. Thompson, and M. M. Watkins (2004), GRACE measurements of mass variability in the Earth system, *Science*, *305*, 503–505, doi:10.1126/science.1099192.

Teuling, A. J., and P. A. Troch (2005), Improved understanding of soil moisture variability dynamics, *Geophys. Res. Lett.*, *32*, L05404, doi:10.1029/2004GL021935.

Teuling, A. J., R. Uijlenhoet, F. Hupet, E. E. van Loon, and P. A. Troch (2006), Estimating spatial mean root-zone soil moisture from point-scale observations, *Hydrol. Earth Syst. Sci.*, *10*(5), 755–767, doi:10.5194/hess-10-755-2006.

Teuling, A. J., et al. (2010a), Contrasting response of European forest and grassland energy exchange to heatwaves, *Nat. Geosci.*, *3*, 722–727, doi:10.1038/ngeo950.

Teuling, A. J., I. Lehner, J. W. Kirchner, and S. I. Seneviratne (2010b), Catchments as simple dynamical systems: Experience from a Swiss pre-alpine catchment, *Water Resour. Res.*, *46*, W10502, doi:10.1029/2009WR008777.

Topp, G. C. (2003), State of the art of measuring soil water content, *Hydrol. Processes*, *17*(14), 2993–2996, doi:10.1002/hyp.5148.

Topp, G. C., and W. D. Reynolds (1998), Time domain reflectometry: A seminal technique for measuring mass and energy in soil, *Soil Tillage Res.*, *47*(1–2), 125–132, doi:10.1016/S0167-1987(98)00083-X.

Vautard, R., P. Yiou, F. D'Andrea, N. de Noblet, N. Viovy, C. Cassou, J. Polcher, P. Ciais, M. Kageyama, and Y. Fan (2007), Summertime European heat and drought waves induced by wintertime Mediterranean rainfall deficit, *Geophys. Res. Lett.*, *34*, L07711, doi:10.1029/2006GL028001.

Veldkamp, E., and J. J. O'Brien (2000), Calibration of a frequency domain reflectometry sensor for humid tropical soils of volcanic origin, *Soil Sci. Soc. Am. J.*, *64*, 1549–1553, doi:10.2136/sssaj2000.6451549x.

Vinnikov, K. Y., and I. B. Yeserkepova (1991), Soil moisture: Empirical data and model results, *J. Clim.*, *4*(1), 66–79, doi:10.1175/1520-0442(1991)004<0066:SMEDAM>2.0.CO;2.

Wagner, W., G. Blöschl, P. Pampaloni, J. C. Calvet, B. Bizzarri, J. P. Wigneron, and Y. Kerr (2007), Operational readiness of microwave remote sensing of soil moisture for hydrological applications, *Nord. Hydrol.*, *38*(1), 1–20, doi:10.2166/nh.2007.029.

Walker, J. P., G. R. Willgoose, and J. D. Kalma (2004), In situ measurement of soil moisture: A comparison of techniques, *J. Hydrol.*, *293*(1–4), 85–99, doi:10.1016/j.jhydrol.2004.01.008.

Weiler, M. H. (2001), Mechanisms controlling macropore flow during infiltration: Dye tracer experiments and simulations, Ph.D. thesis, ETH Zurich, Zurich, Switzerland, doi:10.3929/ethz-a-004180115.

Zreda, M., D. Desilets, T. P. A. Ferré, and R. L. Scott (2008), Measuring soil moisture content non-invasively at intermediate spatial scale using cosmic-ray neutrons, *Geophys. Res. Lett.*, *35*, L21402, doi:10.1029/2008GL035655.

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