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Research

Time domain reflectometry coil probes for measuring thin surface layer soil moisture: Field tests over 21 years (2002–2022) under highly variable climate conditions in Mongolia

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Abstract

A coil probe (CP) for time-domain reflectometry (TDR) with a sensor length of 40 mm (CP_{40}) was developed for long-term field soil moisture measurements in a thin surface soil layer (0–3 cm depth). In laboratory, soil moisture measurements of CP_{40} were nearly identical to those of a traditional two-rod type TDR (2RTDR) probe (rod length: 15 cm, diameter: 0.3 cm, spacing: 3 cm). The CP_{40} measurement accuracy was between 0.01 m^3/m^3 and 0.03 m^3/m^3. For long-term field soil moisture measurements, five CP_{40} units were installed in the highly wetted soil at the Sanzai site (SS), which is in the permafrost area of the Taiga, and dry soil at the Mandalgobi site (MGS) in the semi-arid area of Mongolia. Four units accurately measured soil moisture at both sites over six years (2002–2007and 2008–2009). Three units succeeded in conducting precisely continuous soil moisture measurements between 2008 and 2022 at the MGS. Two units successfully measured soil moisture over 21 years at both the sites. The representativeness of the CP_{40} soil moisture measurements in highly wetted soils was low because of heavy rainfall and soil heterogeneity. The accuracy of CP_{40} soil moisture measurements in highly wetted soils was slightly lower than that of the traditional 2RTDR probe. However, the accuracy of the CP_{40} soil-moisture measurements in the dry soil was comparable to that of the traditional 2RTDR probe. CP_{40} units are durable and their field soil moisture measurements demonstrate stable and precise performance (bias, RMSE), even under severe environmental conditions.

Article highlights

- A 40 mm sensor TDR coil probe (CP_{40}) was effective for near surface long-term field soil moisture measurements.
- The measurement accuracy of CP_{40} was close to that of a traditional 2RTDR probe in the laboratory condition.
- Four CP_{40} units successively succeeded in soil moisture measurements for 8 years and two units for 21 years in Mongolia.

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Keywords Millimeter-scale TDR probe · Long-term field soil moisture measurement · Thin surface soil layer · Natural environmental change · Mongolia

1 Introduction

Soil moisture is a key element of the hydrological cycle. It controls the exchange of water and energy between the atmosphere and soils and affects precipitation [1], daily temperature variability [2], and land surface processes. The soil moisture behavior in the thin surface soil layer (0–3 cm depth) during and after rainfall has immediate and important effects on evapotranspiration, splash erosion, wetting front development in groundwater recharge, soil animal activity, and vegetation development. Li et al. [3] highlighted the importance of characterizing soil layering conditions by including near-surface soil moisture at different depths and the evaporation behavior of an entire drying cycle. Yamanaka et al. [4] reported the effects of soil layering on evapotranspiration. Vermang et al. [5] and Zambon et al. [6] used rainfall simulators to study the splash erosion of soil surfaces under different rain conditions. Based on laboratory experiments on the behavior of soil water in topsoil, Kawamoto and Miyazaki [7] identified three types of wetting fronts and described in detail the mechanism of fingering flow, which influences groundwater recharge. A field monitoring study suggested that communities of soil animals at very small scales might predictably respond to changes in moisture availability, regardless of ecosystem type [8]. Topsoil moisture measurements at depth intervals of 1 cm are crucial for studying precise changes in splash erosion and soil animal activity. As indicated by the classical concept of soil water availability for plants [e.g., 9], plant growth is controlled by the wetness of the entire soil medium. Short-term global and regional observations of surface soil moisture provide data for studying the spatial and temporal variations in near-surface soil moisture. Furthermore, soil moisture measurements at depths of 1 and 2 cm could be useful for the validation and evaluation of satellite soil moisture observations [10, 11].

Nissen et al. [12] used time-domain reflectometry (TDR) to measure variations in soil water content at very small spatial scales. For their laboratory soil moisture measurements, Nissen et al. [12] developed a TDR coil probe (CP), which was a very small cylindrical sensor with a diameter of 4.5 mm and a length of 15 mm. It was used in an experimental study on fingering flow, and the results were excellent [13]. It was also successfully deployed in a laboratory study of soil water retention properties [14]. The results imply that tiny probes can be used to measure soil moisture at depths of less than 3 cm to support studies of soil moisture behaviors, soil surface changes, and the ecology of soil animals in the topsoil and enhance the validation of satellite soil moisture retrievals, as mentioned above. However, CPs and other small probes on the millimeter scale have yet to be used to measure soil moisture in the field. The field deployment of CP units for soil moisture measurement is of great practical value.

This study aims to demonstrate the performance and value of CPs in long-term field measurements at near-surface depths under different severe climatic conditions in Mongolia. In this study, the durability and stability of the CP and the accuracy and representativeness of soil moisture measurements were thoroughly examined during long-term field tests. First, laboratory tests were conducted to quantify the characteristics of CP units with different sensor lengths. After the laboratory tests, the units were installed in the field in Mongolia and tested under severe natural environmental conditions over a long period.

2 Methods

2.1 Description of CP

The CPs used in this study were designed as described by Nissen et al. [12]. This study used the same soil moisture measurement principle, calibration method, sensor structure and shape, production procedure, diameter, and materials as those of the prototype CPs developed by Nissen et al. [12]. Only the sensor lengths were different. Nissen et al. [12] conducted an experimental study on the probe sensitivity in a sand box with low soil moisture (0.099 m^3/m^3) by reducing the height between the CP and the soil surface. The results showed that the CP was sensitive to changes in the dielectric constant within a radius of 2–3 mm from the probe surface [15]. A detailed analysis of the experimental data suggested that the probe could measure the soil moisture in an area within a 4-mm radius from the probe surface. As a result, the CP can measure soil moisture at 1-cm depth at depth intervals of 1 cm. For soil moisture measurements at point sites in the field, the measurement area must be maximized to increase the representativeness of the measurement. The measurement area of CPs can be increased by increasing the probe length. Only one method exists for increasing the CP sensor length to obtain a larger measurement area. According to Nissen et al. [12], a certain wire length is necessary in order to obtain sufficient travel time for electromagnetic waves in the soil. Equation (1) expresses the relationship between the inductance (L) and the length (l) in the coil.

$$L = \mu_0 \mu_r N^2 A / l \tag{1}$$

where μ_0 is the magnetic permeability of free space, μ_r is the relative magnetic permeability, N is the number of turns, and A is the cross-sectional area of the coil. Because L of the coil should be as low as possible, it is desirable to keep l as large and μ_r, A, and N as small as possible.

The permittivity of CP can be approximated using a two-phase dielectric mixing model [12] as follows:

$$K_{a,CP}^n = w_L K_L^n + \left(1 - w_L\right) K_a^n \tag{2}$$

where $K_{a,CP}$ is the apparent relative dielectric permittivities of the mixture of probe materials and soils under investigation, K_L and w_L are the apparent relative dielectric permittivity and weighting factor of the probe materials, respectively, K_a is the apparent relative dielectric permittivity of the soils under investigation, and n is exponent.

However, the optimal CP sensor length for field measurements of soil moisture in thin-surface soil layers is unknown. Long sensors are associated with large errors and technical difficulties during production. The sensor length in the CP prototype proposed by Nissen et al. [12] was 15 mm. Therefore, this study determined to employ a CP with a sensor length of 40 mm (CP_{40}) for the field soil moisture measurement from the combined reasons of experimental experience and to evaluate probe accuracy and stability in the laboratory. First, to check the sensor length effect of the CP, laboratory experiments were carried out to investigate the relationship between the apparent relative dielectric permittivity measured by CP_{15}, CP_{30} (CP with 30 mm sensor length), and CP_{40} and a two-rod-type TDR (2RTDR) probe in air and liquids with known dielectric constants. The wire lengths in CP_{15}, CP_{30}, and CP_{40} were 0.295, 0.590, and 0.790 m, respectively. These values were used to calculate $K_{a,CP}$ from the travel time in the CP.

All of the laboratory experiments were conducted in preparation for the field deployment of the CP_{40}. Five CP_{40} units (CP_{40}T1, CP_{40}T2, CP_{40}T3, CP_{40}T4, and CP_{40}T5) were produced in 2000 for the field soil moisture measurement tests in Mongolia.

2.2 Fundamental performance tests

2.2.1 Calibration

In the experiments by Nissen et al. [12], the results from the 2RTDR probe were used as references. Owing to the presence of the core and coatings in the CP, the apparent relative dielectric permittivity measured by the CP was different from that measured by the 2RTDR probe. Following Nissen et al. [12], 2RTDR probe measurements were applied to conduct the basic calibration of CP_{15}, CP_{30}, and CP_{40}T1 in the laboratory using different media, including air, sunflower seed oil, syrup, ethanol, and a mixture of 50% water and ethanol. The rods (length: 15 cm, diameter: 3 mm, spacing: 30 mm) of the 2RTDR probe without a balun were made of stainless steel and embedded in a polyoxymethylene plastic housing in the shape of a quadrangular prism (width: 5 cm, length: 2 cm, height: 2 cm). All calibrations were made in a circular polyvinyl chloride (PVC) soil box (diameter: 16 cm, height: 19 cm) at air temperatures of 16–26 °C at Hiroshima University. The reference soil moisture was manually obtained using sampling and drying methods [16]. Electromagnetic waves from the CP and 2RTDR probe soil moisture measurements were analyzed using a cable tester (Tektronix, 1502 B, Beaverton, OR, USA).

To examine the range of CP performance, calibration was conducted using two types of experimental soil. These included soil from the Sanzai site (SS; at 48° 7′ 29.3″ N, 106° 53′ 26.3″ E and an elevation height of 1,506 m) and Ōtagawa sand in Hiroshima. The physical properties and particle distributions of the experimental soils are presented in Table 1 and Fig. 1, respectively. Soils from SS and the Mandalgobi site (MGS; at 45° 44′ 34.9 ″ N, 106° 15′ 52.2 ″ E and an elevation height of 1,393 m) were analyzed for the field tests (Sect. 2.3). Organic matter constitutes 8%–10% of the weight of SS soil and is negligible in Ōtagawa sand and MGS soil. Ōtagawa sand and SS soil were examined at Hiroshima University and MGS soil was analyzed in the experimental room (room temperature: 16–26 °C) at the Information and Research Institute of Meteorology, Hydrology and Environment (IRIMHE) in Ulaanbaatar using standard methods for soil physical properties [16].

Table 1 Physical soil properties of experimental soils

Soils	Porosity (m^3/m^3)	Dry density (Mg/m^3)	Saturated hydraulic conductivity (m/sec)
Ōtagawa sand	0.429	1.48	3.23×10^{-5}
Sanzai site soil	0.737	0.25	1.58×10^{-4}
MGS soil	0.381	1.50	5.19×10^{-5}

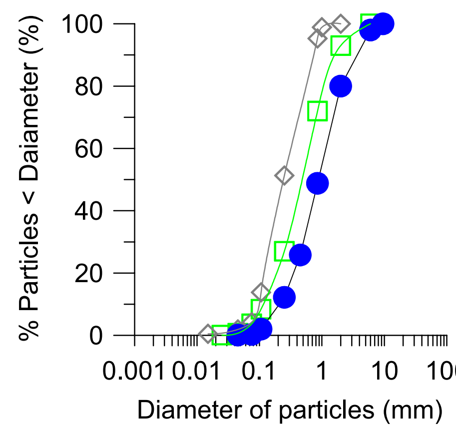


Fig. 1 Soil particle size distribution of experimental soils (filled blue circle: Ōtagawa sand, unfilled green square: MGS soil, unfilled ash diamond: Sanzai site soil)

Figure 1 shows that the soil particle size distributions of Ōtagawa sand and MGS soil are slightly wider than those seen for SS soil and the distribution of Ōtagawa sand is very similar to that of MGS soil. According to Table 1, the physical properties of Ōtagawa sand approximately the same as those of MGS soil. These results mean that MGS soil is obviously sand and can be physically as same as Ōtagawa sand. Unfortunately, the CP_{40} calibration equation for the MGS soil was not obtained because it was forbidden to import MGS soil. Therefore, although there is strictly a slight difference in the physical properties between Ōtagawa sand MGS soil, the calibration equation for Ōtagawa sand can be basically considered to use for CP_{40} soil moisture measurements at MGS while being careful.

2.2.2 Measurement accuracy tests

To quantify the accuracy and error of the CP_{40} units, preliminary laboratory tests were conducted in the central part of the dike sand box (length of the upper part: 1.6 m, length of the bottom part: 5.05 m, width: 2 m, height: 1.7 m) at Hiroshima University campus; the box was made in 2001 and 2002 and was filled homogeneously with Ōtagawa sand [17]. First, all CP_{40} units were placed horizontally in the topsoil of the sand box under temporary rainfall conditions to check whether the units were in good working conditions. Two CP_{40} units and 2RTDR01 probe were installed at a depth of 4 cm. Two CP_{40} units were placed 1 cm apart. The 2RTDR01 probe was placed 10 cm from the CP_{40} units, and the 2RTDR01 probe measurements were used as reference. This test was repeated for the different pairs of CP_{40} units. A rainfall simulator installed at a height of 3 m was used to maintain soil moisture within a range of 0.05–0.35 m^3/m^3. During the tests, rainfall, air pressure, and soil heat flux were measured using two tipping-bucket rain gauges (diameter: 15 cm), a barometer, and a soil heat flux plate (depth: 5 cm). Platinum resistance thermometers were installed at a height of 1.5 m to measure the air temperature and at depths of 1 and 3 cm to measure the soil temperature. CP_{40} units were connected to a TDR soil moisture meter (Campbell TDR100; Logan, UT, USA). A TDR cable tester (Tektronix, 1502 B, Beaverton, OR, USA) and data logger (Campbell, CR10X, Logan, UT, USA) were also used in the tests. Laboratory tests with Ōtagawa sand were carried out to quantify the error and accuracy of the 2RTDR02 and 2RtTDR-FM01 (TRIME-FM, IMKO, Ettlingen, Baden-Württemberg, Germany) probes, respectively. The 2RtTDR-FM01 probe is a portable TDR probe for on-site monitoring of soil moisture measurements. There was a close agreement among the 2RTDR01, 2RtTDR-FM01, and CP_{40} soil moisture values within the range of 0.055–0.338 m^3/m^3 as shown in Fig. S1 in the supplementary material. Relationships between the 2RTDR01 and 2RTDR02 values, and between the 2RTDR01 and 2RtTDR-FM01 values are seen Fig. S2 in the supplementary material. Measurement accuracies and errors of CP_{40}T1, CP_{40}T2, CP_{40}T3, and 2RTDR02 in the soil moisture measurement comparing to 2RTDR01 as reference, and of $CP_{40}T4$ and $CP_{40}T5$ to 2RtTDR-FM01 as reference are shown in Table S1 in the supplementary material.

The bias and RMSE (root mean square error) were calculated as follows:

$$Bias = \sum_{i=1}^{n} \frac{(\theta_i - \theta_t)}{n} \quad (3)$$

$$RMSE = \sqrt{E\left[(\theta_i - \theta_t)^2\right]} \quad (4)$$

where θ is water content, subscripts i and t are measured value and true value, respectively, n is the number of measurements, and E [·] is the expectation operator. Errors were small in $CP_{40}T2$ and $CP_{40}T3$ and negligible in the other CP_{40} units. As K_L and w_L are the apparent relative dielectric permittivity and weighting factor of the probe materials, respectively, the errors in $CP_{40}T2$ and $CP_{40}T3$ are associated with the production and materials in the sensors. The results are presented in the supplementary material (Table S1).

2.3 Field soil moisture measurement tests

Following the laboratory experiments, five CP_{40} units were tested at the two field sites. These were the SS in the Taiga area of the Selbe River basin close to Ulaanbaatar and the MGS in the semi-arid steppe area of the Mongolian Plateau. Four CP_{40} units ($CP_{40}T1$–T4) and five units ($CP_{40}T1$–T5) were horizontally set in the SS and MGS, respectively as described later. In the field tests, the 2RTDR probe that was horizontally installed was employed for comparison with the soil moisture measurement of CP_{40} and made almost good performance.

SS is in the floodplain of the Selbe River. An offline automatic weather station (AWS) was set up, and hourly measurements of some basic meteorological variables were taken. Before installation, the sensors were calibrated and checked using a base marker and/or the Japanese Meteorological Agency standard in the laboratory. The site was almost entirely covered with very short grasses with canopy height of 10-30 cm. The topsoil was dark brown (Photo S1 in the supplemental material) and was always dampened. Soil moisture was exceeded 0.3 m^3/m^3. The topsoil contained organic matter and was nonhomogeneous. The site was covered with snow between mid-autumn and early April. The soils were partly frozen from mid-October to early April, and the permafrost was below 1-m in depth. Unfortunately, AWS were frequently reduced owing to bad weather and power system issues. As a result, continuous meteorological records of the SS between 2002 and 2007 were incomplete. An almost continuous record was available only in 2006. According to 2006 data, the annual precipitation at SS was 554.0 mm. Maximum, minimum, and annual mean air temperatures were 39.8, − 30.7, and − 0.1 °C, respectively. Annual precipitation of Terelj basin, which is next to Selbe basin, was 321.6–266.8 mm between 2002 and 2007.

An offline AWS was also installed mostly on flat terrain at the MGS. It collected half-hourly measurements of basic meteorological and soil hydrology variables [18, 19]. The site was covered with isolated patches of short grass and sparse shrubs. The soil was composed of dry sand (Table 1 and Fig. 1) and was more homogeneous than the SS. The mean annual precipitation (105.9 mm/y) at the MGS for 21 years from 2001 to 2022 was remarkably lower than the annual precipitation in 2006 at the SS. For more understandable discussion in 3.3, a year with annual precipitation of > 105.9 mm/y and < 105.9 mm/y at MGS were defined as a wet year (WY) and dry year (DY), respectively. Namely, the wet years were 2012, 2013, 2018, 2021, and 2022 and the dry years were 2008, 2009, 2010, 2011, 2014, 2015, 2016, 2017, 2019, and 2020 during the observation period from 2008 to 2022. The wettest and driest years were 2013 (170.8 mm/year) and 2010 (70.0 mm/year), respectively.

At the SS, $CP_{40}T1$ and $CP_{40}T2$ were horizontally inserted at a depth of 3-cm depth inside a soil trench, and $CP_{40}T3$ and $CP_{40}T4$ were horizontally inserted at 5-cm and 10-cm depths, respectively. In June 2002, 2RTDR01 was horizontally inserted between $CP_{40}T1$ and $CP_{40}T2$ (see Photo S1 in the supplemental material). The distance between the $CP_{40}T1$ or $CP_{40}T2$ and the 2RTDR01 rods was 3 cm. At 10-cm depth, 2RTDR02 was placed at a horizontal distance of 10 cm from $CP_{40}T4$. Soil temperature sensors (platinum resistance thermometers) were horizontally installed at depths of 3- and 10-cm depths. CP_{40} and 2RTDR units were connected to a TDR soil moisture meter (Campbell TDR100; Logan, UT, USA). A data logger (Campbell CR10X; Logan, UT, USA) was used for the experiments.

The CP_{40} and 2RTDR units were carefully retrieved in June 2007 at the SS, and a cable tester (Tektronix, 1502 B, Beaverton, OR, USA) was used to test the sensors in the laboratory. Laboratory test results showed that the CP_{40} units were functional. However, the 2RTDR units were no longer functional and were not used again in the second field test series because of the deterioration of the rods and/or their connection points. The CP_{40}T1–T4 units were then cleaned. The conditions of CP_{40}T5 retrieved from the dike sand box at Hiroshima University were checked for the subsequent field measurement tests at the MGS. In September 2008, five units were installed at the MGS for the second field test series, which began in mid-September.

The CP_{40}T1 and CP_{40}T2 units were horizontally inserted at 1-cm depth in the bare soil and among the short grass at the MGS. They are separated by a horizontal distance of 10 cm. Similarly, the CP_{40}T3 and CP_{40}T4 were horizontally inserted at 2-cm depth. At 3-cm depth, CP_{40}T5 and 2RtTDR probe (TRIME-IT, IMKO, Ettlingen, Baden-Württemberg, Germany) of the AWS were horizontally set [11]. The 2RtTDR probe, which had the same measurement accuracy as that of 2RtTDR-FM01, was placed at a horizontal distance of 10 cm from the CP_{40}T5. Like the experimental setup at the SS, a TDR soil moisture meter (Campbell, TDR100, Logan, UT, USA) and a data logger (Campbell, CR10X, Logan, UT, USA) were used for the CP_{40} soil moisture measurements. The measurement accuracy of the 2RtTDR probes was tested in the laboratory before installation [19] and was checked annually (except between 2015 and 2021). The accuracy of the 2RtTDR-FM01 probe used for on-site checking of the soil moisture measurement accuracy was also quantified in the laboratory (Fig. S2 in the supplementary material). Accuracies were ± 0.005 m^3/m^3 and ± 0.016 m^3/m^3 for soil moisture values of < 0.1 m^3/m^3 and 0.1–0.40 m^3/m^3, respectively [19]. Automatic and continuous measurements were made between 2008 and 2022.

During the test period of 2008–2022, air temperature varied between 40.3 and – 37.6 °C. The surface soil was frozen from late October to March of each year and covered several times with light snow between mid-autumn and early April. Melting of the frozen surface soil began in early April of each year except in 2017. The meteorological variables were measured by the AWS at intervals of 60 and 30 min at the SS and MGS, respectively. All the meteorological sensors on the AWS at the SS and MGS were calibrated and checked using a base marker and/or the Japanese Meteorological Agency standard in the laboratory before installation [19].

3 Results and discussion

3.1 Principal characteristics of CP_{40}

3.1.1 Effect of sensor length on measurements of apparent relative dielectric permittivity

Figure 2 shows the apparent relative dielectric permittivities measured by CP_{15}, CP_{30}, and CP_{40}T1 ($K_{a,CP}$), and 2RDTR01 ($K_{a,2R}$) in air and liquids with known relative dielectric constants. The relationships are not linear as shown in Nissen et al. [12]. Carefully looking at Fig. 2, the relationship of CP_{15} is slightly different from relationships of CP_{30} and $CP_{40,}$ especially

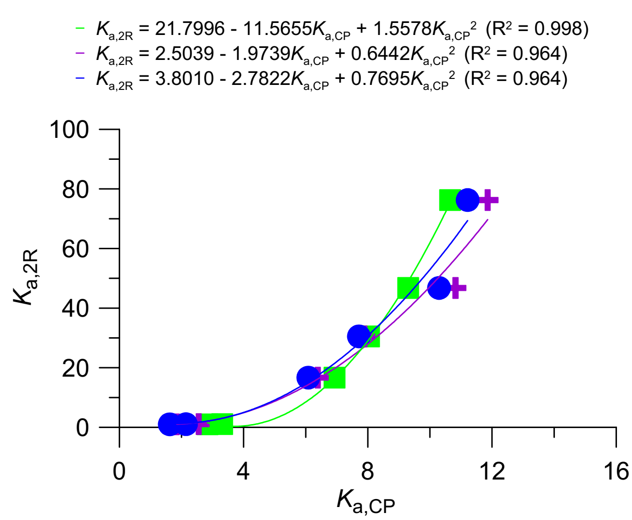


Fig. 2 Relationships between apparent relative dielectric permittivity ($K_{a,CP}$) measured by each CP (filled green square: CP_{15}, violet plus: CP_{30}, filled blue circle: CP_{40}) and that ($K_{a,2R}$) of 2RDTR01 using air and liquids of known dielectric constant (green solid line: regression curve of CP_{15}, violet solid line: regression curve of CP_{30}, blue solid line: regression curve of CP_{40}, R^2: coefficient of determination)

in the higher range more than 8 in $K_{a,CP}$. The effect of sensor length is slightly noticeable at high K_a values. However, these results indicated that CP_{40} can measure soil moisture as well as CP_{15} and 2RTDR.

3.1.2 Calibration results using experimental soils

A close agreement between the apparent relative dielectric permittivity ($K_{a,CP}$) and soil moisture (SM) in the experimental soils is shown in Fig. 3. There are not essentially remarkable differences between CP_{40} T1 and 2RTDR01 in both Ōtagawa sand and Sanzai site soil (SS soil). The physical properties of MGS soil are similar to those of Ōtagawa sand as shown in Fig. 1 and Table 1. However, the $K_{a,CP}$–SM relationship of Ōtagawa sand is considerably different from the $K_{a,CP}$–SM relationship of SS soil in the range more than 0.05 m^3/m^3 of soil water content, because the physical properties of SS soil is obviously different from those of Ōtagawa sand. Furthermore, to conduct more better soil moisture measurement by CP_{40}, on-sit calibrations of CP_{40} at MGS were several times carried out using the soil sampling method in summer of 2009, respectively. Thus, the regression equations for MGS soil and Ōtagawa sand was calculated considering the results. As a result, the regression Eqs. (5) at the SS and (6) at the GS for the soil moisture measurement tests at the SS and MGS were respectively used as follows:

$$SM = 0.000029K_a^3 - 0.001612K_a^2 + 0.043765K_a - 0.023877\left(\mathrm{R}^2 = 0.978\right)(\text{for SS}) \quad (5)$$

$$SM = -0.0000077K_a^3 - 0.000739K_a^2 + 0.036258K_a - 0.070490\left(\mathrm{R}^2 = 0.983\right)(\text{for MGS}) \quad (6)$$

where SM (m^3/m^3) is the soil moisture content and R^2 is coefficient of determination. Equations (5) and (6) were applied to the soil moisture measurements at the SS and MGS, respectively.

3.2 Soil moisture change in wet soils

At the SS, the soil moisture measurements were performed continuously from late June 2002 to May 2007. The AWS frequently stopped functioning because of severe winter weather (e.g., in midwinter, air temperature was below − 35 °C, soil temperature at 3-cm depth was below − 8.0 °C, the data logger was at the extremely low temperature of − 30 °C, and snowfall was abundant), intrusion of livestock, and the poor condition of the solar power system. Because of severe weather conditions, especially during the winter of 2005, some meteorological sensors, a data logger, and the battery of the solar power system broke down, and measurements were made only intermittently.

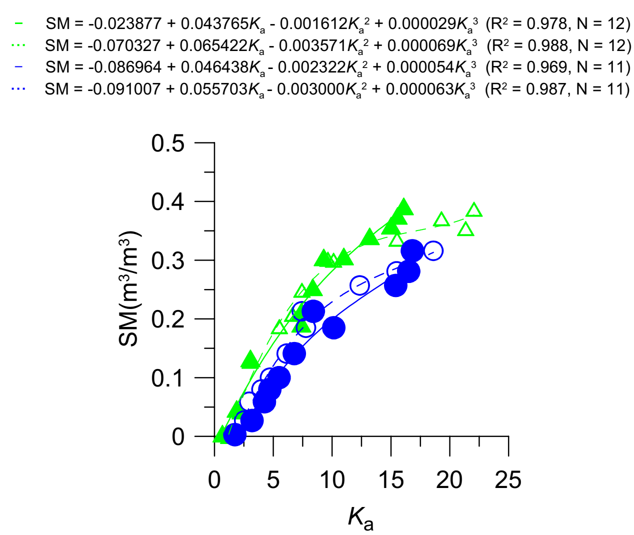


Fig. 3 Apparent relative dielectric permittivity (K_a) measured by CP_{40}T1 and that (K_a) of 2RDTR01 (filled blue circle: CP_{40}T1, unfilled blue circle: 2RTDR01 for Ōtagawa sand and filled green triangle: CP_{40}T1, unfilled green triangle: 2RTDR01 for Sanzai site soil, SM: soil moisture, blue solid line: regression curve of CP_{40}T1 for Ōtagawa sand; blue broken line: regression curve of 2RTDR01 for Ōtagawa sand; green solid line: regression curve of CP_{40}T1 for Sanzai site soil; green broken line: regression curve of 2RTDR01 for Sanzai site soil, R^2: coefficient of determination)

The CP_{40} and 2RTDR soil moisture measurements in the data logger were subjected to two quality control levels. For the first quality control, values that were above 0.737 m^3/m^3 and values that were below 0.0 m^3/m^3 were removed. Table S2 (supplementary material) shows that the data acquisition ratio exceeded about 78%. Effective data were those that passed both the first and second quality controls, as illustrated in Fig. 4. In the second quality control, the data passed in the first control were hydrologically investigated and removed the data deviated extraordinarily from the curves of rising and depletion in soil moisture during and after rainfall. The data of the first quality control less than 2% in the SS case were removed.

The acquisition ratio of the effective data, which is the ratio of the number of measurements that passed both the first and second quality controls to the number of measurements made per unit, was also calculated. The first quality-checked dataset passed the second quality-control step. The data from 2RTDR01 and 2RTDR02 were not subjected to a second quality control. Incidentally, in Fig. 4d, the first quality control data are shown for the discussion of freeze–thaw cycles in autumn and winter in 2005–2007.

A small quantity of data that did not pass the second control quality because of freeze–thaw was linked to low temperatures and probable instability in the TDR100 soil moisture meter and/or solar power system. These facts suggest that the unstable currents generated in the instruments under such conditions may result in fluctuations in L in Eq. (1) and $w_L K_L^n$ of Eq. (2), which influenced the soil moisture measurements.

Figure 4d shows frequent oscillations and instability in the 2RTDR01 soil moisture values from 2006 to 2007 and 2RTDR02 values from 2005 to 2007. This might have been caused by the deterioration of the rods of the 2RTDR units; surface corrosion could have resulted in high-frequency effects, such as the skin effect and dielectric loss [20, 21].

Soil moisture in spring and summer was higher than that in fall and winter by about 0.3 m^3/m^3 (Fig. 4). This is associated with higher rainfall during spring and summer. The responses of all CP_{40} units to rainfall events were very good, as some peaks are seen (e.g., in late June and early July). Although soil moistures of CP_{40}T1and CP_{40}T2 at 3-cm depth, CP_{40}T3 at 5-cm depth, and CP_{40}T4 at 10-cm depth rose instantly after heavy rainfall (Figs. 4a and b), the values and shapes of each peak of soil moisture were obviously different because of the depth effect and soil heterogeneity. After the peaks, the hydrological process continued with an exponential decrease in soil moisture. The correlation between rainfall events and soil moisture decreased gradually with increasing depth.

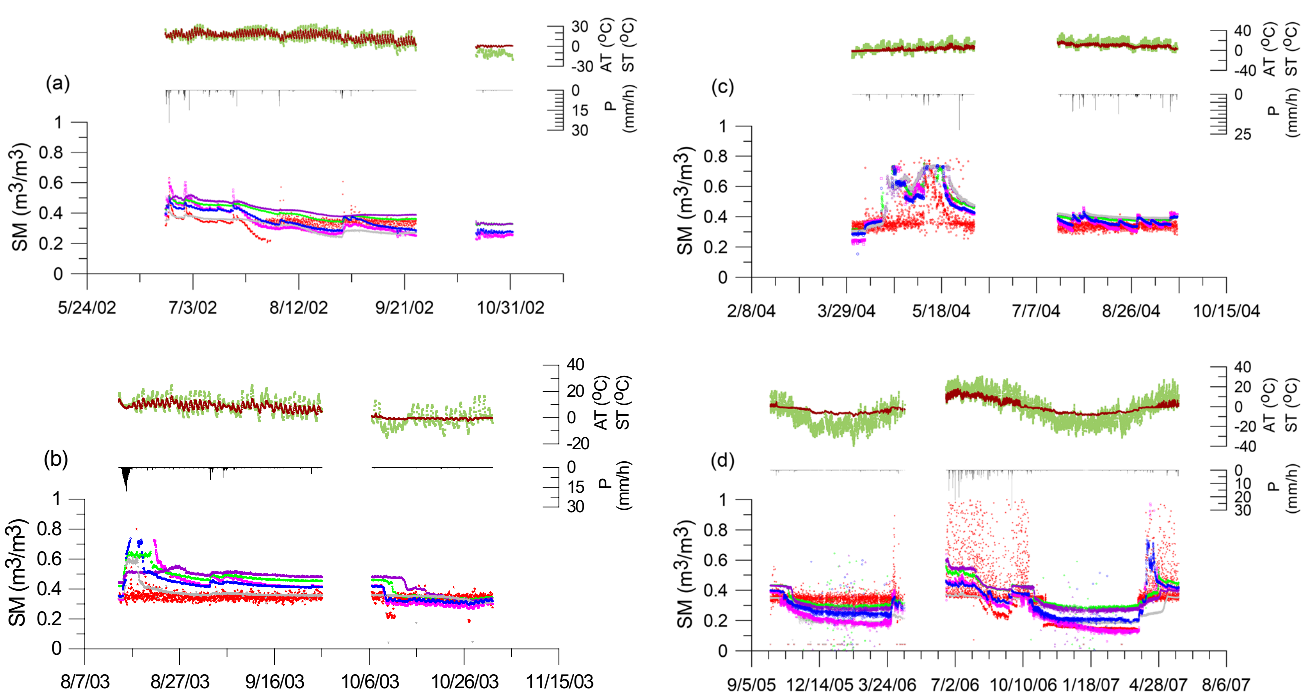


Fig. 4 Time series of soil moisture (SM) changes of CP_{40}s, unfilled blue circle: CP_{40}T1 SM at 3 cm d., unfilled pink square: CP_{40}T2 SM at 3 cm d., unfilled green daimond: CP_{40}T3 SM at 5 cm d., unfilled violet triangle: CP_{40}T4 SM at 10 cm d., unfilled red star:2RTDR01 SM at 3 cm d., unfilled ash inverted triangle: 2RTDR02 SM at 10 cm d., filled brown side triangle: soil temperature (ST) at 3 cm-depth, filled green square: air temperature (AT) at 1.5 m height, and precipitation (P) at SS in 2002 (**a**), 2003 (**b**), 2004 (**c**), and 2005–2007 (**d**)

The responses of both $CP_{40}T1$ and $CP_{40}T2$ at 3-cm depth to rainfall events were satisfactory, and the soil moisture values from the two units were nearly identical, except for 2003 (Fig. 4b). The 2RTDR01 measurements deteriorated with time because of severe weather conditions (Figs. 4b, c, and d). The $CP_{40}T1$ and $CP_{40}T2$ units functioned stably and continuously during most of the study period, with the exception of several outliers during the winter between 2005 and 2007. There were considerable differences between the 2RTDR01 and the $CP_{40}T1$ or $CP_{40}T2$ values, although all three units were at the same depth. The 2RTDR01 probe measured an area larger than that measured by the CP_{40} units. In August 2003 (Fig. 4b), May 2004 (Fig. 4c), and April 2007 (Fig. 4d), the $CP_{40}T1$ and $CP_{40}T2$ values were extremely high, near the soil porosity value of 0.737 (Table 1). The measurement area of CP_{40} decreased as the soil water content increased. In highly wetted soil such as the Sanzai site soils with large porosity, as CP40 is very sensitivity to contacted water with the surface of the sensor, CP_{40} values may reflect only the values of liquid water on the surface. Two CP_{40} units were installed at the same depth, and it is reasonable to assume that at least one unit would have been able to obtain representative soil moisture measurements. Based on this, care must be taken when using CP_{40} in highly wet soils.

Monitoring soil freeze–thaw cycles and their distribution is very important for the study and prediction of methane and carbon dioxide emissions from the soil surface. Since 2015, SMAP (Soil Moisture Active Passive) has been collecting data on soil moisture and freeze–thaw cycles on a global scale ([22] JPL, 2015). In October 2003 and 2006, air and soil temperatures were below 0 °C and CP_{40} and 2RTDR01 values decreased sharply as seen in sky blue broken line open circles (Figs. 4b and d). This indicates that the CP_{40} units were able to capture the soil freeze onset. Furthermore, in mid-October 2005, mid-October 2006, and late March 2007, sharp changes in the soil and air temperatures were reflected in the CP_{40} values, which showed rapid decreases and increases, respectively (Fig. 4d). Time domain reflectometry has been used to measure apparent liquid water content and/or ice content in frozen soil [e.g., 23–25]. However, accurate quantification of unfrozen water content in frozen soils remains elusive, and qualitative detection of soil freeze–thaw cycles appears to be possible using CP_{40}.

3.3 Characteristics of long-term soil moisture measurement using CP_{40}

Near-continuous measurements were well performed for more than 10 years at MGS. Natural disturbances like those at the SS also occurred in the MGS, including heavy snowfall, sand storms, droughts, and lightning. Intrusions of livestock and field mice also result in disturbances in the power system and breakage of AWS sensor cables. Therefore, data from 2008 to 2022 are missing.

3.3.1 Durability and stability

Following Sect. 3.2, all the CP_{40} data were subjected to two levels of quality control. For the first quality control, considering MGS soil porosity, values that were above 0.381 m^3/m^3 and values that were below 0.0 m^3/m^3 were removed. For the second quality control, the continuity and response of CP_{40} values during and after rainfall were examined. Values that reflected reasonable hydrological processes were retained. As well as the SS case, all the first quality data were hydrologically investigated and then the data less than 0.1% in the MGS case were hydrologically not appropriate. Data that passed both the first and second quality controls were referred to as effective data. The acquisition ratios of the five CP_{40} units in the MGS between 2008 and 2022 are listed in Table S3 in the supplementary material. The acquisition ratio of the effective data is the ratio between the number of measurements that passed both the first and second quality controls and the number of measurements made by the unit.

In addition, Table S3 in the supplementary material shows that the five CP_{40} units succeeded in measuring soil moisture in 2008 and 2009, and that $CP_{40}T1$, $CP_{40}T3$, and $CP_{40}T5$ functioned stably and continuously at the field site in Mongolia for 15 years (2008–2022). The acquisition ratios showed that the $CP_{40}T2$ and $CP_{40}T4$ malfunctioned after 2010. Figure 4d shows the oscillations in the $CP_{40}T2$ and $CP_{40}T4$ values, which were like the 2RTDR01 values in 2006 and 2007 at the SS. In 2015, the $CP_{40}T2$ was withdrawn, and an on-site check of the sensor surface was performed. Although the check showed no noticeable damage, it was impossible to repair $CP_{40}T2$. Therefore, the $CP_{40}T2$ values for 2015–2022 were unavailable. As $CP_{40}T1$ recovered spontaneously and perfectly in 2009 (Table S3 in the supplementary material), $CP_{40}T4$ remained in the soil despite the withdrawal of $CP_{40}T2$.

The combined results from SS and MGS showed that $CP_{40}T1$, $CP_{40}T2$, $CP_{40}T3$, and $CP_{40}T4$ successfully measured soil moisture over more than eight years, and the durability and stability of $CP_{40}T1$, $CP_{40}T3$, and $CP_{40}T5$ were extremely high (Tables S2 and S3 in the supplementary material).

3.3.2 Soil moisture variations

Figure 5 illustrates the effective data at the MGS in 2009, 2012, 2015, 2019, and 2022. The effective data in other years are shown in Fig.S3 in the supplementary material. Dynamic variations were observed in CP_{40} soil moisture values (Fig. 5 and Fig S3). All CP_{40} units functioned continuously until 2022, except during periods of AWS malfunction.

The response of CP_{40} values to rainfall events was excellent, as indicated in Fig. 5 (e.g., some peaks of soil moisture of CP_{40} units are seen in April and May, 2009). CP_{40} values rose rapidly during rainfall events and decreased exponentially after the peak, which is consistent with the hydrological process. At 1-cm depth, the change patterns in the $CP_{40}T1$ and $CP_{40}T2$ values in 2009 reflect mostly rainfall events. However, a little difference in the value of soil moisture between both CP_{40} units occurs is seen. At 3-cm depth, there were slightly differences between the 2RtTDR and $CP_{40}T5$ soil moisture values. This may be because the two CP_{40} units measured different soil water movements which were affected by the different micro scale surface conditions and/or soil heterogeneity. The CP_{40} responses to rainfall events below 2 mm/h were poor (Fig. 5a and Fig. 5d: 2012 and 2019, and Fig. S3 in 2018 in the supplemental material) due to the different conditions of soil surface and soil structure above mentioned. In July and August, the soil surface in the MGS and surrounding areas was mostly covered by short rice grass with canopy of about 10–30 cm height, which belongs mainly to *Stipa* spp. [26]. The short rice grass development has an influence on the soil surface condition and the soil structure,

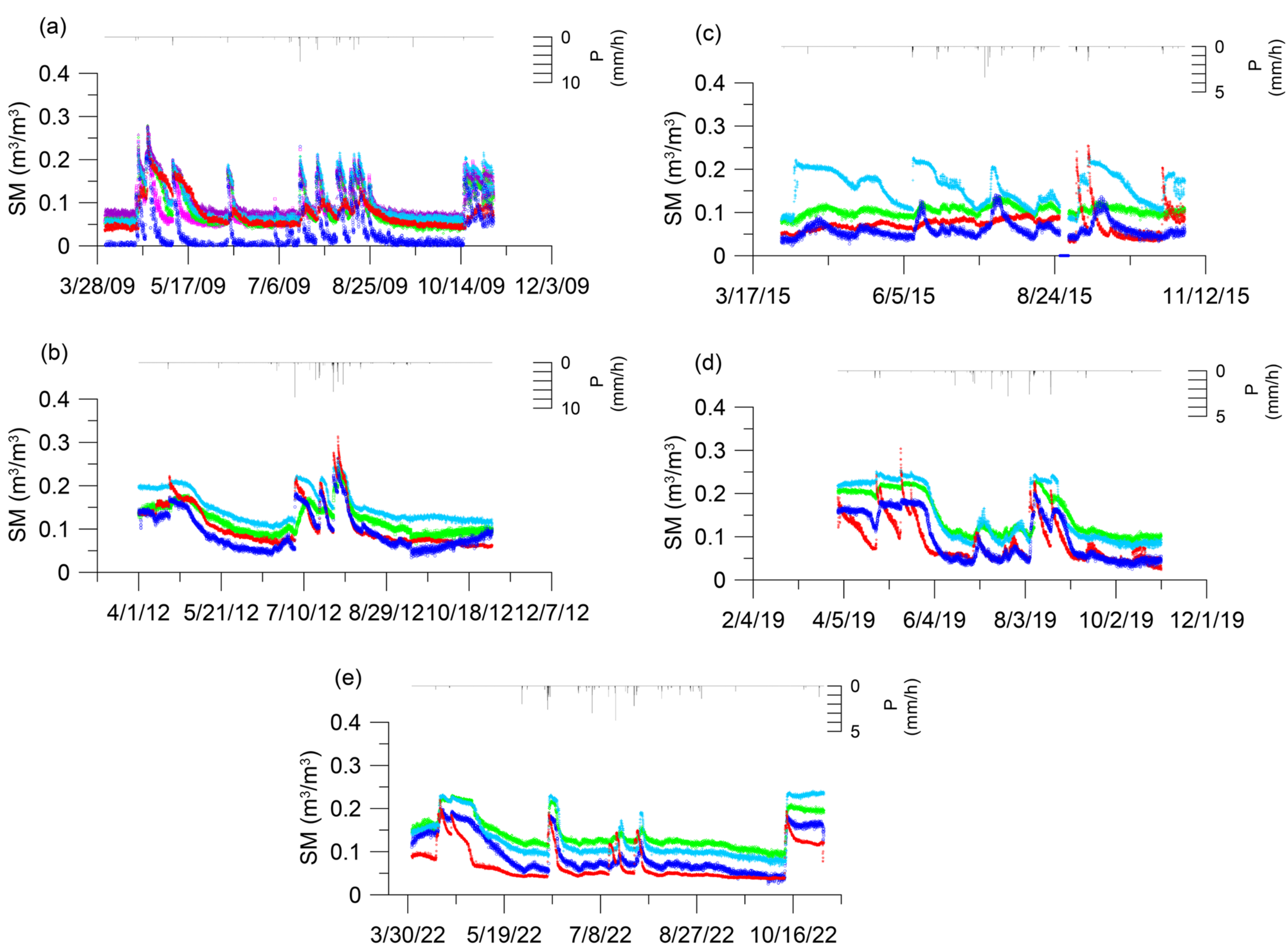


Fig. 5 Time series of soil moisture (SM) changes of CP_{40} units (unfilled blue circle: $CP_{40}T1$ SM at 1 cm-d., unfilled pink square: $CP_{40}T2$ SM at 1 cm-d., unfilled green daimond: $CP_{40}T3$ SM at 2 cm-d., unfilled violet triangle: $CP_{40}T4$ SM at 2 cm-d., and light blue plus: $CP_{40}T5$ SM at 3 cm-d.), unfilled red star: 2RtTDR SM at 3 cm-depth, and precipitation (P) at MGS in 2009, 2012, 2015, 2019, and 2022

and the thin roots like fibrous roots contact with the sensor of CP_{40}. Therefore, it seems that these results affect the soil moisture measurement by CP_{40}. During this period, however, CP_{40} responded correctly to heavy rainfall events (Fig. 5b: 2012 and Fig. S3:2011, 2013, 2014 in the supplemental material).

3.3.3 Representativeness and accuracy

The representativeness of the point soil moisture measurements can be affected by the variability in soil moisture content [27]. Moreover, variability depends on various natural environmental factors such as soil heterogeneity, rainfall, drying (evapotranspiration), and plant development. In particular, soil heterogeneity and rainfall conditions can be considered to mainly affect the representativeness [28]. So, although the soil measurement area of CP_{40} is so small, it is qualitatively meaningful for actual field observations to know how much representativeness there is in soil moisture content measured by CP_{40} unit using the obtained data of soil moisture measurement at the SS and MGS, at least.

Figure 6 shows the relationship between CP_{40}T1 soil moisture (SM) values and CP_{40}T2 SM values at the SS. The CP_{40}T1, CP_{40}T2, and 2RTDR01 units were 3-cm deep. CP_{40} units were placed 9 cm apart on either side of the 2RTDR01 probe. There was an agreement between the CP_{40}T1 SM and CP_{40}T2 SM, except in 2003. For CP_{40}T1 SM of 0.4–0.55 m^3/m^3, CP_{40}T2 SM (blue open squares in Fig. 6) increased independently of CP_{40}T1 SM in 2003. This could have been caused by heavy rainfall (amount: 310 mm, maximum intensity: 18 mm/h) that occurred during August 14–17 (Fig. 4b). In spring of 2004, it rained also heavily as seen in Fig. 4c. Under heavy rainfall, the wetting front becomes wavy and very unstable; consequently, the CP_{40}T2 values may reflect the biased flow of rainwater. CP_{40}T1 SM and CP_{40}T2 SM were both higher than 2RTDR01 SM, and the heavy rainfalls resulted in large discrepancies between the CP_{40} and 2RTDR01 SM values in 2003 and 2004 (Fig. S4 in the supplementary material) was also caused by heavy summer rainfall. The relationship between the CP_{40} and 2RTDR01 SM values deteriorated because soil water flow was very unstable in the highly wetted soil. CP_{40}T4 at 10 cm-depth clearly overestimated the soil moisture values were seen in Fig. S5 in the supplementary material. This implies that partial soil water flow at 10-cm depth, such as the fingering flow and may be affected by soil heterogeneity. Given that the large discrepancies between the CP_{40} and 2RTDR01 SM values in 2003 and 2004 were associated with rainfall conditions, the representativeness of the CP_{40} soil moisture measurements in the highly wetted soils were unstable.

The data analyses of the MGS showed the relationships (a) between CP_{40}T1 SM and CP_{40}T2 SM at 1 cm depth and (b) between 2RtTDR SM and CP_{40}T5 SM at 3 cm depth in the dry soil at the MGS in September and October 2008 (blue circles), April and May 2009 (blue circles), and June to August 2009 (pink crosses), as shown in Fig. 7. Despite the obvious overestimation of CP_{40}T2 soil moisture (Fig. 7a), there was a good correlation between CP_{40}T1 SM and CP_{40}T2 SM. This overestimation can be attributed to heavy rainfall.

Figure 7b shows that the CP_{40}T5 SM values were considerably higher than the 2RtTDR SM values in the summer (June to August). In the relationship between CP_{40}T5 and 2RtTDR, as well as seen in Fig. 6, similar large discrepancies appeared in the range of the soil moisture content from 0.1 m^3/m^3 to 0.23 m^3/m^3 in CP_{40}T5. However, this relationship improved slightly in autumn (September and October 2008) and spring (April to May 2009). Rainfall in summer (June to August 2009; amount: 62.6 mm, maximum intensity: 10.8 mm/h) was higher than that in autumn (September and October 2008;

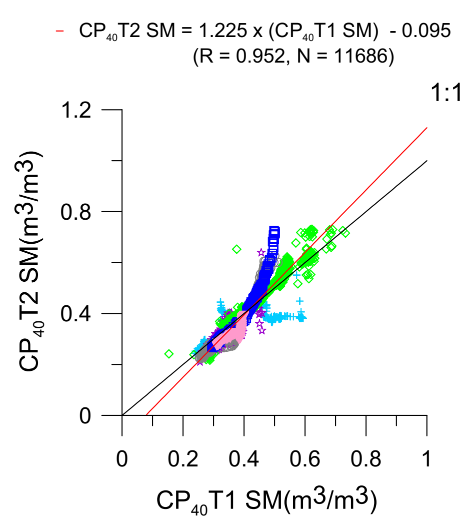
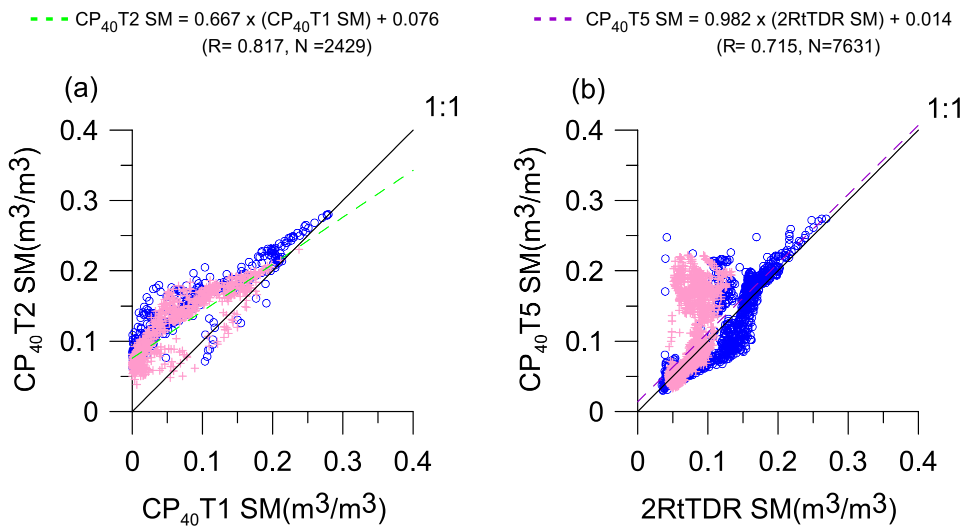


Fig. 6 Relationship between CP_{40}T1 SM (3 cm-depth) and CP_{40}T2 SM(3 cm-depth) at SS from 2002 to 2007 (unfilled ash circle: 2002, unfilled blue square: 2003, unfilled green daimond: 2004, unfilled pink inverted triangle: 2005, unfilled violet star: 2006, light blue plus: 2007, R: the correlation coefficient of the linear regression line, red solid line: the linear regression line for all, N: number of the data)

Fig. 7 Relationships between $CP_{40}T1$ SM at 1 cm-depth and $CP_{40}T2$ SM at 1 cm-depth (**a**), and 2RtTDR SM and $CP_{40}T5$ SM at 3 cm-depth (**b**) at MGS in 2008 and 2009 (unfilled blue circle: September–October in 2008 and April–May in 2009, pink plus: June–August in 2009, R: the correlation coefficient of the linear regression line, N: number of the data)



amount: 1.2 mm) and that in spring (April to May 2009; amount: 11.4 mm). The CP_{40} soil moisture measurements may have been affected by the type of fingering flow that occurs in near-homogenous soil [7] in the thin surface soil layer. Thus, the $CP_{40}T5$ overestimation could be attributed to rainfall conditions.

To quantify the representativeness and accuracy of the $CP_{40}T1$, $CP_{40}T2$, $CP_{40}T4$, and $CP_{40}T5$ SM values, their biases and RMSE were calculated using Eqs. (3) and (4), and their ubRMSE values were derived using the following equation [29]:

$$ubRMSE = \sqrt{E\left\{\left[\left(\theta_i - E\left[\theta_i\right]\right) - \left(\theta_t - E\left[\theta_t\right]\right)\right]^2\right\}} \quad (7)$$

The SM values of $CP_{40}T1$, 2RTDR02, and 2RtTDR were assumed to be true and used as references. Using the data in Figs. 6 and 7, the Bias, RMSE, and ubRMSE for the CP_{40} measurements at SS and MGS were calculated, as shown in Table S4 (SS) in the supplementary material and in Table 2 (MGS), respectively.

The results of these statistical analyses in the SS indicate that the values of the RMSE CP_{40} units with 2RTDR as a reference were not as good (Table S4 in the supplementary material). This suggests that the representativeness of the CP_{40} SM values was low in highly wetted soil, which was not more homogeneous than that of the MGS.

However, the Bias, RMSE, and ubRMSE of $CP_{40}T2$ for the MGS were small (Table 2). For $CP_{40}T2$, Bias, RMSE, and ubRMSE values compared with $CP_{40}T1$ as a reference at the MGS (Table 2) were close to those at the SS (Table S4 in the supplementary material) and small. The distances between $CP_{40}T1$ and $CP_{40}T2$ at the SS and MGS were 9 and 10 cm, respectively. The average of the $CP_{40}T1$ and $CP_{40}T2$ RMSE values from the laboratory tests was 0.017 m^3/m^3 (averaged value) as seen in in Table S1 in the supplementary material, which was a little close to the $CP_{40}T2$ RMSE value (0.034 m^3/m^3) at the MGS (Table 2). Therefore, the laboratory test results indicated that the $CP_{40}T2$ SM value was representative of an area that was at least within 10 cm of the probes, and also inferred that the $CP_{40}T5$ RMSE and ubRMSE values, which were very small (Table 2), were representative of an area that was within 10 cm of the probe, because the distance between the $CP_{40}T5$ and 2RtTDR units at the MGS was also 10 cm. Combining the results from the SS and MGS suggests that CP_{40} soil moisture measurements are likely to be representative of an area within 10 cm of the probe in dry soil, irrespective of the soil properties and rainfall conditions. However, there is insufficient data to discuss representativeness. Therefore,

Table 2 The values (Unit: m^3/m^3) of BIAS, RMSE, and ubRMSE based on the data shown in Fig. 7 (R: the correlation coefficient of the linear regression, N: the number of data)

Sensor No	BIAS	RMSE	ubRMSE	R	N	Remarks
$CP_{40}T2$	0.015	0.034	0.030	0.817	2429	Reference $CP_{40}T1$
$CP_{40}T5$	0.006	0.030	0.030	0.715	7631	Reference 2RtTDR

the field test results regarding representativeness are only one result, and more tests using plural CP_{40} units should be considered in the field.

Although the values of RMSE of CP_{40} units in the dry soil of the MGS (Table 2) were larger than those obtained in the laboratory (Table S1 in the supplementary material), the RMSE values (0.034 m^3/m^3 and 0.030 m^3/m^3, respectively) of CP_{40}T2 and CP_{40}T5 (Table 2) mean that the measurement accuracy of soil measurement of CP_{40} units in the field can be high [30], and the CP_{40} soil moisture measurements in the thin surface soil layer of dry soils are sufficiently precise. However, given the representativeness and precision of soil moisture measurements, care should be taken when using a single CP_{40} unit to measure soil moisture.

4 Conclusions

In this study, five TDR CP_{40} units, each with a sensor length of 40 mm (CP_{40}), which is longer than the CP_{15} tested by Nissen et al. [12], were challengeablly produced and tested. Their principal characteristics, such as accuracy, error, and stability, were studied in a laboratory prior to 2002. In 2002, they were installed in the field in Mongolia, where long-term soil moisture measurement tests were conducted until the autumn of 2022. Laboratory experiments on the apparent relative dielectric permittivity measured by CP_{15}, CP_{40} and 2RDTR in air and liquids with known dielectric constants showed that the soil moisture values of CP were not significantly affected by the sensor length. The measurement accuracy of CP_{40} was close to that of a traditional two-rod-type TDR (2RTDR) probe used as a reference. However, laboratory calibration tests using different soils indicated that the relationship between the apparent relative dielectric permittivity from CP_{40} and that from 2RDTR for the SS soil containing organic matter was slightly different from that of the experimental sand.

Four of the five CP_{40} units succeeded in conducting soil moisture measurements during about 5 years (2002 early autumn—2007 summer) in the highly wetted soil at the SS in the Taiga. Subsequently, four CP_{40} units (CP_{40}T1–T4) from the SS and another CP_{40} unit (CP_{40}T5) were installed in the dry soil at the MGS to conduct long-term field soil moisture measurements from 2008 to 2022. The four units (CP_{40}T1, CP_{40}T2, CP_{40}T3 and CP_{40}T4) conducted soil moisture measurements at the SS for approximately 5 years (2002 early autumn—2007 summer). However, two CP_{40} (CP_{40}T2 and CP_{40}T4) units of the four units did not measure precisely soil moisture from 2010 at the MGS; then, three units (CP_{40}T1, CP_{40}T3, and CP_{40}T5) continued to measure soil moisture stably with the high measurement accuracy for 15 years at the MGS from 2008 to 2022. In summary, two units (CP_{40}T1 and CP_{40}T3) successfully measured the soil moisture over 21 years (2002 and 2022) at the SS and MGS. Soil hydrological processes and soil water movement changes in the field have been continuously and reasonably captured over the long term despite severe environmental conditions. All CP_{40} units withstood severe natural environments for 6 years. This result indicates that the CP_{40} unit is applicable to long-term field soil moisture measurements for 6 years at least.

The representativeness of CP_{40} soil moisture measurements in highly wetted soil was relatively lower than that in dry soil. This is because the measurement area of CP_{40} is smaller than that of a traditional two-rod-type TDR probe, which contains two rods set a few centimeters apart. The representativeness of the CP_{40} soil moisture measurements was dependent on rainfall conditions, and likely on soil heterogeneity. The representativeness of CP_{40} soil moisture measurements was higher in dry soil than in highly wetted soil. Therefore, there is room for further investigation of the representativeness of CP_{40} soil moisture measurements in the field.

Similar to the representativeness, the accuracy of the CP_{40} soil moisture measurements in highly wetted soil (the ubRMSE values of CP_{40} units were between 0.073 m^3/m^3 and 0.118 m^3/m^3) was not as good as that of the traditional two-rod-type TDR, but it remained acceptable. The use of plural CP_{40} units could make the better soil moisture measurement possible. However, in the thin surface layer of dry soil, the accuracy of the CP_{40} soil moisture measurements was comparable to that of the traditional two-rod-type TDR probe, and the stability and durability of the CP_{40} units were outstanding.

In conclusion, CP_{40} is essentially effective for long-term field soil moisture measurements in thin surface soil layers on a scale of several centimeters. By considering representativeness, a few CP_{40} units should be installed at the same depth to measure the soil moisture in the thin surface soil layer. In addition to long-term field soil moisture measurements in the thin surface soil layer, CP_{40} could be suitable for applications that require the sampling of very small volumes of natural elements in porous media. Concretely, CP_{40} can be useful for various natural environmental studies such as soil surface condition change study, soil moisture behavior study, ecological study of small soil animal, and salt accumulation study.

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Author contributions All authors contributed to the study conception and design. Material preparation, data analysis and visualization: IK. Probe design and production: HHN and PM, Data collection: KA, JA, NH, and IK. Writing- original draft: IK. Writing—review and editing: all authors. All authors read and approved the final manuscript.

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Data availability The datasets obtained during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Conflict of Interest The authors declare no conflicts of interest to this study.

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