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Comparison of temporal trends from multiple soil moisture data sets and precipitation: The implication of irrigation on regional soil moisture trend

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ABSTRACT

In this study, soil moisture trend during 1996–2010 in China was analyzed based on three soil moisture data sets, namely microwave-based multi-satellite surface soil moisture product released from European Space Agency's Climate Change Initiative (ESA CCI), ERA-Interim/Land reanalysis, and in-situ measurements collected from the nationwide agro-meteorological network. Taking the in-situ soil moisture as reference, it is found that ESA CCI generally captured soil moisture trend more accurately than ERA-Interim/Land did. From the spatial distribution of trend analysis results, it is seen that significant decreasing trend for summer soil moisture in northwestern China and northern Inner Mongolia, as well as the significant increasing trend for autumn soil moisture in northern China were identified by both ESA CCI and ERA-Interim/Land. This is in alignment with results from gauge-based precipitation provided by Institute of Geographic Sciences and Natural Resources Research (IGSNRR) and satellite-based precipitation from Tropical Rainfall Measuring Mission (TRMM). However, disagreements in derived trends between ESA CCI, ERA-Interim/Land and IGSNRR were observed in the southwest and north of China, especially in major irrigation regions, such as the oases in northern Xinjiang and large areas in Sichuan province. Prominent difference between soil moisture and precipitation exhibited in the extensively irrigated Huang-Huai-Hai Plain. The spatial coincidence between significantly wetting areas (identified by ESA CCI) and heavily irrigated areas, as well as the grid-based Student's *t*-test sampling from various irrigation levels revealed that the observed discrepancy was caused by massive anthropogenic interference in this region. Results indicate that, for regions with great magnitude of human interference, modules considering actual irrigation practice are crucial for successful modeling of soil moisture and capturing the long-term trend. Furthermore, results could provide insights on hindcast of historical irrigation areas using satellite-based precipitation and soil moisture data sets.

1. Introduction

Soil moisture is a crucial driver in water and energy exchange between land surface and atmosphere, as it controls the partitioning of precipitation between runoff and infiltration, the partitioning of incoming radiation between latent and sensible heat fluxes. Information on soil moisture is valuable in many disciplines including agronomy and environmental sciences, e.g., in application of vegetation growth/restoration in semiarid environments (Ahmad et al., 2010), soil erosion rate prediction (Wei et al., 2007) and crop yield estimation (Green and Erskine, 2004; Jaynes et al., 2003). Considering its importance in earth science, soil moisture is recognized as an Essential Climate Variable (GCOS, 2010), and the knowledge of its temporal trend and variability is of essential importance for understanding the effect of climate change on hydrological processes.

Long-term observations of soil moisture are valuable for investigating the trend and dynamics of soil moisture and the severity and duration of drought events. Nevertheless, due to the limited spatial and temporal coverage of ground-based observation networks in

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China, such investigations heavily relied on indirect measurements such as precipitation and air temperature (Wang et al., 2003; Xin et al., 2006; Zhai et al., 2010) and on soil moisture simulations from land surface models (Ma and Fu, 2006; Wang et al., 2011; Zou et al., 2005; Zuo and Zhang, 2007). However, the accuracy of model-based soil moisture is constrained by the quality of model forcing and the large horizontal/vertical heterogeneity of soil properties that are not readily observable (Hain et al., 2011). In addition, it has been proved that influences from anthropogenic activities, such as excessive groundwater-fed irrigation and large-scale water diversion projects will result in significant change in surface soil moisture by altering the sensible and latent heat flux (Chen and Xie, 2010; Zou et al., 2014). Nonetheless, the majority of land surface models lack the consideration of irrigation effect on water redistribution in the terrestrial system, and simulate surface soil moisture without incorporating irrigation module (Drewniak et al., 2013). All these factors have given rise to considerable uncertainties in soil moisture simulated by land surface models in the intensively irrigated region.

Recently, initiated within the Water Cycle Multi-mission Observation Strategy (WACMOS) project, the latest version of soil moisture product (ESA CCI) merging active and passive microwave observations was released to public domain. Through minimizing the effects of differences in sensor specifications, particularly in microwave frequency and spatial resolution, the ESA CCI product provides relatively consistent and reliable information of soil moisture worldwide. At the global scale, this ESA CCI data set has been extensively validated against in-situ network observations and various land surface model simulations (Albergel et al., 2013a,b; Dorigo et al., 2012, 2015; Liu et al., 2012). In addition, the ESA CCI data set covers the period of 1979–2013, longer than any individual microwave soil moisture product, serving as an independent data set from land surface model for studying multi-decadal behavior of soil moisture.

Previous studies on the topics of long-term soil moisture trend and dynamics were mostly conducted on global scales, and there appeared to be a lack of detailed discussion on the inconsistency in trends derived from different soil moisture products. Moreover, most research on soil moisture temporal trend drew their conclusions solely based on land surface models without the consideration of increasingly intensified human interference. In this study, we exploit the readily available soil moisture data set from ESA CCI product, along with ERA-Interim/Land reanalysis and agro-meteorological network observations to examine the long-term soil moisture trend over China. Detailed comparative study is conducted on the performance of three soil moisture data sets in capturing the temporal trend. Following this, the discrepancies in the spatial patterns of trends between precipitation, ground-based, satellite-based, and model-based soil moisture are analyzed, and the underlying factors are discussed in detail, with the main focus on possible human interference impact on long-term soil moisture trend.

2. Materials and methodology

2.1. Soil moisture data sets

2.1.1. ESA CCI product

The ESA CCI product was supported under the framework of European Space Agency's Water Cycle Multi-mission Observation Strategy (WACMOS) project and Climate Change Initiative (http://www.esa-soilmoisture-cci.org). The ESA CCI data set was derived from passive products including observations from Scanning Multichannel Microwave Radiometer (SMMR), Special Sensor Microwave Imager (SSM/I), Tropical Rainfall Measuring Mission Microwave Imager (TMI), Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E), Advanced Microwave Scanning Radiometer-2 (AMSR2), and WindSat; and active products including the Advanced Scatterometer (ASCAT) observations and scatterometer observations on board the European Remote Sensing (ERS) satellite (Liu et al., 2011, 2012; Wagner et al., 2012). The ESA CCI data set provides surface soil moisture information in volumetric unit ($m^3\ m^{-3}$) on a daily basis with a spatial resolution of 0.25°. Apart from the difference in quality of individual data source, uncertainties of ESA CCI product could also result from the selected merging procedure for combining retrievals from different observation systems, different mission designs as well as different retrieval algorithms. Despite some limitations, the ESA CCI product has demonstrated great potential for evaluating model performance (Albergel et al., 2013a,b; Dorigo et al., 2012, 2015; Loew et al., 2013), and for studying the global-scale land-atmosphere interaction (Hirschi et al., 2014). In this study, the latest version (v02.1) of ESA CCI was used for long-term trend analysis.

2.1.2. ERA-Interim/Land reanalysis

ERA-Interim/Land is a newly released global land surface reanalysis data set covering the period 1979–2010. It was produced with the latest version of the Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land (HTESSEL) model using atmospheric forcing from ERA-Interim, with precipitation adjustments based on Global Precipitation Climatology Project (GPCP) v2.1. There are several improvements of land surface parameterization scheme in ERA-Interim/Land compared to ERA-Interim (Balsamo et al., 2015). Four layers of soil (0–7, 7–28, 28–100, and 100–289 cm) are considered in ERA-Interim/Land reanalysis, and soil moisture is provided at 00:00, 06:00, 12:00 and 18:00 UTC with the unit of $m^3\ m^{-3}$ (Albergel et al., 2013a,b). All of the 6-h soil moisture data were used in the analysis to construct the daily average time series. In order to be comparable with the sensing depth of the satellite sensors, only the first layer (0–7 cm) of reanalysis data were used in the study.

2.1.3. In-situ network observations

In-situ soil moisture measurements were collected from nationwide agro-meteorological network (http://data.cma.gov.cn/data/detail/dataCode/AGME_AB2_CHN_TEN.html), and provided by the National Meteorological Information Center of the China Meteorological Administration (CMA). The location and distribution of the stations are shown in Fig. 1. In order to monitor the soil water status in the cropland, measurements were taken on the 8th, 18th and 28th of each month since 1991. At each agro-meteorological station, soil moisture was measured at the depths of 10 cm, 20 cm, 30 cm, 50 cm, 70 cm and 100 cm. No measurements were recorded under frozen soil condition. This data set of in-situ soil moisture measurements from nationwide agro-meteorological network has been widely used for investigating soil moisture spatial and temporal characteristics and validation of microwave soil moisture over China (Qiu et al., 2013; Yuan et al., 2015). Similar to ERA-Interim/Land reanalysis, only the first layer (10 cm) of in-situ soil moisture observations were used in the study. As soil moisture was measured by gravimetric method and recorded as a relative ratio to the field capacity, the global porosity map provided along with the ESA CCI v02.1 product was used to convert them to volumetric unit. Since the absolute magnitude of measurements will not affect trend detection, we adopted a fixed field capacity/porosity ratio during the conversion.

2.2. Precipitation data sets

The precipitation data set used in this study was established by Zhang et al. (2014) from the Institute of Geographic Sciences and Natural Resources Research (IGSNRR). The IGSNRR data set