Evaluation of Evaporation Related Diurnal Change from Dielectrically Measured Soil Moisture

R.G.C. Jeewantinie Kapilaratne*[1], Minjiao Lu[2]

[1,2]Department of Civil and Environmental Engineering, Nagaoka University of Technology, Kamitomioka, 1603-1, Nagaoka, Niigata, 940-2188, Japan

[2]Chongqing Jiaotong University, School of River and Ocean Engineering, 66 Xuefu Ave, Nanan Qu, 400060, China

*[1]k.jeewantinie@gmail.com; [2]lu@nagaokaut.ac.jp

***Abstract*-Separation of physical and apparent diurnal fluctuation from dielectrically measured soil water content (SWC) is critical for accurate estimation of temperature related inaccuracies. Evaporation process at soil surface was simulated under synthetic and semi synthetic conditions in HYDRUS-1D environment. At synthetic conditions daily evaporation rate was assumed as 12 mm while evaporation rates at semi synthetic conditions were estimated using meteorological data. This study used 12 soil moisture monitoring stations which represent various climatic and soil conditions to characterize high and low evaporation levels. Simulated SWC at semi synthetic conditions were agreed well with the observed SWC with hourly NASH value ranging from 0.45-0.6. As a consequence of less evaporation related diurnal fluctuations, amplitude of simulated SWC always lesser than that of the observed SWC after eliminating the rainy days and freezing period. For Mongolian sites 6-16% and 3-9% for Unites States' sites consists of evaporation related amplitude variations of dielectrically measured SWC. Synthetic experiment results indicated that when ground water table getting deeper than 1m evaporation related diurnal fluctuations are disappearing from the near surface soil moisture.**

Keywords- Evaporation; HYDRUS-1D; Dielectric Sensors; Soil Moisture

I. INTRODUCTION

Dielectric sensors are widely used for long term in situ monitoring of near surface soil moisture. The main techniques used by these sensors can be classified as time domain reflectometry (TDR) and frequency domain reflectometry (FDR). Among them non-TDR sensors are extensively used in soil moisture monitoring networks due to their low cost, ease of use and less power consumption. However, those sensors are often criticized due to their high temperature sensitivity. As a consequence, dielectrically measured near surface soil water content (SWC) exhibited a spurious diurnal pattern with higher day time SWC than night time (Fig. 1a). Where [1] experimentally found that day time SWC is smaller than night time as soil profile undergoes evaporation process during the daytime (Fig. 1b). Several studies [2-3] have explained that such diurnal pattern in dielectrically measured SWC is a combination of two components. Those are physical component due to evaporation process and apparent component due to temperature related inaccuracies. Reference [4] Found in their study that apparent diurnal fluctuations are dominant than physical diurnal fluctuations regardless of the meteorological and soil conditions which lead to high and low evaporation levels. Though it is found to be dominant yet there is no method to discriminate the physical and apparent diurnal components.

References [2, 5] stated that it is extremely difficult to separate apparent and physical diurnal effect from dielectric probe measurements as soil temperature being the common leading factor for both the components. However, quantification of aforementioned diurnal components is critical for accurate estimation of temperature related inaccuracies. For instance the proposed temperature calibration by [2] for dielectric sensors is removing both apparent and physical components. Therefore, proper quantification of physical diurnal effects will lead to an accurate estimation of temperature related inaccuracies of dielectric sensors. Thus, this study attempted to evaluate physical diurnal fluctuations of dielectrically measured SWC by simulating the evaporation process in HYDRUS-1D environment at synthetic and semi synthetic conditions. Meteorological and soil property information were used for the semi synthetic condition experiment while 12 mm daily evaporation rate was used for synthetic condition experiment.

II. MATERIALS AND METHODS

A. Study Area

The work presented in this study focuses on 12 soil moisture monitoring stations from two soil moisture monitoring networks of United States and Mongolia. Authors have used aforementioned both moisture monitoring networks for the development of an automated general temperature correction method for dielectric sensors. Through that study both the apparent and physical diurnal fluctuations were removed. Therefore, from this study authors would like to quantify the physical diurnal components which will lead to accurate estimation of temperature related inaccuracies. Consequently this study would be a supportive study for our previous work.

To facilitate the investigation under low and high evaporation conditions, the stations were selected to represent various climatological conditions and soil types. These moisture monitoring stations cover 03 main climates (as classified in [6]) [B:

DOI:10.5963/JWRHE0603002

arid, C: warm temperate, D: snow, W: desert, f: fully humid, s: summer dry, w: winter dry, h: hot arid, k: cold arid, a: hot summer, b: warm summer, c: cool summer, T: polar tundra] and five major soil types. The monitoring networks in the United States consist of three major climates; arid, warm temperate and snow. Automatic weather stations of Mongolia are under arid conditions. Dominant soil types of selected stations range from sandy clay loam to Loam. Further information about geolocation, climate and soil type of individual moisture monitoring station is summarized in Table 1.

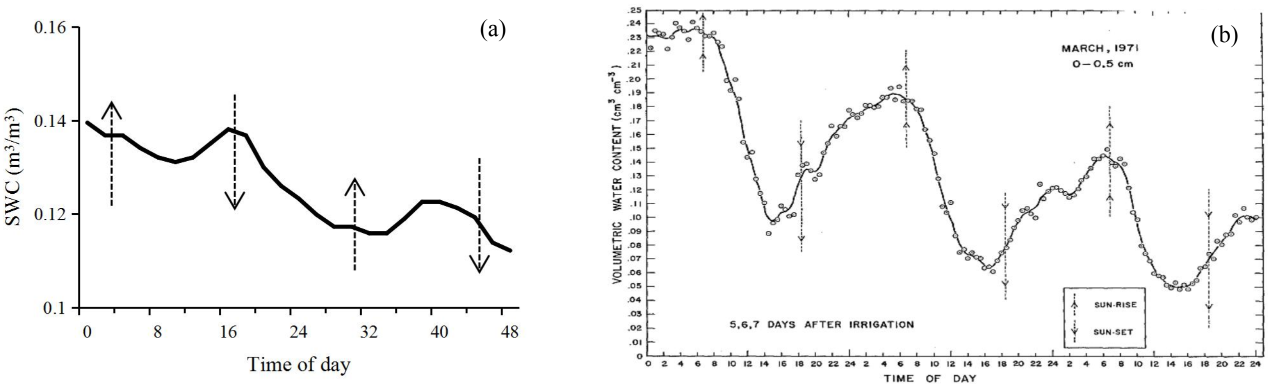

Fig. 1 Comparison of diurnal variation of (a) dielectrically measured SWC DRS station of Mongolia 14-16/09/2008 and (b) gravimetrically measured SWC [1]

TABLE 1 DESCRIPTION OF SOIL MOISTURE MONITORING NETWORKS USED IN THIS STUDY

Country (network name)	Station name	Geolocation (λ, ϕ)	Climate classification	Dominant soil type
Mongolia (Mongolia) [7]	BTS	107.14,46.77	BWk	Sandy loam
	DRS	106.71, 46.21		
	MGS	106.26, 45.74		
United States of America (USCRN) [8]	Williams-35-NNW	-112.34, 35.76	Dsb	Loam
	Socorro-20-N	-106.89, 34.36	BSk	Loam
	Riley-10-WSW	-119.69, 43.47	BWk	Loam
	Redding-12-WNW	-122.61, 40.65	Csa	Sandy clay loam
	Las-Cruces-20-N	-106.74, 32.61	BSk	Loam
	Goodwell- 2-E	-101.60, 36.60	BSk	Loam
	Fallbrook-5-NE	-117.19, 33.44	BSk	Loam
	Corvallis-10-SSW	-123.33, 44.42	Csb	Loam
	Cortez-8-SE	-108.50, 37.25	Dfa	Loam

B. Data Description

The near surface SWC and temperature data used in this study were obtained from International Soil Moisture Monitoring Network (ISMN) [9-11] and accessed from 27/02/2017- 25/03/2017 and Japan Aerospace eXploration Agency (JAXA). The meteorological data of USCRN network was obtained from sub-hourly data directory of National Oceanic and Atmospheric Administration (NOAA) (https://www.ncdc.noaa.gov/crn/qcdatasets.html). 09 moisture monitoring stations from USCRN (United States Climate Reference Network) [8] network of United States and remaining 03 are from individual moisture monitoring network of Mongolia. Seven meteorological data were used for this study. Those are Precipitation, surface temperature, air temperature, radiation, humidity, wind speed and SWC. All data are measured at sub hourly intervals. Description of soil moisture sensor setups used in this study and periods can be found at Table 2.

TABLE 2 SENSOR SETUPS OF SOIL MOISTURE MONITORING STATIONS USED IN THIS STUDY

Station name	Soil moisture sensor	Measurement depth	Period
BTS	TDR	0.03-0.03 m	2004-2008
DRS			2003-2007
MGS			2004-2008
Williams-35-NNW	Stevens Hydraprobe-II	0.05-0.05 m	2012-2016
Socorro-20-N			
Riley-10-WSW			
Redding-12-WNW			
Las-Cruces-20-N			
Goodwell- 2-E			
Fallbrook-5-NE			
Corvallis-10-SSW			
Cortez-8-SE			

DOI:10.5963/JWRHE0603002

C. Model Description

This study has used HYDRUS-1D model to simulate the variation of water content of soil profile with surface evaporation. HYDRUS-1D model can be used to simulate the solute and water movement in unsaturated or fully saturated porous media [12]. In HYDRUS-1D, potential evaporation is calculated by using either Penman-Monteith [13] or Hargreaves [14] formula. For this study we have selected Penman-Monteith equation to estimate evaporation with the data availability. HYDRUS-1D requires users to enter values directly for potential evaporation or meteorological and time variable boundary conditions for the atmosphere boundary conditions which can be used to calculate it. Thereafter, the model calculates the values of evaporation (using meteorological data) based on the availability of water in the soil profile.

D. Simulation with HYDRUS-1D

In this study simulations were carried out using heat and water transport program of HYDRUS-1D. Two types of simulations were carried out in this study. The first sets of simulations are completely under synthetic conditions. For that daily evaporation rate are assumed to be high as 12 mm. the other sets of simulations under semi synthetic conditions using meteorological and soil property data. There are two distinct steps in each simulation. The objective of the first part is to create an accurate initial soil profile. During the second part obtained vertical profile of first part used as initial soil profile.

1) Synthetic Conditions Experiment

During the first part in this experiment we have assumed hydrostatic condition as initial condition and a constant evaporation rate of 12 mm/day as time variable boundary condition to create an equilibrium soil profile of the first part. Thereafter, created equilibrium soil profile used as initial condition of the second part and sinusoidal form of 12 mm/day evaporation used as time variable boundary condition to estimate the SWC at each node. The experiment was tested for 12 main soil types available in HYDRUS-1D with varying ground water table (GWT) from 0.25-2 m. The schematic of the experiment under synthetic condition is shown in Fig. 2. Finally, simulated water content at 3 cm depths was compared and amplitude of simulated and observed SWC of DRS site of Mongolia was also compared.

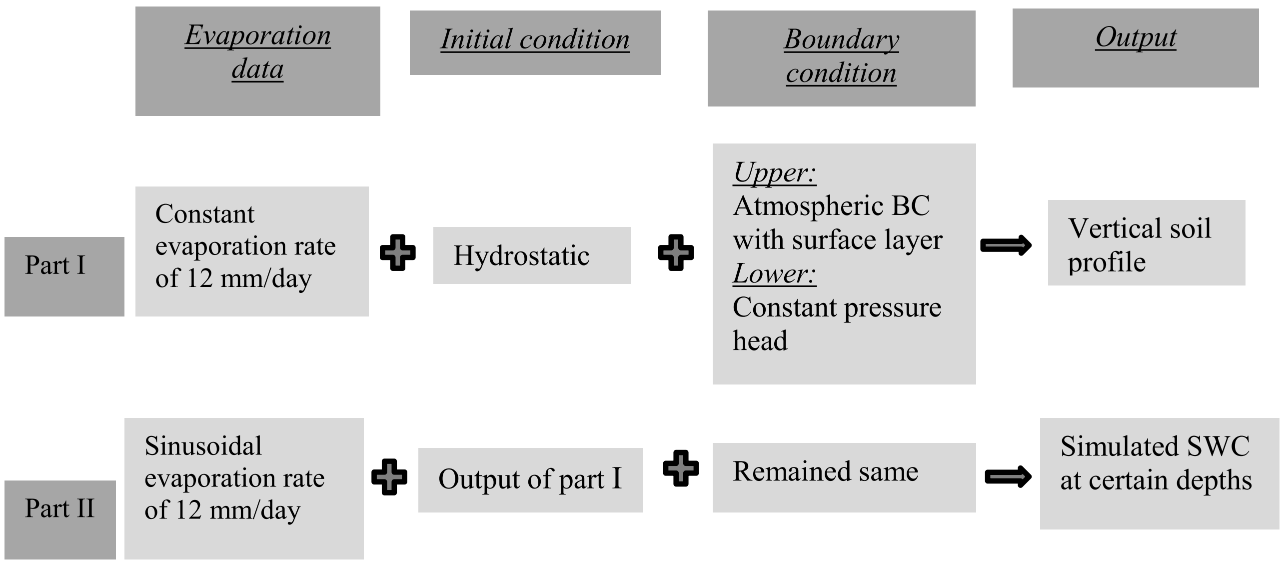

Fig. 2 Schematic of simulation process (Synthetic conditions)

DOI:10.5963/JWRHE0603002

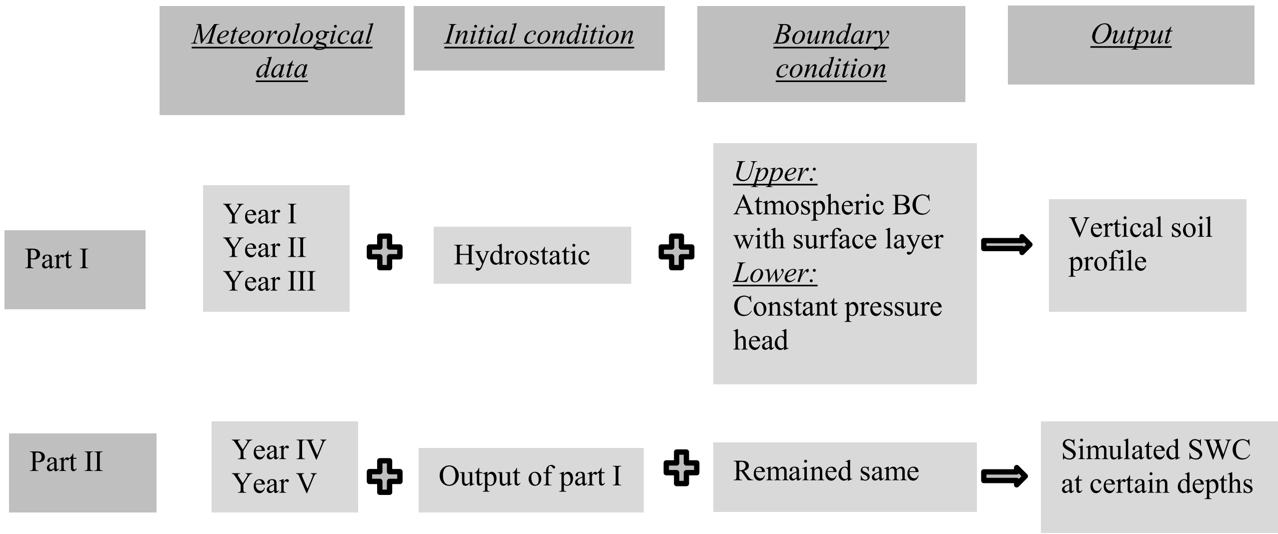

Fig. 3 Schematic of simulation process (Semi synthetic conditions)

2) Semi Synthetic Conditions Experiment

During the first step initial soil profile was created using meteorological data of three years. Atmospheric boundary condition with surface layer and constant pressure head were used as upper boundary condition and lower boundary condition respectively. Initial condition of the soil profile assumed to be hydrostatic. Thereafter, output soil profile from the first part is used as the initial condition of the second part. Other boundary conditions kept unchanged along with the new set (two years) of meteorological data (Fig. 3). Finally, water content of simulated depths (3 cm for Mongolian sites and 5 cm for United States sites) were compared with observed SWC measurements. To verify the accuracy of the HYDRUS-1D model, simulated and observed SWC of first part were compared by visually and calculating the Nash-Sutcliffe (NASH) efficiency [15]. Finally, amplitudes of simulated and observed SWC were calculated as half the differences between the maximum and the minimum of the diurnal cycles.

III. Results and Discussion

A. Synthetic Conditions Experiment

Simulation for each soil type consists of several simulations with different ground water tables. Simulated SWC of a selected soil type was compared only with the simulated SWC at different GWTs of respective soil type. Simulated SWC and amplitudes of sandy loam soil type was compared with observed SWC of DRS site of Mongolia. From Fig. 4a it is clear when GWT getting deeper and deeper the diurnal fluctuations of surface soil moisture are disappearing (at 1 m). Further, amplitude of observed SWC agreed well with simulated SWC with GWT at 35 cm depth. However, for the tested site actual GWT depth is ranging from 5-10 m depth. Results of synthetic condition experiment indicate that evaporation related diurnal fluctuations are quite small for the sites with deeper GWTs.

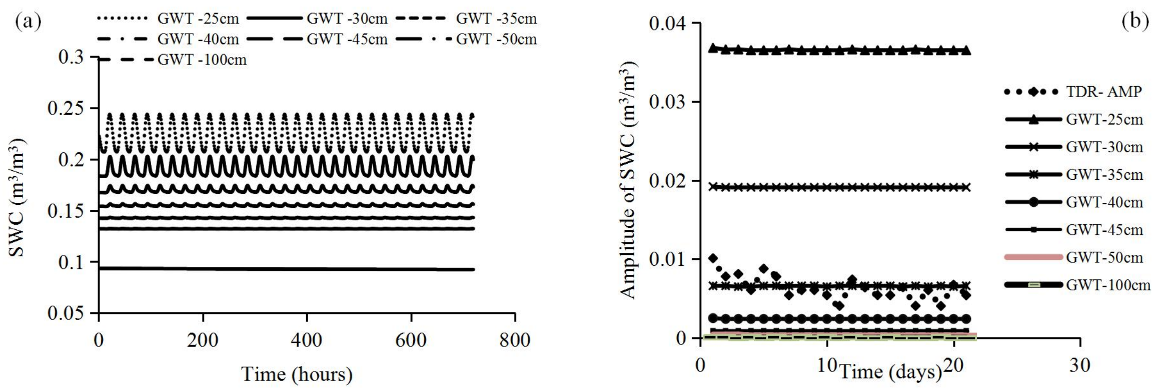

Fig. 4 Comparison of (a) simulated SWC at different GWT depths (b) amplitudes of observed SWC of DRS (year 2006) site of Mongolia and simulated SWC

DOI:10.5963/JWRHE0603002

B. Observed and Simulated SWC

Relatively a good agreement was observed between simulated and the observed SWC except at the freezing season. Estimated hourly NASH values of the tested sites ranged from 0.45-0.60. Agreement between observed and simulated SWC for other sites showed a similar trend with Fig. 5. Moreover, Fig. 6 revealed that the observed and simulated SWC are in opposite phase in such a way that higher SWC at night time than that of day time which agrees with the observed diurnal pattern of gravimetrically measured SWC by [1].

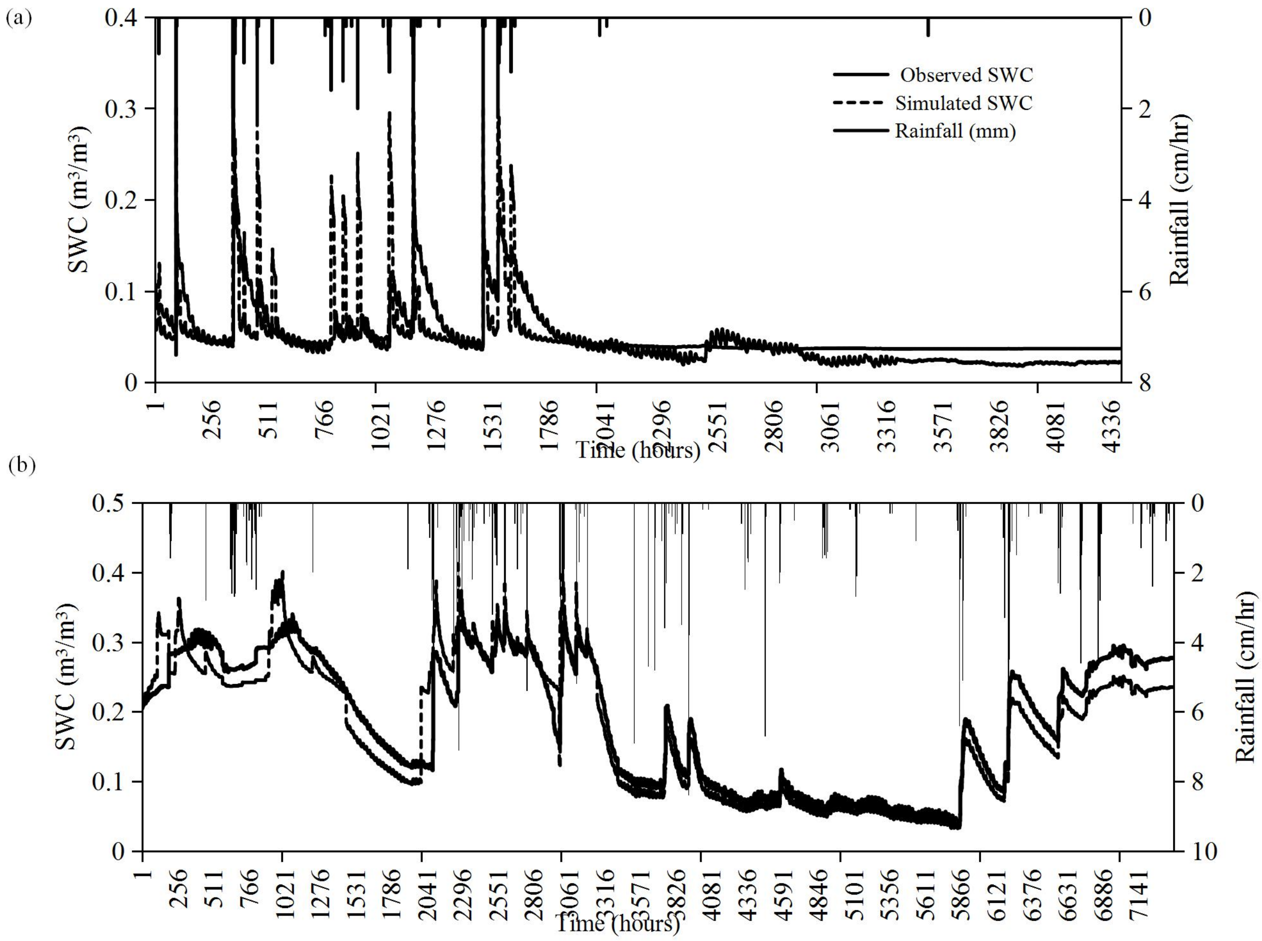

Fig. 5 Comparison of observed and simulated SWC (a) DRS (year 2006) of Mongolia and (b) Cortez-8-SE (year 2014) of United States

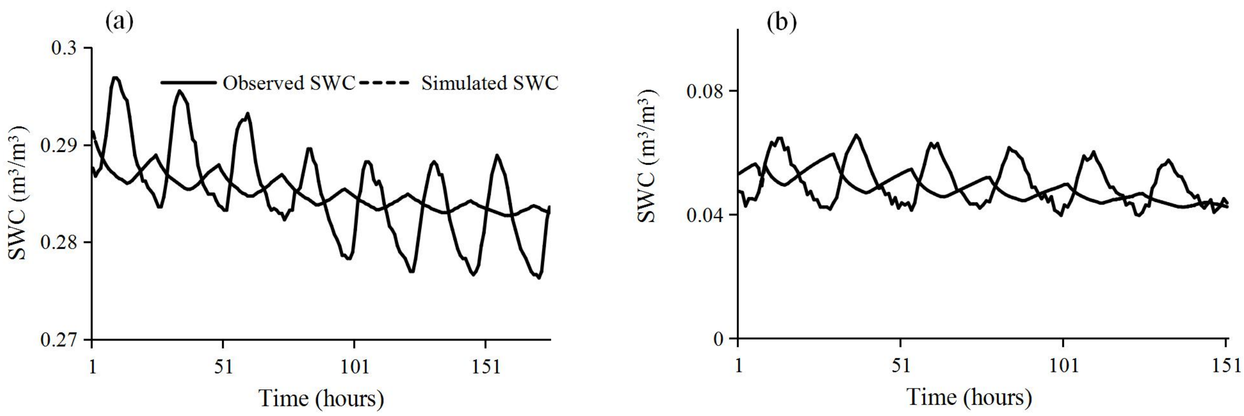

Fig. 6 Comparison of observed and simulated SWC recessions (a) DRS site of Mongolia (year 2008) and (b) Cortez-8-SE of United States (year 2016)

DOI:10.5963/JWRHE0603002

C. Amplitude Comparison of Observed and Simulated SWC

Observed SWC (dielectrically measured) amplitudes consist of two components. Those are amplitude variation due to temperature effect (apparent part) and evaporation (physical part). While simulated SWC consist of amplitude variations solely due to evaporation process. Fig. 7 represents the comparison of simulated and observed SWC amplitudes. As shown in Fig. 7 regardless of the level of evaporation, amplitude of simulated SWC measurements are always lesser than that of observed SWC measurements. This implies the lesser contribution of evaporation related diurnal course to the resultant diurnal pattern of dielectrically measured SWC.

Percentage ratio between average amplitude of simulated and observed SWC were estimated by eliminating the rainy days along with previous day rainy events and freezing days to avoid abrupt amplitude changes in SWC due to rainy events and at freezing. At Mongolian sites, 6-16% of the observed amplitude variations are due to the effect of evaporation and it is in a range of 3-9% for the selected sites in United States. Percentage ratio between average amplitude of simulated and observed SWC for all the stations are presented in Table 3. Table 3 results also reveal that the effect of physical diurnal component is comparatively less prominent in dielectrically measured SWC. And also Table 3 indicates that the Stevens Hydraprobe sensor having larger temperature related diurnal fluctuations than TDR sensor. This agreed well with the finding of [16-17].

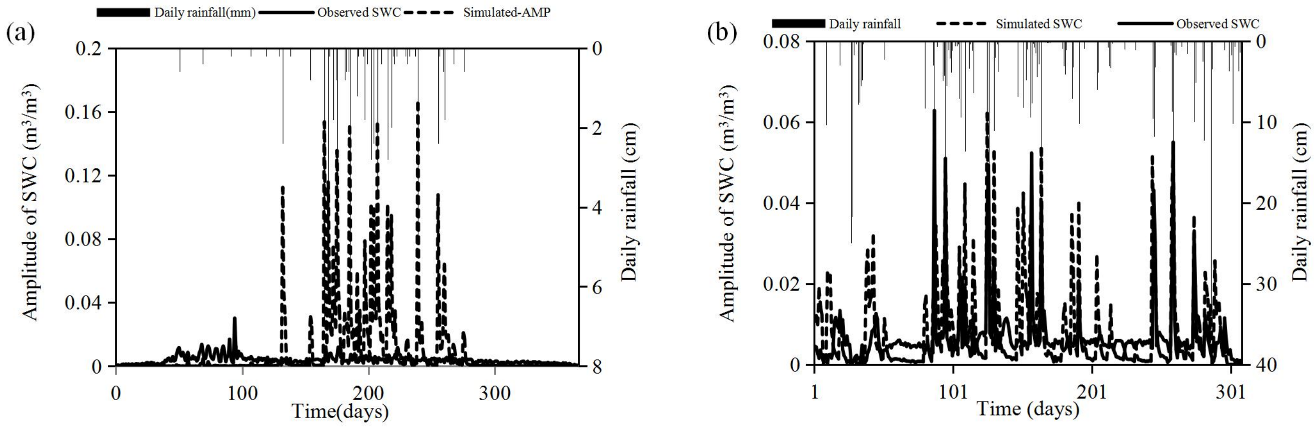

Fig. 7 Amplitude comparison of observed and simulated SWC (a) DRS of Mongolia (year 2008) (b) Cortez-8-SE monitoring station of United States (year 2016)

D. Amplitude Comparison of Observed , Simulated and Temperature Corrected SWC

As the proposed temperature correction algorithm by [2] removed both apparent and physical diurnal effects, the major concern of this study was to quantify those components. The temperature corrected SWC were obtained using the proposed algorithm by [2]. Figure 8 compared the observed, simulated and temperature corrected SWC. It is obvious from Fig. 8 except for the rainy and freezing days, amplitude of temperature corrected SWC values are always lower than that of the simulated and the observed SWC. In general amplitude change due to temperature related inaccuracies can be obtained by subtracting the amplitudes of simulated and temperature corrected SWC from observed SWC. From Fig. 8 it is obvious that in comparison to the temperature related diurnal fluctuations physical diurnal fluctuation is only a small fraction. Similar trend has been found for the remaining 11 stations as well.

TABLE 3 PERCENTAGE RATIO BETWEEN AVERAGE AMPLITUDE OF SIMULATED AND OBSERVED SWC

Station name	Percentage ratio
BTS	10.1
DRS	16.2
MGS	6.1
Williams-35-NNW	5.2
Socorro-20-N	2.7
Riley-10-WSW	3.1
Redding-12-WNW	5.2
Las-Cruces-20-N	3.7
Goodwell- 2-E	7.9
Fallbrook-5-NE	2.6
Corvallis-10-SSW	5.7
Cortez-8-SE	9.2

DOI:10.5963/JWRHE0603002

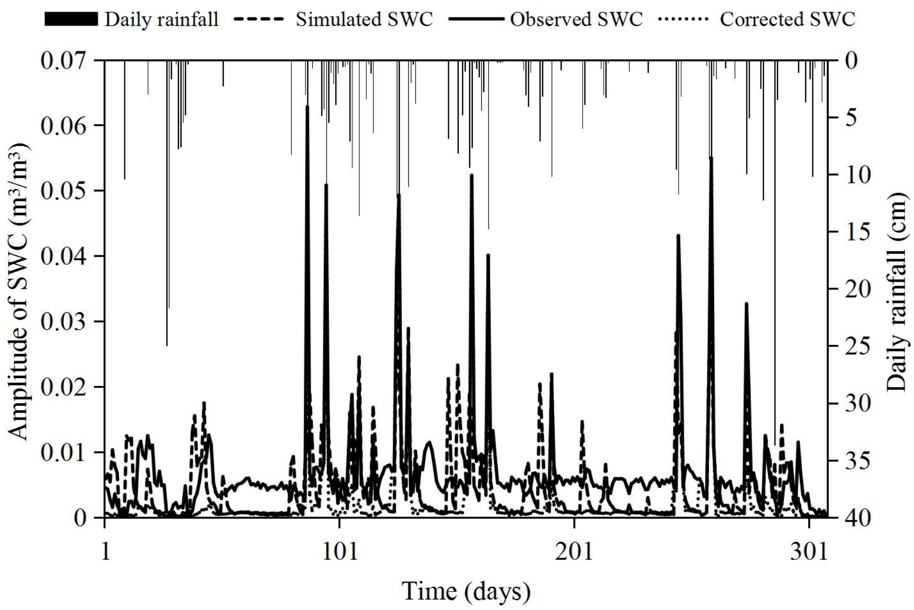

Fig. 8 Amplitude comparison of observed, simulated and temperature corrected SWC of Cortez-8-SE monitoring station of United States (year 2016)

IV. CONCLUSIONS

Dielectrically measured near surface soil water content (SWC) shows anomalous diurnal fluctuations. Such fluctuation is a combined result of physical diurnal effect due to evaporation process and apparent diurnal effect due to sensor's sensitivity to diurnal temperature variations. Discrimination of the apparent and physical diurnal fluctuation is critical as some of the existing temperature correction methodologies removing both the diurnal fluctuations. Separation of physical and apparent components becomes extremely difficult as temperature being the common primary factor controlling them. However, it is extremely important to know magnitude of each of these components for better understanding of commonly found temperature related inaccuracies of dielectrically measured SWC. Therefore, this study attempted to simulate an evaporation of soil surface under synthetic and semi-synthetic conditions in HYDRUS-1D environment using constant daily evaporation rate of 12 mm and meteorological data respectively.

Synthetic conditions experiment carried out for 12 main soil types given in HYDRUS-1D at different GWT depths ranging from 0.25-2 m. Simulations for semi synthetic conditions were carried out for 12 moisture monitoring stations from two soil moisture monitoring networks of United States and Mongolia. Each experiment used meteorological data of consecutive five years period, among them three years were used to calibrate the model and create an accurate initial soil profile and remaining two years for the estimation of the near surface SWC and compare with the in situ measurements. Tested 12 stations represent various climatic and soil conditions which lead to high and low evaporation levels. Simulated SWC relatively well agreed with the observed SWC with hourly NASH value range 0.45-0.6. Diurnal fluctuations of simulated SWC solely due to the evaporation process while dielectrically measured SWC is a combination of evaporation effects and temperature related inaccuracies. Consequently, amplitude variation of simulated SWC and observed SWC was estimated. Results indicated that 6-16% of amplitude variation of Mongolian sites and 3-9% of USCRN sites are due to evaporation process. Further the amplitude variations of simulated, temperature corrected and observed SWC indicated that evaporation related amplitude fluctuation is a small fraction compared to the amplitude fluctuations removed through temperature correction algorithm. From the experiment under synthetic conditions found that, evaporation related diurnal fluctuations are disappearing for the deeper groundwater table regions.

ACKNOWLEDGMENT

R.G.C. Jeewantinie Kapilaratne acknowledges support from the Japanese Ministry of Education, Culture, Sports, Science, and Technology provided through the MEXT scholarship. The authors would like to thank Japan Aerospace eXploration Agency (JAXA) for providing support in creating data sets.

REFERENCES

[1] R. D. Jackson, "Diurnal changes in soil water content during drying," *Field Soil Water Regime*, Soil science society of America, vol. 5, pp. 37-55, 1973.

[2] M. Lu, J. Kapilaratne, and I. Kaihotsu, "A data-driven method to remove temperature effects in TDR-measured soil water content at a Mongolian site," *Hydrological Research Letters*, vol. 9, pp. 8-13, 2015.

DOI:10.5963/JWRHE0603002

[3] D. Or and J. M. Wraith, “Temperature effects on soil bulk dielectric permittivity measured by time domain reflectometry: A physical model,” *Water Resource Research*, vol. 35, pp. 371-383, 1999.

[4] R.G.C.J. Kapilaratne and M. Lu, “Automated general temperature correction method for dielectric sensors,” *Journal of Hydrology*, vol. 551, pp. 203-216, 2017.

[5] J. Halbertsma, E. E. Van den, E. E., H. Bohl, and W. Skierucha, “Temperature effects in soil water content determined with time domain reflectometry,” *Zeszyty Problemowe Postepow Nauk Rolniczych-Polska Akademia Nauk* , vol. 436, pp. 65-74, 1996.

[6] M. Kottek, J, Grieser, C. Beck, B. Rudolf, and F. Rubel, “World map of the Köppen-Geiger climate classification updated,” *Meteorologische Zeitschrift*, vol. 15(3), pp. 259-263, 2006.

[7] T. Yamanaka, I. Kaihotsu, D. Oyunbaatar, and T. Ganbold, “Summertime soil hydrological cycle and surface energy balance on the Mongolian steppe”, *Journal of Arid Environments*, vol. 69(1), pp. 65-79, 2007.

[8] J. E. Bell, M. A. Palecki, C. B. Baker, W. G. Collins, J. H. Lawrimore, R. D. Leeper, M. E. Hall, J. Kochendorfer, T. P. Meyers, T. Wilson, and H. J. Diamond, “U.S. Climate Reference Network soil moisture and temperature observations”, *Journal Of Hydrometeorology*, vol. 14, pp. 977-988, 2013.

[9] W. A. Dorigo, W. Wagner, R. Hohensinn, S. Hahn, C. Paulik, A. Xaver, A. Gruber, M. Drusch, S. Mecklenburg, and P. Oevelen, “The International Soil Moisture Network: a data hosting facility for global in situ soil moisture measurements,” *Hydrology and Earth System Sciences*, vol. 15, pp. 1675-1698, 2011.

[10] W. A. Dorigo, A. Xaver, M. Vreugdenhil, A. Gruber, A. Hegyiová, A. D. Sanchis-Dufau, D. Zamojski, C. Cordes, W. Wagner, and M. Drusch, “Global automated quality control of in situ soil moisture data from the International Soil Moisture Network,” *Vadose Zone Journal*, vol. 12(3), 2013, doi: 10.2136/vzj2012.0097.

[11] A. Robock, K. Y. Vinnikov, G. Srinivasan, J. K. Entin, S. E. Hollinger, N. A. Speranskaya, S. Liu, and A. Namkhai, “The global soil moisture data bank,” *Bulletin of the American Meteorological Society*, vol. 81, pp. 1281-1299, 2000.

[12] J. Šimůnek, M. van Genuchten, and M. Šejna, “Development and applications of the HYDRUS and STANMOD software packages and related codes,” *Vadose Zone Journal*, vol. 7(2), pp. 587-600, 2008.

[13] W. R. N. Edwards and N. W. M. Warwick, “Transpiration from a kiwifruit vine as estimated by the heat pulse technique and the Penman-Monteith equation,” *New Zealand Journal of Agricultural Research*, vol. 27(4), pp. 537-543, 1984.

[14] G. H. Hargreaves and A. S. Zohrab, “Reference crop evapotranspiration from temperature,” *Applied Engineering in Agriculture*, vol. 1(2), pp. 96-99, 1985.

[15] J. E. Nash and J. V. Sutcliffe, “River flow forecasting through conceptual models part-I: A discussion of principles,” *Journal of Hydrology*, vol. 10, pp. 282-290, 1970.

[16] J. P. Walker, G. R. Willgoose and J. D. Kalma, “In situ measurement of soil moisture: A comparison of techniques,” *Journal of Hydrology*, vol. 293(1), pp. 85-99, 2004.

[17] A. W. Western and M. S. Seyfried, “A calibration and temperature correction procedure for the water-content reflectometer,” *Hydrological Processes*, vol. 19, pp. 3785- 3793, 2005.

DOI:10.5963/JWRHE0603002