Physical insights into soil water storage in the soil–plant–atmosphere system

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Abstract This paper provides insights into preferential states of soil water storage that are active in the soil–plant–atmosphere system. Considerations are based on *in situ* soil moisture data and the NOAA-NCEP/NCAR re-analysis data. The major findings are: (1) re-analysis data generally reproduce the dynamics of the soil moisture detected by *in situ* observations, (2) analysis of the propagation of preferential wetness states has lead to the separation of wet and dry conditions, and (3) the applied theoretical framework sufficiently links chosen parameters of soil and climate to the relative frequency of wetness states and provides a tool for the simulation of the probability of wetness states.

Key words soil water storage; data sets; preferential states; frequency; central Poland

INTRODUCTION

The moisture content of the upper soil layers plays an important role in the soil–vegetation–atmosphere system and is integral to most of the processes present at the land–atmosphere interface. Moreover, soil moisture essentially controls relationships between precipitation, infiltration, evapotranspiration and groundwater recharge (Harter & Hopmans, 2005). Although the importance of the vadose zone in the hydrological cycle has been recognized for a long time, the dynamics of soil water is rarely controlled through regular *in situ* monitoring. Therefore the *in situ* data collected from reference sites are still an integral part of the regional monitoring and research strategies, because they provide reliable, direct estimates for the verification of conceptual models and theories. Soil moisture parameters can also be retrieved from the re-analysis of remote sensing data. One of the most widely known soil moisture re-analysis data sets is available from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) that operate in the USA within NOAA (National Oceanic & Atmospheric Administration) (Kistler *et al*., 2001).

The aim of this study is to provide insights into soil water storage by comparing *in situ* measurements with the re-analysis data sets. In particular, the study investigates the existence of wet and dry modes of soil water storage, as hypothesized by D'Odorico & Porporato (2004). The specific objectives of this study were: (1) to investigate the possibility of using soil moisture re-analysis data to support *in situ* observations; (2) to document and define the propagation of preferential wetness states on seasonal and inter-annual time scales; and (3) to display the interactions between effective soil water storage and essential climate traits. Following the approach proposed by Porporato *et al*. (2004), the probability density function of effective relative soil moisture was simulated as an analytical solution of a simplified stochastic model of soil water balance. This approach links the plant-available soil water storage with rainfall and evapotranspiration parameters. An example of wetness conditions detected and modelled in the small basin of the Lasica Channel in central Poland, in moderate climate (52°13′N–52°26′N and 20°15′E–20°57′E) is presented.

DATA

A data set of soil moisture inferred from the *in situ* measurements was used for this study (Somorowska, 2005). It covers a 10-year period (1995–2004) of measurements conducted at 14 experimental sites in the Lasica basin. In addition, soil moisture data from two soil layers (0–10 cm and 10–200 cm) were inferred from surface variables of the NOAA-NCEP/NCAR re-analysis project. The extracted data was from the grid point 52.38°N, 20.625°E, which completely covers the area of the analysed basin. They were retrieved in the netCDF-format and processed using the NetCDF Toolbox of Matlab.

Data from the MARS-STAT Data Base Project (Monitoring Agricultural Statistics with Remote Sensing Project) were also used (Goot, 1997). Thus the data retrieved consisted of daily precipitation as well as Penman potential evaporation and transpiration at a horizontal resolution of 1°. The area of the analysed basin corresponded to their internal grid number 62074.

METHODS OF ANALYSIS

Comparison of soil moisture *in situ* data with re-analysis

Using 10 years of *in situ* soil moisture data from 1995 to 2004, a comparison of soil moisture observations with re-analysis data was conducted. The values of effective relative soil moisture are compared. The effective relative soil moisture is defined in this study as $x = (s - s_w)/(s_{fc} - s_w)$, where s is relative soil moisture, s_{fc} is relative soil moisture at field capacity, s_w is relative soil moisture at the wilting point. Relative soil moisture s can be expressed as $s = \theta_v/n$, where: θ_v is fractional volumetric soil moisture, n is porosity. Thus, the effective relative soil moisture is a dimensionless parameter that can be alternatively expressed as $x = (\theta_v - \theta_{min})/(\theta_{max} - \theta_{min})$, where θ_{min} is minimum measured volumetric soil moisture relative to the wilting point and θ_{max} is maximum measured volumetric soil moisture relative to field capacity. Effective relative soil moisture derived from *in situ* data is denoted as $x_{insitu.}$ For the re-analysis data it is denoted as x_{noaa}. Since the land surface scheme in the re-analysis data has two soil layers (0–10 and 10–200 cm), both of them were retrieved, processed and presented as time series of the effective relative soil moisture. As the *in situ* soil moisture data set (1995–2004) consisted of discrete measurements, a continuous record of soil moisture was reconstructed with two-week time steps using groundwater monitoring conducted in years 1999–2004, and relations established between soil moisture and groundwater level. The set of soil moisture scaled to the effective relative soil moisture (x_{insitu}) comprises 157 values calculated at two week intervals for years 1999–2004 with a two-week interval. These values were related to the scaled re-analysis soil moisture (x_{noaa}) using regression in form of exponential function: $x_{noaa} = a \cdot \exp(b \cdot x_{insitu})$. The value of x_{insitu} was calculated for three types of soil profiles representing different soil texture, as well as for an average value derived as their mean. Both values of x_{insitu} and x_{noaa} represent effective relative soil moisture averaged over the depth, giving an insight into average wetness conditions present in the soil layer.

Propagation of wetness states

Histograms of the relative frequency of effective relative soil moisture were constructed for separate months from March to October using the daily re-analysis data from 1995 to 2004. In this way the preferential wetness states were displayed in each month, presenting a switch from wet to dry states. Additionally, the relative frequency histogram was constructed jointly for months March–October for years 1995–2004, providing an insight into preferential wetness states within vegetation period. This histogram was then applied as a background to the values of probability distribution simulated by the analytical function.

Simulating probability density function of effective relative soil moisture

Identified input values to the model simulating the probability density function of the soil moisture comprise the parameters of rainfall frequency λ (0.325 day^{-1}), mean rainfall depth α (0.48 cm), and maximum evapotranspiration ET_{max} (0.49 cm day^{-1}). All of these parameters were estimated from the MARS-STAT data base. Maximum soil water storage w_0 available to plants in the top soil layer of 0–30 cm was estimated from *in situ* data (w_0 = 6 cm). Following Porporato *et al.* (2004), the master equation of the probability density function of the soil moisture $p(x)$ can be obtained from a simple stochastic model for soil moisture dynamics. The applied equation is: $p(x) = (N/\eta)x^{(\lambda/\eta)-1}\exp(-\gamma x)$ for $0 < x \leq 1$, with normalization constant N assumed as $N = (\eta\gamma^{\lambda/\eta})/[\Gamma(\lambda/\eta) - \Gamma(\lambda/\eta,\gamma)]$, where Γ is the gamma function, γ is defined as $\gamma = w_0/\alpha$ (–/–), and η is defined as $\eta = ET_{max}/w_0$ (–/–).

RESULTS

In the course of the effective relative soil moisture, the seasonal and inter-annual fluctuations are present (Fig. 1). The comparison of the soil moisture *in situ* data with the re-analysis is presented in

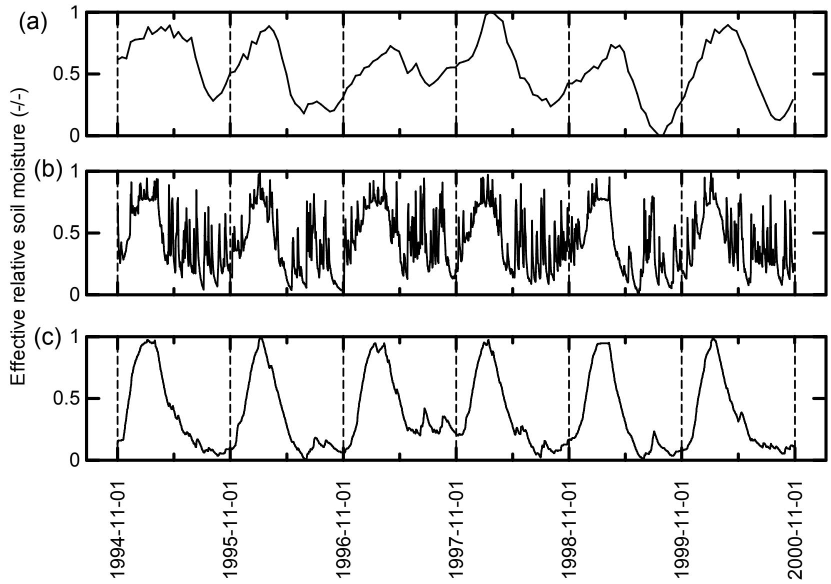

Fig. 1 Variation of the effective relative soil moisture in years 1999–2004: (a) derived from the *in situ* data as an average in three different types of soil profiles; (b) retrieved from re-analysis, averaged over the depth of 0–10 cm; and (c) retrieved from re-analysis, averaged over the depth of 10–200 cm.

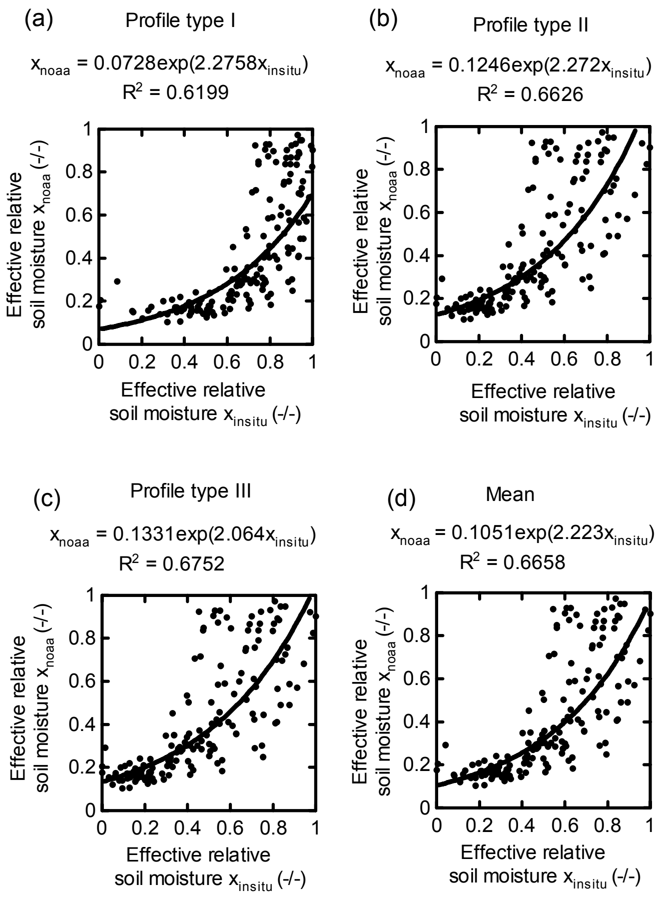

Fig. 2 Relationship between values of the effective relative soil moisture retrieved from re-analysis as dependent on the *in situ* data: (a) profile type I, (b) profile type II, (c) profile type III, (d) mean value.

Fig. 2. The effective relative soil moisture was derived for three different types of soil moisture profiles and for their mean. The value of the coefficient of determination R^2 shows that most of the variance between the considered variables is explained by the regression. However, its value is the smallest for the profile type I, which is highly influenced by very shallow groundwater level and high retention capacity in the upper soil layers. The model has higher R^2 values and a better overall fit for type II and III profiles which are generally of drier regime. Assuming that most of the variance is explained by the regression, it is concluded that the re-analysis data generally reproduce the dynamics of the soil moisture detected in the *in situ* observations.

The dominant states of wetness conditions on a monthly basis are presented in Fig. 3. In March the dominant state detected has an effective relative soil moisture between 0.7 and 0.8, 0.4 and 0.5 in April, and in 0.2–0.3 in May–October. Thus there is a gradual propagation of wet state conditions in March to dry state conditions between May and October. The dominant state detected for the whole season March–October is within the range of 0.2–0.3 (Fig. 4(a)). The simulated relative frequency of effective relative soil moisture presented in Fig. 4(b) generally reproduces the values estimated in the histogram. Comparison of empirical and simulated values is presented in Fig. 4(c). The simulated frequencies generally fit the empirical values (Fig. 5).

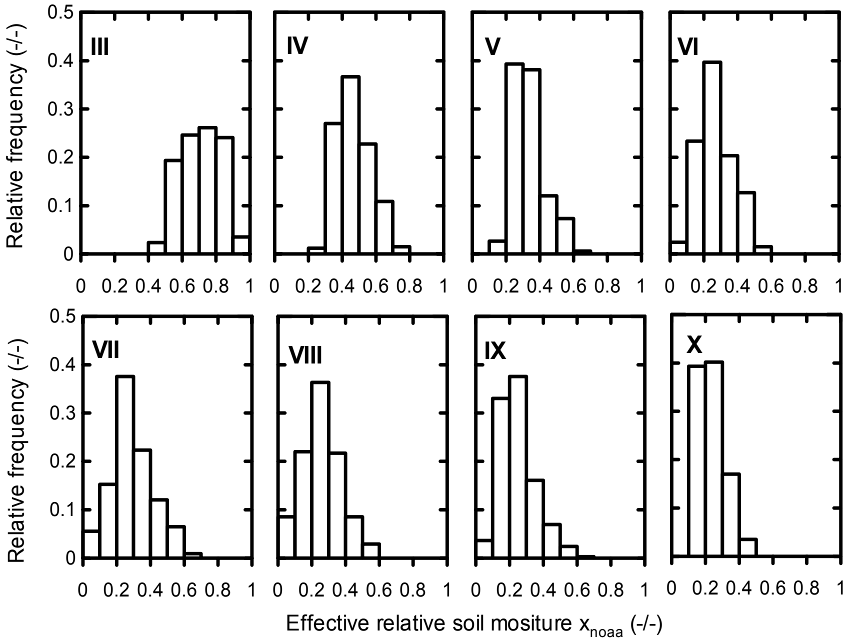

Fig. 3 Frequency histograms of the effective relative soil moisture in particular months of the March–October season in years 1995–2004, based on the re-analysis data.

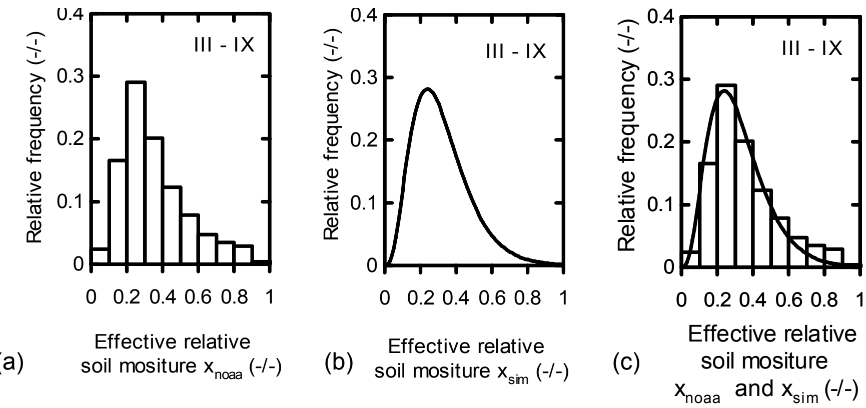

Fig. 4 Simulation of the relative frequency of the effective relative soil moisture in months March–October in years 1995–2004: (a) empirical relative frequency, (b) relative frequency based on probability density function according to Rodriguez-Iturbe & Porporato (2004), (c) comparison of the empirical and simulated values of relative frequencies.

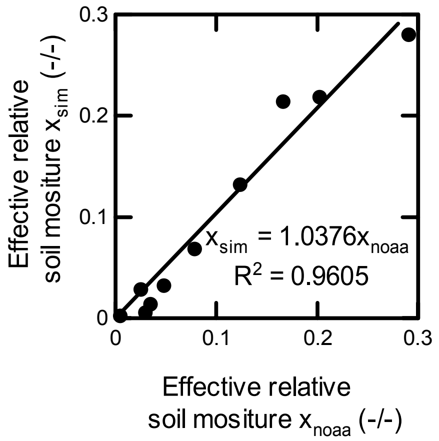

Fig. 5 Values of the simulated relative frequencies as related to the empirical relative frequencies retrieved from re-analysis.

Thus it can be concluded that the applied theoretical framework sufficiently links the chosen parameters of soil and climate and provides a tool for simulations in modified climate conditions. Re-analysis data can be applied in support of *in situ* data however further investigations on discrepancies are required.

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