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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,

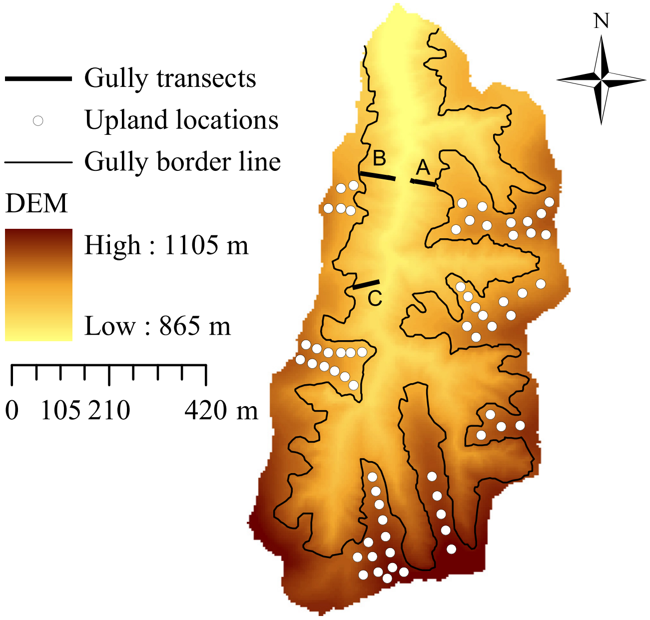

Fig. 1. The distribution of sampling locations in the Yuanzegou catchment.

2014) for more details in soil properties, topography, and land use types in the catchment.

2.2. Soil moisture dataset

The dataset contains soil moisture observations collected at both hillslopes (uplands) and gully in the Yuanzegou catchment measured by the TRIME-IPH TDR system (IMKO, Germany). There are 59 sampling locations over hillslopes and 19 over gully sidewall. Soil moisture at gully bottom was not collected because most of the gully bottom is exposed to bedrock. In general, these sampling locations are along transects at different slopes and cover various land use types and topography. The soil moisture was measured in the 0–160 cm with a depth interval of 20 cm from 2009 to 2011 with a total of 38 sampling campaigns. In this study, only soil moisture measurements in the 0–80 cm (0–20, 20–40, 40–60 and 60–80 cm) were used for analyses because (1) dry roots weight in this layer accounts for approximately 90% of that in the top 200 cm for the large majority of vegetation species (Gao et al., 2011, 2014); (2) soil moisture in the 80–160 cm varies weakly during the growing period at each year compared to that in shallower layers. Detailed information on the description of spatial distribution of sampling locations in uplands and gullies and soil moisture calibration process could refer to Gao et al. (2011, 2013a, 2013b).

In this study, we aimed to characterize spatiotemporal variability of absolute and temporal anomaly soil moisture at the catchment scale. Therefore, here the soil moisture measurements from hillslopes and gullies will be integrated as a whole to represent soil moisture conditions of the catchment.

2.3. Methods

2.3.1. Statistics

Here we mainly focused on the relationship of spatial means versus spatial variability, and contribution of different variance components to the total variance. Following Mittelbach and Seneviratne (2012), the mean, variance, and standard deviation for a variable are denoted as μ, σ^2, and σ, respectively. The subscript $\hat{n}$ and $\hat{t}$ are used for spatial and temporal statistics, respectively. Define a soil moisture observation at location n and time t as θ_{tn}, its spatial mean, spatial variance and temporal mean are defined, respectively, as follows:

$$\mu_{\hat{n}}(\theta_{tn}) = \frac{1}{N}\sum_{n=1}^{N}\theta_{tn} \tag{1}$$

$$\sigma^2_{\hat{n}}(\theta_{tn}) = \frac{1}{N-1}\sum_{n=1}^{N}(\theta_{tn} - \mu_{\hat{n}}(\theta_{tn}))^2 \tag{2}$$

and

$$\mu_{\hat{t}}(\theta_{tn}) = \frac{1}{T}\sum_{t=1}^{T}\theta_{tn} \tag{3}$$

where N is the number of sampling locations, and T is the number of samples in a time series. For the sake of clarity, M_{tn} will be used to refer to $\mu_{\hat{t}}(\theta_{tn})$ following Mittelbach and Seneviratne (2012). By subtracting temporal mean at a location from absolute moisture content, the temporal anomalies, A_{tn}, at corresponding location and time is defined as:

$$A_{tn} = \theta_{tn} - M_{tn} \tag{4}$$

Using Eqs. (2) and (4), according to Mittelbach and Seneviratne (2012), the spatial variance of absolute soil moisture, $\sigma^2_{\hat{n}}(\theta_{tn})$, can be decomposed into spatial variance of temporal mean, $\sigma^2_{\hat{n}}(M_{tn})$, spatial variance of temporal anomalies, $\sigma^2_{\hat{n}}(A_{tn})$, and the covariance between temporal mean and temporal anomalies:

$$\sigma^2_{\hat{n}}(\theta_{tn}) = \sigma^2_{\hat{n}}(M_{tn}) + \sigma^2_{\hat{n}}(A_{tn}) + 2\mathrm{cov}(M_{tn}, A_{tn}) \tag{5}$$

where $2\mathrm{cov}(M_{tn}, A_{tn})$ is the covariance term. The contribution of different variance components to the total variance can be calculated through Eq. (5).

2.3.2. Time stability analysis

Following Vachaud et al. (1985), the relative difference for θ_{tn} with respect to its spatial means can be described as:

$$\delta\theta_{tn} = \frac{\theta_{tn} - \mu_{\hat{n}}(\theta_{tn})}{\mu_{\hat{n}}(\theta_{tn})} \tag{6}$$

The temporal mean (MRD) and temporal variance (VRD) of the relative difference can be then calculated as follows:

$$\mu_{\hat{t}}(\delta\theta_{tn}) = \frac{1}{T}\sum_{t=1}^{T}(\delta\theta_{tn}) \tag{7}$$

and

$$\sigma^2_{\hat{t}}(\delta\theta_{tn}) = \frac{1}{T-1}\sum_{t=1}^{M}(\delta\theta_{tn} - \mu_{\hat{t}}(\delta\theta_{tn}))^2 \tag{8}$$

where $\mu_{\hat{t}}(\delta\theta_{tn})$ represents the "accuracy" metric MRD which measures the bias of soil moisture content for a given sampling location relative to spatial mean. The $\sigma^2_{\hat{t}}(\delta\theta_{tn})$ represents the "precision" metric VRD which measures the degree of temporal persistence of relative difference, and a lower $\sigma^2_{\hat{t}}(\delta\theta_{tn})$ means the bias for a given location is more temporally stable.

Mittelbach and Seneviratne (2012) used the difference (Δ) between a variable (θ_{tn}, M_{tn} or A_{tn}) and the corresponding spatial mean to characterize the relations of time stability of absolute soil moisture and its components in terms of the "accuracy" metric MRD. However, this is not allowed to analyze the relations of the "precision" metric between absolute soil moisture and temporal mean because the latter is temporally invariant. To fill this gap, here we propose a new and effective way to link absolute soil moisture, temporal mean and temporal anomalies to one benchmark, i.e., the spatial mean of absolute soil moisture. Here we defined two variables as follows:

$$\delta M_{tn} = \frac{M_{tn} - \mu_{\hat{n}}(\theta_{tn})}{\mu_{\hat{n}}(\theta_{tn})} \tag{9}$$

and

$$\delta A_{tn} = \frac{A_{tn} - \mu_{\hat{n}}(\theta_{tn})}{\mu_{\hat{n}}(\theta_{tn})} \tag{10}$$

where $\delta(M_{tn})$ and $\delta(A_{tn})$ are the relative difference of time-invariant and -variant components to spatial mean of absolute soil moisture, respectively. Eq. (6) can be then rewritten as:

$$\delta\theta_{tn} = \frac{M_{tn} - \mu_{\hat{n}}(\theta_{tn})}{\mu_{\hat{n}}(\theta_{tn})} + \frac{A_{tn} - \mu_{\hat{n}}(\theta_{tn})}{\mu_{\hat{n}}(\theta_{tn})} + 1 = \delta M_{tn} + \delta A_{tn} + 1 \tag{11}$$

Calculate temporal mean at the two sides of Eq. (11), and then one has:

$$\mu_{\hat{t}}(\delta\theta_{tn}) = \mu_{\hat{t}}(\delta M_{tn}) + \mu_{\hat{t}}(\delta A_{tn}) + 1 \tag{12}$$

To decompose VRD of ASM into time-invariant and -variant components, the following procedure is performed. Define $\delta_{tn} = \delta M_{tn} + \delta A_{tn}$, then Eq. (11) can be rewritten as:

$$\delta\theta_{tn} = \delta_{tn} + 1 \tag{13}$$

Mathematically, for a variable X, $\sigma^2(X) = \sigma^2(X + C)$, where C is a constant. Therefore,

$$\sigma_t^2(\delta\theta_{tn}) = \sigma_t^2(\delta_{tn}) \tag{14}$$

According to Eq. (5), one then will have:

$$\sigma_t^2(\delta\theta_{tn}) = \sigma_t^2(\delta M_{tn}) + \sigma_t^2(\delta A_{tn}) + 2\text{cov}(\delta M_{tn}, \delta A_{tn}) \tag{15}$$

where $\sigma_t^2(\delta\theta_{tn})$, $\sigma_t^2(\delta M_{tn})$ and $\sigma_t^2(\delta A_{tn})$ represent the temporal variance of $\delta\theta_{tn}$, δM_{tn} and δA_{tn}, respectively, and the last term in the right side represents the covariance.

Mittelbach and Seneviratne (2012) analyzed the relations of time stability of absolute soil moisture and its components by comparing the ranks of MRD. Generally, more similar ranks mean stronger correlations for MRD, and *vice versa*. Therefore, here we used Spearman rank correlation coefficient (r_s) to characterize the relations of time stability of absolute soil moisture and its components for both “accuracy” and “precision” terms through Eqs. (12) and (15), respectively.

3. Results and discussion

3.1. Time series of absolute soil moisture and temporal anomalies

Time series of absolute soil moisture and temporal anomalies at different depths are shown in Fig. 2. As expected, the spatial means of these two variables show similar temporal trends. The average of the spatial means of absolute soil moisture is 16.9% in the surface layer (i.e. the topmost 20 cm of the soil), which is somewhat lower than that in the subsurface layers (ranging from 19.6% to 19.8%). Both absolute soil moisture and temporal anomalies increased when there was a significant precipitation event and decreased in the no-rain periods. There were nearly monotonic decreases in the growing season from April to end of July.

The spatial standard deviation of absolute soil moisture increases with depth, from 2.11% at 0–20 cm to 2.68% at 60–80 cm. This is consistent with the findings of Hu et al. (2010) in a small catchment on the Loess Plateau. However, Gao et al. (2011) found that soil moisture standard deviation in a large gully decreased as soil depth increased from 0–20 to 80–160 cm, and subsequently Gao and Shao (2012) reported a decline in standard deviation with increasing soil depth from 0–100 cm to 200–300 cm in a hillslope on the Loess Plateau. The differences between these results can be attributed to the different vertical distributions of absolute soil moisture in hillslope and gully locations (Gao et al., 2013a). The steep slopes of gully sidewalls (which are generally between 30° and 90°) mean that most of the rainfall tends to run off rather than infiltrating into the deeper soil layers (van den Elsen et al., 2003). Conversely, greater levels of deep soil infiltration can be expected on hillslopes that are much less steep. Therefore, the difference in absolute soil moisture for the relatively gentle hillslope and deeply sloped gully locations increases with soil depth, raising the spatial variability of absolute soil moisture.

Similar with previous findings (Brocca et al., 2014; Koster et al., 2009; Mittelbach and Seneviratne, 2012), the spatial standard deviation of absolute soil moisture is much higher than that of temporal anomalies for all 38 soil moisture sampling campaigns. When the temporal mean is removed from absolute soil moisture, a reduction of 27.4–44.3% in SD for temporal anomalies is observed compared with absolute soil moisture, which agrees with Brocca et al. (2014) who reported a reduction of 47% on average. In contrast to the situation for absolute soil moisture, the highest standard deviation (1.58%) for temporal anomalies occurs at the depth of 20–40 cm. This implies that absolute soil moisture and temporal anomalies have different vertical patterns of spatial variability.

3.2. Spatial variability versus spatial means

Unlike with Mittelbach and Seneviratne (2012) and Brocca et al. (2014), spatial means of absolute soil moisture were related to various components of total variance here. This was done because (1) spatial means of absolute soil moisture and those of temporal anomalies behave very similarly in time (see also in Brocca et al. (2014) and Mittelbach and Seneviratne (2012)) and are highly and positively correlated ($R^2 = 0.999$); (2) it allows us to compare changes in different variance components as the soil wetness changes. The relationship between the spatial mean of absolute soil moisture and its total variance as well as the variance of its components is shown in Fig. 3. There is a clear upward convex relationship between the variance and spatial means of absolute soil moisture at different depths. This is consistent with the results of previous studies conducted in temperate regions (Brocca et al., 2010; Gao et al., 2013a). Specifically, the spatial variance of absolute soil moisture peaked when the spatial mean was between 15% and 20% and decreased gradually with increasing soil depth. The low moisture contents were observed around late July and early August each year. At this time, the plant’s evapotranspiration demand is the highest in the growing season and consequently plants would exhaust soil moisture in the root zone in gullies and hillslopes (Wang et al., 2012), resulting in reduced spatial variability in absolute soil moisture. In late August and September, the amounts of rainfall are relatively large and the excess water recharges soil in the root zone in both gullies and hillslopes (Li et al., 2014), which effectively shrinks the difference between gullies and hillslopes. Therefore, both high evapotranspiration and excessive rainfall would homogenize soil moisture spatial variability.

Overall, the changes in spatial variance of temporal anomalies with increasing soil wetness are noticeably different to the corresponding changes in that of absolute soil moisture. We observed no significant relations between spatial variance of temporal anomalies and the soil wetness at any soil depth. However, in the subsurface layers, spatial variance of temporal anomalies tends to be lowest at intermediate wetness levels, although this trend is not very pronounced. For the study site here, the primary controls on spatial variance of temporal anomalies can be topography (slope gradient and curvature) and land use types because of the low spatial variation in soil texture and precipitation at small scales. The response of soil moisture to precipitation for place with low slope gradient and that with high slope gradient would be substantially different (Gao et al., 2016). Therefore, at high wetness condition, the spatial variance of temporal anomalies should be relatively high (Grayson et al., 1997). At low wetness condition, the spatial variance of temporal anomalies can be also relatively high because the diverse land use types here are expected to cause high spatial variation in evapotranspiration. Mittelbach and Seneviratne (2012) also found that the spatial variance of temporal anomalies was lowest at intermediate wetness levels (under these conditions, the spatial mean of temporal anomalies approached zero) but their data yielded a clear and pronounced parabolic curve, with the spatial variance of temporal anomalies at both low and high wetness levels being substantially greater than at the intermediate level. Similarly, Brocca et al. (2014) revealed a parabolic relationship between the spatial mean of absolute soil moisture and the spatial variance of temporal anomalies at three of the six soil moisture networks located in different parts of the world. The relationship observed for the other three sites was less clear.

The covariance behaves very similarly to the total variance in terms of its relationship with the mean soil moisture: at all depths examined, the covariance peaked at intermediate soil wetness levels. This means that the upward convex relationship between

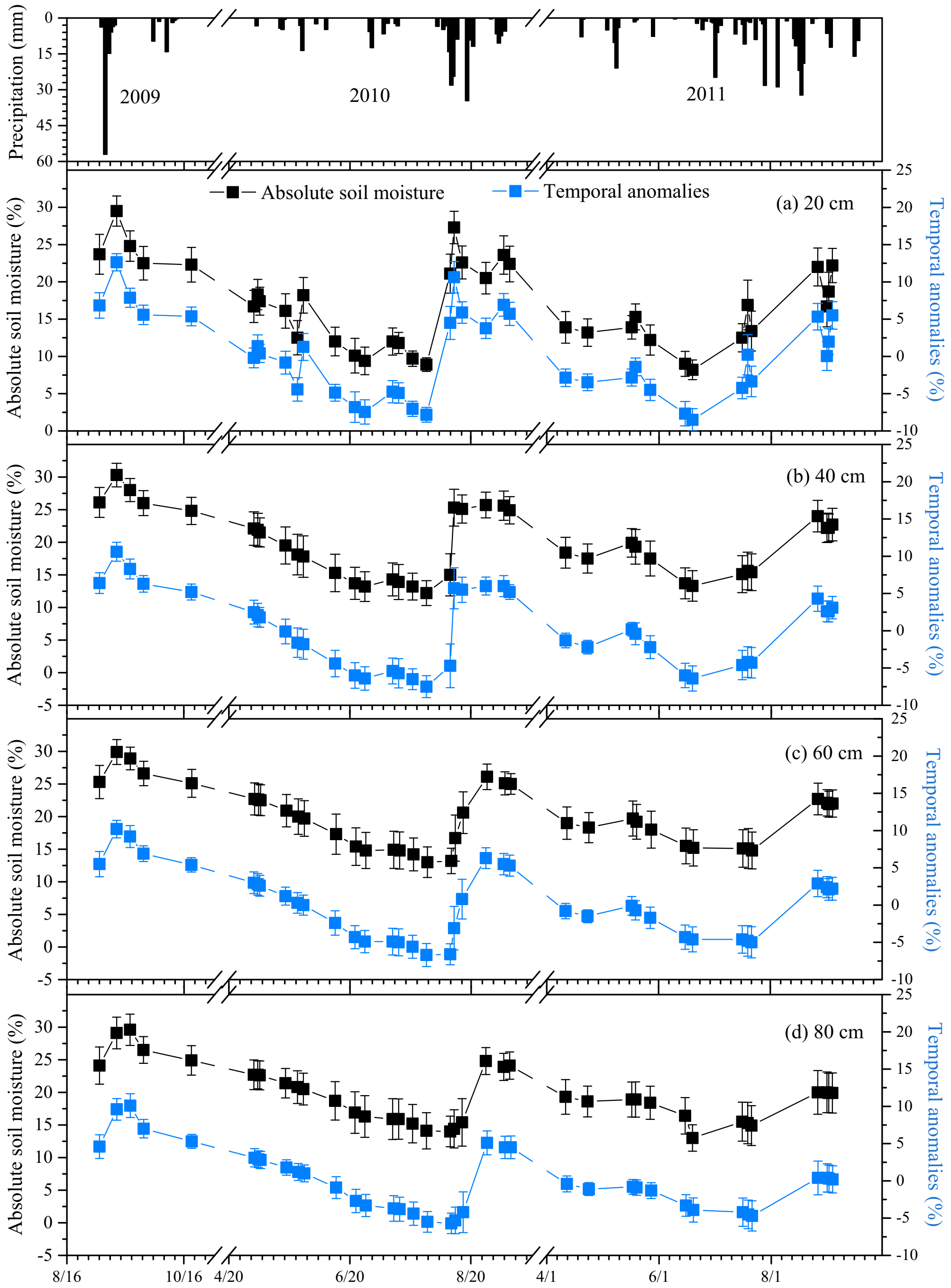

Fig. 2. Time series of absolute soil moisture and temporal anomalies during the study period at different depths. Error bar represents ± one standard deviation.

spatial variance and means of absolute soil moisture is primarily characterized by the covariance. Although we are not sure about why covariance and the total variance behave similarly with soil wetness, it at least suggested that (1) as soil wetness changes the primary controls on covariance and the total variance behave in similar ways; and (2) the positive interaction of the primary factors controlling temporal mean (e.g., soil properties) and those controlling temporal anomalies (e.g., slope gradient and land use) is strengthened. Moreover, we observed positive covariance when the soil wetness was intermediate and negative covariance when it was high or low. This means that temporal anomalies and temporal mean are positively correlated at intermediate wetness condition.

3.3. Contribution to total variance

As shown in Eq. (5), the spatial variance of absolute soil moisture at any given measurement date is composed of the spatial variances of temporal anomalies and temporal mean, and the covariance at that date. The contributions of different variance components to the total variance changed with time (Fig. 4). The contributions clearly varied significantly over the entire study period and exhibited strong seasonality. In the surface layer (0–20 cm), the variance contributions of temporal mean (time-invariant) and temporal anomalies (time-variant) exhibit similar temporal patterns; higher values are observed in summer (June, July and early August) with lower values in spring (April and

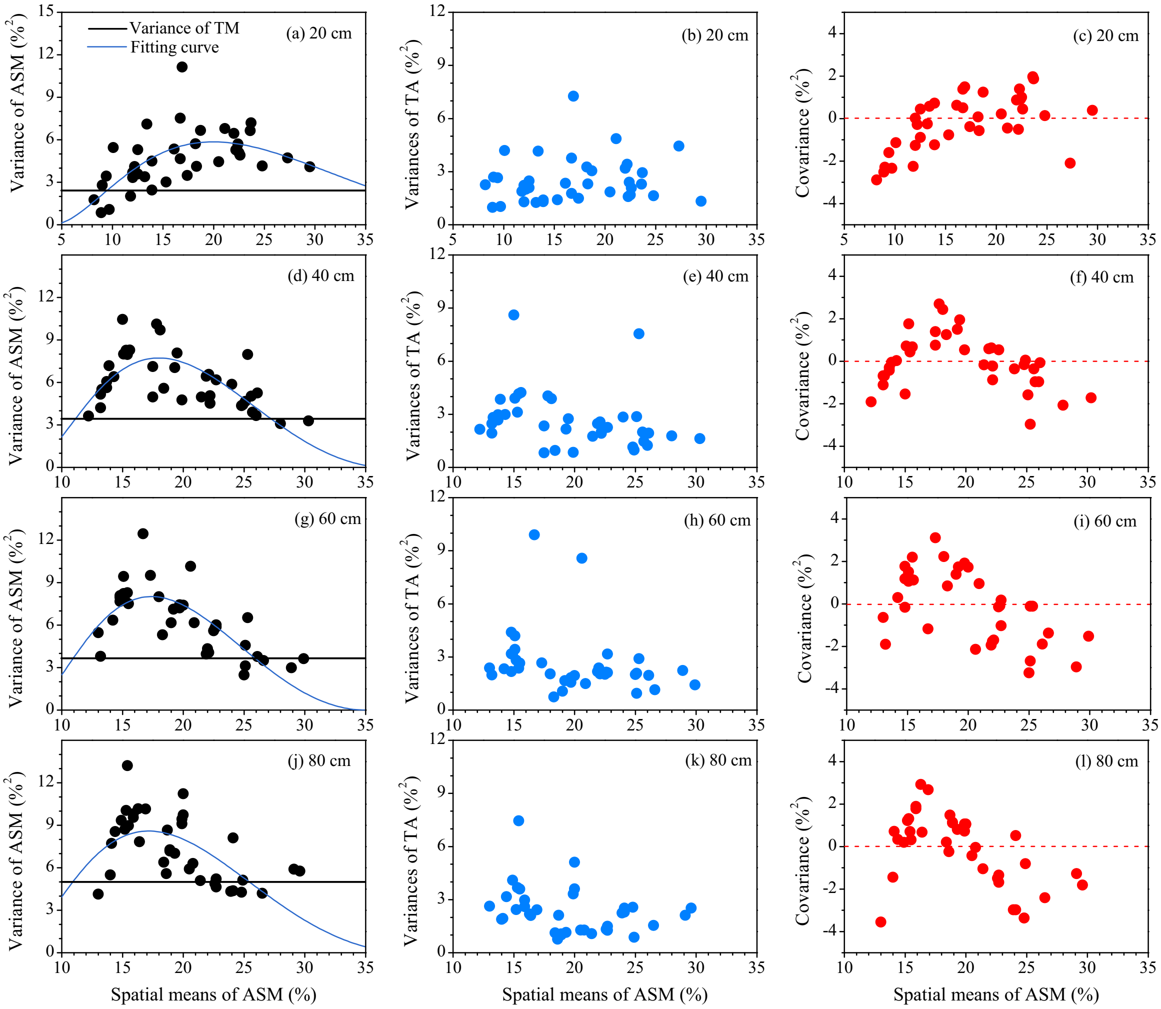

Fig. 3. Relationship between spatial means of absolute soil moisture (ASM) and different variances: spatial variance of ASM (a, d, g, j); spatial variance of temporal anomalies (TA, b, e, h, k); and covariance (c, f, i, l).

May) and fall (late August and September). Furthermore, the spatial variance of temporal mean generally makes a greater contribution than temporal anomalies. Often, the covariance (time-variant) takes negative values in summer and near-zero values otherwise. A negative contribution means negative values of covariance. Therefore, a negative contribution may means the negative interaction of the primary factors controlling temporal mean and those controlling temporal anomalies is strengthened. Similarly, Brocca et al. (2014) observed higher contributions of both time-variant and -invariant components during summer, and near-zero covariance values during winter in their studies on various soil moisture datasets collected in Australia, Spain and Illinois. However, Mittelbach and Seneviratne (2012) found that the contribution of the time-invariant component was lowest (and that of the time-variant component highest) during the summer based on studies of a soil moisture network in Switzerland. Quantitatively, the contribution to the total variance ranges from 21.4% to 282.2% with an average of 66.8% from the spatial variance of temporal mean, from 29.6% to 128.9% with an average of 57.4% from the spatial variance of temporal anomalies, and from −298.7% to 29.6% with an average of −24.2% from the covariance (Table 1). The average combined contribution of the time-variant components (i.e. the summed average contributions of the covariance and the spatial variance of temporal anomalies), is 33.2% (Table 1). This indicates that the time-invariant component is the primary contributor to the total variance. This may imply that time-invariant factors (e.g., soil properties) are the main factors affecting spatial variability of soil moisture. Mittelbach and Seneviratne (2012) also reported that the time-invariant component made a greater contribution than the spatial variance of temporal anomalies. However, the magnitude of the contribution from the time-variant component in this work was much greater. They found that the time-invariant component was the absolutely dominant contributor to the total variance, with average contributions of up to 94% while the average contribution of temporal anomalies was only 9%. The difference in magnitude in the two studies may be partly due to the different spatial scales considered; Mittelbach and Seneviratne (2012) examined an area of 31,500 km^2 whereas the study area in this work was only 0.6 km^2. In theory, spatial heterogeneity of time-invariant factors in terms of soil texture, vegetation and climate variables should be low at small scales. Therefore, the contribution of time-invariant component at small scales is expected to be lower compared with that observed at large scales (Brocca et al., 2014). Nonetheless, Hu and Si (2014) showed that time-invariant factors such as soil texture dominated soil moisture distribution at a small catchment on the Loess Plateau. Furthermore, the complex topography in our site is expected to produce greater spatial heterogeneity of soil properties; for instance, fine soil particles can be concentrated at positions with lower elevation and slope gradient (Famiglietti et al., 1999; Gao et al., 2011). As a result, time-invariant component

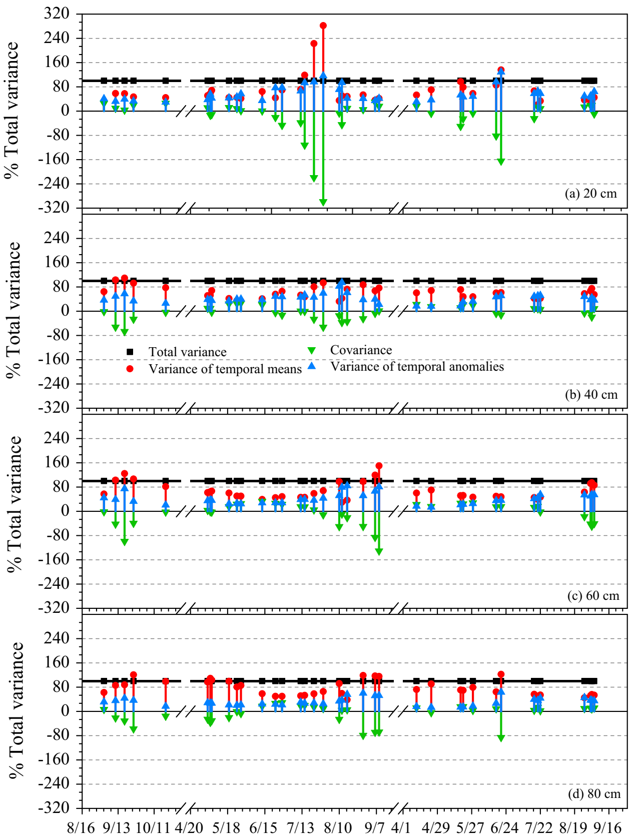

Fig. 4. Temporal patterns of contribution of different variance components to total variance at different depths.

is still the primary contributor to the total variance but time-variant component contributes greatly here. Moreover, analyses of ASCAT soil moisture data conducted by Rötzer et al. (2015) indicated that the contribution of the time-invariant component was always lower than that of the time-variant part in most regions of the world, showing that studies of remote sensing measurements can yield very different results to those based with *in situ* measurements. This may be partly attributed to the very low penetration depth (<2–3 cm) and the noise of satellite soil moisture data (Brocca et al., 2011).

The temporal changes in the relative contributions of the time-variant and -invariant components in the subsurface layers were very different to (and sometimes the exact opposite of) those observed for the surface layer. Based on Fig. 4 and Table 1, the results for the subsurface layer differ from those for the surface layer in four key respects: (1) the contribution for each component is larger during the fall and lower during summer and spring; (2) the covariance takes negative values during fall and near-zero values during summer and spring; (3) the extreme values for the relative contributions of different components are much smaller; and (4) the contribution of the spatial variance of temporal anomalies appears to be smaller and that of the covariance is less negative. This means that the temporal patterns in the contributions of the time-invariant and -variant components in the surface layer cannot be assumed to reflect those in the subsurface layers. However, it should be noted that the time-invariant component remained the dominant contributor to the total variance with average contribution exceeding 60% at any subsurface soil layers.

Table 1
Contribution of variance components to total variance at different depths.

Depth (cm)	Contribution of variance components (%)			
	$\sigma_n^2(M_{tn})$	$\sigma_n^2(A_{tn})$	$2\mathrm{cov}(M_{tn}, A_{tn})$	$\sigma_n^2(A_{tn}) + 2\mathrm{cov}(M_{tn}, A_{tn})$
20	66.8	57.4	−24.2	33.2
40	61.7	43.2	−4.9	38.3
60	67.3	41.7	−9.0	32.7
80	76.2	32.2	−8.4	23.8

$\sigma_n^2(M_{tn})$: spatial variance of temporal mean; $\sigma_n^2(A_{tn})$: variance of temporal anomalies; $2\mathrm{cov}(M_{tn}, A_{tn})$: covariance term.

It is generally hard to identify any consistent seasonal trends in the contributions of different components between different study sites. This is because each site will have its own distinctive climate, precipitation regime and underlying surface conditions including topography, soils and vegetation. In this work, we conducted detailed analyses to qualitatively characterize the effects of soil wetness on the contribution of different variance components. As shown in Fig. 5, the contributions of the spatial variances of temporal mean and temporal anomalies generally decline exponentially as soil wetness increases in the surface layer (0–20 cm), whereas the contribution of the covariance initially becomes less negative as the wetness increases and then fluctuates around zero once the spatial mean of absolute soil moisture exceeds approximately 15%. However, for the subsurface layers, plots of the contributions of the spatial variance in temporal mean and temporal anomalies as functions of the soil wetness take the form of open-up parabolic curves; the contributions of the spatial variances of temporal mean and temporal anomalies are minimized at spatial mean ASM values of approximately 16% and 20%, respectively. The results for the subsurface contribution of the covariance exhibit the opposite trend; when plotted as a function of the soil wetness, a clear open-down parabola is obtained; the contribution of the covariance is maximized at a spatial mean of around 17%. Clearly, soil wetness levels significantly affect the contributions of the time-invariant and -variant components to the total variance. A comparison of Figs. 4 and 5 reveals that although different (and in some cases, opposing) seasonal trends are seen at different depths, the relationships between the contributions of different variance components and the soil wetness are broadly similar throughout. This means that the seasonality of a particular contribution is primarily controlled by processes that are related to the soil wetness conditions.

3.4. Time stability analysis

The primary objective of this section was to characterize the relations of time stability of absolute soil moisture and its components considering both the “accuracy” metric MRD and the “precision” metric VRD rather than to estimate spatial means from point measurements. Spearman rank correlation coefficient (r_s) was used to characterize the relations of time stability of absolute soil moisture with its time-invariant and -variant patterns. A higher r_s indicates the ranks of time stability metric (MRD or VRD) of absolute soil moisture is more similar with that of its component. The r_s for the “accuracy” metric MRD between absolute soil moisture and its components are shown in Table 2. The r_s values for MRD between absolute soil moisture and temporal mean are generally above 0.99. However, much lower r_s values were observed between absolute soil moisture and temporal anomalies. This means that for the “accuracy” metric MRD, the time stability of absolute soil moisture primarily reflect time-invariant patterns in the small catchment. This is in accordance with the finding of Mittelbach and Seneviratne (2012) based on the large-scale observations by comparing ranks of MRD between absolute soil moisture and its time-invariant and -variant parts. At a regional scale, Jia et al. (2015) found that time-invariant factors including soils texture, organic carbon and field capacity were the main factors affecting MRD.

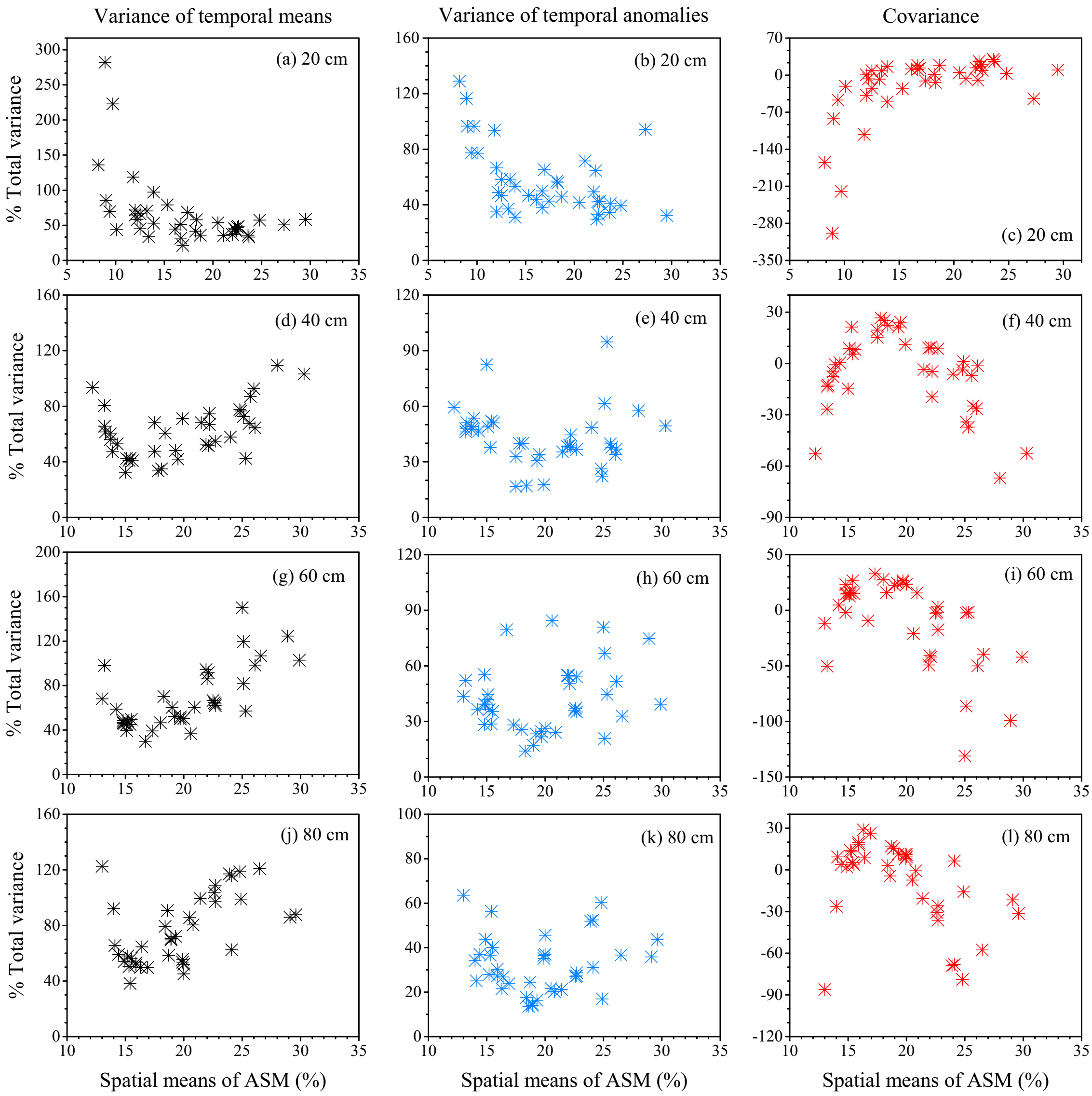

Fig. 5. Relationship between contribution of different variance components and soil wetness conditions (spatial means of absolute soil moisture (ASM)).

Table 2
Spearman rank correlation coefficient (r_s) of mean relative difference (MRD) for absolute soil moisture (ASM) and its different components.

Depth (cm)	ASM *vs.* TM		ASM *vs.* TA	
	r_s	P	r_s	P
20	0.990	<0.001	−0.477	<0.001
40	0.993	<0.001	0.170	0.136
60	0.995	<0.001	0.427	<0.001
80	0.998	<0.001	0.487	<0.001

ASM: absolute soil moisture; TM: temporal mean; TA: temporal anomalies.

Table 3
Spearman rank correlation coefficient (r_s) of variance of relative difference (VRD) for absolute soil moisture (ASM) and its different components.

Depth (cm)	ASM *vs.* TM		ASM *vs.* TA		ASM *vs.* COV	
	r_s	P	r_s	P	r_s	P
20	0.076	0.507	−0.007	0.952	0.081	0.483
40	0.152	0.184	0.019	0.871	0.139	0.225
60	0.090	0.432	0.140	0.221	0.127	0.267
80	−0.075	0.514	0.163	0.154	0.226	0.047

ASM: absolute soil moisture; TM: temporal mean; TA: temporal anomalies; COV: covariance.

At small catchment scale, Hu et al. (2010) found that time stability of soil moisture was also mainly affected by time-invariant factors including soil particle size distribution and topography. This means that time-invariant factors primarily control soil moisture time stability for the "accuracy" metric MRD at both small and large scales.

The values of r_s for the "precision" metric VRD between absolute soil moisture and its components are indicated in Table 3. Generally, all of the three components exhibit relatively low correlations with absolute soil moisture. It means that time stability of absolute soil moisture characterizes neither time-invariant nor -variant patterns for the "precision" metric. Generally, the magnitude of VRD here is determined by the difference between a variable and the spatial means of absolute soil moisture (Eq. (8)). One may do not understand why the correlations of VRD between temporal anomalies and absolute soil moisture are so weak (r_s from −0.007 to 0.163) since they show very similar temporal patterns in moisture content (Fig. 2). This can be attributed into that absolute soil moisture includes only positive values but TA includes both positive and negative ones. Therefore, when temporal anomalies is rescaled by using Eq. (10), parts of relative difference should be enlarged and thus the corresponding VRD would increase. These results suggest that the relationship of time stability between absolute soil moisture and its components is dependent on the metric under consideration, and time-invariant component not always play the leading role.

4. Conclusions

In this study, we characterized spatiotemporal variability and time stability of soil moisture in a small catchment of the Loess Plateau by decomposing absolute soil moisture into time-invariant temporal mean, and time-varying temporal anomalies. It is found that temporal anomalies showed clearly lower spatial variability than absolute soil moisture and the spatial standard deviation of the former was reduced by 27.4–44.3% for different depths compared with the latter. The upward convex relationship between spatial variance and spatial means for absolute soil moisture is primarily due to the covariance between temporal mean and temporal anomalies. Overall, spatial variance of temporal mean is the major contribution (61.7–76.2%) to the total variance and spatial variance of temporal anomalies is also an important contributor (32.2–57.4%). This is slightly different from results based on *in situ* measurements at large scales, where the time-invariant component is found to be the dominant contributor. The contribution of variance components shows clear seasonality and this seasonality is highly dependent on soil depth. The variation of contribution at different seasons can be explained by soil wetness conditions. In general, the variances of temporal mean and temporal anomalies make relatively modest contributions while the contributions of the covariance become less negative (and may even become positive) at intermediate soil wetness levels, although this relationship is not very strong in the surface layer. Finally, we analyzed the relations of time stability between absolute soil moisture and its time-invariant and -variant components. For the "accuracy" metric mean relative difference, the time stability of absolute soil moisture primarily characterizes time-invariant patterns ($r_s > 0.99$). However, as the "precision" metric variance of relative difference is considered, time stability of absolute soil moisture characterizes little of time-invariant and -variant patterns.

At the small catchment scale, it is also found that absolute soil moisture and temporal anomalies have significantly different characteristics in spatiotemporal variability and time stability. By considering the significance of temporal anomalies in hydrological, meteorological and agricultural applications, it is suggested to consider both absolute and temporal dynamic soil moisture in spatiotemporal analysis across spatial scales. Furthermore, for other widely used relative soil moisture such as available soil moisture (the difference between absolute soil moisture and permanent soil moisture) which is of great importance in agricultural application, there is a need to investigate its spatiotemporal variability and whether there is difference with absolute soil moisture.

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References

Arora, V.K., Boer, G.J., 2006. The temporal variability of soil moisture and surface hydrological quantities in a climate model. J. Clim. 19, 5875–5888.

Biswas, A., Si, B.C., 2011. Revealing the controls of soil water storage at different scales in a hummocky landscape. Soil Sci. Soc. Am. J. 75, 1295–1306.

Brocca, L., Morbidelli, R., Melone, F., Moramarco, T., 2007. Soil moisture spatial variability in experimental areas of central Italy. J. Hydrol. 333 (2–4), 356–373.

Brocca, L., Melone, F., Moramarco, T., Morbidelli, R., 2009. Soil moisture temporal stability over experimental areas in Central Italy. Geoderma 148 (3–4), 364–374.

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., Hasenauer, S., Lacava, T., Melone, F., Moramarco, T., Wagner, W., Dorigo, W., Matgen, P., Martinez-Fernandez, J., Llorens, P., Latron, J., Martin, C., Bittelli, M., 2011. Soil moisture estimation through ASCAT and AMSR-E sensors: an intercomparison and validation study across Europe. Remote Sens. Environ. 115, 3390–3408.

Brocca, L., Tullo, T., Melone, F., Moramarco, T., Morbidelli, R., 2012. Catchment scale soil moisture spatial–temporal variability. J. Hydrol. 422–423, 63–75.

Brocca, L., Zucco, G., Mittelbach, H., Moramarco, T., Seneviratne, S.I., 2014. Absolute versus temporal anomaly and percent of saturation soil moisture spatial variability for six networks worldwide. Water Resour. Res. 50. http://dx.doi.org/10.1002/2014WR015684.

Champagne, C., Berg, A.A., McNairn, H., Drewitt, G., Huffman, T., 2012. Evaluation of soil moisture extremes for agricultural productivity in the Canadian prairies. Agric. Forest Meteorol. 165, 1–11.

Famiglietti, J.S., Devereaux, J.A., Laymon, C.A., Tseaye, T., Houser, P.R., Jackson, T.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.

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., Zhang, B.Q., 2011. Soil moisture variability along transects over a well-developed gully in the Loess Plateau, China. Catena 87, 357–367.

Gao, X.D., Wu, P.T., Zhao, X.N., Zhang, B.Q., Shi, Y.G., Wang, J.W., 2013a. Estimating the spatial means and variability of root-zone soil moisture in gullies using measurements from nearby uplands. J. Hydrol. 476, 28–41.

Gao, X.D., Wu, P.T., Zhao, X.N., Wang, J.W., Shi, Y.G., Zhang, B.Q., Tian, L., Li, H.B., 2013b. 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.

Gao, X.D., Wu, P.T., Zhao, X.N., Wang, J.W., Shi, Y.G., 2014. Effects of land use on soil moisture variations in a semi-arid catchment: implications for land and agricultural water management. Land Degrad. Dev. 25, 163–172.

Gao, X.D., Zhao, X.N., Wu, P.T., Brocca, L., Zhang, B.Q., 2016. Effects of large gullies on catchment-scale soil moisture spatial behaviors: a case study on the Loess Plateau of China. Geoderma 261, 1–10.

Gao, L., Shao, M.A., 2012. Temporal stability of soil water storage in diverse soil layers. Catena 95, 24–32.

Grayson, R.B., Western, A.W., Chiew, F.H.S., 1997. Preferred states in spatial soil moisture patterns: local and nonlocal control. Water Resour. Res. 33 (12), 2897–2908.

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.

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.

Hu, W., Shao, M.A., Han, F.P., Reichardt, K., 2011. Spatio-temporal variability behavior of land surface soil water content in shrub- and grass-land. Geoderma 162, 260–272.

Hu, W., Si, B.C., 2014. Revealing the relative influence of soil and topographic properties on soil water content distribution at the watershed scale in two sites. J. Hydrol. 516, 107–118.

Jia, X.X., Shao, M.A., Zhang, C.C., Zhao, C.L., 2015. Regional temporal persistence of dried soil layer along south–north transect of the Loess Plateau, China. J. Hydrol. 528, 152–160.

Koster, R.D., Guo, Z., Yang, R., Dirmeyer, P.A., Mitchell, K., Puma, M.J., 2009. On the nature of soil moisture in land surface models. J. Clim. 22, 4322–4335.

Lawrence, J.E., Hornberger, G.M., 2007. Soil moisture variability across climate zones. Geophys. Res. Lett. 34, L20402.

Li, H.C., Zhao, X.N., Gao, X.D., Wang, J.W., Shi, Y.G., 2014. Effects of scale-like pit and mulching measures on soil moisture of dryland jujube orchard in North Shaanxi province, China. Chin. J. Appl. Ecol. 25 (8), 2297–2303 (in Chinese).

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

Meng, L., Quiring, S.M., 2010. Examining the influence of spring soil moisture anomalies on summer precipitation in the U.S. Great Plains using the Community Atmosphere Model version 3. J. Geophys. Res. 115, D21118. http://dx.doi.org/10.1029/2010JD014449.

Mittelbach, H., Seneviratne, S.I., 2012. A new perspective on the spatio-temporal variability of soil moisture: temporal dynamics versus time invariant contributions. Hydrol. Earth Syst. Sci. 16, 2169–2179.

Niu, J., Chen, J., Sun, L.Q., 2015. Exploration of drought evolution using numerical simulations over the Xijiang (West River) basin in South China. J. Hydrol. 526, 68–77.

Rodriguez-Iturbe, I., D'odorico, P., Porporato, A., Ridolfi, L., 1999. On the spatial and temporal links between vegetation, climate, and soil moisture. Water Resour. Res. 35, 3709–3722.

Rötzer, K., Montzka, C., Vereecken, H., 2015. Spatio-temporal variability of global soil moisture products. J. Hydrol. 522, 187–202.

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.

Tang, K.L., 2004. Soil and Water Conservation in China. Science Press, Beijing, p. 845 (in Chinese).

Tetzlaff, D., Birkel, C., Dick, J., Geris, J., Soulsby, C., 2014. Storage dynamics in hydropedological units control hillslope connectivity, runoff generation, and the evolution of catchment transit time distributions. Water Resour. Res. 50 (2), 969–985.

Vachaud, G., 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.

van den Elsen, E., Xie, Y., Liu, B.Y., Stolte, J., Wu, Y.Q., Trouwborst, K., Ritsema, C.J., 2003. Intensive water content and discharge measurement system in a hillslope gully in China. Catena 54 (1–2), 93–115.

Vereecken, H., Kamai, T., Harter, T., Kasteel, R., Hopmans, J., Vanderborght, J., 2007. Explaining soil moisture variability as a function of mean soil moisture: a stochastic unsaturated flow perspective. Geophys. Res. Lett. 34, L22402. http://dx.doi.org/10.1029/2007GL031813.

Vereecken, H., Huisman, J.A., Packepsky, Y., Montzka, C., Van der Kruk, J., Bogena, H., Weihermüller, L., Herbst, M., Martinez, G., Vanderborght, J., 2014. On the spatio-temporal dynamics of soil moisture at the field scale. J. Hydrol. 516, 76–96.

Wang, S., Fu, B.J., Gao, G.Y., Yao, X.L., Zhou, J., 2012. Soil moisture and evapotranspiration of different land cover types in the Loess Plateau, China. Hydrol. Earth Syst. Sci. 16, 2883–2892.

Zhou, X., Lin, H., Zhu, Q., 2007. Temporal stability of soil moisture spatial variability at two scales and its implication for optimal field monitoring. Hydrol. Earth Syst. Sci. Discuss. 4, 1185–1214.

Zhu, Q., Lin, H., 2011. Influences of soil, terrain, and crop growth on soil moisture variation from transect to farm scales. Geoderma 163 (1–2), 45–54.