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Regional scale spatio-temporal variability of soil moisture and its relationship with meteorological factors over the Korean peninsula

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SUMMARY

An understanding soil moisture spatio-temporal variability is essential for hydrological and meteorological research. This work aims at evaluating the spatio-temporal variability of near surface soil moisture and assessing dominant meteorological factors that influence spatial variability over the Korean peninsula from May 1 to September 29, 2011. The results of Kolmogorov–Smirnov tests for goodness of fit showed that all applied distributions (normal, log-normal and generalized extreme value: GEV) were appropriate for the datasets and the GEV distribution described best spatial soil moisture patterns. The relationship between the standard deviation and coefficient of variation (CV) of soil moisture with mean soil moisture contents showed an upper convex shape and an exponentially negative pattern, respectively. Skewness exhibited a decreasing pattern with increasing mean soil moisture contents and kurtosis exhibited the U-shaped relationship. In this regional scale (99,720 km^2), we found that precipitation indicated temporally stable features through an ANOVA test considering the meteorological (i.e. precipitation, insolation, air temperature, ground temperature and wind speed) and physical (i.e. soil texture, elevation, topography, and land use) factors. Spatial variability of soil moisture affected by the meteorological forcing is shown as result of the relationship between the meteorological factors (precipitation, insolation, air temperature and ground temperature) and the standard deviation of relative difference of soil moisture contents (SDRD$_t$) which implied the spatial variability of soil moisture. The SDRD$_t$ showed a positive relationship with the daily mean precipitation, while a negative relationship with insolation, air temperature and ground temperature. The variation of spatial soil moisture pattern is more sensitive to change in ground temperature rather than air temperature changes. Therefore, spatial variability of soil moisture is greatly affected by meteorological factors and each of the meteorological factors has certain duration of effect on soil moisture spatial variability in regional scale.

The results provide an insight into the soil moisture spatio-temporal patterns affected by meteorological and physical factors simultaneously, as well as the design criteria of regional soil moisture monitoring network at regional scale.

1. Introduction

Soil moisture controls hydrological, meteorological and ecological processes as well as interactions between the land surface and atmosphere by distributing precipitation to infiltration, runoff and surface storage (Entekhabi et al., 1995; Famiglietti et al., 1999; Jacobs et al., 2004). Above all, soil moisture plays an essential role in climate-change prediction, ecological patterns affecting plant growth (Rodriguez-Iturbe, 2000) and meteorological feedback at the local, regional and global scales (Teuling et al., 2007; Seneviratne et al., 2010).

As a growing need for regional scale as well as global scale observations of spatial distribution of soil moisture has promoted the development of remote sensing techniques (Schmugge et al., 2002; Jackson et al., 2010). However, satellite microwave sensors have limitations due to spatial resolution (10–50 km) and uncertainty of the soil moisture contents affected by soil surface roughness, attenuation and emission by vegetation cover (Njoku and Entekhabi, 1996). For this reason, a number of distributed ground-based soil moisture samples are needed to obtain the mean soil moisture contents and to validate remotely sensed soil moisture measurements within a remote sensing footprint. These ground-based samples are used for analysis of soil moisture variability for the purpose to overcome limitations and uncertainty due to the remote sensing methods (Famiglietti et al., 1999; Ryu and Famiglietti, 2005; Choi and Jacobs, 2007; Brocca et al., 2010).

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Spatial variability of soil moisture plays a role in validating and calibrating remotely sensed soil moisture products and designing of in situ soil moisture networks (Dorigo et al., 2013). Besides, the understanding of spatio-temporal variability of soil moisture across multi scales can help to improve the weather prediction and climate modeling (Famiglietti and Wood, 1994; Robock et al., 1998; Koster and the GLACE Team, 2004; Starks et al., 2006), scientific and operational applications such as flood prediction (Brocca et al., 2010), drought (Dai et al., 2004; Tang and Piechota, 2009) and agricultural modeling (Bolten et al., 2010).

The concept of temporal stability proposed by Vachaud et al. (1985) was used to determine the stability of temporal patterns for spatial locations. It has been used in terms of time stable, rank stability and temporal persistence in several previous studies (Grayson and Western, 1998; Mohanty and Skaggs, 2001; Cosh et al., 2004; Jacobs et al., 2004; Pachepsky et al., 2005; Choi and Jacobs, 2007; Brocca et al., 2009; Hu et al., 2010; Gao et al., 2011, 2013; Heathman et al., 2012; Vanderlinden et al., 2012; Sur et al., 2013; Zhang and Shao, 2013; Martínez et al., 2013a,b). This concept has been applied to validate and calibrate soil moisture data measured by remotely sensed instruments in many previous studies under various field conditions (Mohanty and Skaggs, 2001; Jacobs et al., 2004, 2010; Cosh et al., 2004, 2008; Bosch et al., 2006; Choi and Jacobs, 2007; Vivoni et al., 2008).

Spatial scales decide the variations which affect the soil moisture variability in time or space. Soil moisture variability was categorized into two groups according to spatial scales (Vinnikov and Robock, 1996; Robock et al., 1998; Entin et al., 2000; Seneviratne et al., 2010). Entin et al. (2000) emphasized the characteristics of spatial variability determined with two different scales: the soil properties (local scale), and the meteorological forcing (large scale). Seneviratne et al. (2010) divided spatial variability of soil moisture into local scale ($\sim$20 km) and regional scale (50–400 km) according to dominant impacting factors. However, it is difficult to find predominant factors affecting soil moisture dynamics at the regional scale, because multiple factors, including meteorological and physical characteristics, have a complex effect on the spatio-temporal variability of soil moisture. Furthermore, Vanderlinden et al. (2012) mentioned the occurrence of combined effects of influencing factors rather than single factors dominating temporal variability.

Several studies investigated the effect of climate and seasonality on spatio-temporal variability (Martínez-Fernández and Ceballos, 2003; Vanderlinden et al., 2012; Rosenbaum et al., 2012; Martínez et al., 2013a). Martínez-Fernández and Ceballos (2003) found that temporal stability of soil moisture is higher in dry conditions than wet conditions. Martínez et al. (2013a) assessed the effect of climate type and soil hydraulic properties on temporal stability and showed that summer season was highly probable with interannual difference in soil moisture variability.

In this study, the primary objective is to improve understanding of soil moisture spatio-temporal variability at regional scale (300 km) and to estimate meteorological forcing which influence on soil moisture variability through the Korean peninsula in northeast Asia. This region is in temperature climate conditions. Mostly used at footprint size (local scale), the temporal stability analysis was conducted in this investigation (regional scale). The 31 ground based measurement sites were used to investigate the temporal stability features of near surface soil moisture and associated meteorological or physical properties for widely dispersed points during the growing season (May 1–September 29) in 2011 over the Korean peninsula.

Characteristics of soil moisture temporal stability may be interpreted by an analysis of variance (ANOVA), using the relative difference values of soil moisture with meteorological (precipitation, insolation, air temperature, ground temperature and wind speed) and physical (soil texture, elevation, topography and land use) dataset in study area. Finally, the relationship of meteorological factors (precipitation, insolation, air temperature, and ground temperature) with the time lag soil moisture and with spatial variability of soil moisture, in terms of standard deviation value of the relative difference (SDRD_t), were analyzed. A time lag was used in several previous studies at different meteorological areas (Schnur et al., 2010; Wang et al., 2007). We assumed that the 31 measuring points represent their local conditions. On the basis of these analyses, the understanding of soil moisture spatio-temporal dynamics can be useful for remote sensing and modeling application as well as for climate change projection.

2. Study region and materials

Fig. 1 shows the southern part of the Korean peninsula in extent of 33–39°N in latitude and 124–131°E in longitude. The Korean peninsula, located in northeast Asia, has a temperate humid climate. The annual precipitation ranges from 900 to 1700 mm (Lee et al., 2008). More than half of the total rainfall amount is concentrated in June and July (Kim et al., 2002), while precipitation of winter is less than 10% of the total precipitation (Min et al., 2011). In other words, precipitation in Korea is unpredictable and has large spatio-temporal variability due to the Asian monsoon season (Qian et al., 2002; Chen et al., 2004; KMA, 2006). Therefore, Korea often suffers from drought or flood even though with high annual precipitation (Lee et al., 2011).

The framework of the study areas and the main characteristics of the experimental locations are given in Table 1. We used data sets from the Rural Development Administration (RDA, http://rda.go.kr). The ground based soil moisture measurements were obtained at a depth of 10 cm at 31 RDA locations on an hourly basis. Choi and Hur (2012) have conducted a disaggregated AMSR-E soil moisture validation using in situ soil moisture measured at RDA sites. The RDA sites were installed CS615 or CS616 water content reflectometers, one of the Time Domain Reflectometry (TDR) sensors. Time Domain Reflectometry (TDR) is now widely used to measure volumetric soil moisture contents (Dirksen and Dasberg, 1993; Topp, 2003). This type is based on the relationship between volumetric soil moisture contents (θ) and dielectric constant. CS615/CS616 is specified to have an accuracy of ±2.5% v/v when applied to typical mineral soils using the manufacturer's standard calibration relationship (Campbell Scientific Inc., 1996, 2012; Walker et al., 2004). This method gauges an electromagnetic pulse generated by the CS615/CS616. The elapsed time and pulse reflection are then measured and used to calculate the volumetric water content in soil (Campbell Scientific Inc., 2012).

The RDA sites are located to represent the soil physical characteristics of the region including its surrounding area. Soil textures on the surface were mainly loam and sandy loam (Korean soil information system, http://soil.rda.go.kr). The predominant land use of these locations is agricultural (80%), with rice paddy the major crop (59%). Besides soil moisture contents, the RDA also collects the meteorological factors such as precipitation, amount of insolation, air temperature, ground temperature and wind speed at the same points. In 2011, the annual precipitation range from 972 to 2064 mm and the precipitation especially during the growing season (May 1–September 29) range from 628 to 1754 mm. Air temperature ranges from 17.7 to 24.1 °C and ground temperature ranges from 19.2 to 30.9 °C during the same period. Annual insolation is approximately 4580 MJ m^{-2}. These data were obtained from the Korean agricultural meteorological information service (http://weather.rda.go.kr).

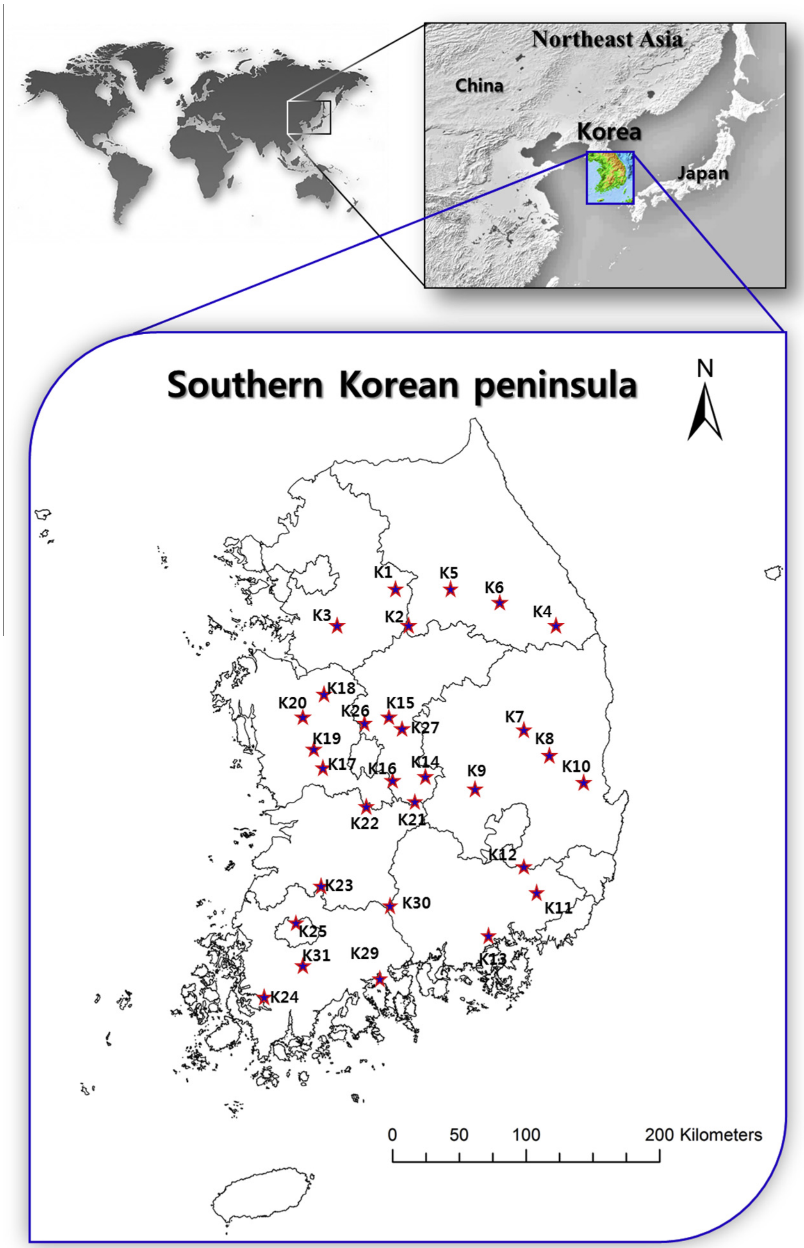

Fig. 1. Study area with the locations of the Rural Development Administration (RDA) 31 sites over the Korean peninsula.

3. Methods

3.1. K–S test

Firstly, the soil moisture measurements were analyzed for statistical distributions. The Kolmogorov–Smirnov test (Massey, 1951; Lilliefors, 1967) was conducted to test the normality of the soil moisture data distribution. In statistics, the K–S test is a nonparametric test for the equality of the similarity by comparing soil moisture measurement data with a reference probability distribution (one-sample K–S test). The K–S test can provide a statistical distribution of goodness of fit by rank order among normal, log-normal and generalized extreme value (GEV). The standard deviation, coefficient of variation (CV), skewness and kurtosis represent width, skewness and peakedness of the probability distribution of a ground-based soil moisture measurement dataset.

3.2. Spatio-temporal variability

This approach is based on the parametric analysis of the relative differences, first introduced by Vachaud et al. (1985). The relative difference ($\mathrm{RD}_{i,t}$) can be expressed as:

$$\mathrm{RD}_{i,t} = \frac{\theta_{i,t} - \bar{\theta}_t}{\bar{\theta}_t} \tag{1}$$

where $\theta_{i,t}$ is individual daily measurement of soil moisture at location i and time t, and $\bar{\theta}_t$ is the spatial average soil moisture of $\theta_{i,t}$ at time t.

For each location i, the mean relative difference (MRD_i) and the standard deviation of the relative difference (SDRD_i) are calculated by

$$\mathrm{MRD}_i = \frac{1}{N_t}\sum_{t=1}^{N_t}\mathrm{RD}_{i,t} \tag{2}$$

Table 1
The characteristics of study area with the 31 locations of the Rural Development Administration (RDA) over the Korean peninsula.

Site ID	Location	Latitude (degree)	Longitude (degree)	Total precipitation (mm)	Number of raining days (day)	Amount of insolation (MJ/m^2/day)	Average air temperature (°C)	Average ground temperature (°C)	Wind speed (m/s)	Soil texture	Elevation (m)	Slope (%)	Land use
K1	Yangpyeong	37°30′	127°30′	1754.5	64	14.65	21.54	23.87	0.70	Loam	186	30–60%	Rice paddy
K2	Yeoju	37°15′	127°38′	1630.5	60	12.58	22.12	20.86	0.41	Sandy loam	87	7–15%	Grass
K3	Hwaseong	37°13′	126°56′	1438.5	61	5.72	23.31	19.21	0.64	Loam	44	15–30%	Grass
K4	Taebaek	37°10′	128°59′	1437.5	65	13.55	17.77	19.68	0.44	Fine sandy loam	700	0–2%	Field
K5	Pyeongchang	37°22′	128°23′	1661.2	68	14.82	22.70	24.41	0.58	Fine sandy loam	307	0–2%	Field
K6	Hoengseong	37°31′	127°57′	1503.5	58	5.32	22.72	23.59	0.79	Sandy loam	143	0–2%	Rice paddy
K7	Andong	36°32′	128°48′	1032	57	11.06	21.57	25.52	0.96	Sandy loam	106	0–2%	Field
K8	Cheongsong	36°23′	129°04′	733	55	15.84	20.47	26.74	1.21	Sandy loam	220	0–2%	Field
K9	Chilgok	36°02′	128°22′	753	43	0.38	24.08	28.05	1.22	Loam	32	0–2%	Rice paddy
K10	Pohang	36°06′	129°18′	628.5	48	11.35	22.08	25.16	1.43	Loam	41	0–2%	Rice paddy
K11	Gimhae	35°12′	128°52′	965	49	13.69	22.13	23.26	1.92	Sandy clay loam	4	0–2%	Rice paddy
K12	Miryang	35°26′	128°45′	767	56	15.07	22.71	24.14	1.84	Silt loam	8	0–2%	Rice paddy
K13	Tongyeong	34°52′	128°24′	1403	56	14.66	21.92	23.90	1.57	Silt loam	17	7–15%	Rice paddy
K14	Yeongdong	36°09′	127°45′	1076	62	15.17	21.91	25.90	0.67	Sandy clay loam	142	2–7%	Field
K15	Cheongju	36°37′	127°25′	1123	61	14.56	22.63	25.33	0.34	Sandy loam	53	2–7%	Rice paddy
K16	Geumsan	36°07′	127°29′	1205	64	15.82	22.46	20.71	0.33	Loam	150	30–60%	Grass
K17	Buyeo	36°15′	126°50′	1601.5	57	13.48	22.04	23.61	–	Silt loam	21	7–15%	Grass
K18	Yesan	36°44′	126°48′	1316.5	56	14.37	21.74	25.97	1.10	Loam	39	7–15%	Grass
K19	Chengyang	36°25′	126°46′	1271	44	16.65	21.76	28.52	1.09	Silt loam	102	2–7%	Rice paddy
K20	Hongseong	36°35′	126°38′	1365.5	60	48.58	21.52	30.95	1.63	Sandy clay loam	49	2–7%	Field
K21	Muju	36°00′	127°40′	742.5	53	0.13	23.05	25.01	0.93	Loam	204	7–15%	Field
K22	Wanju	35°59′	127°13′	–	–	11.36	22.69	23.64	0.48	Sandy loam	53	0–2%	Rice paddy
K23	Jangseong	35°19′	126°48′	768.5	56	11.58	22.49	22.81	1.96	Loam	66	2–7%	Field
K24	Jindo	34°30′	126°17′	704.5	41	4.61	22.55	26.05	1.74	Loam	25	2–7%	Rice paddy
K25	Hampyeong	35°03′	126°32′	730	43	0.17	22.61	23.91	1.33	Loam	30	7–15%	Grass
K26	Sejong	36°34′	127°17′	1268	65	5.38	22.69	24.65	1.32	Sandy loam	26	0–2%	Rice paddy
K27	Cheongwon	36°35′	127°30′	1364	64	–	22.33	26.68	1.16	Fine sandy loam	57	0–2%	Rice paddy
K28	Goheung	34°36′	127°17′	1149	40	0.39	23.09	25.60	1.35	Loam	45	2–7%	Field
K29	Gokseong	35°16′	127°17′	919	55	0.23	23.48	25.97	1.30	Loam	76	2–7%	Field
K30	Gurye	35°11′	127°27′	1328	62	10.20	22.93	24.84	0.89	Sandy loam	34	2–7%	Rice paddy
K31	Yeongam	35°19′	126°48′	870.5	51	11.65	22.78	25.86	1.89	Loam	66	0–2%	Rice paddy

$$\mathrm{SDRD}_i = \sqrt{\frac{1}{N_t - 1}\sum_{t=1}^{N_t}(\mathrm{RD}_{i,t} - \mathrm{MRD}_i)^2} \tag{3}$$

Eqs. (2) and (3) are used to identify the most temporally stable sites. The temporal stability analysis is used to investigate the representative points of the temporal behavior of the whole area. This concept characterizes time invariant connection between spatial location and statistical parametric values (Jacobs et al., 2004; Vanderlinden et al., 2012; Martínez et al., 2013a).

The mean relative difference at a sample site signifies the location's bias and checks whether location is drier or wetter than the average of the area for *t* days. The SDRD_i indicates the location's degree of temporal stability. Therefore, if the MRD_i is close to zero and SDRD_i is relatively low, this is "representative" location of the temporal pattern of the study area (Jacobs et al., 2004; Cosh et al., 2004; Starks et al., 2006; Choi and Jacobs, 2007, 2011; Brocca et al., 2009, 2010, 2012; Heathman et al., 2009, 2012; Sur et al., 2013; Zhang and Shao, 2013).

The root mean square error (RMSE_i) of the relative difference includes both MRD_i and SDRD_i (Jacobs et al., 2004; Choi and Jacobs, 2007; Martínez et al., 2013b). Zhao et al. (2010) and Penna et al. (2013) addressed this concept as the index of temporal stability (ITS).

$$\mathrm{ITS} = \mathrm{RMSE}_i = \sqrt{\mathrm{MRD}_i^2 + \mathrm{SDRD}_i^2} \tag{4}$$

Here, we used the term ITS, instead of RMSE_i. ITS is a criterion to identify the representative locations. The location *i* with the lowest ITS will have the highest temporal stability.

To estimate spatial variability, we define the standard deviation of the relative differences at time *t* (SDRD_t):

$$\mathrm{SDRD}_t = \sqrt{\frac{1}{N_i - 1}\sum_{i=1}^{N_i}(\mathrm{RD}_{i,t} - \mathrm{MRD}_t)^2} \tag{5}$$

If the SDRD_t has the largest value at day *t*, one would estimate that there is a big variation between area-averaged soil moisture and soil moisture content for location *i*. The SDRD_t is an indicator to evaluate the spatial variability as it will increase with increasing spatial variability of soil moisture.

3.3. ANOVA test and data standardization

In this study, statistically dominant parameters are identified among the several physical or meteorological factors by conducting an analysis of variance, ANOVA test (Jacobs et al., 2010; Choi and Jacobs, 2011; Sur et al., 2013; Zhang and Shao, 2013). An ANOVA test is used to estimate differences among more than two groups of data. We performed a one-way ANOVA test to identify whether significant differences of temporal stability values exist among groups. These groups were divided into three or four groups by the degree of successive data (precipitation, insolation, air temperature, ground temperature, wind speed and elevation) and by the type of categorical data (soil texture, topography and land use).

We used a standardization method to rescale the data of meteorological factors and to identify relationships each other. Data standardization is well known for rescaling data. When using standardization, we made an assumption that the data have been generated with a Gaussian law (with a certain mean and standard deviation). The standardized variable of a raw variable *x* was calculated as:

$$x_{\mathrm{standardized}} = \frac{x - \mu}{\sigma} \tag{6}$$

where μ is the mean, σ is the standard deviation of data. To obtain the gradient of the mean soil moisture change versus the meteorological factors change, we calculate daily change amount (Δx_t):

$$\Delta x_t = x_t - x_{t-1} \tag{7}$$

where x_t is the value of variable at time t and x_{t-1} is the value of variable at time $t - 1$.

4. Results and discussions

4.1. Statistical distributions and descriptives

The K–S tests for the study period were performed to validate the statistical distribution of soil moisture measurements. The results showed that all distributions (normal, log-normal and GEV) were appropriate for the datasets. The acceptance of all distributions indicated that the soil moisture measurements have statistical distributions across the whole study area. Several previous studies support this result that it is more likely that soil moisture follows a normal distribution as the extent of study area increases (Martínez-Fernández and Ceballos, 2005; Ryu and Famiglietti, 2006; Brocca et al., 2010; Choi and Jacobs, 2011). We evaluated a goodness of fit test for comparing between distributions of the soil moisture dataset and normal, log-normal and generalized extreme value (GEV) distributions. Ground soil moisture distribution which based on the 31 measurement sites was best fitted with GEV distribution for 101 days, followed by log-normal (29 days) and normal (22 days) distributions during the study period (152 days). These results signified that the soil moisture measurements had a skewed distribution with frequent extreme value, because the summer monsoon rainfall patterns had wide variations between regions during June and July (Kim et al., 2002). Rainfall occurred through the entire study period, but was more frequent during June and July. Temporal variation of mean soil moisture value showed an increasing pattern after a rainfall event which gradually decreased up to the next rainfall event.

Fig. 2a shows the standard deviation of soil moisture content versus its mean value, for each day. The relationship showed an upper convex shape in the Korean peninsula area. It indicates an increase in the standard deviation or absolute variability, with increasing mean soil moisture content up to 35% moisture content. On the other hand, soil moisture variability showed a negative relationship at wetter conditions (greater than 35%). This result corresponds with previous findings (Famiglietti et al., 1998, 2008; Choi and Jacobs, 2007; Ryu and Famiglietti, 2005; Rosenbaum et al., 2012; Sur et al., 2013). Famiglietti et al. (2008) showed an increasing standard deviation with increasing scale extent. The relationship between CV and mean soil moisture content is shown in Fig. 2b. The coefficient of variation showed a negative relationship with mean soil moisture content. It is consistent with the previous studies by Owe et al. (1982), Brocca et al. (2007), Choi and Jacobs (2007), Choi et al. (2007), Famiglietti et al. (2008) and Choi and Jacobs (2011). Famiglietti et al. (2008) have mentioned that a distinct increase in the CV with increasing from 2.5 m to 50 km scale. Although this study scale is larger than 50-km scale, CV values did not exceed 0.4 in contrast to previous results (Famiglietti et al., 2008). These low CV values can be explained with relatively high mean soil moisture content caused by frequent rainfall events during the study period.

Fig. 2c shows changes in skewness with the mean soil moisture content on a regional scale. Skewness can distinguish normal and non-normal distributions according to positive/negative skew or near zero. Our data indicated that skewness commonly decreases

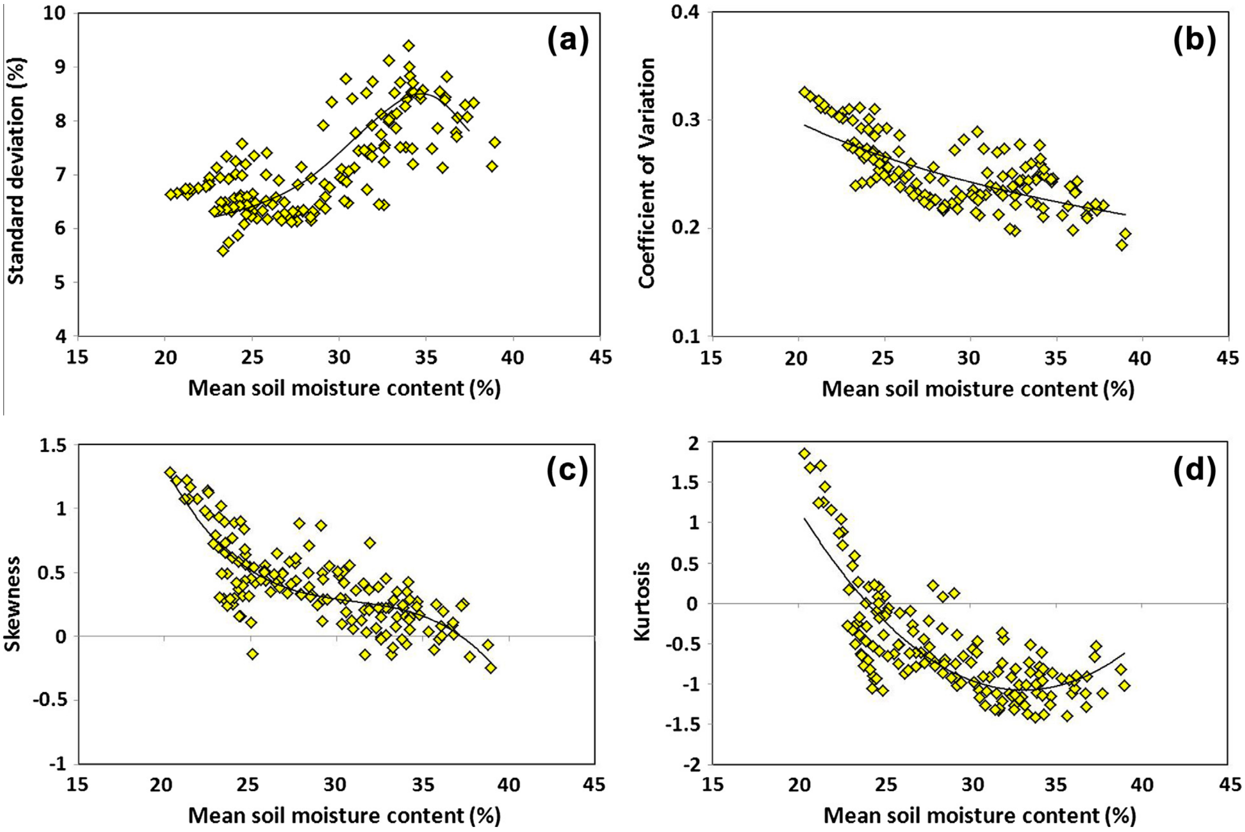

Fig. 2. Soil moisture (a) standard deviation, (b) coefficient of variation (CV), (c) skewness and (d) kurtosis versus mean soil moisture content over the Korean peninsula areas during from May 1 to September 29 in 2011.

with increasing mean soil moisture content. It was obtained that soil moisture data had positively skewed/non-normal distributions in drier conditions, normal distributions in somewhat higher moisture conditions (32–36%), and negatively skewed/non-normal distributions under the wettest conditions (higher than 36%). Fig. 2c shows that positively skewed values are 91% of the total days, in contrast with the previous results (Famiglietti et al., 1999). This is because in the monsoon season more than 10 mm rainfall events occur for about 50 days over the whole area. Fig. 2d confirms the certain relationship between kurtosis and mean soil moisture content. This relationship has a U-shaped that kurtosis rapidly decreases with increasing soil moisture content under the relatively dry conditions, but its value increases when the soil moisture content goes beyond 33%. This result corresponded with the previous study that the sign and size of the kurtosis values are agreed with the observed soil moisture content distributions (Famiglietti et al., 1999). If kurtosis values are near zero, we can predict that this moisture content is a shape of the normal distribution, and if kurtosis values are low/high, it might be implied to a shape of the non-normal distribution.

4.2. Temporal stability of soil moisture

Selecting stable sampling points provides an efficient substitute for random data of many points if a region has temporally stable characteristics (Jacobs et al., 2004). To select a representative point of the mean soil moisture value, we perform an analysis of temporal stability (Vachaud et al., 1985). Fig. 3 shows the results of the relative difference analysis conducted in the study areas. The mean relative differences for 31 locations ranked from smallest to largest with standard deviations (vertical bar) and root mean square errors. The group of locations below the zero relative difference values underestimated the average soil moisture content while locations having positive values overestimate the average values.

Mean relative difference (MRD_i) ranged from – 34% (K22) to 43% (K19). The standard deviation of relative difference (SDRD) and index of time stability (ITS) ranged from 5.34% (K18) to 24% (K19) and 10% (K23) to 49.7% (K19). Grayson and Western (1998) suggested a simple method to select representative locations where the mean relative difference is close to zero. Jacobs et al. (2004) identified the best sampling points for considering both the MRD_i and ITS. Martínez-Fernández and Ceballos (2005) selected a representative point by considering only the MRD_i even if the chosen point exhibited a large $SDRD_i$. Hu et al. (2010) introduced the mean absolute bias error (MABE). Brocca et al. (2009, 2010) carried out statistical analysis (i.e. R^2 and $RMSE_k$) for soil moisture contents of representative locations. Zhang and Shao (2013) compared four methods, minimal SDRD, ITS, MABE (mean absolute bias error) and RMSE for estimating mean soil moisture content of representative locations.

We selected five representative locations with MRD_i and ITS close to zero. The mean relative difference values close to zero followed by K25 (Hampyeong, −1.4%), K8 (Cheongsong, −3.3%), K11 (Gimhae, 4.0%), K5 (Pyeongchang, −4.2%) and K23 (Jangsung, 4.9%). The index of time stability (ITS) values close to zero followed by K23 (Jangsung, 10%), K8 (Cheongsong, 11.2%), K5 (Pyeongchang, 11.3%), K24 (Jindo, 13.3%) and K7 (Andong, 14.3%). Then 3 overlapped sites were selected by rank, K5, K8 and K23 locations. The comparison of the mean soil moisture content versus the in situ soil moisture content of the representative locations "K5", "K8" and "K23" are shown in Fig. 4. Time series of the average precipitation, mean soil moisture and these representative soil moisture

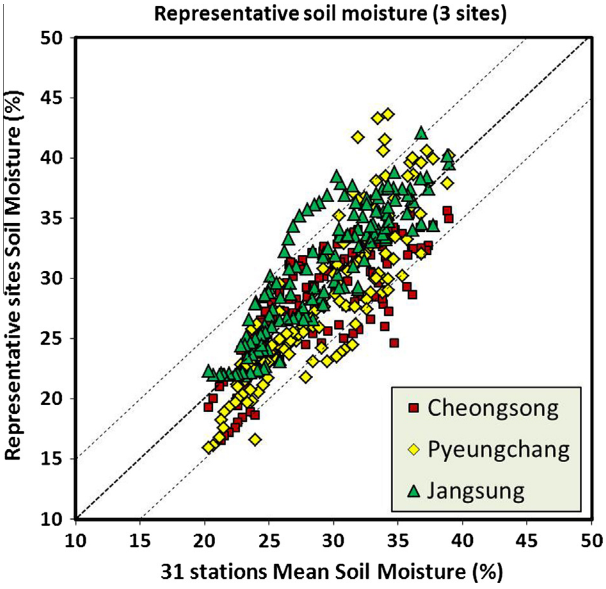

Fig. 4. Comparison of the mean soil moisture content versus the in situ soil moisture content of the representative locations for the study area.

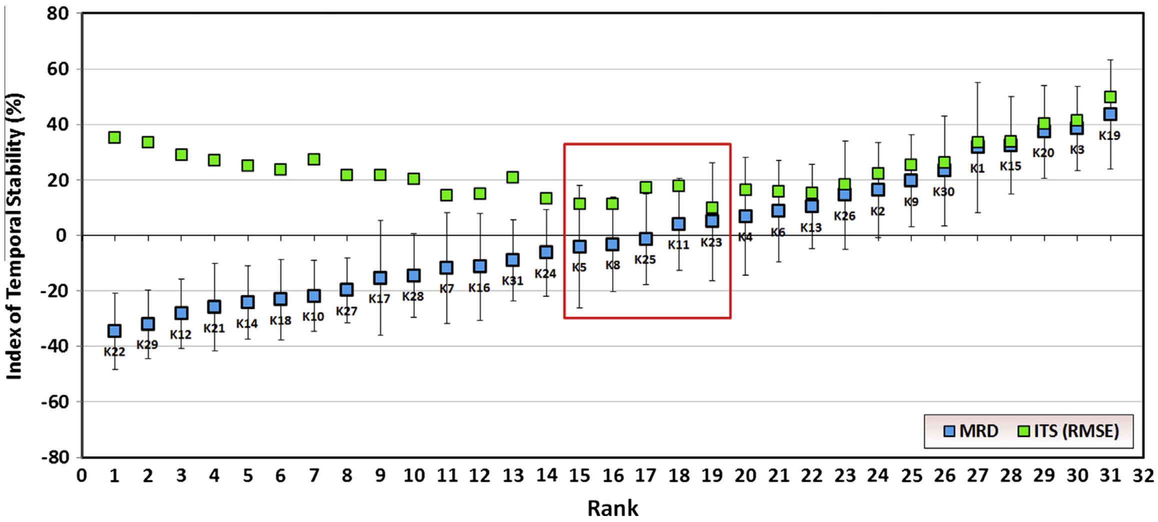

Fig. 3. Rank ordered mean relative difference (MRD) with standard deviation (vertical bars) and the index of time stability (ITS) for each sampling locations.

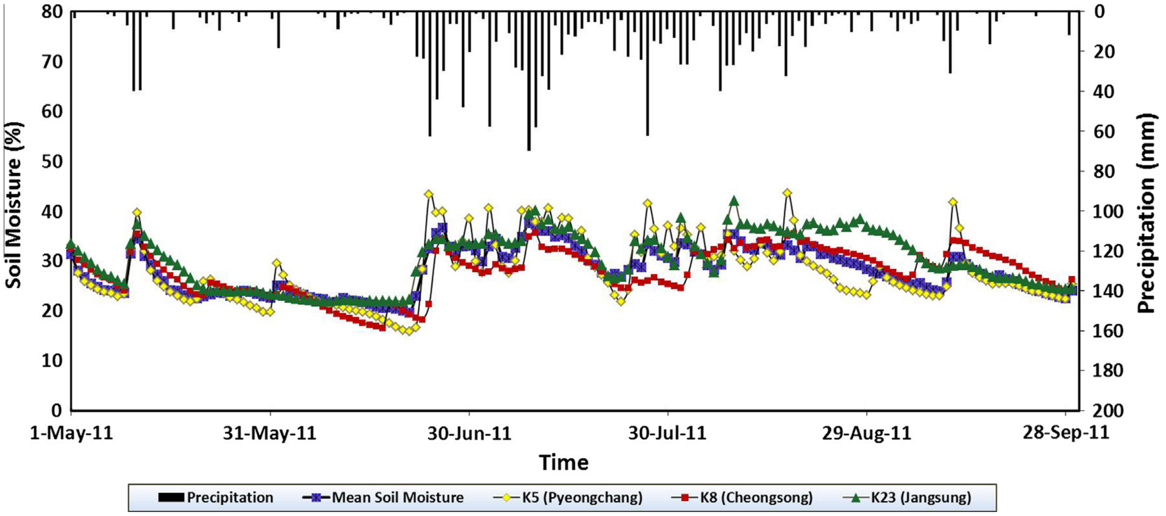

Fig. 5. Time series of the average precipitation, mean soil moisture and representative soil moisture contents (K5, K8 and K23).

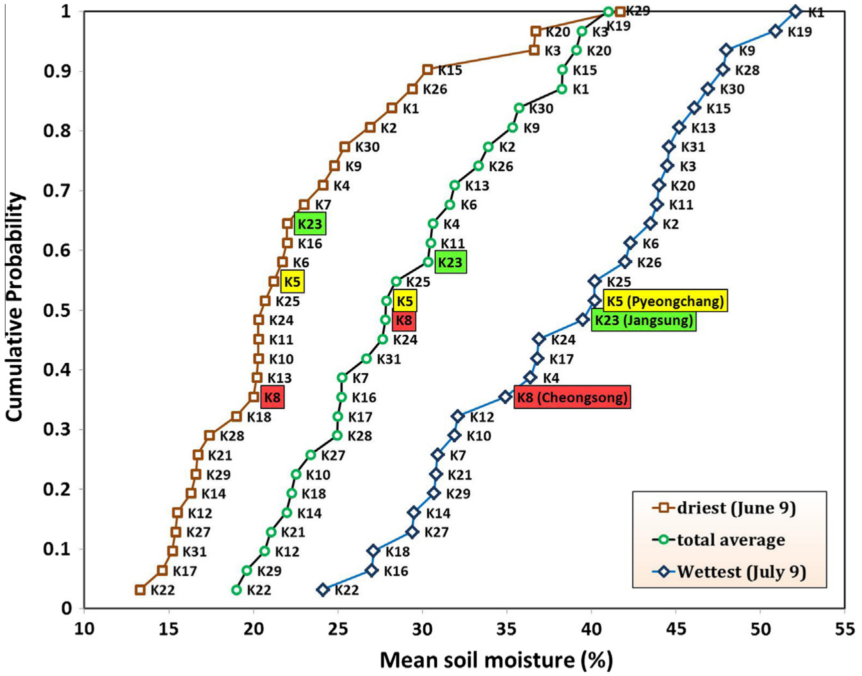

Fig. 6. Cumulative probability functions for driest, total average and wettest conditions for 31 locations with K5, K8 and K23 representing locations (colored). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

contents are shown in Fig. 5. The soil moisture values in Fig. 4 were within ±5% error of the soil moisture contents (90%). A percentage of data outside ±5% error range were about 9% for K8 (Cheongsong), 13% for K5 (Pyeongchang) and 9% for K23 (Jangsung) locations. Interestingly, the K8 location has several lower values than mean soil moisture contents in wet conditions of mean values. On the contrary, mean soil moisture values for K5 ranged between 26% and 32% and for K3 locations ranged between 32% and 34% have some higher values than average soil moisture for whole areas. The obtained results were because of locational differences of soil moisture contents due to heavy rainfall events during the monsoon in the region (see Fig. 5).

Cumulative probability functions for driest, total average and wettest conditions for 31 locations during the study period are shown in Fig. 6. This graph displays the change in cumulative probability of locations in three different soil conditions (Starks et al., 2006; Brocca et al., 2009; Heathman et al., 2012). We can measure the degree of temporal stability in each location (cumulative probability = 0.5). Observation of the plots suggested that different ranges of soil moisture conditions resulted in a very dynamic set of soil moisture at the 10 cm depth within the study period. Soil moisture values ranged from 13.3% to 41.7% at driest condition, 19% to 41% in total average and 24.1% to 52.1% at wettest condition. K5 (Pyeongchang) maintained ranking among three representative locations. This location had a temporal stability in dry and wet conditions. However, K8 (Cheongsong) and K23 (Jangsung) relatively changed the cumulative probability depending on the soil conditions. K8 (Cheongsong) moved down four positions from its total average ranking, on the other hand, K23 (Jangsung) moved up two positions under driest conditions and down three positions

Table 2
ANOVA test for the mean relative difference of soil moisture.

Components	F-value	p-Value
Meteorological factors		
Precipitation	4.054	0.028*
Insolation	0.475	0.627 (NS)
Air temperature	0.660	0.525 (NS)
Ground temperature	0.325	0.725 (NS)
Wind speed	0.199	0.896 (NS)
Physical factors		
Percentage of silt	0.034	0.966 (NS)
Percentage of sand	0.384	0.685 (NS)
Percentage of clay	0.879	0.510 (NS)
Elevation	0.390	0.905 (NS)
Slope	0.939	0.403 (NS)
Land use	0.731	0.490 (NS)

NS indicates non-significant difference at the 0.05 probability level.
* Indicates significance at the 0.05 probability level.

under wettest conditions. This result indicated that temporal stability of soil moisture contents may be determined by dry/wet soil conditions during sampling period (Martínez-Fernández and Ceballos, 2003; Brocca et al., 2009; Gao et al., 2011; Heathman et al., 2012). Additionally, one thing to remember is that length of the research period and climate conditions of study area influence on the evaluation of temporal variability of soil moisture. Martínez-Fernández and Ceballos (2003) showed greater temporal stability under dry conditions. On the other hand, greater temporal stability was found under wet conditions (Martínez et al., 2013b). This inconsistency could be caused by the homogeneity/heterogeneity in soil texture or climate conditions (Martínez et al., 2013b). Therefore, application improvement of these results obtained under growing season will require further study under the other region and season/climate conditions.

4.3. Meteorological factors affecting the spatio-temporal variability

Seneviratne et al. (2010) mentioned the important scale issues of soil moisture variability which can be represented by different factors according to spatial scale. Several previous studies also showed that local scale was dominated by physical factors such as soil, vegetation and topography characteristics (Brocca et al., 2007; Jacobs et al., 2010; Choi and Jacobs, 2011; Sur et al., 2013) and a regional scale was dominated by meteorological forcing, such as precipitation, temperature and evapotranspiration (Entin et al., 2000; Seneviratne et al., 2010).

By considering these points, we conducted an ANOVA statistical tests to look for dominant factors among the relationships between the mean relative difference of soil moisture and meteorological (precipitation, insolation, air temperature, ground temperature and wind speed) or physical factors (soil texture, elevation, topography and land use). Interestingly, Table 2 shows the result for the ANOVA test that only p-value of precipitation was within the significance level, the other factors do not satisfy the 0.05 significance level. This may imply that precipitation has great effect on temporal stability characteristic of surface soil moisture under wet condi-

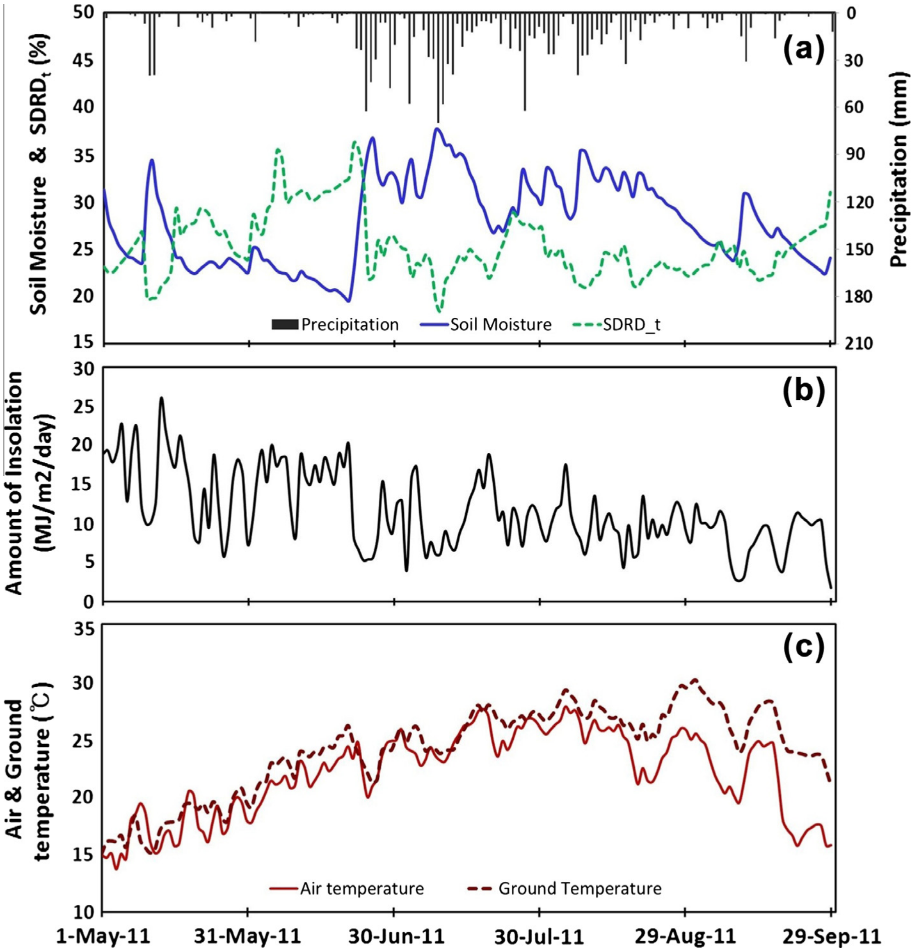

Fig. 7. Time series of the (a) precipitation, mean soil moisture, SDRD$_t$, (b) amount of insolation and (c) air and ground temperature for 31 locations.

tions and the other components are elusive because these exert a soil moisture conditions by introducing, transporting or removing moisture into/from the soil simultaneously (Famiglietti et al., 2008).

Fig. 7 shows the relationship of the precipitation, mean soil moisture, $SDRD_t$, amount of insolation and air (ground) temperature for 31 locations. Gradient between the mean precipitation change and mean soil moisture change indicated the positive relationship at 31 RDA sites in Fig. 8a. It means that the soil moisture increases after precipitation events and decreases before the next rainfall events. Figs. 7a and 9a indicate that $SDRD_t$ has an obvious relationship (inverse) with mean soil moisture content as well as daily average precipitations. This result was supported by Kim and Barros (2002) that spatial variability of surface soil moisture was dominantly controlled by precipitation patterns under wet conditions. We investigated the effect of the meteorological factors through relationships between mean soil moisture contents and insolation and (air and ground) temperature as well as precipitation to identify spatio-temporal patterns during the experimental period in Korean peninsula. Entin et al. (2000) found that the atmosphere spatial scale for study areas (Russia, Mongolia, China) is about 500 km.

Insolation is a measurement value of solar radiation energy. Although amount of insolation was fluctuating sharply with time, the relationship of insolation with soil moisture displayed a general inverse tendency in Fig. 7b. Thus, we can clearly identify the negative relationship in the amount of insolation change and mean soil moisture change though Fig. 8b. This is because insolation is a direct cause of the evaporation on the surface in shallow depth of soil.

Time series of mean soil moisture and air (ground) temperature follow an inverse relationship, soil moisture decreases as temperature increases in Fig. 7c (Lakshmi et al., 2003; Giraldo et al., 2009). Lakshmi et al. (2003) mentioned that the temporal

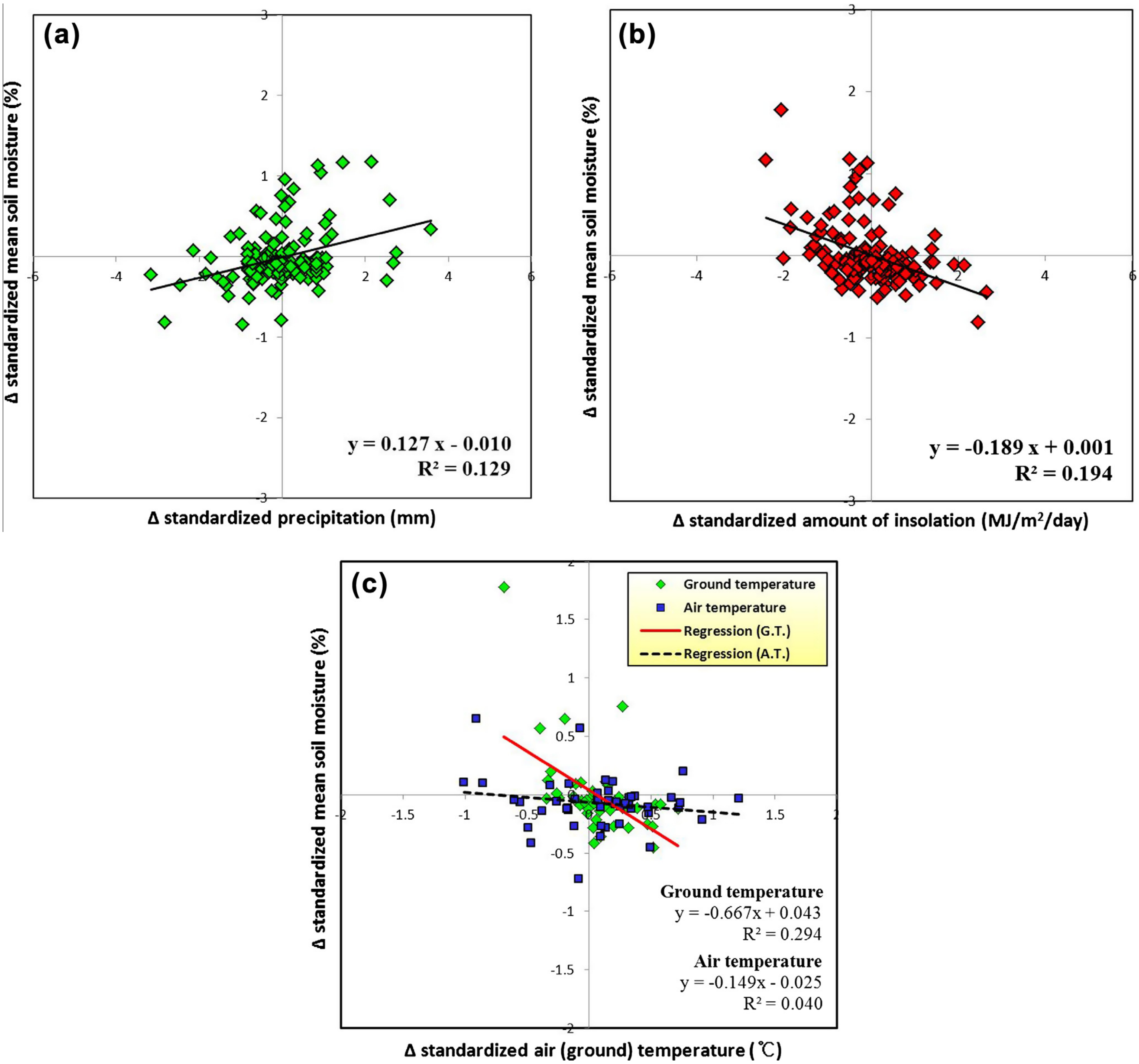

Fig. 8. Relationship between the mean soil moisture change and (a) precipitation change, (b) amount of insolation change and (c) air and ground temperature change.

evolution of soil moisture and temperature had the inverse relationship with all land-cover types. Fig. 8c also shows the negative relationship of mean soil moisture change with air (ground) temperature change, the gradient of the ground temperature showed slightly higher slope than the gradient of air temperature. It is clear that the soil moisture change is more sensitive to the ground temperature than air temperature. Fig. 9b and c show the relationships between SDRD$_t$ and (b) insolation and (c) air and ground temperature. The SDRD$_t$ implied how much variation or dispersion from the mean relative differences over the whole area per each day. The amount of insolation was positively connected with the spatial variability characteristics. Air and ground temperature also had a positive relationship with SDRD$_t$. It shows that SDRD$_t$ exhibits an increasing pattern with increase in the spatial variability during only a part of the whole study period (May 1 through June 21). This period is prior to the beginning of a heavy rainfall in 2011.

Fig. 10 shows the correlation coefficient between meteorological factors and time lag of soil moisture and SDRD$_t$. Fig. 10a presents a best correlation value of −0.79 (no lag), −0.70 (no lag), −0.53 (1 day lag) and 0.68 (1 day lag) for ground temperature, air temperature, insolation and precipitation. These results indicate that there is an immediate correlation with soil moisture, while with precipitation and insolation, there is about 1 day delay to reach the maximum *R*. The *R* values of precipitation and insolation gently decrease after reach maxima (1 day lag) while the *R* values of air (ground) temperature rapid decrease after maxima (no lag). This means that precipitation and insolation influence on soil moisture dynamics longer than air (ground) temperature, though the *R* values of precipitation and insolation are higher than air (ground) temperature.

Fig. 10b shows that the correlation of SDRD$_t$ displays reverse patterns compared with the correlation of soil moisture (Fig. 10a). The best correlation values are obtained with ground temperature (0.87, 1 day lag), air temperature (0.79, 1 day lag), precipitation (−0.40, 1 day lag) and insolation (0.50, 3 days lag). These values are higher than the values between soil moisture and these factors, besides it remained for about 4 days delay, respectively. Therefore, we realized that soil moisture and its spatial variability significantly correlated with ground temperature, followed by air temperature, insolation and precipitation and each

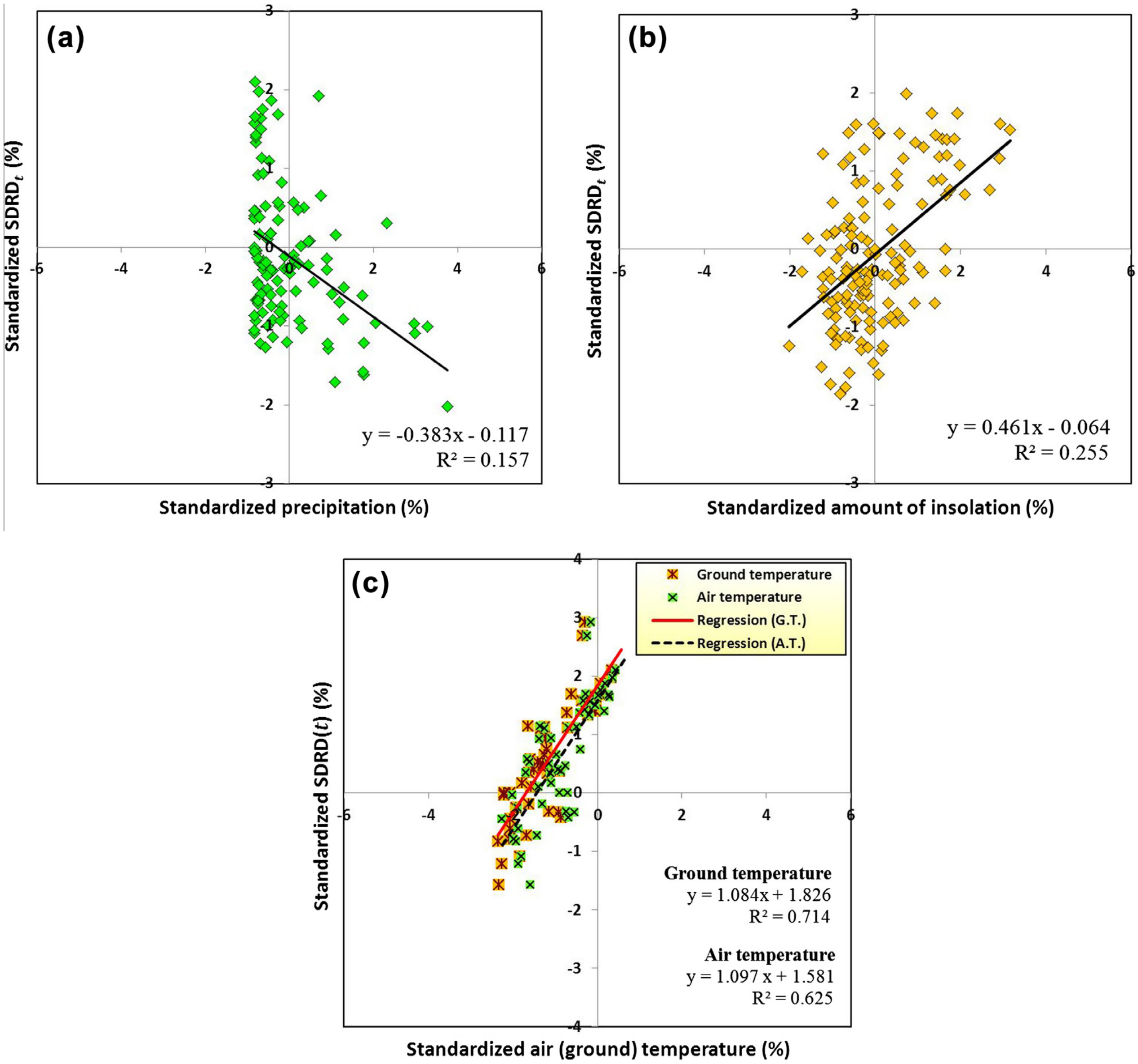

Fig. 9. Gradients of the SDRD$_t$ versus (a) precipitation, (b) amount of insolation and (c) air and ground temperature.

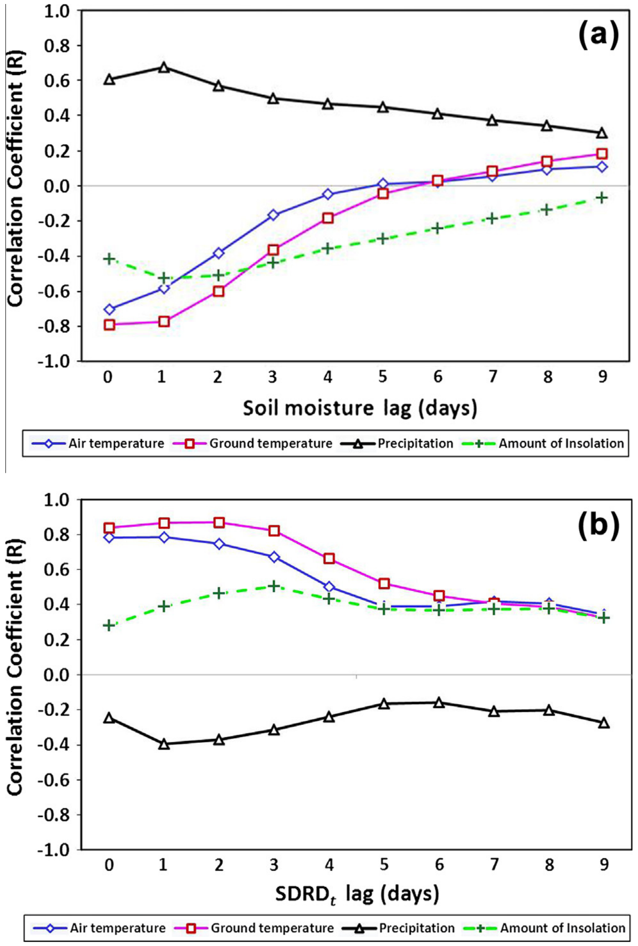

Fig. 10. Correlation coefficient between the meteorological factors and (a) time lag of soil moisture and (b) time lag of the SDRD$_t$.

of these factors has certain duration of effect on spatial variability of soil moisture in regional scale (Entin et al., 2000; Seneviratne et al., 2010). To obtain a more detailed result, further studies are needed to examine the correlation classified seasonal types and climate regimes (Martínez et al., 2013a).

5. Summary and conclusions

This study focused on the analysis of the spatio-temporal variability of soil moisture data collected at 31 locations over the Korean peninsula. The following results can be summarized:

(1) The results of the K–S test showed that all distributions were appropriate for the datasets and GEV distribution was most acceptable through a goodness of fit test among three distributions (normal, log-normal and GEV). It may result from the disparity in soil moisture values between measurement sites because of the frequent extreme values under the summer monsoon rainfalls. Soil moisture variations showed that the standard deviation–mean moisture content relationship displays an upper convex shape, the coefficient of variation (CV) with mean moisture content has a negative relationship and CV values did not exceed 0.4 though this study at a scale larger than 50 km in contrast to previous results (Famiglietti et al., 2008). It can be explained that the mean soil moisture content, the denominator of CV, is higher because of the monsoon season during the study period, relatively. Skewness also decreases with increasing mean moisture content while kurtosis with increasing mean soil moisture content exhibited the U-shaped relationship, which was suggested by Famiglietti et al. (1999).

(2) At regional scale (300 km), temporally stable three locations (K5, K8 and K23) selected by mean relative difference (MRD$_i$) and index of time stability (ITS) can be used to estimate 90% data of mean soil moisture contents within ±5% error. K5 is the most representative location among these selected locations in the cumulative frequency function on the driest, total average and wettest conditions. The uncertainty of the results may be due to the regional heavy rainfalls sporadically at several days during the study period.

(3) The result of the ANOVA test conducted to investigate the factors affecting temporal stability of soil moisture indicated that only p-value of precipitation (meteorological factor) was within significance level. The standard deviations of relative differences (SDRD$_t$) signifying spatial variability characteristics showed the positive relationship with average precipitation, and negative relationship with insolation, air temperature and ground temperature. The soil moisture spatial variation is more sensitive to the ground temperature change than air temperature changes. Each of the meteorological factors has certain duration of effect on spatial variability of soil moisture. These results provide insight to design the soil moisture monitoring network at the regional scale.

The agreement with previous studies may be applicable to regions with similar weather, land surface and topographic features. Although the results of this work are limited in terms of the short period and specific area, it is enough to show the insight of understanding the soil moisture dynamics at a regional scale and the relationship between meteorological factors (precipitation, insolation, air temperature, and ground temperature). Results can be utilized to better validate remotely sensed soil moisture and to select in situ measurement sites on considering priority of dominant factors first according to the extent of spatial scale. Therefore, further study will be required to assess the applicability of different climate zone, meteorological and physical conditions across spatial or temporal scales.

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References

Bolten, J.D., Crow, W.T., Zhan, X., Jackson, T.J., Reynolds, C.A., 2010. Evaluating the utility of remotely sensed soil moisture retrievals for operational agricultural drought monitoring. IEEE J. Selct. Top. Appl. Earth Observ. Remote Sens. 3 (1), 57–66, doi: http://dx.doi.org/10.1109/JSTARS.2009.2037163.

Bosch, D.D., Lakshmi, V., Jackson, T.J., Choi, M., Jacobs, J.M., 2006. Large scale measurements of soil moisture for validation of remotely sensed data: georgia soil moisture experiment of 2003. J. Hydrol. 323, 120–137. http://dx.doi.org/10.1016/j.jhydrol.2005.08.024.

Brocca, L., Morbidelli, R., Melone, F., Moramarco, T., 2007. Soil moisture spatial variability in experimental areas of Central Italy. J. Hydrol. 333, 356–373. http://dx.doi.org/10.1016/j.jhydrol.2006.09.004.

Brocca, L., Melone, F., Moramarco, T., Morbidelli, R., 2009. Soil moisture temporal stability over experimental areas in Central Italy. Geoderma 148, 364–374. http://dx.doi.org/10.1016/j.geoderma.2008.11.004.

Brocca, L., Melone, F., Moramarco, T., Morbidelli, R., 2010. Spatial–temporal variability of soil moisture and its estimation across scales. Water Resour. Res. 46, W02516. http://dx.doi.org/10.1029/2009WR008016.

Brocca, L., Tullo, T., Melone, T., Moramarco, T., Morbidelli, R., 2012. Catchment scale soil moisture spatial–temporal variability. J. Hydrol. 422-423, 63–75. http://dx.doi.org/10.1016/j.jhydrol.2011.12.039.

Campbell Scientific, Inc., 1996. Instruction Manual: CS615 Water Content Reflectometers. Revision: 10/96. Campbell Scientific, Inc., Logan, Utah.

Campbell Scientific, Inc., 2012. Instruction Manual: CS616 and CS625 Water Content Reflectometers. Revision: 10/12. Campbell Scientific, Inc., Logan, Utah.

Chen, T.-C., Wang, S.-Y., Huang, W.-R., Yen, M.-C., 2004. Variation of the East Asian summer monsoon rainfall. J. Clim. 17 (4), 744–762.

Choi, M., Hur, Y., 2012. A microwave-optical/infrared disaggregation for improving spatial representation of soil moisture using AMSR-E and MODIS products. Remote Sens. Environ. 124, 259–269. http://dx.doi.org/10.1016/j.rse.2012.05.009.

Choi, M., Jacobs, J.M., 2007. Soil moisture variability of root zone profiles within SMEX02 remote sensing footprints. Adv. Water Resour. 30 (4), 883–896. http://dx.doi.org/10.1016/j.advwatres.2006.07.007.

Choi, M., Jacobs, J.M., 2011. Spatial soil moisture scaling structure during Soil Moisture Experiment 2005. Hydrol. Process. 25 (6), 926–932. http://dx.doi.org/10.1002/hyp.7877.

Choi, M., Jacobs, J.M., Cosh, M.H., 2007. Scaled spatial variability of soil moisture fields. Geophys. Res. Lett. 34, L01401. http://dx.doi.org/10.1029/2006GL028247.

Cosh, M.H., Jackson, T.J., Bindlish, R., Prueger, J.H., 2004. Watershed scale temporal and spatial stability of soil moisture and its role in validating satellite estimates. Remote Sens. Environ. 92, 427–435. http://dx.doi.org/10.1016/j.rse.2004.02.016.

Cosh, M.H., Jackson, T.J., Moran, S., Bindlish, R., 2008. Temporal persistence and stability of surface soil moisture in a semi-arid watershed. Remote Sens. Environ. 112, 304–313. http://dx.doi.org/10.1016/j.rse.2007.07.001.

Dai, A., Trenberth, K.E., Qian, T., 2004. A global dataset of Palmer Drought Severity Index for 1870–2002: relationship with soil moisture and effects of surface warming. J. Hydrometeorol. 5 (6), 1117–1130. http://dx.doi.org/10.1175/JHM-386.1.

Dirksen, C., Dasberg, S., 1993. Improved calibration of time domain reflectometry of soil water content measurements. Soil Sci. Soc. Am. J. 57, 660–667.

Dorigo, W.A., Xaver, A., Vreugdenhil, M., Gruber, A., Hegyiová, A., Sanchis-Dufau, A.D., Zamojski, D., Cordes, C., Wagner, W., Drusch, M., 2013. Global automated quality control of in situ soil moisture data from the international soil moisture network. Vadose Zone J. 12 (3). http://dx.doi.org/10.2136/vzj2012.0097.

Entekhabi, D., Rodriguez-Iturbe, I., Castelli, F., 1995. Mutual interaction of soil moisture state and atmospheric processes. J. Hydrol. 184 (1), 3–18.

Entin, J.K., Robock, A., Vinnikov, K.Y., Hollinger, S.E., Liu, S., Namkhai, A., 2000. Temporal and spatial scales of observed soil moisture variations in the extratropics. J. Geophys. Res. 105, 11865–11877.

Famiglietti, J.S., Wood, E.F., 1994. Multiscale modeling of spatially variable water and energy balance processes. Water Resour. Res. 30, 3061–3078. http://dx.doi.org/10.1029/94WR01498.

Famiglietti, J.S., Rudnicki, J.W., Rodell, M., 1998. Variability in surface moisture content along a hillslope transect: Rattlesnake Hill, Texas. J. Hydrol. 210, 259–281. http://dx.doi.org/10.1016/S0022-1694(98)00187-5.

Famiglietti, J.S., Devereaux, J.A., Laymon, C.A., Tsegaye, T., Houser, P.R., Jackson, T.J., Graham, S.T., Rodell, M., van Oevelen, P.J., 1999. Ground-based investigation of soil moisture variability within remote sensing footprints during the Southern Great Plains 1997 (SGP97) Hydrology Experiment. Water Resour. Res. 35, 1839–1851. http://dx.doi.org/10.1029/1999WR900047.

Famiglietti, J.S., Ryu, D., Berg, A.A., Rodell, M., Jackson, T.J., 2008. Field observations of soil moisture variability across scales. Water Resour. Res. 44, W01423. http://dx.doi.org/10.1029/2006WR005804.

Gao, X.D., Wu, P.T., Zhao, X.N., Shi, Y.G., Wang, J.W., 2011. Estimating spatial mean soil water contents of sloping jujube orchards using temporal stability. Agric. Water Manage. 102, 66–73. http://dx.doi.org/10.1016/j.agwat.2011.10.007.

Gao, X.D., Wu, P.T., Zhao, X.N., Wang, J.W., Shi, Y.G., Zhang, B.Q., Tian, L., Li, H.B., 2013. Estimation of spatial soil moisture averages in a large gully of the Loess Plateau of China through statistical and modeling solutions. J. Hydrol. 486, 466–478. http://dx.doi.org/10.1016/j.jhydrol.2013.02.026.

Giraldo, M.A., Bosch, D., Madden, M., Usery, L., Finn, M., 2009. Ground and surface temperature variability for remote sensing of soil moisture in a heterogeneous landscape. J. Hydrol. 368 (1–4), 214–223. http://dx.doi.org/10.1016/j.jhydrol.2009.02.010.

Grayson, R.B., Western, A.W., 1998. Towards areal estimation of soil water content from point measurements: time and space stability of mean response. J. Hydrol. 207, 68–82.

Heathman, G.C., Larose, M., Cosh, M.H., Bindlish, R., 2009. Surface and profile soil water spatio-temporal analysis during an excessive rainfall period in the Southern Great Plains, USA. Catena 78, 159–169. http://dx.doi.org/10.1016/j.catena.2009.04.002.

Heathman, G.C., Cosh, M.H., Merwade, V., Han, E., 2012. Multi-scale temporal stability analysis of surface and subsurface soil moisture within the Upper Cedar Creek Watershed, Indiana. Catena 95, 91–103. http://dx.doi.org/10.1016/j.catena.2012.03.008.

Hu, W., Shao, M.A., Han, F.P., Reichardt, K., Tan, J., 2010. Watershed scale temporal stability of soil water content. Geoderma 158, 181–198. http://dx.doi.org/10.1016/j.geoderma.2010.04.030.

Jackson, T.J., Cosh, M.H., Bindlish, R., Starks, P.J., Bosch, D.D., Seyfried, M., Goodrich, D.C., Moran, M.S., Du, J., 2010. Validation of advanced microwave scanning radiometer soil moisture products. IEEE Trans. Geosci. Remote Sens. 48 (12), 4256–4272.

Jacobs, J.M., Mohanty, B.P., En-Ching, H., Miller, D., 2004. SMEX02: field scale variability, time stability and similarity of soil moisture. Remote Sens. Environ. 92, 436–446. http://dx.doi.org/10.1016/j.rse.2004.02.017.

Jacobs, J.M., Hsu, E.C., Choi, M., 2010. Time stability and variability of electronically scanned thinned array radiometer soil moisture during Southern Great Plains hydrology experiments. Hydrol. Process. 24, 2807–2819. http://dx.doi.org/10.1002/hyp.7703.

Kim, G., Barros, A.P., 2002. Space-time characterization of soil moisture from passive microwave remotely sensed imagery and ancillary data. Remote Sens. Environ. 81, 393–403. http://dx.doi.org/10.1016/S0034-4257(02)00014-7.

Kim, B.-J., Kripalani, R.H., Oh, J.-H., Moon, S.-E., 2002. Summer monsoon rainfall patterns over South Korea and associated circulation features. Theor. Appl. Climatol. 72 (1–2), 65–74. http://dx.doi.org/10.1007/s007040200013.

Korea Meteorological Administration, 2006. In: Annual Climatological Report, 11-1360000-000016-10.

Koster, R.D., the GLACE Team, 2004. Regions of strong coupling between soil moisture and precipitation. Science 305, 1138–1140. http://dx.doi.org/10.1126/science.1100217.

Lakshmi, V., Jackson, T.J., Zehrfuhs, D., 2003. Soil moisture-temperature relationships: results from two field experiments. Hydrol. Process. 17 (15), 3041–3057.

Lee, Y., Kim, J., Hong, J., 2008. The simulation of water vapor and carbon dioxide fluxes over a rice paddy field by modified Soil-Plant-Atmosphere Model (mSPA). Asia-Pac. J. Atmos. Sci. 44 (1), 69–83.

Lee, C., Chang, K.-H., Cha, J.-W., Choi, Y.-J., 2011. Strategy for the meteorological and environmental airborne observations over the Korean Peninsula. Asia-Pac. J. Atmos. Sci. 47, 91–96. http://dx.doi.org/10.1007/s13143-012-0003-9.

Lilliefors, H.W., 1967. On the Kolmogorov–Smirnov test for normality with mean and variance unknown. J. Am. Stat. Assoc. 62 (318), 399–402. http://dx.doi.org/10.1080/01621459.1967.10482916.

Martínez, G., Pachepsky, Y.A., Vereecken, H., 2013a. Temporal stability of soil water content as affected by climate and soil hydraulic properties: a simulation study. Hydrol. Process. (in press). Doi: http://dx.doi.org/10.1002/hyp.9737.

Martínez, G., Pachepsky, Y.A., Vereecken, H., Hardelauf, H., Herbst, M., Vanderlinden, K., 2013b. Modeling local control effects on the temporal stability of soil water content. J. Hydrol. 481, 106–118.

Martínez-Fernández, J., Ceballos, A., 2003. Temporal stability of soil moisture in a large-field experiment in Spain. Soil Sci. Soc. Am. J. 67, 1647–1656.

Martínez-Fernández, J.M., Ceballos, A., 2005. Mean soil moisture estimation using temporal stability analysis. J. Hydrol. 312, 28–38. http://dx.doi.org/10.1016/j.jhydrol.2005.02.007.

Massey Jr, F.J., 1951. The Kolmogorov–Smirnov test for goodness of fit. J. Am. Stat. Assoc. 46 (253), 68–78. http://dx.doi.org/10.1080/01621459.1951.10500769.

Min, Y.-M., Kryjov, V.N., An, K.-H., Hameed, S.N., Sohn, S.-J., Lee, W.-J., Oh, J.-H., 2011. Evaluation of the weather generator CLIGEN with daily precipitation characteristics in Korea. Asia-Pac. J. Atmos. Sci. 47 (3), 255–263. http://dx.doi.org/10.1007/s13143-011-0014-y.

Mohanty, B.P., Skaggs, T.H., 2001. Spatio-temporal evolution and time-stable characteristics of soil moisture within remote sensing footprints with varying soil, slope and vegetation. Adv. Water Resour. 24, 1051–1067. http://dx.doi.org/10.1016/S0309-1708(01)00034-3.

Njoku, E.G., Entekhabi, D., 1996. Passive microwave remote sensing of soil moisture. J. Hydrol. 184, 101–129.

Owe, M., Jones, E.B., Schmugge, T.J., 1982. Soil moisture variation patterns observed in Hand County, South Dakota. Water Resour. Bull. 18, 949–954.

Pachepsky, Ya.A., Guber, A.K., Jacques, D., 2005. Temporal persistence in vertical distributions of soil moisture contents. Soil Sci. Soc. Am. J. 69, 347–352.

Penna, D., Brocca, L., Borga, M., Dalla Fontana, G., 2013. Soil moisture temporal stability at different depths on two alpine hillslopes during wet and dry periods. J. Hydrol. 477, 55–71. http://dx.doi.org/10.1016/j.jhydrol.2012.10.052.

Qian, W., Kang, H.-S., Lee, D.-K., 2002. Distribution of seasonal rainfall in the East Asian monsoon region. Theor. Appl. Climatol. 73, 151–168. http://dx.doi.org/10.1007/s00704-002-0679-3.

Robock, A., Schlosser, C.A., Vinnikov, K.Y., Speranskaya, N.A., Entin, J.K., Qiu, S., 1998. Evaluation of the AMIP soil moisture simulations. Global Planet. Change 19 (1–4), 181–208. http://dx.doi.org/10.1016/S0921-8181(98)00047-2.

Rodriguez-Iturbe, I., 2000. Ecohydrology: a hydrologic perspective of climate-soil-vegetation dynamics. Water Resour. Res. 36 (1), 3–9.

Rosenbaum, U., Bogena, H.R., Herbst, M., Huisman, J.A., Peterson, T.J., Weuthen, A., Western, A.W., Vereecken, H., 2012. Seasonal and event dynamics of spatial soil moisture patterns at the small catchment scale. Water Resour. Res. 48, W10544. http://dx.doi.org/10.1029/2011WR011518.

Ryu, D., Famiglietti, J.S., 2005. Characterization of footprint-scale surface soil moisture variability using Gaussian and beta distribution functions during the Southern Great Plains 1997 (SGP97) hydrology experiment. Water Resour. Res. 41 (W12433), 13. http://dx.doi.org/10.1029/2004WR003835.

Ryu, D., Famiglietti, J.S., 2006. Multi-scale spatial correlation and scaling behavior of surface soil moisture. Geophys. Res. Lett. 33, L08404. http://dx.doi.org/10.1029/2006GL025831.

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

Schnur, M., Xie, H., Wang, X., 2010. Estimating root zone soil moisture at distant sites using MODIS NDVI and EVI in a semi-arid region of Southwestern USA. Ecol. Inform. 5 (5), 400–409. http://dx.doi.org/10.1016/j.ecoinf.2010.05.001.

Seneviratne, S.I., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., Lehner, I., Orlowsky, B., Teuling, A.J., 2010. Investigating soil moisture–climate interactions in a changing climate: a review. Earth Sci. Rev. 99, 125–161. http://dx.doi.org/10.1016/j.earscirev.2010.02.004.

Starks, P.J., Heathman, G.C., Jackson, T.J., Cosh, M., 2006. Temporal stability of soil moisture profile. J. Hydrol. 342, 400–411. http://dx.doi.org/10.1016/j.jhydrol.2005.09.024.

Sur, C., Jung, Y., Choi, M., 2013. Temporal stability and variability of field scale soil moisture on mountainous hillslopes in Northeast Asia. Geoderma 207–208, 234–243. http://dx.doi.org/10.1016/j.geoderma.2013.05.007.

Tang, C., Piechota, T.C., 2009. Spatial and temporal soil moisture and drought variability in the upper Colorado river basin. J. Hydrol. 379 (1–2), 122–135. http://dx.doi.org/10.1016/j.jhydrol.2009.09.052.

Teuling, A.J., Hupet, F., Uijlenhoet, R., Troch, P.A., 2007. Climate variability effects on spatial soil moisture dynamics. Geophys. Res. Lett. 34 (6), L06406. http://dx.doi.org/10.1029/2006GL029080.

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

Vachaud, G.A., Passerat de Silans, A., Balabanis, P., Vauclin, M., 1985. Temporal stability of spatially measured soil water probability density function. Soil Sci. Soc. Am. J. 49, 822–828. http://dx.doi.org/10.2136/sssaj1985.03615995004900040006.

Vanderlinden, K., Vereecken, H., Hardelauf, H., Herbst, M., Martinez, G., Cosh, M., Pachepsky, Y., 2012. Temporal stability of soil water contents: a review of data and analyses. Vadose Zone J. 11 (4). http://dx.doi.org/10.2136/vzj2011.0178.

Vinnikov, K.Y., Robock, A., 1996. Scales of temporal and spatial variability of mid latitude soil moisture. J. Geophys. Res. 101, 7163–7174.

Vivoni, E.R., Gebremichael, M., Watts, C.J., Bindlish, R., Jackson, T.J., 2008. Comparison of ground-based and remotely-sensed surface soil moisture estimates over complex terrain during SMEX04. Remote Sens. Environ. 112, 314–325. http://dx.doi.org/10.1016/j.rse.2006.10.028.

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

Wang, X., Xie, H., Guan, H., Zhou, X., 2007. Different responses of MODIS-derived NDVI to root-zone soil moisture in semi-arid and humid regions. J. Hydrol. 340, 12–24. http://dx.doi.org/10.1016/j.jhydrol.2007.03.022.

Zhang, P., Shao, M., 2013. Temporal stability of surface soil moisture in a desert area of north western China. J. Hydrol 505, 91–101.

Zhao, Y., Peth, S., Wang, X.Y., Lin, H., Horn, R., 2010. Controls of surface soil moisture spatial patterns and their temporal stability in a semi-arid steppe. Hydrol. Process. 24 (18), 2507–2519. http://dx.doi.org/10.1002/hyp.