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Evaluation of soil moisture data products over Indian region and analysis of spatio-temporal characteristics with respect to monsoon rainfall

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ABSTRACT

Soil moisture (SM) is an essential climate variable of greater relevance in the monsoon scenario, hence validation and understanding of its spatio-temporal variability over the Indian region is of high significance. In the present study, five SM products are evaluated against *in situ* SM measurements conducted by India Meteorological Department and the selected data product is used for spatio-temporal characterization of SM in relation to monsoon rainfall. The data products evaluated are: European Space Agency's merged satellite SM, Modern-Era Retrospective analysis for Research and Applications (MERRA) Land SM, ECMWF's ERA interim SM, Climate Forecast System Reanalysis SM, and Global Land Data Assimilation System Noah Land Surface Model SM. Comparisons show that seasonal SM patterns in all products generally follow the characteristics of rainfall, even though there are certain differences in details. The statistical estimates indicate fairly good agreement between *in situ* and the five products, with some variations among them and over the homogeneous rainfall regions. On comparison, MERRA SM is found appropriate for further analyses on spatio-temporal characteristics, which are then carried out with the 20 year (1993–2012) SM data. Stability analyses revealed SM patterns indicative of relative SM variability as well as persistence. The spatial stability analysis depicts dry and wet patterns and their seasonal variations over different geographical locations in relation to all India spatial average. Large temporal variations are found over central, western and northern Indian regions caused by large intraseasonal variability in rainfall. In brief, intraseasonal and interannual soil moisture variations broadly follow the rainfall pattern, with long-term influences attributed to SM memory effects. The soil moisture persistence and dominant scales of variability are explored with autocorrelation and wavelet transform techniques. Seasonal persistence is large over regions receiving excessive rainfall, while drought years are noted to have large intraseasonal SM persistence compared to that of surplus year. Wavelet decomposition demonstrates that low periodicity (2–10 days) SM modes match that of rainfall during initial periods of monsoon. The occurrence of significant higher periodicity modes are dominant in drought years compared to surplus, which also vary with geographical locations.

1. Introduction

Soil moisture (SM) and its spatio-temporal variations are very significant in controlling the exchange of water and energy at the land-atmosphere interface, and thus have profound impact on the atmospheric boundary layer, weather and climate processes. Soil moisture is also important for monitoring land surface conditions that can enhance extreme events such as droughts, heat waves, and floods. The SM distribution is influenced by several factors such as precipitation, soil characteristics, topography, geographical location and meteorological conditions. Being a parameter with large memory, and considering its influence on weather and climate processes, SM has been introduced as one of the 'Essential Climate Variables (ECV)' in 2010 by Global Climate Observing System (Blunden et al., 2013). Studies involving SM often require spatially distributed long-term datasets. Several potential SM data products have been introduced in recent years based on satellite observations, reanalysis, and land data assimilation system.

Satellite based microwave remote sensing techniques, both active and passive, have been in use to derive surface soil moisture information (e.g. Jackson, 2005; Rüdiger et al., 2009; Gruhier et al.,

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2010; Albergel et al., 2012; Liu et al., 2012; Parinussa et al., 2015). Liu et al. (2012) presented a merged long-term global SM data product combining four passive products (Scanning Multichannel Microwave Radiometer SMMR, Special Sensor Microwave Imager SSM/I, Tropical Rainfall Measuring Mission Microwave Imager TMI, Advanced Microwave Scanning Radiometer - Earth Observing System AMSRE-E) and two active microwave products (European Remote Sensing ERS Scatterometer and Advanced Scatterometer ASCAT) covering the period 1978–2010. This SM product from European Space Agency's Climate Change Initiative (ESA CCI) is now available until 2014. In addition to the satellite based soil moisture products, many of the reanalysis and land data assimilation products also provide global surface as well as layered soil moisture data. These include reanalysis products such as ECMWF's ERA-Interim (Dee et al., 2011) Modern-Era Retrospective analysis for Research and Applications Land data product (Rienecker et al., 2011; Reichle et al., 2011), Climate Forecast System Reanalysis (Saha et al., 2010) and Global Land Data Assimilation System land surface model product (Rodell et al., 2004).

The use of derived soil moisture data products for research and applications require prior validation, but the lack of appropriate *in situ* data as well as disparity in spatial scales between datasets have been constraints (Wagner et al., 2007; Jackson et al., 2010). The global SM data are at coarse spatial resolution, i.e. over large grids having differing soil characteristics, vegetation, topography and meteorological conditions; whereas *in situ* measurements are highly localized in representativeness. Several studies have been reported from across the world on the validation of different SM data products with *in situ* observations. Some examples include evaluation of ECMWF's numerical model together with two satellite soil moisture products, ASCAT and SMOS, using *in situ* soil moisture data from more than 200 stations located globally (Albergel et al., 2012), evaluation of AMSR-E, ASCAT and SMOS over southeast Australia (Su et al., 2013), West Africa (Gruhier et al., 2010), Europe (Albergel et al., 2009; Brocca et al., 2011), Australia (Draper et al., 2009; Mladenova et al., 2011), and the United States (Collow et al., 2012), and evaluation of merged ESA soil moisture using available global *in situ* observations (Dorigo, 2015). SMEX datasets have been extensively used for validation of different remote sensing data products (e.g. Jacobs et al., 2004; Vivoni et al., 2008). Both active as well as passive products have been found reliable over bare to moderately vegetated surfaces, but their performance have been rather poor over densely vegetated surfaces. Chaurasia et al. (2011) used once-a-week gravimetric measurements at selected locations for validation of AMSR-E SM data over Indian region. Mishra et al. (2014) reported validation of the Variable Infiltration Capacity (VIC) model SM, simulated with meteorological forcings representative of Indian region, against the ESA CCI soil moisture, GLDAS-Noah and *in situ* observations. Reanalysis as well as land data assimilation data products have also been evaluated, regionally as well as globally with *in situ* observations (e.g. Yi et al., 2011; Albergel et al., 2012; Stillman et al., 2016).

The focus of soil moisture studies over the Indian region was mainly on the feedback and coupling between SM and monsoon rainfall and their impact on seasonal and interannual variability using numerical simulations (Douville et al., 2001; Koster et al., 2004; Lodh et al., 2013). Shukla and Mintz (1982) suggested that SM anomalies could persist long enough to modify the atmospheric circulation over seasonal to interannual timescales. Regional climate model simulations by Asharaf and Ahrens (2013) showed that SM memory lengths increase with soil depth and significant geographical variability exist during monsoon. Studies have also shown that pre-monsoon SM conditions influence the monsoon onset and precipitation (Asharaf et al., 2012). Saha et al. (2012) studied the ISO – soil moisture feedback considering intraseasonal variation of SM memory. Spatial and temporal variations of monthly SM over India were studied by Singh et al. (2005) using Indian Remote Sensing satellite data, which showed strong geographical variations during monsoon. Mishra et al. (2014) investigated soil moisture drought variability in a changing climate in relation to two major crop growing seasons in India using VIC model simulated soil moisture. Shah and Mishra (2014) evaluated MERRA, ERA-Interim and the NCEP – CFSR reanalysis products in the context of monsoon season droughts over the Indian region.

Reliable information on soil moisture and its variability over the Indian subcontinent is essential to better understand surface-atmosphere interaction in relation to the monsoon, drought related studies and various numerical modeling applications. Despite the importance, studies on SM validation and analysis are sparse over the Indian region, though several global SM data products are presently available based on satellite observations, reanalysis, land data assimilation, etc. These products need to be evaluated with reference to unique monsoon conditions, before they can be used for SM characterization and applications. Hence, the present study is carried out with two important objectives: (i) to evaluate different SM products (three recent reanalysis products, one land data assimilation product, and one satellite remote sensing product) against spatially distributed *in situ* measurements carried out by India Meteorological Department and (ii) to investigate spatio-temporal variations, memory and dominant scales of SM variations with respect to Indian monsoon and its variability. In Section 2, details of different datasets used as well as analysis methods are presented. The results and discussion are presented in Section 3, followed by conclusions in Section 4.

2. Data and methods

2.1. Data

The study region consists of the Indian landmass bound by 6.5° to 38.5°N and 66.5° to 100°E. The SM datasets used are: (i) *In situ* SM observations carried out by the India Meteorological Department (IMD) at selected agromet automatic weather stations (IMD_SM), (ii) European Space Agency's Climate Change Initiative soil moisture dataset (ESA_SM), (iii) MERRA-Land global reanalysis soil moisture dataset (MERRA_SM), (iv) European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA_SM), (v) National Center for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR_SM) and (vi) Global Land Data Assimilation System Land Surface Model (GLDAS_SM). Statistical evaluations of products are carried out for the year 2010 as *in situ* IMD_SM observations are available only for this particular year. Further, analyses of detailed SM characteristics are performed using 20-year MERRA_SM during 1993–2012. It has to be noted that the six datasets used are different in terms of underlying principles of measurement/estimation, representative depth, and spatial and temporal resolution. The study also employs IMD's high spatial resolution (0.25° × 0.25°) daily gridded rainfall data (Pai et al., 2014) for the analysis of SM in relation to monsoon rainfall.

In situ volumetric soil moisture measurements are carried out by IMD at nearly 130 locations spread over India (Fig. 1) using SM sensor (Theta Probe, Delta-T Devices, UK) installed at 20 cm depth. The IMD SM measurements were initiated in 2009, and the year 2010 has better coverage. However, large gaps exist in the data at several locations, and only locations with at least 50% quality checked data are present during the study period are used for analyses. The 20 cm depth IMD_SM is used in the study as no other extensive *in situ* surface SM measurements are available, and also considering the fact that surface soil moisture exhibits