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Catchment-scale variability of absolute versus temporal anomaly soil moisture: Time-invariant part not always plays the leading role

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SUMMARY

Recently, the characterization of soil moisture spatiotemporal variability is recommended to consider temporal soil moisture anomalies because of their distinctive behaviors with absolute soil moisture and their importance in hydrological applications. Here we characterized soil moisture spatiotemporal variability in the Yuanzegou catchment (0.58 km^2) on the Loess Plateau of China, considering both absolute soil moisture and temporal anomalies. The dataset contained soil moisture observations in the 0–80 cm between 2009 and 2011 at 78 sampling locations. The spatial variance of time-invariant temporal means was shown to be the primary contributor (61.7–76.2%) to the total variance but the magnitude of this contribution was much lower than observed in large-scale studies. The seasonal variation in contribution can be attributed into differences in soil wetness conditions; lower contribution was found at intermediate wetness for spatial variances of temporal mean and temporal anomalies. Furthermore, the upward-convex relationship between spatial variance and spatial means of absolute soil moisture was mainly characterized by the covariance of temporal mean and temporal anomalies. Time stability of absolute soil moisture and its components were analyzed by using both the "accuracy" metric mean relative difference (MRD) and the "precision" metric variance of relative difference (VRD). As MRD was considered, time stability of absolute soil moisture primarily characterized time-invariant patterns. However, as VRD was used, the time stability of absolute soil moisture characterized only a small part of time-invariant or -variant pattern.

1. Introduction

Root zone soil moisture is a key variable in land-surface hydrology, ecology, and agriculture in arid and semiarid regions (Rodriguez-Iturbe et al., 1999). Consequently, the characterization of its spatial–temporal variability is vital for improving predictions of hydrological and ecological processes (Vereecken et al., 2014) and agricultural productivity (Champagne et al., 2012). At small scales (e.g., hillslope or small watershed scale), soil moisture variability is important for hydrologic connectivity, runoff generation, and precision management (Tetzlaff et al., 2014). In hydrological and meteorological applications, absolute soil moisture is often decomposed into the time-invariant temporal mean and the time-varying temporal anomalies (Arora and Boer, 2006; Meng and Quiring, 2010; Niu et al., 2015), and the latter is usually of greater interest because most of the informative content of soil moisture data relates to the dynamics of soil moisture rather than its absolute content (Brocca et al., 2014). In agriculture, soil moisture anomalies from normal conditions are also more useful than absolute moisture data for identifying droughts that may affect agricultural productivity (Champagne et al., 2012).

The spatial variability of soil moisture is usually described as a function of spatial means (Vereecken et al., 2007). When absolute soil moisture is considered, the upward-convex (Brocca et al., 2010, 2012; Famiglietti et al., 2008; Gao et al., 2011, 2013a; Sur et al., 2013) or monotonic increasing/decreasing (Brocca et al., 2007; Famiglietti et al., 1999; Martinez-Fernandez and Ceballos, 2003) relationship between spatial variance (standard deviation) and spatial means has been observed dependent on the duration of spatial period (Brocca et al., 2010) or the climate zone under consideration (Lawrence and Hornberger, 2007; Hu et al., 2011; Rötzer et al., 2015). Recently, Mittelbach and Seneviratne (2012)

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suggested that spatial variance of absolute soil moisture could be decomposed into spatial variance of temporal mean, that of temporal anomalies, and a covariance of temporal mean and temporal anomalies. The relationship between spatial variability and spatial means for temporal anomalies differs appreciably from that for absolute soil moisture. After analyzing data from a soil moisture network across Switzerland, Mittelbach and Seneviratne (2012) found relatively low spatial variance for temporal anomalies but relatively high spatial variance for absolute soil moisture at intermediate spatial means. Brocca et al. (2014) reported similar findings based on six worldwide soil moisture datasets. To our knowledge, however, only these two studies by far characterized the relationship by considering both absolute soil moisture and temporal anomalies.

Quantifying the contribution of different components to the total variance (spatial variance of absolute soil moisture) is important to understand its structure. The findings based on *in situ* soil moisture measurements showed that total variance was dominated by the time-invariant part, and that the covariance generally contributed negatively (Brocca et al., 2014; Mittelbach and Seneviratne, 2012). Rötzer et al. (2015) studied the contributions of time-invariant (spatial variance of temporal mean) and time-varying (the sum of the covariance and spatial variance of temporal anomalies) components to the total variance globally by using various remote sensing soil moisture datasets. They found that the results obtained using different sources of soil moisture data and for different regions differed significantly. However, all of the existing studies primarily focus on large scales (from 250 to 150,000 km^2). Since soil moisture variability depends strongly on spatial scales (Biswas and Si, 2011; Zhu and Lin, 2011), there is a need to investigate the contribution of different components to total variance at small scales. Furthermore, the above studies showed strong seasonality of the contribution for different variance components. However, the characterization of seasonality varies greatly among different study sites. For instance, Brocca et al. (2014) found that negative contribution in covariance was mainly in the period of March, April and May for the Swiss site, but was primarily in the period of June, July and August for the Illinois site. Since soil moisture spatial variability is highly dependent on soil wetness conditions, it is interesting to test whether the contribution for variance components can be described as a function of soil wetness conditions.

Generally, intensive samplings in space and time are required to understand soil moisture spatiotemporal variability at field and catchment scales. Alternatively, the concept of time stability analysis, introduced by Vachaud et al. (1985), is an effective avenue to reduce spatial sampling counts without losing critical information of spatial means. In applications, the key of time stability analysis is to identify the representative location of spatial means and/or the location having the most temporally stable rank (Grayson and Western, 1998; Zhou et al., 2007; Brocca et al., 2009; Hu et al., 2010; Gao et al., 2013b). In particular, by considering soil moisture dynamics, Mittelbach and Seneviratne (2012) found that time stability (the rank of mean relative difference) of absolute soil moisture mostly reflected time-invariant patterns and showed weak relations with that of temporal anomalies. Generally, the mean and variance (or standard deviation) of relative difference are two most popular metrics for soil moisture time stability analysis. Temporal mean relative difference (MRD) represents the relative bias at a location (between the spatial mean at a time and the measurement at the location) averaged over time and thus is the "accuracy" term. Temporal variance of relative difference (VRD) reflects temporal persistence of the "accuracy" and therefore is the "precision" term. However, it is unclear whether time stability of absolute soil moisture also primarily characterizes time-invariant patterns if the "precision" metric is considered.

On these basis, the main objectives of this study are: (1) to investigate how spatiotemporal variability of absolute soil moisture differs from its components at small catchment scale, and the difference with large-scale studies; (2) to characterize how soil wetness conditions affect the contribution of different components to the total variance; and (3) to probe whether time stability of absolute soil moisture also primarily characterize the time-invariant patterns if the "precision" term is considered. Here a dataset including 3-yr soil moisture measurements gathered at 78 sampling locations was used for analyses, with measurements being conducted at four depths (20, 40, 60, and 80 cm) at each location.

2. Materials and methods

2.1. Site description

The Yuanzegou catchment (37°14′N, 110°20′E, Fig. 1), located in the northern part of Loess Plateau of China, is selected as the study site. This catchment has an area of 0.58 km^2 wherein 53.4% of the total area is covered by gullies. Based on meteorological data from 1956 to 2006 provided by Weather Bureau of Shaanxi province, this region has a semiarid continental climate: annual average precipitation of 505 mm, 70% of which falls in July, August, and September; a mean annual temperature of 8.6 °C, with mean monthly temperatures ranging from −6.5 °C in January to 22.8 °C in July. As indicated in Fig. 1, the elevation of the catchment rises from 865 to 1105 m. The uplands comprise hillslopes of tens to hundreds of meters, with relatively gentle gradients (<30°). The gullies have much steep slopes generally ranging from 30° to 90°. The main gully direction extends from south to north. Most of the gully bottom comprises exposed bedrock with only a thin soil layer (generally < 20 cm). The gullies here may be developed tens of thousands of years ago, and now most of them are stable in morphology and topography (Tang, 2004). The whole catchment is covered by thick silt loam loess soils with 19.8% sand, 63.0% silt and 17.2% clay on average. There are mainly three land use types on uplands: croplands, abandoned croplands with different years, and jujube orchards. The gullies are covered by sparse annual and perennial grass. The reader is referred to Gao et al. (2011,

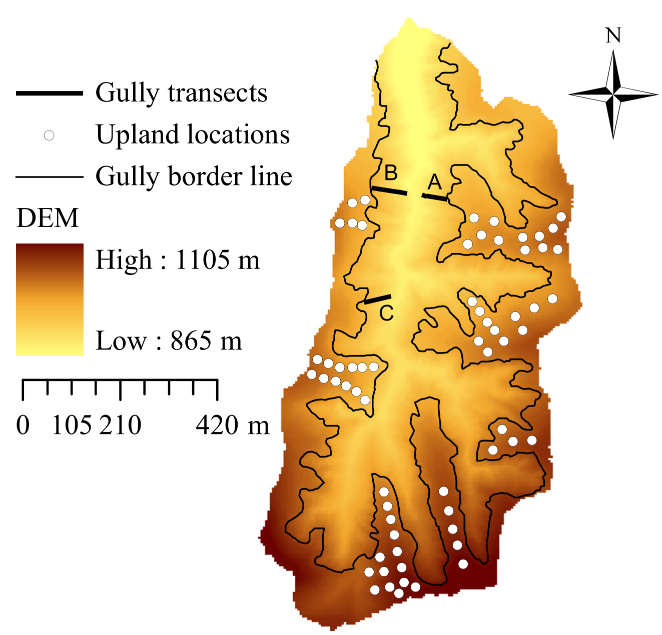

Fig. 1. The distribution of sampling locations in the Yuanzegou catchment.