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Characterizing scale specific depth persistence of soil water content along two landscape transects

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SUMMARY

Information on depth persistence of soil water content (*SWC*) is useful for adopting data assimilation techniques in integrating remote sensing data and soil water modeling. The objective of this study was to investigate the scale- and season-specific depth persistence of 0–1.0 m *SWC* distribution in two transects (having different soils and plant cover) in a watershed on the Chinese Loess Plateau, by combining multivariate empirical mode decomposition (MEMD) with Spearman's rank correlation analysis. Three or four intrinsic mode functions (IMFs) representing specific scales were separated out for *SWC* of each soil layer. The dominant scales in terms of explaining the spatial variance of *SWC* for Transect 1 were about 376 m (IMF1) and 677 m (IMF2), and those for Transect 2 were about 639 m (IMF2) and 1304 m (IMF3). Depth persistence of *SWC* varied with scale, and was the strongest at the dominant scales. The multi-scale depth persistence was weaker along Transect 1 than along Transect 2 due to the higher degree of landscape fragmentation resulting from greater human activity along Transect 1. Weaker depth persistence at each scale was mainly observed at wet conditions for Transect 1. Strong season-related depth persistence was also mainly observed at the dominant scales for both transects. The results of this study are useful for developing sampling strategies for soil water measurements, since information about depth persistence reduces the efforts involved in measuring *SWC* in deeper layers.

1. Introduction

Soil water content (*SWC*) is a key determinant factor with which to characterize hydrological and biological processes (Heathman et al., 2003; She et al., 2010). Surface *SWC* data of the upper 5-cm soil layer are readily available through remote sensing techniques, especially over larger areas (Brocca et al., 2010). However, information about *SWC* in soil layers below the surface soil layers, i.e. the subsurface *SWC*, is often insufficient to understand hydrological processes (Heathman et al., 2003; She et al., 2014). Soil water content exhibits a great degree of spatio-temporal heterogeneity, which makes it expensive and time consuming to obtain sufficient and reliable subsurface *SWC* data by *in situ* measurement. Hence, there is an increasing interest in correlating the more readily-measured surface *SWC* to the soil water at depth based on *SWC* depth persistence at various soil depths (Heathman et al., 2003; Biswas and Si, 2011).

Similar to the description of time stability, depth persistence is defined as the persistence of the spatial pattern of soil water with depth, i.e. there is a high probability that the rank of the *SWC* at different locations does not change with depth (Vachaud et al., 1985; Biswas and Si, 2011). Various methods have been used to describe the depth persistence of the *SWC* spatial pattern, e.g., Spearman non-parametric test (Biswas and Si, 2011), parametric test of relative difference (She et al., 2014), and empirical orthogonal function analysis (Korres et al., 2010). Different factors and processes may operate at different scales and at different intensities, which makes the depth persistence of *SWC* highly scale-dependent. Identifying the scales and the similarities among these scales of *SWC* at different depths could lead to the development of a scale-specific relationship between the *SWC* of the surface and subsurface layers (Si, 2008; Biswas and Si, 2011).

Multi-scale analyses have employed various methods (Blöschl and Sivapalan, 1995; Kravchenko et al., 2000; Zeleke and Si, 2006; Si, 2008). For example, Biswas and Si (2011) used wavelet coherency analysis to examine the depth persistence of spatial

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patterns of soil water storage as a function of scale in a hummocky landscape. However, these methods follow the principle of superposition and assume that *SWC* and related processes are linear (She et al., 2013). In actuality the spatial patterns of *SWC* and the related processes may be both non-stationary and nonlinear (Hu and Si, 2014). The nonlinear characteristics of *SWC* distributions are more obvious on the Loess Plateau of China, where a patchwork or mosaic pattern of land uses, which results from the extensive destruction of the natural vegetation and long-term revegetation projects, cultivation, etc., characterizes the landscape (She et al., 2010; She and Shao, 2009). In order to reveal the multi-scale characteristics of such non-stationary and nonlinear processes, Hu and Si (2013) employed multivariate empirical mode decomposition (MEMD) to identify the scale-specific factors that control *SWC* on the Loess Plateau. The MEMD is a relatively recent development having been developed by Huang et al. (1998). In 2004, Flandrin and Goncalves attempted to lend some statistical weight to the method. Despite the demonstrable usefulness of the method, it has yet to be widely applied to resolve soil property scaling. The MEMD is well known for its ability to accommodate multiple spatial series simultaneously in the decomposition of data, and then to align "common scales" existing within the multiple spatial data series. Therefore, MEMD could identify common scales of *SWC* from multiple measurement depths. We assumed that it would also possible to reveal the scale-specific depth persistence of multi-depth *SWC* spatial patterns simultaneously by combining MEMD with Spearman's rank correlation analysis.

In the Loess Plateau landscape, although scale-specific control and time stability of *SWC* have been investigated, including at different depths (Hu and Si, 2013; She et al., 2014), there is limited information on whether the depth persistence of the spatial patterns on different measurement dates is scale- and season-dependent. Therefore, the purpose of this study was to investigate the scale- and season-specific depth persistence of *SWC* distribution along two transects having different soils and plant cover in a watershed on the Chinese Loess Plateau. Specific objectives were (i) to compare the dominant scale of variation of *SWC* between the two landscape transects and (ii) to determine the similarity of these scales at different depths within and between periods of water recharge and discharge occurring during the wet and dry seasons.

2. Materials and methods

2.1. Study site description

Experiments were conducted in the Liudaogou watershed, which is located on the northern Loess Plateau, China (110°21′–110°23′E and 38°46′–38°51′E), with a maximum elevation of 1256 m above sea level (Fig. 1). The watershed covers an area of 6.89 km^2. The area is characterized by a semiarid climate, with a mean annual rainfall of 437 mm, about 70% of which falls in intense storms between June and September. The mean annual temperature is 8.4 °C (the minimum temperature is −9.7 °C in January and the maximum is 23.7 °C in July). The annual potential evapotranspiration is 785.4 mm, with a desiccation degree of 1.8. More detailed information about the watershed can be found in She et al. (2010).

2.2. Experimental design

Two south–north transects passing through different landscape types on each side of the main gully of the Liudaogou watershed were selected (Fig. 1). Transects 1 and 2 were 3411 m and 3587 m long, respectively. The main differences between the two transects were the distributions of soil properties and land use cover. The dominant soil of Transect 1 is a loessal mein soil (Calcaric regosol), which has a textural class that is predominantly silt loam with some inclusions of sandy loam. In Transect 2, the dominant soil is an aeolian sand soil (Calcaric arenosol), which has a textural class that is predominantly sandy loam with some inclusions of sand. In addition, extensive destruction of natural vegetation and widespread re-vegetation projects has resulted in the establishment of a patchwork or mosaic pattern of land uses. Transect 1 was covered by three main land use types, i.e. grassland and forage, which together comprised 40% of the length of the transect, and shrubland (12%). Transect 2 was mainly covered by shrubland (31%) and forest (23%). Other land uses included cropland, man-made structures, orchards, and gullies. Land use cover changed more frequently (about every 50–100 m) along Transect 1 than along Transect 2 due to a greater degree of anthropogenic influence along Transect 1. The topography along the two transects was similar. Based on data from the sampling sites (see below), Transect 1 had a mean elevation of 1181 m (coefficient of variation, CV = 2.8%) and elevations ranged between 1126 and 1251 m; the mean slope gradient was 10.5° (CV = 68%) and slopes ranged from 0.5° to 23.3°. Transect 2 had a mean elevation of 1199 m (coefficient of variation, CV = 2.5%) and elevations ranged from 1124 to 1241 m; the mean slope gradient was 10.9° (CV = 36%) and slopes ranged from 0.5° to 18.7°. Both transects thus had a similar range of elevations and slope gradients, although the slope gradient along Transect 1 demonstrated greater variability. In Fig. 1, it can be seen that Transect 1 crosses slightly more major side channels than Transect 2, which likely contributes to this greater variability.

Sampling was carried at 27 sampling points at 131 m intervals along Transect 1 and at 30 sampling points at 124 m intervals along Transect 2. At each sampling point, disturbed soil samples were collected from the upper 1.0 m soil layer in 0.1 m increments on seven occasions between July 2007 and June 2008 for gravimetric *SWC* measurement. Each time, three sets of samples were removed from three different points at the sampling site. The three samples for a given layer were then mixed together to form a composite sample. The seven *SWC* datasets were designated as *SWC1*, *SWC2*, *SWC3*, *SWC4*, *SWC5*, *SWC6*, and *SWC7*, corresponding to the samples collected on July 3–4, August 3–4, September 9–10, and October 17–18 in 2007, and on April 16–17, May 17–18, and June 20–21 in 2008, respectively. Soil samples were collected within two days on each sampling occasion to reduce the *SWC* variability over time. In addition, undisturbed soil samples were collected from the 0 to 0.1 m layer at each site. These samples were used to determine the bulk density and the contents of soil organic matter, sand (>0.05 mm), silt (0.002–0.05 mm), and clay (<0.002 mm), which are given in Table 1 (She et al., 2013).

The beginning of the sampling period occurred in the first part of the rainy season following the end of the dry season, which was a period of soil water discharge. The rainy summer season resulted in soil water recharge until October 17, 2007 (*SWC4*), after which drier conditions returned resulting in soil water discharge conditions. Rainfall data from the Shenmu meteorological station showed that between January 1 and July 3, 2007, a total of 132 mm of rain fell in the study area. The amounts of rainfall between sampling dates were then: *SWC1* and *SWC2* (11 storms, total 61.1 mm); *SWC2* and *SWC3* (9 storms, total 95.8 mm); *SWC3* and *SWC4* (12 storms, total 130.1 mm); *SWC4* and *SWC5* (16 storms, total 53 mm); *SWC5* and *SWC6* (5 storms, total 22.8 mm); and *SWC6* and *SWC7* (7 storms all occurring in June, total 86 mm). The end of the dry season and a new period of water recharge can be taken as occurring close to the collection of the samples for *SWC6*. The temporal variations of the mean soil water content, calculated from the soil moisture content in the entire 0–1.0 m soil layer for each site within each of the two transects, as well as the corresponding daily rainfall, are shown in Fig. 2.