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Comparative study of soil moisture estimations from SMOS satellite mission, GLDAS database, and cosmic-ray neutrons measurements at COSMOS station in Eastern Poland

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ABSTRACT

The paper presents a detailed comparative study of three surface soil moisture datasets retrieved from Cosmic-Ray Soil Moisture Observing System (COSMOS) in situ neutron measurement, CATDS Soil Moisture Ocean Salinity (SMOS) satellite microwave observations, and modelled data of the Global Land Data Assimilation System (GLDAS). Subsurface datasets were also calculated from the in situ and satellite measurements by using an exponential filter and were compared with the GLDAS estimates. For these comparisons, the Triple Collocation (TC) method, Nash–Sutcliffe Efficiency (NSE) coefficients, trend charts, and scatterplots were used.

The main goal of this work was to verify the concordance of cosmic-ray neutron measurements with low-resolution soil moisture data from the CATDS SMOS and GLDAS products. The second objective was to determine the possibility of obtaining comparable subsurface soil moisture products from the aforementioned soil moisture data source.

The obtained results show that data from the COSMOS sensor, which assesses soil moisture in an area 600 m in diameter, agree reasonably well with the CATDS SMOS and GLDAS data having spatial resolution of about 25 km. These conclusions suggest that COSMOS Derlo measurements can be particularly useful for validation of low-resolution satellite soil moisture observations as well as modelled values.

The results obtained by using the TC method also revealed satisfactory agreement among all studied surface soil moisture data.

However, the performed analysis shows some preponderance of SMOS and COSMOS data over GLDAS products. Although GLDAS data show a noticeable smoothing effect, COSMOS and CATDS SMOS more effectively reveal temporal soil moisture changes. Thus, for some applications, the use of CATDS SMOS estimates rather than GLDAS products may be more appropriate.

Results retrieved by using an exponential filter are significant and encouraging. In particular, subsurface soil moisture values calculated from CATDS SMOS show stronger correlation with COSMOS Derlo data than those of GLDAS. Furthermore, COSMOS Derlo data also respond more intensively to surface soil moisture changes.

1. Introduction

Soil moisture is an important state variable governing the partitioning of rainfall into runoff and water that infiltrates into soil. Although the water contained in soil is only a tiny fraction of all water on the earth, it influences important extreme events such as floods and droughts (Dai et al., 2004). Numerous techniques of obtaining this variable are available from remote sensing as well as in situ measurements (Ochsner et al., 2013; Wigneron et al., 2003; Wagner et al., 2007). Moreover, soil moisture is typically used to correct land surface fluxes or to improve parameterisation by assimilation in land surface models (Bolten et al., 2010; Brocca et al., 2012a; Draper et al., 2009; Montzka et al., 2011; Pan and Wood, 2006; Reichle et al., 2007).

Traditional in situ measurements are useful for providing information on soil moisture at different soil depths. Many field techniques are available such as oven-drying, neutron probe, Time/Frequency Domain Reflectometry (TDR/FDR), and capacitance measurements (Lekshmi et al., 2014). However, these methods are very expensive and time consuming when used for measurements on large areas. Most allow point measurement, which provides information on soil moisture content at specific points only. However, because soil moisture changes with time and space, simultaneous or very fast multiple point measurement must be performed to obtain representative values quickly, even in small areas. This method leads to upscaling issues inherent in estimating the soil moisture mean value for a given area from numerous point measurements. However, such upscaling is often not trivial. For

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example, in the case of a small number of point measurements, the arithmetical mean value has been shown to be a poor estimator of the mean soil moisture value for the studied area (Crow et al., 2012). Numerous studies have been dedicated to the development of proper upscaling algorithms (Crow et al., 2012) including the proper selection of measurement sites by using time stability concepts and the use of block Kriging or land surface modelling to develop a correct upscaling function. Alternatively, remote-sensing is considered as a solution for determining soil moisture changes in larger areas.

It is well-known that in the wide-ranging electromagnetic spectrum, measurements in low-frequency microwaves (C- and L-band) are strongly related to soil moisture content. Such measurements are independent of weather conditions that significantly influence optical measurements. In addition to these advantages, microwave sensors derive soil moisture values that are directly related to the surface of the soil layer at 0.2 to 5 cm (Escorihuela et al., 2010). However, in many applications, subsurface soil moisture values are needed, particularly for the root zone. Moreover, the assimilation of both surface and root zone soil moisture values has an important influence on the performance of hydrological models (Brocca et al., 2012b). In some cases, it is possible to calculate one of the numerous vegetation indices such as Enhanced Vegetation Index or Normalized Difference Vegetation Index, which are strongly correlated with root zone soil moisture (Santos et al., 2014; Zawadzki et al., 2016). This approach is useful when optical data are applied. However, in the case of radar and radiometric data, other algorithms are applied to retrieve root zone soil moisture from surface soil moisture. These algorithms could be as complex as artificial neural networks (Kornelsen and Coulibaly, 2014) or the soil moisture analytical relationship (SMAR) based on physical soil parameters (Manfreda et al., 2014). Despite its complexity, the exponential filter method (Wagner et al., 1999) is widely used by researchers as a relatively fast and effective method.

In this work, we used the Cosmic-Ray Soil Moisture Observing System (COSMOS) station data (Derlo in Poland), in which soil moisture is measured indirectly by using the cosmic-ray neutron method (Zreda et al., 2015). This method allows an estimate of average soil moisture in the neighbourhood of the sensor to be obtained. The measurements are based on the fact that the intensity of fast, highly energetic neutrons >10 eV coming to Earth from space depends on the soil moisture content. Each station belonging to the COSMOS network has two sensors: one for measuring fast neutrons for soil moisture measurement and one for measuring thermal electrons which allows for determination of the water content in plants or snow. Data are sent automatically to the central server in Arizona, where they are processed and made publicly available. In this study, we use data from the COSMOS Derlo station, which is the only station in Poland belonging to COSMOS network. According to COSMOS Derlo station metadata, measurements provide an estimation of soil moisture at different depths from 0.00 to 0.24 m; thus the effective measurement mean depth is considered to be 0.20 m (20 cm).

In this study, we compare small-scale measurement from the COSMOS Derlo station with large-scale estimates. As stated in previous research (Hornbuckle et al., 2012), COSMOS can be a valuable soil moisture data source for validation of soil moisture information obtained from microwave sensors from missions such as Soil Moisture Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP), particularly during vegetation growth periods. The validation of SMOS data has been widely discussed in the literature for Eastern Poland (Marczewski et al., 2010). However, conclusions in such research were based on Time Domain Reflectometry (TDR) ground measurements, which give a value at a specific point and ignore the sensor values over the entire area. Soil moisture measurements using FDR (Heathman et al., 2012) have demonstrated that it is difficult to properly describe the entire field of measurement by using permanent point sensor measurements. The number of works dedicated to SMOS or SMAP validation using COSMOS data is limited. For example, SMOS has been validated by using few in situ network soil moisture datasets in the United States (Collow et al., 2012). However, promising results in terms of standard deviation and root mean square error (RMSE) value have been obtained for COSMOS data.

1.1. Objectives

The objectives of the study are as follows:

1. To compare soil moisture temporal changes of three different datasets including those modelled from the Global Land Data Assimilation System (GLDAS) database, microwave satellite observations from the CATDS SMOS mission, and ground measurements from COSMOS Derlo station and to evaluate their quality by using the Triple Collocation (TC) method.
2. To retrieve subsurface soil moisture estimates from CATDS SMOS and Derlo data and to evaluate them against GLDAS data that describe soil moisture in 10–40 cm and 40–100 cm soil layers

Because the measurement technique used at the COSMOS Derlo station is relatively new, it was interesting to check whether the commonly used exponential filter (Albergel et al., 2008) method allows for retrieval of valuable information on subsurface soil moisture from cosmic neutron measurement. To answer this question, we used three datasets of the Derlo station including cosmic neutron measurements and the values from the nearest GLDAS and Centre Aval de Traitement des Données SMOS (CATDS) pixels. All datasets refer to the year 2013.

We did not analyse in detail the radio frequency interference (RFI) influence on the CATDS SMOS data quality or two reasons. Firstly, although RFI contamination in Central Europe from 2010 to 2012 was very high (Zawadzki and Kedzior, 2015) it is currently decreasing (Oliva et al., 2012). It is worth to notice that forest influence is a more important factor than RFI for many areas (Leroux et al., 2013). Secondly, we used reprocessed products retrieved with improved RFI detection and the mitigation algorithm which is reflected in the Data Quality Index (DQX) of the products.

2. Material and methods

2.1. Study area

Vistula is the largest river in Poland, and its catchment occupies 59% of Polish territory. The study area was limited to one pixel of GLDAS and CATDS SMOS data situated in the Vistula catchment area (Fig. 1). These pixels have comparable sizes of 25 km × 25 km and partially overlap each other.

The selected pixels are covered by relatively homogeneous soil cover. Although the COSMOS sensor is situated in agricultural areas, most the analysed area consists of forests: >50% of Corine Land Cover pixels belongs to the class ‘forest and semi-natural areas’. Analysis conducted using the ASTER Global Digital Elevation Model (DEM) V2 with a spatial resolution of 30 m, proved that topography is homogeneous and relatively flat over the almost whole study area.

2.2. Cosmic-ray neutrons

Only part of the primary cosmic rays which are galactic or solar in origin have sufficient energy for creating particle cascades that can penetrate the ground level (Zreda et al., 2012, 2008). Protons make up >90% of the primary incoming cosmic rays; those that are sufficiently energetic can penetrate the geomagnetic field. When protons enter the atmosphere, secondary particles composed of high-energy cascade neutrons are created as a result of their collision with nuclei and the associated nuclei disintegration. This results in a chain reaction in which new particles collide with the next nuclei, leading to the creation of new particles. Neutron energy decreases with every collision; as a result, each subsequent disintegration of the nuclei becomes less likely.