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Application of multivariate empirical mode decomposition for revealing scale-and season-specific time stability of soil water storage

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ABSTRACT

Spatial patterns of soil water storage (SWS), the total amount of water stored in soil at a given depth interval, tend to be similar if we measure at different times. This is characterized as time stability and can be used to optimize sampling design. The objective of this study was to examine the scale- and season-specific time stability of SWS spatial patterns at seven depth intervals (at every 20 cm down to 140 cm) in a hummocky landscape. Soil water content was measured 20 times using time domain reflectometry and a neutron probe along a transect of 128 points over a four-year period and converted to SWS by multiplying by the depth intervals. Multivariate empirical mode decomposition (MEMD) was used to decompose the spatial series of SWS into six or seven (depending on depth) components known as intrinsic mode functions (IMFs). Each IMF represents a specific scale of SWS. Spearman's rank correlation coefficients between IMFs from different measurement dates were used to characterize the time stability of SWS at different scales. The variance of each IMF and its ratio to the variance of the original SWS series was calculated. The dominant scale, which has the maximum ratio of variance to the original variances, was 104–128 m (IMF5) for the depth intervals of 0–20 cm to 60–80 cm and 315–412 m (IMF7) for the depth intervals of 80–100 cm to 120–140 cm. Time stability gradually increased with spatial scales and was the strongest at the dominant scale. At any scale, time stability was the strongest within the same season and the weakest between different seasons. This study indicates that MEMD combined with Spearman's rank correlation analysis has great potential for revealing the scale specific time stability of SWS.

1. Introduction

Soil water storage (SWS) plays a critical role in agriculture and hydrology (Moiwo et al., 2011; Western et al., 2004). In spite of strong spatio-temporal variability, repeated measurements indicate that the spatial patterns of SWS are time stable, i.e. the rank of the SWS at different locations does not change with time at a high probability (Brocca et al., 2010; Hu et al., 2009; Joshi et al., 2011; Martínez-Fernández and Ceballos, 2003; Vachaud et al., 1985). The concept of time stability can be used to simplify and optimize the measurement of SWS for monitoring and modeling (Gao et al., 2011; Martínez-Fernández and Ceballos, 2005).

Various methods have been used to examine the time stability of SWS spatial patterns. Spearman's rank correlation analysis is the most widely used method (Bosch et al., 2006; Gao and Shao, 2012; Heathman et al., 2012; Hu et al., 2010a; Jacobs et al., 2004; Schneider et al., 2008; Vachaud et al., 1985). Other methods such as regression analysis (Kachanoski and de Jong, 1988), Pearson correlation analysis (Cosh et al., 2004, 2006), and empirical orthogonal function analysis (Perry and Niemann, 2007) were also used. However, these methods can only be used to determine the time stability of SWS at the spatial scale from which measurements are taken.

Time stability of SWS is scale dependent as different factors and processes may operate at different scales and at different intensities. Spatial coherency analysis was used to examine the time stability of spatial patterns as a function of scale (Kachanoski and de Jong, 1988). However, this method is only applicable to stationary systems (Kachanoski et al., 1985; Si, 2008). More often than not, the spatial patterns of SWS are non-stationary. Biswas and Si (2011c) investigated the scale dependency of time stability of non-stationary SWS in a hummocky landscape using wavelet coherency analysis. This method assumes that the data originated from a linear system (Huang et al., 1998). However, the effect of different processes may not be additive and nor follow the principle of superposition (Biswas and Si, 2011b; Yan and Gao, 2007), therefore these processes are nonlinear.

The empirical mode decomposition (EMD) separates the data series into a finite and often small number of intrinsic mode functions (IMFs) at different spatial scales plus a residue (Huang et al., 1998). Unlike spatial coherency analysis and wavelet coherency analysis, EMD does not require any assumptions about the data and identifies scales inherent in the data (Huang and Wu, 2008). Therefore, it is suitable for analysis

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of non-stationary and nonlinear processes (Park et al., 2011; Shafqat et al., 2011).

Multivariate empirical mode decomposition (MEMD) has been developed from the EMD to accommodate multiple spatial series simultaneously in the decomposition (Rehman and Mandic, 2010). It can align "common scales" existing within multiple spatial series (equivalent to multivariate data) and helps to make use of similar scales (Rehman and Mandic, 2010). Recently, MEMD was used to reveal the dominant control of SWS in a Canadian prairie region and soil water content in the Chinese Loess Plateau (Hu and Si, 2013). Therefore, MEMD may provide a possibility to identify common scales of SWS from multiple measurement dates and then reveal the scale specific time stability of SWS spatial patterns along with the Spearman's rank correlation analysis.

In the hummocky landscape, scale specific time stability of SWS for the whole soil profile (0–140 cm) was identified using the wavelet coherency analysis (Biswas and Si, 2011c). However, it remains unclear whether the time stability of the spatial patterns for different depth intervals is scale- and season-dependent.

Therefore, this study aimed to investigate whether the time stability of the spatial patterns for different depth intervals is scale- and season-dependent using the MEMD and the Spearman's rank correlation analysis. Specifically, depth-wise time stability of SWS spatial patterns within a season (intra-season), between different seasons in the same year (inter-season), and between the same seasons of different years (inter-annual) was determined.

2. Materials and methods

2.1. Site description

This study was conducted at St. Denis National Wildlife Area (SDNWA) (52°12′ N, 106°50′ W), located about 40 km east of Saskatoon, Saskatchewan, Canada (Fig. 1). Mollisols (American System of Soil Classification) dominate this area (Acton and Ellis, 1978). The landscape is characterized by a sequence of slopes with varying sizes of rounded depressions and irregular to complex knolls and knobs (Yates et al., 2006) (Fig. 1). This area has a humid continental climate (Dfb) based on the Köppen–Geiger climate classification (Peel et al., 2007) with a mean annual air temperature of 2 °C and mean annual precipitation of 360 mm (90 year average). Detailed information about this site can be found in Biswas and Si (2011a, b, and c).

2.2. Data collection

A sampling transect of 576 m long (128 points at 4.5 m intervals) extending north–south was established in 2003 (Fig. 1; Yates et al., 2006). Plastic (Polyvinyl Chloride, PVC) tubes of 5 cm diameter and 200 cm long were installed at each sampling location. A CPN 501 DR Depth probe (CPN International Inc., Martinez, California, USA) was used to measure soil water content from 20 cm to 140 cm with a depth interval of 20 cm. The neutron probe was calibrated for the study site in 2007–2009 in different soil water conditions and at selected topographic locations, following the standard calibration procedure. The calibration equation was used to convert the neutron count to the soil water content. The average soil water content for the surface layer of 0–20 cm was measured using a vertically-installed time domain reflectometry probe and a metallic cable tester (model 1502B, Tektronix, Beaverton, OR, USA). A standard calibration equation following Topp and Reynolds (1998) was used to calculate the surface soil water content. Soil water storage at each depth interval was estimated by multiplying the thickness (20 cm) with volumetric soil water content calculated from the calibration relationships. Field soil water measurements were recorded for 20 dates from 17 July 2007 to 14 June 2010 under various environmental conditions.

2.3. MEMD theory

MEMD is the multivariate extension of EMD. EMD, a part of the Hilbert–Huang transform, has been used in geosciences to separate the overall variability in any measured spatial series into a limited number of IMFs with specific scales and a residue. The decomposition is based on the assumption that at any given location, different simple oscillatory modes or frequencies (presenting different scales of underlying soil processes) may superimpose one another (Huang et al., 1998; Rilling et al., 2007). For example, high frequency or small scales processes can operate simultaneously with low frequency or large scale processes

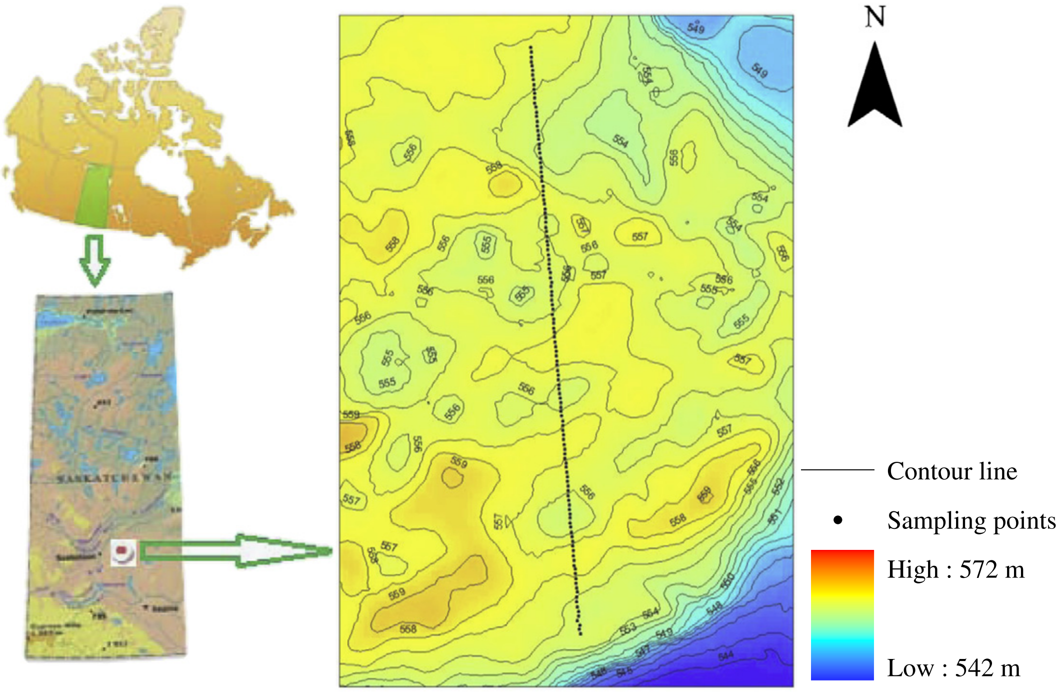

Fig. 1. Geographic location of study site and the transect position on a rolling landscape at St. Denis National Wildlife Area (SDNWA), Saskatchewan, Canada.