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Evaluation of SMOS soil moisture retrievals over the central United States for hydro-meteorological application

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ABSTRACT

Soil moisture has been widely recognized as a key variable in hydro-meteorological processes and plays an important role in hydrological modelling. Remote sensing techniques have improved the availability of soil moisture data, however, most previous studies have only focused on the evaluation of retrieved data against point-based observations using only one overpass (i.e., the ascending orbit). Recently, the global Level-3 soil moisture dataset generated from Soil Moisture and Ocean Salinity (SMOS) observations was released by the Barcelona Expert Center. To address the aforementioned issues, this study is particularly focused on a basin scale evaluation in which the soil moisture deficit is derived from a three-layer Xinanjiang model used as a hydrological benchmark for all comparisons. In addition, both ascending and descending overpasses were analyzed for a more comprehensive comparison. It was interesting to find that the SMOS soil moisture accuracy did not improve with time as we would have expected. Furthermore, none of the overpasses provided reliable soil moisture estimates during the frozen season, especially for the ascending orbit. When frozen periods were removed, both overpasses showed significant improvements (i.e., the correlations increased from $r = -0.53$ to $r = -0.65$ and from $r = -0.62$ to $r = -0.70$ for the ascending and descending overpasses, respectively). In addition, it was noted that the SMOS retrievals from the descending overpass consistently were approximately 11.7% wetter than the ascending retrievals by volume. The overall assessment demonstrated that the descending orbit outperformed the ascending orbit, which was unexpected and enriched our knowledge in this area. Finally, the potential reasons were discussed.

1. Introduction

Although soil moisture comprises only 0.01% of the total amount of water on the earth (Prigent et al., 2005), the existence of soil moisture is significant for many application areas such as agriculture, meteorology, and climate investigations (Beljaars et al., 1996; Dai et al., 2004; Jung et al., 2010; Koster et al., 2004; Ookouchi et al., 1984; Seneviratne et al., 2010; Suseela et al., 2012; Wang and Qu, 2009; Yeh et al., 1984). In addition, there is abundant evidence that hydrological processes are significantly conditioned by a river basin's antecedent wetness state (Brocca et al., 2008; Western and Grayson, 1998). Many studies have shown that the distribution of a basin's water is influenced by soil moisture storage, with runoff generated instantaneously when a certain storage threshold is reached (Latron and Gallart, 2008; Spence, 2010; Tromp-van Meerveld and McDonnell, 2006). Therefore, monitoring soil moisture accurately is important in stream forecasting. Although land surface models have been able to produce global soil moisture information, they tend to be deficient owing to their lack of access to reliable data on soil and vegetation properties and atmospheric forcing as well as the time drift problem (i.e., accumulation of errors) (Collow et al., 2012). Conventional point-based observations are currently limited to discrete measurements at particular locations because the cost of direct observation of soil moisture over a large number of sites is very high (Vinnikov et al., 1999). Furthermore, ground-based measurements of soil moisture are made at localized points—typically 0.0025 m^2—and are not suitable for basin-level studies (Al-Shrafany et al., 2013; Srivastava et al., 2013b; Walker et al., 2004; Wang and Qu, 2009).

Alternatively, satellite remote sensing techniques are a major tool in retrieving soil moisture information on a large scale (Engman and Chauhan, 1995) and are able to scan the entire earth daily and provide soil moisture observations globally (Kerr et al., 2001). In particular, the data acquired by microwave sensors, both active and passive, have been employed to provide detailed soil

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moisture variability in recent years (Calvet et al., 2011). The launch of the Soil Moisture and Ocean Salinity (SMOS) mission in November 2009 clearly reveals the significance and determination of the global scientific community to support an advanced soil moisture observation system from space. It has been indicated by Kerr et al. (2001) that SMOS was developed to have an error less than 0.04 m^3/m^3 and a spatial resolution better than 50 km. In addition to SMOS, there are other similar missions, including the Advanced Microwave Scanning Radiometer on Earth Observing System (AMSR-E; from 6.9 to 89.0 GHz; (Njoku et al., 2003)), which operated on the AQUA satellite between 2002 and 2011, and the Scanning Multichannel Microwave Radiometer (SMMR; 6.63 GHz; (Reichle et al., 2004)). It is anticipated that those soil moisture datasets would provide accurate soil moisture information for hydrological modelling such as real-time flood forecasting.

SMOS makes both ascending (6 a.m. local solar time (LST)) and descending (6 p.m. LST) overpasses every three days, and the performance of both retrievals remains unclear (Dente et al., 2012; Jackson et al., 2012; Rowlandson et al., 2012; Sanchez et al., 2012). Based on the literature review, previous studies mainly focused on the downscaling, assimilation, and evaluation of the SMOS ascending overpass in order to minimize the observation error caused by the daytime soil drying effect and the impact of vertical soil-vegetation temperature gradients (Jackson et al., 2012; Lacava et al., 2012; Njoku et al., 2003; Piles et al., 2011; Srivastava et al., 2013b). There also exists a significant problem when evaluating coarse-resolution satellite soil moisture products with point-based measurements owing to the disparity of spatial scales between the two datasets (Jackson et al., 2010; Rudiger et al., 2011). Based on previous studies, no particular attention is given for their evaluation over a basin scale, particularly for hydrological applications. It is expected that satellite soil moisture measurements are more accurate in the hours near dawn when the soil profile has the most time to return to an equilibrium state from the previous day's fluxes (Jackson, 1980). Hence, based on this hypothesis, it is more likely to be true that ascending soil moisture measurements would have better performance than their descending counterparts (Jackson et al., 2012). In addition, based on evaporation demand, it is expected that soil would be wetter at night and drier during the day; in other words, the ascending pass should hold higher soil moisture values than the descending pass (Collow et al., 2012).

In this context, the objective of this paper is to appraise both ascending and descending observations of SMOS through the Xinanjiang (XAJ) model-derived soil moisture deficit (SMD) over the Pontiac basin in the central U.S. to determine whether there are any substantial differences between the two and to judge whether they are suitable for hydrological modelling. In particular, the study covers the period from January 1, 2010 to December 31, 2013, thereby allowing us to evaluate the capability of both overpasses to capture the transitions from dry to wet conditions as well as from frozen to unfrozen seasons. Moreover, the multiyear soil moisture records allow us to investigate the possible improvement of SMOS accuracy through time. This paper has the following structure. In Section 2, the study area, soil moisture datasets, and methodology for SMOS soil moisture evaluations are described. Section 3 presents the results and discussion. Finally, Section 4 draws the conclusion of this study.

2. Data and methodology

2.1. Study area and datasets

The Vermilion River at Pontiac (1500 km^2) is chosen as the study basin and is located in Illinois, which is in the central U.S. (40.878°N, 88.636°W). It is influenced primarily by a hot summer continental climate (Peel et al., 2007), and its land cover is predominantly cropland (Bartholomé and Belward, 2005; Hansen et al., 1998) on Mollisols (Webb et al., 2000). The average altitude of the catchment is 188 m MSL (mean sea level), and the average annual rainfall is 867 mm. The layout of the Pontiac basin is shown in Fig. 1 along with the location of its flow gauge, NLDAS-2 grids, and distribution of river networks.

The NLDAS-2 (Mitchell et al., 2004) precipitation (P) and evapotranspiration (ET) at 0.125° spatial resolution and daily temporal resolution (converted from an hourly resolution) are first processed as data inputs to the XAJ model. The ET is generated from NARR (North American Regional Reanalysis). The precipitation data are calculated from the temporal disaggregation of the gauged daily precipitation data from NCEP/CPC (National Centers for Environmental Prediction/Climate Prediction Center) with an orographic adjustment based on the monthly climatological precipitation of the parameter-elevation regressions on independent slopes model (PRISM) (Daly et al., 1994). As presented in Fig. 1, there are a total of 20 NLDAS-2 grid points/grids covering the Pontiac basin. Both ET and P datasets have been converted into one basin-scale dataset using the weighted average method for use in the lumped XAJ model (i.e., if a grid is completely in the catchment, it is counted as 1. If a grid partially covers the catchment (e.g., 20% of its grid area), it is counted as 0.2. All values are then added to become the denominator, and the numerator comprises the sum of the products of individual grid counts and the grid ET/P value. The average ET and P of the catchment are thus derived. For the Pontiac basin, the USGS daily flow data from January 2010 to April 2011 has been used for the calibration of the XAJ model, and the period of May to December 2011 has been used for the validation purpose. The SMOS soil moisture dataset evaluated in this study is available for the period from January 2010 to December 2013 and is obtained from the SMOS Barcelona Expert Center (SMOS-BEC).

2.2. The SMOS product

The SMOS satellite was launched at the end of 2009 and has been providing soil moisture data for almost six years. SMOS acquires the brightness temperature at a frequency of 1.4 GHz (L-band), which is a function of the emissivity and therefore of near-surface soil moisture (approximately 5 cm). The spatial resolution of SMOS products is 35–50 km (Kerr et al., 2001, 2010) with a soil moisture retrieval unit in m^3/m^3.

In this study, the SMOS-BEC (http://cp34-bec.cmima.csic.es) is used, which has been recently released with various temporal resolutions: daily, 3-day, 9-day, monthly, and annually. These products are generated in the NetCDF format on two types of grids: the ISEA 4H9 grid (Icosahedral Snyder Equal Area projection with aperture 4, resolution 9) with hexagonal cell shape (Pinori et al., 2008), which utilizes the same grid as the Level-2 product, and the EASE (Equal Area Scalable Earth) grid with a pixel size of $\sim$25 km $\times$ 25 km. In this study, the daily soil moisture product with the EASE grid is used, because the EASE grid is more widely utilized. The main method implemented to retrieve surface soil moisture is the same as that employed by the European Space Agency (ESA) operational algorithm for generating standard Level-2 soil moisture products (Kerr et al., 2012). This study separates the two SMOS passes in order to determine whether there are any differences between them and which pass is more suitable for hydrological applications.

2.3. XAJ hydrological model

The XAJ model is employed as a rainfall–runoff simulation model in this study, because it is well known and capable of