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A new perspective on the spatio-temporal variability of soil moisture: temporal dynamics versus time invariant contributions

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Abstract

Knowledge about the spatio-temporal variability of soil moisture is essential to understand and predict processes in climate science and hydrology. A significant body of literature exists on the characterization of the spatial variability and the ranks stability (also called temporal stability) of absolute soil moisture. Yet previous studies were generally based on short-term measurement campaigns and did not distinguish the respective contributions of time varying and time invariant components to these quantities. In this study, we investigate this issue using measurements from 14 grassland sites of the SwissSMEX soil moisture network (spatial extent of approx. 150 × 210 km) over the time period May 2010 to July 2011. We thereby decompose the spatial variance of absolute soil moisture over time in contributions from the spatial variance of the mean soil moisture at all sites (which is time invariant), and components that vary over time and are related to soil moisture dynamics. These include the spatial variance of the temporal soil moisture anomalies at all sites and the covariance between the sites' anomalies to the spatial mean at a given time step and those for the temporal mean values. The analysis demonstrates that the time invariant term contributes 50–160 % (on average 94 %) of the spatial soil moisture variance at any point in time, while the covariance term generally contributes negatively to the spatial variance. On the other hand the spatial variance of the temporal anomalies, which is overall most relevant for climate and hydrological applications because it is directly related to soil moisture dynamics, is relatively limited and constitutes at most 2–30 % (on average 9 %) of the total variance. Nonetheless, this term is not negligible compared to the temporal anomalies of the spatial mean. These results suggest that a large fraction of the spatial variability of soil moisture assessed from short-term campaign is time invariant. Moreover, we find that the rank (or "temporal") stability concept when applied to absolute soil moisture, mostly characterizes the time-invariant patterns. Indeed, sites that best represent the mean soil moisture dynamics of the network are not the same as those that best reflect mean soil moisture at any point in time. Overall this study shows that conclusions

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derived from the analysis of the spatio-temporal variability of absolute soil moisture do generally not apply to temporal soil moisture anomalies, and hence to soil moisture dynamics.

1 Introduction

Soil moisture is an essential variable in climate and hydrological science through its impact on the energy and water balance (see Seneviratne et al., 2010, for a review). Knowledge about soil moisture and its spatio-temporal variability, which is impacted by the heterogeneity of different characteristics, such as soil texture, vegetation, topography, and meteorological conditions, is essential to improve climate and hydrological modeling, remote sensing-based soil moisture estimates, and to optimize soil moisture monitoring networks (e.g. Vinnikov et al., 1996; Western et al., 2002; Jacobs, 2004; Koster et al., 2004; Seneviratne et al., 2006; Robinson et al., 2008; Brocca et al., 2010).

Frequently used frameworks to investigate spatio-temporal variability of soil moisture patterns include geostatistical methods (Famiglietti et al., 2008; Western et al., 2004; Entin et al., 2000), the relationship between the spatial variance and the spatial mean soil moisture (e.g. Famiglietti et al., 1999; Brocca et al., 2010), and rank stability analyses (e.g. Vachaud et al., 1985; Martínez-Fernández and Ceballos, 2003; Tallon and Si, 2004; Zhou et al., 2007). These approaches are used to analyze and compare the spatial variability of soil moisture at multiple depths, across spatial scales and under different moisture conditions. Furthermore, several studies have analyzed the spatial variability of soil moisture and its relation to the spatial mean by using ground observations but also by stochastic analysis (e.g. Famiglietti et al., 1999; Teuling et al., 2006; Vereecken et al., 2007). Investigations of the potential controls on soil moisture variability are for instance provided in Western et al. (1999); Albertson and Montaldo (2003); Cosh (2004); and Teuling and Troch (2005), and generally focus on parameters or variables such as soil texture, vegetation cover, topography, as well as land surface fluxes. The role of meteorological and climate forcing for spatial soil moisture variability

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has only be considered in few studies (Vinnikov et al., 1996; Robock et al., 1998; Entin et al., 2000). For its part, the concept of temporal stability proposed by Vachaud et al. (1985) aims at identifying the most representative soil moisture site within a given network and has been suggested to be relevant for improving monitoring strategies or for the upscaling of soil moisture (e.g. Kamgar et al., 1993; Guber et al., 2008; Brocca et al., 2009).

Most of the mentioned studies are based on data sets that were collected during short-term field campaigns. These studies often include observations for wet and dry conditions but no continuous long-term time series. However, already Bell et al. (1980) emphasized the need for long-term measurements to study the spatial variability over a large range of spatial mean moisture contents.

Long-term time series are essential to investigate soil moisture dynamics, i.e. variations of soil moisture in time. Previous analyses (Seneviratne, 2003; Seneviratne et al., 2004) indicated that temporal soil moisture variations may be more stable in space than absolute soil moisture. However, no extensive analyses were provided on this topic so far. In the present study we use continuous 15-month long soil moisture measurements from 14 sites of the SwissSMEX soil moisture network (Sect. 3.1), which cover a spatial extent of 150 × 210 km. The time series are decomposed in their temporal mean and anomalies. We apply the concepts of spatial variability and temporal stability to the decomposed time series, to assess to which extent they respectively contribute to the overall spatial soil moisture variability. In addition, we also investigate whether commonly applied concepts such as that of temporal stability are relevant from the point of view of soil moisture dynamics.

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2 Methods

2.1 Framework to distinguish between time varying and time invariant contributors to spatial variability

Spatio-temporal variability of soil moisture is characterized by the spatial and temporal statistics of soil moisture. The spatial variability of soil moisture has been investigated in a number of previous studies using the relation between the spatial variance and the spatial mean of absolute soil moisture (e.g. Famiglietti et al., 1999; Brocca et al., 2007; Famiglietti et al., 2008). Here we propose a new approach, whereby we consider the respective contributions of time varying and time invariant factors to the overall spatial variability of soil moisture at any point in time.

For more clarity we will denote hereafter the mean μ, variance σ^2, and standard deviation σ with the subscript $\widehat{n}$ for the spatial statistics, and with the subscript $\widehat{t}$ for the temporal statistics. Let S_{tn} be the soil moisture of site $n \subset [1,\ldots N]$ at time $t \subset [1,\ldots T]$. Its spatial mean $\mu_{\widehat{n}}(S_{tn})$ and spatial variance $\sigma^2_{\widehat{n}}(S_{tn})$ at any time step t are defined as:

$$\mu_{\widehat{n}}(S_{tn}) = \frac{1}{N}\sum_{n=1}^{N}(S_{tn}), \tag{1}$$

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

Similarly, the temporal mean of soil moisture at any site n is defined as:

$$\mu_{\widehat{t}}(S_{tn}) = \frac{1}{T}\sum_{t=1}^{T}(S_{tn}) = m_n. \tag{3}$$

Note that of ease for notation we will use the symbol m_n to refer to the temporal mean $\mu_{\widehat{t}}(S_{tn})$.

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Here we extend the classical framework that generally compares $\mu_{\hat{n}}(S_{tn})$ and $\sigma^2_{\hat{n}}(S_{tn})$ by decomposing S_{tn} into its temporal mean m_n and its temporal anomalies a_{tn}. This allows us to distinguish between spatio-temporal aspects that are time invariant and those related to soil moisture dynamics. Formally, this is expressed as follows:

$$S_{tn} = m_n + a_{tn}. \tag{4}$$

The corresponding equation for the mean of all sites is

$$\mu_{\hat{n}}(S_{tn}) = \mu_{\hat{n}}(m_n) + \mu_{\hat{n}}(a_{tn}) = m_{\hat{n}} + a_{t\hat{n}}. \tag{5}$$

Using Eqs. (4) and (5), it is possible to decompose $\sigma^2_{\hat{n}}(S_{tn})$ in time varying and time invariant components by resolving Eqs. (4) and (5) into Eqs. (1) and (2):

$$\sigma^2_{\hat{n}}(S_{tn}) = \frac{1}{N}\sum_{n=1}^{N}[(m_n + a_{tn}) - (m_{\hat{n}} + a_{t\hat{n}})]^2. \tag{6}$$

Equation (6) can then be reexpressed as follows:

$$\begin{aligned}\sigma^2_{\hat{n}}(S_{tn}) = \frac{1}{N}\sum_{n=1}^{N}[&(m_n - m_{\hat{n}})^2 \\ &+2\mathrm{cov}(m_n - m_{\hat{n}})(a_{tn} - a_{t\hat{n}}) \\ &+(a_{tn} - a_{t\hat{n}})^2],\end{aligned} \tag{7}$$

resulting in the following Equation:

$$\sigma^2_{\hat{n}}(S_{tn}) = \sigma^2_{\hat{n}}(m_n) + 2\mathrm{cov}(m_n, a_{tn}) + \sigma^2_{\hat{n}}(a_{tn}), \tag{8}$$

where $\sigma^2_{\hat{n}}(m_n)$ is the spatial variance of temporal mean soil moisture, $\sigma^2_{\hat{n}}(a_{tn})$ is the spatial variance of anomalies, and $\mathrm{cov}(m_n, a_{tn})$ is the spatial covariance between the temporal mean soil moisture of a site and its respective anomaly.

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Note that Eq. (8) can also be expressed as follows:

$$\sigma^2_{\hat{n}}(S_{tn}) = \sigma^2_{\hat{n}}(m_n) + 2\rho(m_n, a_{tn})\sigma(m_n)\sigma(a_{tn}) + \sigma^2_{\hat{n}}(a_{tn}), \tag{9}$$

where $\rho(m_n, a_{tn})$ refers to the temporal correlation between m_n and a_{tn}.

Equation (8) allows to analyze the spatio-temporal variability of soil moisture considering its temporal mean m_n state and its dynamics a_{tn}. Furthermore, the temporal evolution of the spatial variance and the contribution of its single components can be investigated. Note that $\sigma^2_{\hat{n}}(m_n)$ is time invariant, while $\sigma^2_{\hat{n}}(a_{tn})$ and $\mathrm{cov}(m_n, a_{tn})$ vary over time.

2.2 Relating the rank stability concept to time varying and time invariant soil moisture components

The concept of temporal stability, proposed by Vachaud et al. (1985) is used in several previous studies to identify sites where soil moisture is considered to be most representative of the spatial mean soil moisture within a network (e.g. Kamgar et al., 1993; Teuling et al., 2006; Brocca et al., 2010). Following Vachaud et al. (1985), the difference ΔS_{tn} between the soil moisture S_{tn} and the spatial mean soil moisture $\mu_{\hat{n}}(S_{tn})$ is defined as:

$$\Delta S_{tn} = S_{tn} - \mu_{\hat{n}}(S_{tn}). \tag{10}$$

Its relative difference is:

$$\delta S_{tn} = \frac{\Delta S_{tn}}{\mu_{\hat{n}}(S_{tn})}, \tag{11}$$

and its temporal mean $\mu_{\hat{t}}(\delta S_{tn})$ and temporal standard deviation $\sigma_{\hat{t}}(\delta S_{tn})$ are estimated as:

$$\mu_{\hat{t}}(\delta S_{tn}) = \frac{1}{T}\sum_{t=1}^{T}(\delta S_{tn}), \tag{12}$$

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$$\sigma_{\hat{t}}(\delta S_{tn}) = \sqrt{\frac{1}{T}\sum_{t=1}^{T}(\delta S_{tn} - \mu_{\hat{t}}(\delta S_{tn}))^2}. \tag{13}$$

The $\mu_{\hat{t}}(\delta S_{tn})$ or $\mu_{\hat{t}}(\Delta S_{tn})$ of the sites are ranked from the smallest to the largest difference. Sites closest to $\mu_{\hat{n}}(S_{tn})$, i.e. $\mu_{\hat{t}}(\delta S_{tn}) \approx 0$ are considered to be the most representative of the overall network.

Using Eq. (4), the temporal stability analyses (Eqs. 10–13) can be extended by including the different contributors to absolute soil moisture. As a_{tn} can have negative values the absolute value of the difference for a_{tn} and m_n are used:

$$|\Delta a_{tn}| = |a_{tn} - \mu_{\hat{n}}(a_{tn})|, \tag{14}$$

$$|\Delta m_n| = |m_n - \mu_{\hat{n}}(m_n)|. \tag{15}$$

The temporal mean and standard deviation of the anomalies $\mu_{\hat{t}}(\Delta a_{tn})$ and $\sigma_{\hat{t}}(\Delta a_{tn})$ can be analyzed to provide a ranking of the sites according to their respective deviation from the overall mean. Similarly, the absolute deviation of the temporal mean Δm can also provide a ranking. To relate the new ranking to the ranking of the overall soil moisture, the framework by Vachaud et al. (1985) is adapted here by considering the absolute terms $|\delta S|$ and $|\Delta S|$, respectively.

In this study, we are interested in the ranking of the single sites and not in the differences themself. The comparison of the rank of the absolute soil moisture S_{tn} with the ranks of its decomposed parts m_n and a_{tn} allows us to make a statement on how the framework of rank stability (Vachaud et al., 1985) incorporates the soil moisture dynamics.

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3 Application to the SwissSMEX network

3.1 Studied network and data

The Swiss Soil Moisture Experiment (SwissSMEX) network (http://www.iac.ethz.ch/url/research/SwissSMEX) has a spatial extent of about 150 × 210 km and consists of overall 19 sites, covering different land use and climatic regimes of Switzerland. For further information about the set up and instrumentation of the network see Mittelbach et al. (2011). In the present study 14 grassland sites with no slope are included. Their location, respective climatic region (Müller, 1980), and average soil texture over 50 cm are shown in Fig. 1. At each site, measurements of volumetric water content (VWC) at 5, 10, 30, and 50 cm depth as well as precipitation (P) and 2-m air temperature (T_{air}) are available. The VWC at the different depths were integrated over 50 cm using the trapezoidal method (e.g. Hupet et al., 2004) including an additional value of VWC at the surface, which is set equal to the measurement in 5 cm depth. The analysis is based on daily aggregated data for the time period 1 May 2010 to 31 July 2011, including the particular dry months April and May 2011.

3.2 Relation between spatial variance and spatial mean

Brocca et al. (2007) investigate the relation between $\sigma^2_{\hat{n}}(S_{tn})$ and $\mu_{\hat{n}}(S_{tn})$, as well as the relation between the coefficient of variation ($CV = \sigma(S_{tn})/\mu_{\hat{n}}(S_{tn})$) and $\mu_{\hat{n}}(S_{tn})$, based on measurements from several networks. Based on these data they identified an increasing spatial variability with decreasing mean soil moisture for humid climates. The corresponding relation for the measurements used in the current study with their temporal occurrence is shown in Fig. 2a and b. Similar to Brocca et al. (2007) an increasing variability with decreasing spatial mean is found. However, the values of spatial variability scatter more widely when spatial mean soil moisture decreases (Fig. 2a). The nearly steady spatial variability with decreasing spatial mean soil moisture for April and May 2011 is particularly seen for $\sigma^2_{\hat{n}}(S_t)$. The relation for the anomalies (Fig. 2c) shows

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the behavior of soil moisture, when the temporal mean state of each site is removed and only its dynamics are considered. A parabolic shape with expected smallest variability for moisture conditions close to the spatial mean $m_{\widehat{n}}$, with $\mu_{\widehat{n}}(a_{tn}) \approx 0$, is found. Interestingly, the dry period of April and May 2011 is not as outstanding for the soil moisture anomalies (Fig. 2c) as when considering the absolute soil moisture (Fig. 2a, b), given that it shows an increase in variability similar to that seen in July and August 2010. For both absolute soil moisture as well as its anomalies, a temporal dependency in the sequence of the relation is found. Indeed, for the absolute soil moisture, highest spatial mean related to lowest spatial variance, e.g. for the DJF season, and lowest spatial mean related to highest spatial variance, e.g. for May to August, are found. On the other hand, the relation of the anomalies reflect the longer dry period from July 2010 to the beginning of August 2010 and the particularly dry April and May 2011 (see Fig. 3a for the spatial P and T_{air} during these periods).

3.3 Time series of spatial variability

Figure 3 displays the time series of the spatial mean and spatial standard deviation for P and T_{air} (Fig. 3a), which show a higher and more fluctuating variability in P and a more spatially homogeneous T_{air}. Figure 3b shows the spatial mean $\mu_{\widehat{n}}(S_{tn})$ and spatial standard deviation $\sigma_{\widehat{n}}(S_{tn})$ of absolute soil moisture. The term $\mu_{\widehat{n}}(S_{tn})$ is positively related to P and negatively related to T_{air} and shows smallest variability during the winter months. While the time series of spatial mean of the anomalies $\mu_{\widehat{n}}(a_{tn})$ (Fig. 3c) show a similar behavior to $\mu_{\widehat{n}}(S_{tn})$, its standard deviation $\sigma_{\widehat{n}}(a_{tn})$ (Fig. 3c, grey band) displays a higher variability than $\sigma_{\widehat{n}}(S_{tn})$. A notable increase in $\sigma_{\widehat{n}}(a_{tn})$ is visible during longer-lasting periods with no rain over the whole network, such as in July to August 2010 and April to May 2011, but also during longer lasting periods with rain at all sites, such as the end of August 2010.

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3.4 Time series of decomposed spatial variability

The temporal evolution of the spatial variance of absolute soil moisture and its components according to Eq. (8) are shown in Fig. 3d. Their respective percentage is shown in Fig. 3e and summarized over the DJF, MAM, JJA, and SON seasons in Fig. 4a. As indicated in Fig. 3c, $\sigma^2_{\hat{n}}(S_{tn})$ displays clear lower variability for the winter and spring months compared with the summer and autumn seasons. The time invariant $\sigma^2_{\hat{n}}(m_n)$ contributes most to $\sigma^2_{\hat{n}}(S_{tn})$ with percentages ranging from about 50 to 160 %, with largest percentages and exceedance of $\sigma^2_{\hat{n}}(S_{tn})$ during the DJF and MAM seasons, but also during particularly wet or dry conditions, such as in May 2010 as well as in April and May 2011. This exceedance is compensated by the time variant contributors $\sigma^2_{\hat{n}}(a_{tn})$ and $\mathrm{cov}(m_n,a_{tn})$, and reflects a negative contibution of $\mathrm{cov}(m_n,a_{tn})$ of about 50 % during these periods. The contribution of $\sigma^2_{\hat{n}}(a_{tn})$ is smallest and ranges between about 2 to 30 % and is highest for MAM and JJA with an average percentage of 10 % (Fig. 4a). Interestingly, $\sigma^2_{\hat{n}}(a_{tn})$ shows an increase during particularly dry periods, such as in July 2010 as well as in April and the mid of May 2011, which are not seen in $\sigma^2_{\hat{n}}(S_{tn})$. Summarized by seasons (Fig. 4a), the smallest percentages of $\sigma^2_{\hat{n}}(m_n)$ and highest percentages of the summed $\sigma^2_{\hat{n}}(a_{tn})$ and $\mathrm{cov}(m_n,a_{tn})$ are found for the summer season (JJA). This indicates that the soil moisture dynamics has the largest impact on the spatial variability in this season. Figure 4b confirms that the spatial variance of absolute soil moisture is equal to the sum of the single terms in Eq. (8). The discrepancies from the 1:1 line correspond to missing values at single sites.

The relation between the single contributors can be seen in the scatter plots of Fig. 5. The scatter plot between $\sigma^2_{\hat{n}}(a_{tn})$ and $\sigma^2_{\hat{n}}(S_{tn})$ (Fig. 5a) shows a general positive relation between these two terms. However, for $\sigma^2_{\hat{n}}(S_{tn}) < \sigma^2_{\hat{n}}(m_n)$ the data scatters more widely, and moreover, the particular dry May enhances this scatter, indicating the above mentioned dynamics, which is not found in the total soil moisture variance. A positive, mostly linear, relation between $\mathrm{cov}(m_n,a_{tn})$ and $\sigma^2_{\hat{n}}(S_{tn})$ is identified in Fig. 5b. The contribution of $\mathrm{cov}(m_n, a_{tn})$ results in positive but also negative values, where negative values occur for $\sigma^2_{\hat{n}}(S_{tn}) < \sigma^2_{\hat{n}}(m_n)$. The different sign of $\mathrm{cov}(m_n, a_{tn})$ for $\sigma^2_{\hat{n}}(S_{tn})$ above or below $\sigma^2_{\hat{n}}(m_n)$ implies a change in the relation between $\sigma^2_{\hat{n}}(m_n)$ and $\sigma^2_{\hat{n}}(a_{tn})$, which depends on the structure of anomalies, as the variability in the mean stays the same over time.

3.5 Temporal stability of absolute soil moisture and its dynamics

The rank ordered temporal mean of relative difference δS_{tn} as well as of absolute difference ΔS_{tn} after Vachaud et al. (1985) with one standard deviation is shown in Fig. 6a, b. The temporal mean of δS_{tn} varies between −35 % and 39 %, its standard deviation varies between 3 % and 10 %. These values are comparable to values found in the literature using observations from networks with a smaller spatial extent (see e.g. Brocca et al., 2009, for a summary of the characteristics of temporal stabilty of different studies).

The rank ordered absolute value of differences for the total and decomposed soil moisture ($|\mu_{\hat{t}}(\delta S_{tn})|, |\mu_{\hat{t}}(\Delta S_{tn})|$, $|\Delta m_n|$, and $\mu_{\hat{t}}(|\Delta a_{tn}|)$) with one standard deviation, are shown in Fig. 6c, d and Fig. 7, respectively. As expected, the ranks of $|\mu_{\hat{t}}(\delta S_{tn})|$ and $|\mu_{\hat{t}}(\Delta S_{tn})|$ have the same order. In this study we focus on the ordered ranks of $|\mu_{\hat{t}}(\Delta S_{tn})|$ and we analyze their relation to the time-varying and time-invariant contributions by comparing the ranks of $|\mu_{\hat{t}}(\Delta S_{tn})|$ (Fig. 6d) with the ranks of the absolute differences of the decomposed soil moisture $|\Delta m_n|$ and $\mu_{\hat{t}}(|\Delta a_{tn}|)$ (Fig. 7a, b). Considering the ranks of the decomposed S_{tn} (Fig. 7), it is seen that the ranks of $|\mu_{\hat{t}}(\Delta S_{tn})|$ (Fig. 6d) are mostly reflected by the ranks of $|\Delta m_n|$ (Fig. 7a). The ranks of the temporal mean of the anomalies $\mu_{\hat{t}}(|\Delta a_n|)$ (Fig. 7b) show a contrasting sequence for the sites. The scatter plots of Fig. 8 indicate that the rank stability of S_{tn} contains information about the temporal mean of soil moisture, but is not related to the dynamics of soil moisture. Hence, this suggests that the evaluation of the stability of the rank ordering of $\mu_{\hat{t}}(\delta S_{tn})$ proposed by Vachaud et al. (1985) is a measure of the rank stability of mean soil

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moisture conditions within the SwissSMEX network but does not provide information on the varying spatio-temporal characteristics of the network.

4 Discussion

In this study we expand frequently used hydrological frameworks for the analysis of the spatio-temporal variability of soil moisture within a given network to distinguish between the contribution of the temporal mean and anomalies of soil moisture. Furthermore, we focus on how the dynamics of soil moisture is represented in these frameworks. Previous studies on related topics (e.g. Kamgar et al., 1993; Famiglietti et al., 1999; Teuling et al., 2006; Brocca et al., 2007) were mostly based on non-continuous observations or short-term campaigns and focused on the investigation of absolute soil moisture values. By contrast, this study is based on 15-months long continuous soil moisture measurements from 14 grassland sites of the SwissSMEX network. It analyzes the decomposed absolute soil moisture, including its time invariant temporal mean and its time variant dynamics, expressed as anomalies. The time invariant term is influenced by factors, that do not significantly change over time, such as the topography, soil texture, and land cover, while the time variant dynamics are controlled by factors that change at synoptic scale, such as climate variables. Another aspect contributing to the time invariant component is the climate regime over the considered time frame, which strictly speaking could be time varying if the analyzed time series spanned a longer time period, such as several years or decades. The decomposition enables us to investigate the spatio-temporal variability of absolute soil moisture with a focus on the contribution of its single components. Using long-term measurements provides furthermore the possibility to analyze the temporal evolution of the spatial variability of soil moisture.

First comparisons of the relation between the spatial variance and the spatial mean absolute soil moisture as well as for the temporal stability indicates an overall behavior that is consistent with previous reports from the literature (see Brocca et al., 2007, 2010, for a summary). Regarding the relation between the spatial variance and spatial

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mean absolute soil moisture, the relation for absolute soil moisture and its anomalies, respectively, are analyzed. Comparing both relations, a different variability is mainly found for average dry moisture contents. The particularly dry 2011 spring shows almost constant absolute soil moisture during the recession of the spatial mean moisture content, while the variability of the anomalies indicates an increased variability during this period.

Regarding the temporal evolution of the spatial variability of absolute soil moisture and the contribution of its time varying and time invariant parts, the results reveal that the variance of the time invariant mean is with 50 to 160 % the largest contributor to the overall spatial variability. The variance of temporal anomalies contributes by about 5 to 30 %. The covariance term of the temporal mean and anomalies results in correlations of both negative and positive signs, including periods of almost no correlation. For the DJF season the relation is continously negative with low variability over the whole period, whereas in the other seasons the correlation changes between positive and negative values, influenced by the meteorological conditions, with mainly positive values for JJA and SON. For periods with particularly wet but also particularly dry soil moisture conditions, as in the case of the dry 2011 spring, the correlation results in negative values and appears to get more negative with longer lasting duration. This implies that the sequence of the sites with respect to their mean status is not the same for their anomalies. Indeed, for the studied period the particularly dry 2011 spring shows the strongest increase of a negative correlation between the spatial variance of absolute soil moisture and anomalies, resulting in different potential controls of spatial variability during such periods. Furthermore, this suggests that the dynamics can vary strongly for the different sites, while their mean state stays similar. Findings of the rank stability analyses confirm that the ordered ranks of the temporal mean absolute soil moisture are similar to the ranks of its mean state, while the ranks of the soil moisture dynamics are not consistent with this ranking. Indeed, sites which are identified as being most representative for the spatial mean do not correspond to the sites that are most representative for the soil moisture dynamics within the network.

5 Conclusions

From the analyses of this study, we conclude that frequently used frameworks assessing spatio-temporal characteristics of soil moisture networks do generally not apply to temporal soil moisture anomalies. For the investigated data set, the analyses of the decomposed soil moisture reveals a small contribution of the dynamics to the overall variability of soil moisture. Reversely, this indicates a smaller spatial variability of the temporal dynamics than possibly inferred from the spatial variability of the mean soil moisture. Although the spatial variability of anomalies contributes with a smaller percentage to the whole spatial variance, its contribution is nonetheless not negligible compared to the actual values of the temporal anomalies. Based on our results we strongly encourage further analyses investigating the spatio-temporal characteristics of temporal soil moisture anomalies, in addition to those assessing temporal mean or absolute soil moisture. This is essential for investigations focusing on soil moisture dynamics e.g. on runoff generation, drought development, and land-atmosphere interactions (e.g. Entekhabi et al., 1996; Seneviratne et al., 2010), weather and seasonal forecasting (e.g. Beljaars et al., 1996; Koster et al., 2010; Weisheimer et al., 2011) or climate change applications. To our knowledge this is the first study focusing on the spatio-temporal variability of soil moisture that provides a separate analysis for its time varying and time invariant components. The presented framework could be easily applied to further long-term data sets to investigate the spatial and temporal variability of soil moisture and its dynamics under various climate conditions.

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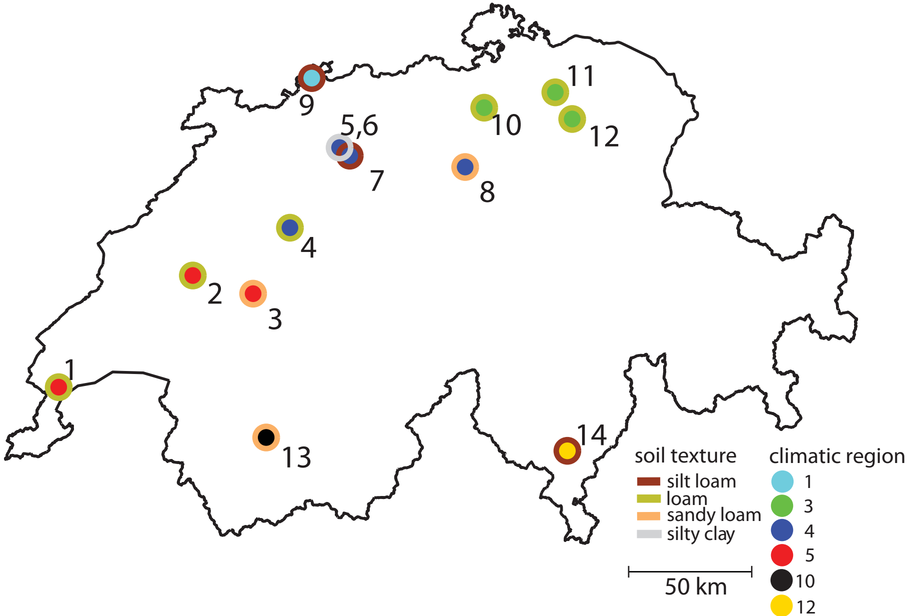

Fig. 1. Map of Switzerland showing the location, climatic region, and soil texture (according to USDA taxonomy and averaged over 50 cm depth) of the 14 investigated grassland sites of the SwissSMEX network. The indicated climate regions are based on the classification of Müller (1980).

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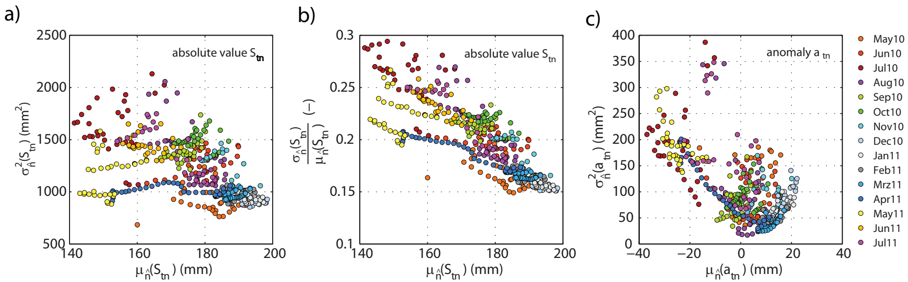

Fig. 2. Scatter plots of **(a)** the spatial mean ($\mu_{\hat{n}}(S_{tn})$) vs. spatial variance ($\sigma^2_{\hat{n}}(S_{tn})$) of daily absolute soil moisture, **(b)** the coefficient of variation ($\sigma_{\hat{n}}(S_{tn})/\mu_{\hat{n}}(S_{tn})$) vs. the spatial mean ($\mu_{\hat{n}}(S_{tn})$) of daily absolute soil moisture, as well as **(c)** the spatial mean ($\mu_{\hat{n}}(a_{tn})$) vs. spatial variance ($\sigma^2_{\hat{n}}(a_{tn})$) of daily anomalies. The different colors indicate daily data of the single months.

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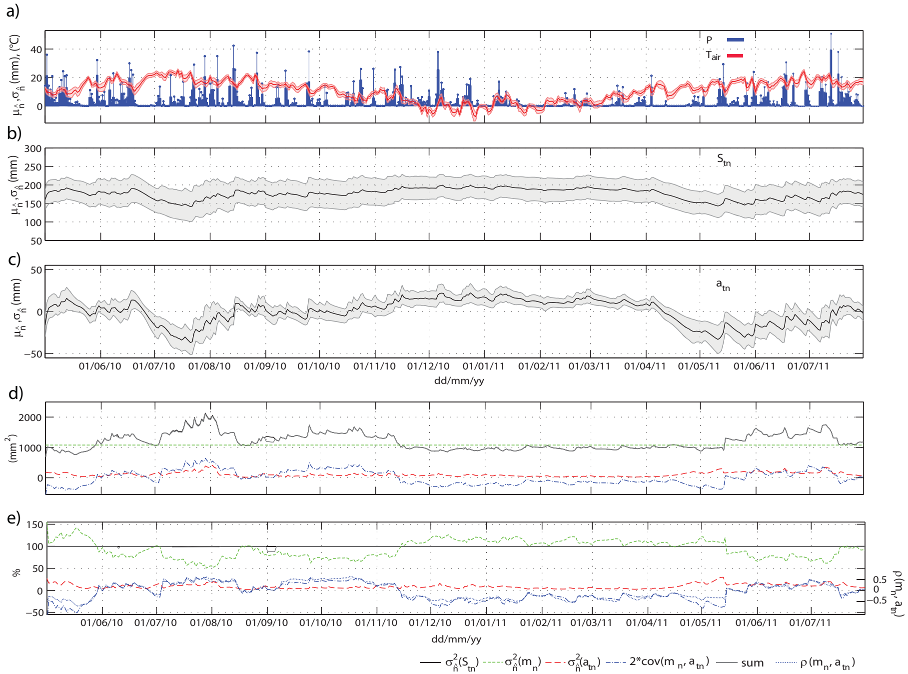

Fig. 3. Time series of spatial mean and spatial standard deviation (shaded areas) for **(a)** precipitation and 2-m air temperature, **(b)** absolute soil moisture, and **(c)** anomalies of absolute soil moisture. Decomposition of spatial variance of absolute soil moisture into its contributors according to Eq. (7) expressed **(d)** in mm^2 and **(e)** as percentage.

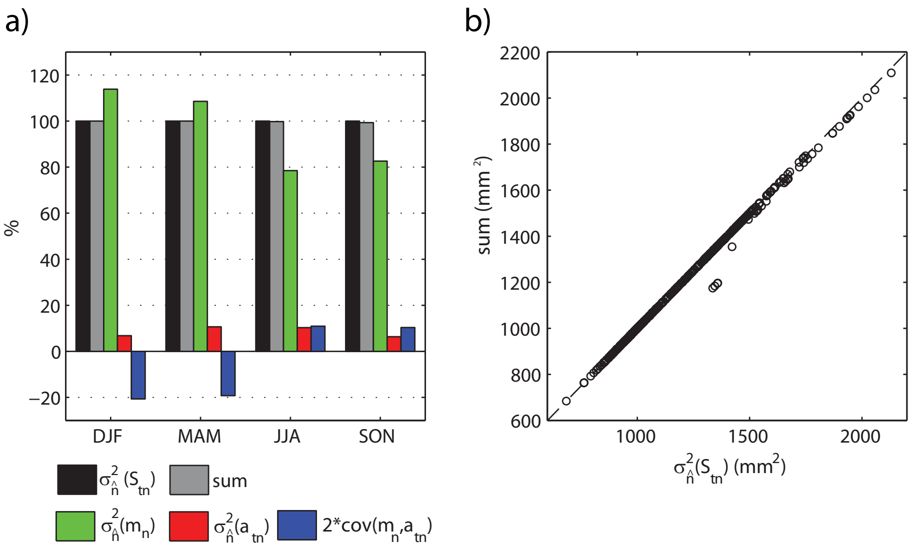

Fig. 4. (a) Percentage of the single contributors to the spatial variance of absolute soil moisture ($\sigma^2_{\hat{n}}(m_n)$, $\sigma^2_{\hat{n}}(a_{tn})$ and $2*\mathrm{cov}(m_n, a_{tn})$) averaged over the seasons DJF, MAM, JJA, and SON. **(b)** Scatter plot of the spatial variance of absolute soil moisture vs. the sum of the single contributors.

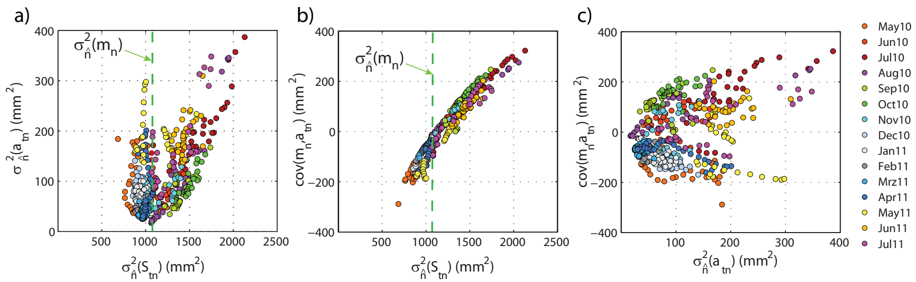

Fig. 5. Scatter plots of **(a)** the spatial variance of absolute soil moisture ($\sigma^2_{\hat{n}}(S_{tn})$) vs. spatial variance of anomalies ($\sigma^2_{\hat{n}}(a_{tn})$), **(b)** spatial variance of absolute soil moisture vs. spatial covariance of mean and anomalies $2*\mathrm{cov}(m_n, a_{tn})$, and of **(c)** spatial variance of anomalies vs. the spatial covariance between the mean and anomalies. The green dotted line represents the variance of spatial temporal mean ($\sigma^2_{\hat{n}}(m_n)$).

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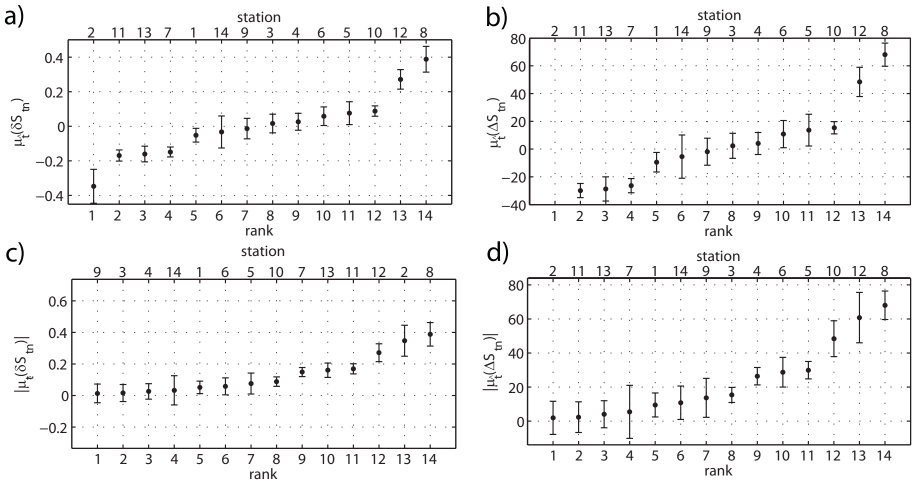

Fig. 6. Rank stability plots of **(a)** the temporal mean of relative difference of absolute soil moisture $\mu_{\hat{t}}(\delta S(_{tn}))$, **(b)** the temporal mean of difference of absolute soil moisture $(\mu_{\hat{t}}(\Delta S_{tn}))$, **(c)** the absolute values of temporal mean of the relative difference of absolute soil moisture $|\mu_{\hat{t}}(\delta S(_{tn}))|$, and **(d)** the absolute values of temporal mean of difference of absolute soil moisture $|\mu_{\hat{t}}(\Delta S(_{tn}))|$. The vertical lines represent ± one standard deviation. The sites have been ranked according to their mean differences.

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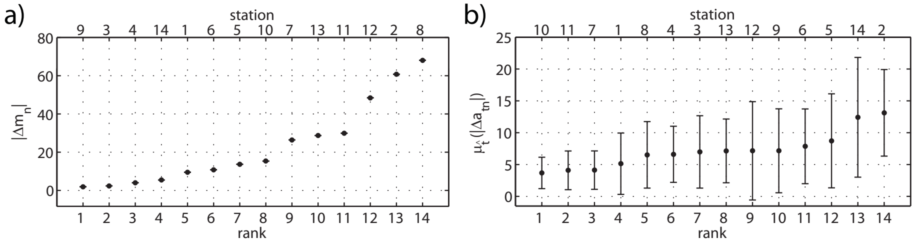

Fig. 7. Rank stability plots of **(a)** the absolute value of temporal mean ($|m_n|$), and **(b)** the temporal mean of the absolute values of differences of anomalies ($\mu_{\hat{t}}(|\Delta a_{tn}|)$). The vertical lines represent ± one standard deviation. The sites have been ranked according to their mean differences.

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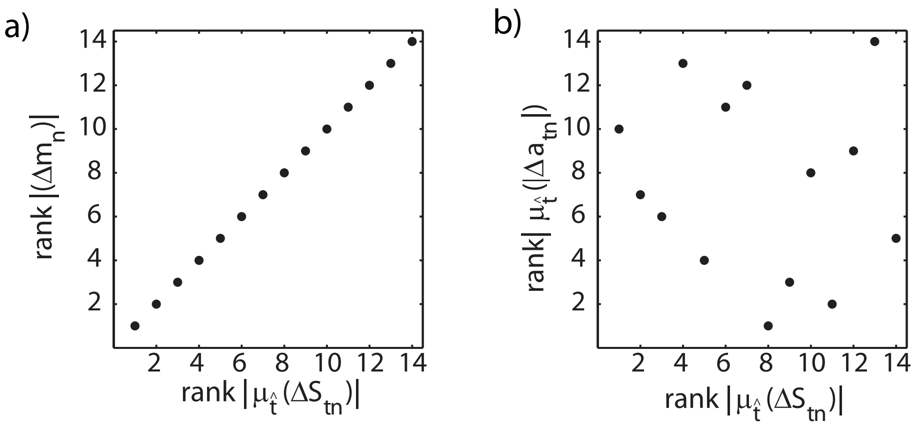

Fig. 8. Scatter plots of **(a)** the rank of absolute value of temporal mean ($|m_n|$) vs. the rank of absolute values of temporal mean difference of absolute soil moisture ($|\mu_{\hat{t}}(\Delta S_{tn})|$) and **(b)** the rank of absolute values of temporal mean difference of absolute soil moisture vs. the rank of temporal mean of absolute values of differences of anomalies ($\mu_{\hat{t}}(|\Delta a_{tn}|)$).

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