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Screening long-term variability and change of soil moisture in a changing climate

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SUMMARY

Soil moisture is an essential component of water variability and change in the landscape. This paper develops a conceptual and analytical framework for linking hydro-climatic change at the surface and soil-groundwater conditions in the subsurface, and quantifying long-term development of soil moisture statistics in a changing climate. Soil moisture is evaluated both in the unsaturated zone and over a fixed soil depth that may also include a variable groundwater table. Long-term variability and change of soil moisture are assessed for a hydro-climatic observation record that extends over the whole 20th century in a major Swedish drainage basin. Frequencies of particularly dry and wet soil moisture events are investigated for different 20-year climatic periods. Results show major increase in the frequency of dry events from the beginning to the end of the 20th century. This indicates increased risk for hydrological and agricultural drought even though the risk for meteorological drought, in terms of precipitation, has decreased in the region. The developed quantification framework can also be used to screen future scenarios of soil moisture change under projected climate change.

1. Introduction

Soil moisture variability and change in a landscape plays a central role for land-climate interactions in the climate system, and for hydrological and biogeochemical cycling, waterborne solute and pollutant transport, and vegetation, ecosystem and agricultural conditions in the landscape (Destouni and Cvetkovic, 1989, 1991; Seneviratne et al., 2010). Soil moisture is often quantified in terms of volumetric water content (ratio of water volume to bulk soil volume, with values between zero and soil porosity) and/or degree of saturation (ratio of water volume to total pore volume in a given bulk soil volume, with values between zero and one). Both of these quantities relate to some bulk soil volume, which may extend over different spatial scales (Brocca et al., 2010) – from centimeters to kilometers – depending on the question of interest and the measurement method used to answer it.

Measurement methods include local ground and soil sample measurements, which may be aggregated to represent soil moisture statistics over depth (e.g., Destouni, 1991, 1992), field plots (e.g., Graham et al., 1998) and possible larger landscape scales by consideration of available database networks (Dorigo et al., 2011). Measurement methods may also include ground-based, air-borne, and space-borne remote sensing techniques that capture multiple spatial scales (Kerr et al., 2001; Mohanty et al., 2013).

Soil moisture commonly refers to conditions in the unsaturated (vadose) soil zone, where pore water pressure is less than air pressure, and the pore water fills only part of the available pore space except in a capillary fringe just above the groundwater table. However, the unsaturated zone extent down to the groundwater table is not constant because the position of the groundwater table (by definition where water pressure equals air pressure) is not constant. Both the unsaturated zone extent and the groundwater table vary temporally with forcing weather and hydro-climatic conditions at the surface, and spatially, for instance depending on topography and soil type distribution, over the landscape (Destouni and Cvetkovic, 1989; Bosson et al., 2012). Soil moisture over a fixed soil depth may thus, at different points in space and time, include and reflect conditions in both the unsaturated zone above and the groundwater zone below the groundwater table, with water content in the latter equaling porosity and degree of saturation equaling one.

Soil moisture models address different soil depth extents in different contexts and for different types of questions. For example, a water balance equation may be set up over some hydrologically active soil depth (e.g., the root zone, or the whole unsaturated zone)

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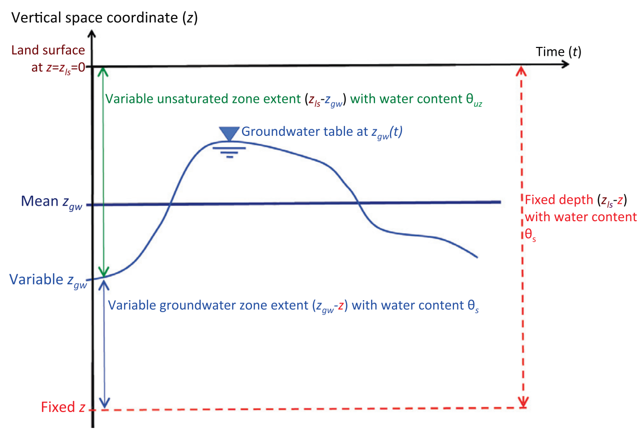

Fig. 1. Schematic conceptualization of different soil moisture quantities.

to investigate soil moisture interactions with surface hydro-climate (e.g., Rodriguez-Iturbe et al., 1991) and with hydrological flows through the landscape (Botter et al., 2007). Furthermore, soil moisture is also included as a variable in constitutive relations of soil hydraulic properties (e.g., Morel-Seytoux et al., 1996), which differ depending on soil type and are, for instance, used in model expressions of long-term, field-scale solute transport through the unsaturated zone (e.g., Destouni, 1993; Russo, 1998) and the integrated soil-groundwater systems (Destouni and Graham, 1995).

There are thus different, complementary ways of viewing and quantifying soil moisture conditions in a landscape, with a water balance-focused model, e.g., accounting explicitly for hydro-climatic variability and change at the surface, and a soil-focused model, e.g., accounting primarily for conditions in the subsurface. A novel contribution of the present study is to conceptually and analytically link these different approaches to soil moisture modeling. The linkage enables relatively simple first order quantification and screening of long-term field-scale variability and change in soil moisture and its statistics under a changing climate.

The developed linked analytical framework is further concretely evaluated for historically observed hydro-climatic conditions and different soils in a major Swedish hydrological drainage basin (Norrström; Darracq et al., 2005; Jaramillo et al., 2013). The evaluation includes soil moisture in the unsaturated zone and over a fixed soil depth with variable unsaturated-groundwater zone extents. The main evaluation focus is on the change in frequency of particularly dry and wet soil moisture events from the beginning to the end of the 20th century.

2. Materials and methods

2.1. Conceptualization and quantification framework

We consider a soil profile of depth extent z_{ls}–z [L], with the vertical z-axis being positive upwards and z_{ls} being the land surface position along z (Fig. 1). The generally variable groundwater table position at z_{gw} determines the variable depth extent of the unsaturated zone, z_{ls}–z_{gw}, and that of the groundwater zone, z_{gw}–z, within the considered total depth z_{ls}–z. In the following, we will without loss of generality set the land surface position $z_{ls} = 0$.

The dynamics of soil moisture are analyzed in terms of depth-average volumetric water content θ_{uz} [−] (referred to as just water content in the following) in the unsaturated zone, and corresponding water content θ_z [−] over the whole soil depth $-z$ (Fig. 1). Using the soil constitutive relations of Brooks and Corey (1964), the unsaturated hydraulic conductivity K [LT^{-1}] in the unsaturated zone may be expressed as function of water content θ_{uz} as:

$$K(\theta_{uz}) = K_s\left(\frac{\theta_{uz}-\theta_{ir}}{\theta_s-\theta_{ir}}\right)^{1/\beta} \quad (1)$$

where K_s [LT^{-1}] is the hydraulic conductivity and θ_s [−] is the soil water content at saturation; the latter may be assumed equal to porosity (Entekhabi et al., 2010; Kumar, 1999). Furthermore, θ_{ir} [−] is a residual soil water content, and $\beta = 1/(3 + 2\alpha)$ [−] and α [−] are characteristic soil parameters linked to the pore size distribution of different soil types (Rawls et al., 1982; Saxton et al., 1986); the Brooks and Corey (1964) parameters values needed to evaluate Eq. (1) are also readily related to corresponding ones in alternative constitutive relations of van Genuchten (1980) and vice versa (Morel-Seytoux et al., 1996).

We further utilize the field-scale unsaturated flow and transport model of Dagan and Bresler (1979) and Bresler and Dagan (1981) for steady vertical gravity-driven flow, for which a unit hydraulic gradient may be assumed and the unsaturated hydraulic conductivity K in Eq. (1) can be equated with the average vertical soil water flux q [LT^{-1}] of groundwater recharge. This modeling approach is approximate but has been found sufficiently applicable for statistical analysis of field-scale water content by its original developers (Dagan and Bresler, 1979; Bresler and Dagan, 1981) and in multiple subsequent studies (e.g., Destouni and Cvetkovic, 1989, 1991; Destouni, 1993; Destouni and Graham, 1995). Reorganization of Eq. (1) with use of $K \approx q$ quantifies then a depth-averaged (regularized) unsaturated water content θ_{uz} above the groundwater table (Destouni, 1991, 1992] (rather than the detailed variability of water content with depth) as:

$$\theta_{uz} = \left(\frac{q}{K_s}\right)^{\beta}(\theta_s-\theta_{ir}) + \theta_{ir} \quad (2)$$

For realistic transience of daily water flux q, numerical experimentation has shown a standard error of $\leqslant$10% for use of this approximate model of regularized water content over soil depths of 1–1.8 m (Destouni, 1991; Table 7 in that study for results of arithmetic depth-averaging and consideration of root water uptake in total evapotranspiration). In the approximate Eq. (2), the flux q was then average groundwater recharge over time periods ranging from four months to five years (depending on average travel time of infiltrated water to the different soil depths in different soil types) and results were compared with those from fully transient modeling. Furthermore, field experimentation has shown that use of such regularized water content works well as basis for statistical quantification of field-scale solute transport through the unsaturated zone also for much smaller scales of temporal q

Table 1
Observation data for precipitation P, actual evapotranspiration ET and runoff R in the Norrström drainage basin and their sources.

Parameter	Dataset used	Time period of used data	Source
P	Monthly global 0.5° × 0.5° grid data (CRU TS 2.1)	1901–2002	Mitchell and Jones (2005)
ET	Monthly global 0.05° × 0.05° grid data (MODIS-16 ET)	2000–2010	ORNL DAAC (2011)
R	Daily discharge of the Ovre SMHI station	1901–2002	SMHI (2010)