Agricultural and Forest Meteorology 188 (2014) 76–88

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Inversion of soil hydraulic properties from the DEnKF analysis of SMOS soil moisture over West Africa

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ARTICLE INFO

Article history:
Received 12 August 2013
Received in revised form
16 December 2013
Accepted 20 December 2013

Keywords:
SMOS surface soil moisture
ISBA land surface parameterization
DEnKF
SVAT model
Parameter inversion
Soil and hydraulic property in semi-arid regions

ABSTRACT

The application of Soil-Vegetation-Atmosphere-Transfer (SVAT) scheme into the estimation of soil moisture profile in semi-arid regions is largely constrained by a scarcity of spatially distributed soil and hydraulic property information. Especially, on a large scale in very dry and sandy soils or other extreme conditions, it is difficult to accurately map soil and hydraulic properties with soil maps-based Pedo-Transfer Functions (PTFs), because PTFs are usually semi-empirically defined for specific sites. One strategy to overcome this limitation is to employ satellite data for a purpose of calibration. This paper provides an operational framework of inverting the SVAT soil hydraulic variables from the deterministic ensemble Kalman filter (DEnKF) analysis of Soil Moisture and Ocean Salinity (SMOS) surface soil moisture product. This inverse calibration was first verified with the Analyses Multidisciplinaires de la Mousson Africaine (AMMA) super site data representative of a single grid cell (0.25°) of satellite data. At this local scale, the results demonstrated that the mis-estimation problems of soil surface variable C_1 and equilibrium soil moisture θ_{geq} were successfully solved after calibration, demonstrating a better agreement with the field measurement of soil moisture profile than the SMOS product and un-calibrated SVAT scheme using soil maps-based PTFs. On the meso scale, the calibrated SVAT scheme using inverted surface variables appropriately captured a non-linear relationship between surface and root zone soil moisture by showing a typical soil moisture profile in dry climates, where dry surface soil moisture is spatially consistent with rainfall events, but wet root zone soil moisture shows low correlations with surface soil moisture distributions and rainfall events. In contrast, the un-calibrated SVAT scheme using soil maps-based PTFs significantly overestimated surface soil moisture and rainfall effect. This approach suggests several operational merits in that there is no need to heavily rely on empirically defined PTFs or recalibrate land surface parameters for different land surface conditions, and this can be applied even when parameter measurements are unavailable or highly uncertain.

1. Introduction

1.1. Significance of meso-scale soil moisture distribution in West Africa

The Sahara is the largest desert in the world except the polar areas. West Africa around this arid region is in a unique climatic condition. The northeasterlies transport dry air to the Sahara, while the southwesterlies from the Atlantic Ocean deliver moisture to the Sudanian Savannas (Descroix et al., 2009; Lebel et al., 2010). Owing to the Meso-scale Convective System (MCS) developed by a large potential temperature gradient between the Sahara on the North and the Gulf of Guinea on the South, precipitation exhibits a negative gradient from the South to North, resulting in the development of the similar spatial variability in vegetation and soil moisture (Boulain et al., 2009; Ramier et al., 2009). Other large-scale factors influencing the West African Monsoon (WAM) include Azores anticyclone over the Atlantic Ocean, the Libyan anticyclone over the Inter-Tropical Convergence Zone (ITCZ) and Saharan thermal heat-low as well as the cold-tongue (i.e., a rapid decrease of tropical eastern Atlantic sea surface temperature, coinciding with the onsets of WAM) being developed around the Gulf of Guinea (Lebel et al., 2009, 2010; Nguyen et al., 2011; Peugeot et al., 2011; Séguis et al., 2011). In this context, Taylor et al. (2011) addressed the significance of soil moisture spatial patterns on meso and synoptic scales. The boundary layer convection activity largely enhanced in dry soils diminishes the intensity of the African Easterly Jet (AEJ, the easterlies with the maximum seasonal mean wind speed), which

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http://dx.doi.org/10.1016/j.agrformet.2013.12.009

consequently weakens the development of MCSs. On the other hand, the latent heat indirectly influenced by wet surface conditions contributes to the Sahelian rainfall, which is further related to Atlantic hurricane frequency (AMMA-ISSC, 2010). In short, a spatial distribution of soil moisture conditions largely influences the development of energy transfer as well as WAM. Thus, in terms of moisture transport, atmospheric circulation and weather forecast, the acquisition of soil moisture spatial patterns on the meso-scale is very significant in West Africa. However, several previous studies found that there are several limitations in the direct application of the SVAT scheme into very dry and sandy soils. In order to simulate the meso-scale soil moisture in Niger, Pellarin et al. (2009) re-calibrated the soil and hydraulic parameters of Interactions between Soil-Biosphere-Atmosphere (ISBA) land surface model with several reference data such as Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) data and MSG-SEVIRI (Meteosat Second Generation-Spinning Enhanced Visible and Infra-red Imager) land surface temperature products. By minimizing a mismatch between simulated and observed brightness temperature, they re-calibrated equilibrium surface volumetric soil moisture θ_{geq} and wilting point information originally formulated by PTFs (Montaldo and Albertson, 2001). Braud et al. (1993) and Giordani et al. (1996) also found that soil coefficient parameterization in ISBA models needs to be modified, due to vapour phase transfer in dry soils. They newly formulated the soil surface variable C_1 as functions of land surface temperature and wilting point. However, some recent studies suggested that a validity of the ISBA soil coefficient parameterization by Braud et al. (1993) and Giordani et al. (1996) is limited. Due to the overestimation, Juglea et al. (2010) re-calibrated several soil hydraulic parameters according to Cosby et al. (1984) and Boone et al. (1999), and could finally make a better estimation of soil moisture. However, in practical terms, because such recalibration approach is inefficient, Calvet and Noilhan (2000) previously proposed a renormalization method, and successfully retrieved root zone soil moisture by performing a variational assimilation with surface soil moisture data.

1.2. Inverse method for the estimation of soil hydraulic properties

As discussed above, a scarcity of spatially distributed soil hydraulic property information is a major source of uncertainty in SVAT scheme, especially on dry and sandy conditions. They are usually parameterized by the PTFs expressed as a function of clay or sand fraction. This soil information is obtained from the Food and Agriculture Organization (FAO) soil maps or ECOCLIMAP, due to its global availability (Champeaux et al., 2005). However, it was previously suggested that the relationship between soil texture and soil hydraulic properties is uncertain, empirical and site-specific (Soet and Stricker, 2003; Gutmann and Small, 2007; Pellarin et al., 2009; Brimelow et al., 2010). Hence, there is a limitation in the application of the same PTF to various bio-climatic conditions on the meso scale. To overcome the limitation of PTFs, another global map relevant to soil hydraulic parameters (e.g. wilting point, porosity or saturated hydraulic conductivity), the International Satellite Land Surface Climatology Project (ISLSCP) II was suggested, based upon the FAO soil maps and Neural Network Analysis (Schaap et al., 1998). However, its applicability may also be limited, when it is utilized for soil composition and bio-climatic conditions different from their bootstrap soil sample data base. Therefore, the applicability would be much wider if directly extracting the spatially distributed soil and hydraulic property from globally available satellite data rather than the use of empirically defined PTFs or locally sampled soil data base.

As a strategy to overcome the empirical approach, an inverse method was previously suggested. The term of 'inverse' is defined as the estimation of input values from the model states, in contrast to the forward method determining the model states from input values. In other words, it selects the optimal parameters matching the model simulations with the observations (Wigneron et al., 1993; Zhou, 2011; Li et al., 2012). Gutmann and Small (2007) applied an inverse method to the soil hydraulic input parameters of NOAH land surface model, noting that a linear relationship between soil texture and soil hydraulic parameters is obscure (Brimelow et al., 2010). They selected the specific soil hydraulic parameters that showed a best fit to field measured latent heat. Their result was also compared with the existing soil texture approach, concluding that an inverse method is better in the estimation of latent heat. For future works, they suggested applying this inverse method into soil moisture retrieved from the satellite. Kunstmann (2008) and Intsiful and Kunstmann (2008) also applied a stochastic inverse method to the SVAT land surface parameters including roughness length, wilting point soil moisture and field capacity. They stochastically generated several input parameters, and selected certain input parameters when satisfying given constraints or minimizing the objective functions (Goegebeur and Pauwels, 2007). On the other hand, some previous studies employed ensemble filterings for a purpose of calibrating soil hydraulic parameters (Li and Ren, 2011; Montzka et al., 2011). Hendricks-Franssen and Kinzelbach (2009) and Vrugt et al. (2005) regarded EnKF as the inverse calibration requiring less computational cost than other Monte-Carlo methods. Parameters and states were jointly updated with the observations (Li et al., 2012). Sabater et al. (2008) also proposed a joint update of parameter and state through data assimilation, demonstrating that it can capture time-variant vegetation biomass and hydraulic properties. However, some studies encountered the limitations of joint state-parameter EnKF methods such as long parameter adaptation time, a premature reduction in ensemble spread, a divergence of a perturbed parameter or a linear update scheme applied to a non-linear system (Moradkhani et al., 2005; Qin et al., 2009; Kurtz et al., 2012). Furthermore, the joint state-parameter EnKF approach usually defines the error covariance based upon parameter measurements. However, it is uncertain whether we can appropriately define a non-linear relationship between state and parameter with a cross-error covariance when the parameter measurements are not available as at a large scale. Recently, Pauwels et al. (2007) and Santanello et al. (2007) retrieved soil hydraulic parameters of land surface models from multi-temporal active or passive microwave retrieved surface soil moisture. Pollacco and Mohanty (2012) also inverted SVAT hydraulic parameters from satellite-retrieved soil moisture and evapotranspiration, and compared them with up-scaled point measurements, suggesting that the non-uniqueness of inverted hydraulic parameters needs to be reduced.

The objective of our study is (1) to provide the operational framework of inverting the SVAT soil hydraulic variables often erroneous in dry and sandy soils from the EnKF analysis of SMOS surface soil moisture and (2) to ultimately improve the SVAT models with inverted soil and hydraulic variables. Because this study is aimed for the meso-scale spatial analysis exploiting the satellite data, the observation error condition is different from a local point scale study in which the measurements for parameter and state are available. Thus, EnKF was employed to alleviate any discrepancy between land surface model and satellite data and to reduce the satellite measurement errors presumably propagated into parameter inversion. Advantage of this approach is that this inverse calibration does not heavily rely on the empirically defined PTFs (Brimelow et al., 2010; Gutmann and Small, 2007; Schaap et al., 1998). With respect to joint parameter-state estimation through EnKF, this approach is more flexible because this does not require the precise parameter error characterization and accordingly can