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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 (~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).