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Catchment scale soil moisture spatial–temporal variability

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SUMMARY

The characterization of the spatial–temporal variability of soil moisture is of paramount importance in many scientific fields and operational applications. However, due to the high variability of soil moisture, its monitoring over large areas and for extended periods through in situ point measurements is not straightforward. Usually, in the scientific literature, soil moisture variability has been investigated over short periods and in large areas or over long periods but in small areas. In this study, an effort to understanding soil moisture variability at catchment scale (>100 km^2), which is the size needed for some hydrological applications and for remote sensing validation analysis, is done. Specifically, measurements were carried out in two adjacent areas located in central Italy with extension of 178 and 242 km^2 and over a period of 1 year (35 sampling days) with almost weekly frequency except for the summer period because of soil hardness. For each area, 46 sites were monitored and, for each site, 3 measurements were performed to obtain reliable soil moisture estimates. Soil moisture was measured with a portable Time Domain Reflectometer for a layer depth of 0–15 cm. A statistical and temporal stability analysis is employed to assess the space–time variability of soil moisture at local and catchment scale. Moreover, by comparing the results with those obtained in previous studies conducted in the same study area, a synthesis of soil moisture variability for a range of spatial scales, from few square meters to several square kilometers, is attempted. For the investigated area, the two main findings inferred are: (1) the spatial variability of soil moisture increases with the area up to ~10 km^2 and then remains quite constant with an average coefficient of variation equal to ~0.20; (2) regardless of the areal extension, the soil moisture exhibits temporal stability features and, hence, few measurements can be used to infer areal mean values with a good accuracy (determination coefficient higher than 0.88). These insights based on in situ soil moisture observations corroborate the opportunity to use point information for the validation of coarse resolution satellite images. Moreover, the feasibility to use coarse resolution data for hydrological applications in small to medium sized catchments is confirmed.

1. Introduction

Understanding soil moisture variability across spatial–temporal scales is of great interest in many scientific and operational applications such as flood prediction and forecasting (Brocca et al., 2010c; Koster et al., 2010), numerical weather prediction (Entekhabi, 1995; Albergel et al., 2010), climate (Koster et al., 2004) and agricultural modeling (De Wit et al., 2007; Bolten et al., 2010), to cite a few. At present, soil moisture variability at large scale (>100 km^2) is poorly understood due to the difficulties of conducting soil moisture measurements. In fact, it is widely known that the classical techniques based on point sampling furnish accurate soil moisture estimates (errors less than 2% vol/vol) but the measurement support is limited to few square meters (see e.g. Hupet and Vanclooster, 2002; Brocca et al., 2007; Penna et al., 2009). On the other hand, larger areas can be monitored through sensors on board of satellite platforms, but the satellite products are characterized by a limited spatial–temporal resolution and their accuracy has still to be tested (Brocca et al., 2010b, 2011). Geophysical techniques can be employed to fill the resolution gap between satellite and in situ measurement methods even though the retrieval of soil moisture from these techniques is still at an early stage (see e.g. Robinson et al., 2008; Calamita et al., submitted for publication).

In the scientific literature, studies analyzing soil moisture campaigns for long time periods but over limited areas (e.g. Teuling et al., 2006; De Lannoy et al., 2007; Hu et al., 2010) or for large areas but for a narrow time span (e.g. Jacobs et al., 2004; Choi and Jacobs, 2007, 2010; Famiglietti et al., 2008; Merlin et al., 2008; Panciera et al., 2008) can be easily found. By setting up specific continuous monitoring networks, few studies have investigated soil moisture variability over large areas (>100 km^2) and for a long time period (at least one year) (Vinnikov et al., 1996; Entin et al., 2000; Fernandez and Ceballos, 2005).

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The two most important results obtained by these studies on soil moisture variability over large areas can be summarized as follows:

(1) Soil moisture spatial pattern can be represented by a small scale component dominated by soil type, topography and vegetation, and a large scale component due to atmospheric quantities, such as precipitation and evapotranspiration (Entin et al., 2000).
(2) Soil moisture spatial pattern exhibits temporal stability (Vachaud et al., 1985), or more appropriately "rank stability" (Chen, 2006), for a wide range of scales as derived from studies based on in situ measurements and/or modeling approaches (Grayson and Western, 1998; Loew and Schlenz, 2011).

As concerns the point (2), the relationship between soil moisture temporal pattern at large and point scale has provided the opportunity to exploit local measurements for the validation of coarse resolution satellite soil moisture estimates (Cosh et al., 2004; Koster et al., 2009; Entekhabi et al., 2010; Mascaro et al., 2010; Miralles et al., 2010; Loew and Schlenz, 2011). For instance, Loew and Schlenz (2011), for a small sub-catchment located in Southern Germany, investigated different approaches to infer the error of the satellite product from the uncertainties associated to the up-scaling of in situ soil moisture observations showing that the point-to-area sampling error is very low. Miralles et al. (2010) obtained very similar results analyzing four experimental watersheds in US and concluded that it is feasible to validate satellite footprint-scale soil moisture products using existing low-density ground networks.

For similar reasoning, it is expected that areal measurements of soil moisture through coarse resolution satellite sensors could be representative for smaller areas (Loew and Mauser, 2008; Wagner et al., 2008), and, hence, these data might be valuably embedded in rainfall-runoff models applied for medium sized catchments with extension lower than 400 km^2 (Brocca et al., 2010b). In particular, by analyzing long ENVISAT ASAR (Advanced Synthetic Aperture Radar) imagery time series, Wagner et al. (2008) showed that simple linear time-invariant models can be used to predict radar backscatter at point and local scales based on regional observations, and viceversa. These models have been used for downscaling coarse resolution (25 km) satellite soil moisture estimates from ASCAT (Advanced SCATterometer) to ASAR (1 km) resolution (e.g. Matgen et al., 2011).

Based on the above discussion, it is clear that the characterization of soil moisture spatial–temporal variability for areas larger than 100 km^2 is fundamental for the development of upscaling and downscaling techniques and, particularly, for flood prediction and forecasting purposes. For some basins located in central Italy, several studies have investigated the soil moisture spatial–temporal variability both at the plot (less or equal to 0.01 km^2) (Brocca et al., 2007, 2009) and at the small catchment scale (up to 60 km^2) (Brocca et al., 2010a). In these works statistical, spatial variability and temporal stability analyses were carried out to fully characterize the soil moisture behavior. In particular, it was found that: (i) soil moisture spatial variability increases with the size of the investigated area and, (ii) all soil moisture spatial fields are characterized by a significant temporal stability.

The main objective of this paper is to extend the results previously obtained on the spatial–temporal variability of soil moisture from the small to the medium catchment scale. For this purpose, two study areas of 178 and 242 km^2 are considered for which weekly soil moisture field campaigns were carried out in 46 sites during a period of 1-year, thus obtaining a total of 35 sampling days. Two specific points are addressed in the study: (i) how the spatial variability of soil moisture varies increasing the investigated area, and (ii) which is the optimal number of point measurements for estimating the average soil moisture temporal pattern of the entire area.

2. Methods

Methods of analysis used are summarized in the sequel. Henceforth, for sake of clarity, we explain the terminology used in this article. "Point" is the ground location in which the measurement is carried out; "site" represents the mean location of a group of points; "area" is the region where a group of sites are located; "sampling day" refers to a single day during which a number of measurements is made; and "campaign" stand for the entire set of sampling days for a given area.

2.1. Statistical method

The analysis regards the characterization of the statistical properties of soil moisture samples. In particular, the main statistical features of each campaign are analyzed in terms of their variability in space and in time.

Let θ_{ijk} the soil moisture observed at point i, site j and sampling day k, then the spatial mean of the site j and sampling day k, $\overline{\theta_{jk}}$, is given by:

$$\overline{\theta_{jk}} = \frac{1}{N_p}\sum_{i=1}^{N_p}\theta_{ijk} \tag{1}$$

where N_p is the number of measurement points at the site j. As a consequence, the spatial mean of each sampling day, $\overline{\theta_k}$, is given by:

$$\overline{\theta_k} = \frac{1}{N}\sum_{j=1}^{N}\overline{\theta_{jk}} \tag{2}$$

where N is the number of sites. Similarly, the temporal mean for each site, $\overline{\theta_j}$, can be defined as:

$$\overline{\theta_j} = \frac{1}{M}\sum_{k=1}^{M}\overline{\theta_{jk}} \tag{3}$$

where M is the number of sampling days.

The coefficient of variation of each sampling day in space, CV_k, is calculated as follows:

$$CV_k = \frac{\sigma_k}{\overline{\theta_k}} = \frac{\sqrt{\frac{1}{N-1}\sum_{j=1}^{N}\left(\overline{\theta_{jk}}-\overline{\theta_k}\right)^2}}{\overline{\theta_k}} \tag{4}$$

where σ_k is the standard deviation. Similarly, the coefficient of variation, CV_j, and the standard deviation, σ_j, of each sampling site in time can be defined.

For each sampling day, a "local" coefficient of variation, CV_k^{local}, is computed by averaging the ones determined for each site as follows:

$$CV_k^{local} = \frac{1}{N}\sum_{j=1}^{N}CV_{jk} = \frac{1}{N}\sum_{j=1}^{N}\left(\frac{\sigma_{jk}}{\overline{\theta_{jk}}}\right) \tag{5}$$

where σ_{jk} and CV_{jk} are the standard deviation and the coefficient of variation, respectively, of the sampling site j and sampling day k. In other words, CV_k^{local} is the average of the coefficients of variation computed for each of N sites where N_p measurements are done.

The knowledge of the standard deviation, σ, allows to determine the Number of Required Samples, NRS, for estimating the mean value within a specific absolute error and it is given by the following implicit equation (Wang et al., 2008):

$$\mathrm{NRS} = t^2_{1-\alpha/2,NRS-1}\frac{\sigma^2}{\mathrm{AE}^2} \tag{6}$$