Journal of Hydrology 522 (2015) 187–202

Contents lists available at ScienceDirect

Journal of Hydrology

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

Spatio-temporal variability of global soil moisture products

K. Rötzer *, C. Montzka, H. Vereecken

Institute of Bio- and Geosciences: Agrosphere (IBG-3), Forschungszentrum Jülich GmbH, 52428 Jülich, Germany

ARTICLE INFO

Article history:
Received 19 September 2014
Received in revised form 11 December 2014
Accepted 13 December 2014
Available online 24 December 2014
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Juan V. Giraldez, Associate Editor

Keywords:
SMOS
ASCAT
ERA Interim
Spatio-temporal analysis
Temporal stability
Scaling

SUMMARY

Being an important variable for various applications, for example hydrological and weather prediction models or data assimilation, a large range of global soil moisture products from different sources, such as modeling or active and passive microwave remote sensing, are available. The diverse measurement and estimation methods can lead to differences in the characteristics of the products. This study investigates the spatial and temporal behavior of three different products: (i) the Soil Moisture and Ocean Salinity (SMOS) Level 2 product, retrieved with a physically based approach from passive microwave remote sensing brightness temperatures, (ii) the MetOp-A Advanced Scatterometer (ASCAT) product retrieved with a change detection method from radar remote sensing backscattering coefficients, and (iii) the ERA Interim product from a weather forecast model reanalysis. Results show overall similar patterns of spatial soil moisture, but high deviations in absolute values. A ranking of mean relative differences demonstrates that ASCAT and ERA Interim products show most similar spatial soil moisture patterns, while ERA and SMOS products show least similarities. For selected regions in different climate classes, time series of the ASCAT product generally show higher variability of soil moisture than SMOS, and especially than ERA products. The relationship of spatial mean and variance is, especially during wet periods, influenced by sensor and retrieval characteristics in the SMOS product, while it is determined to a larger degree by the precipitation patterns of the respective regions in the ASCAT and ERA products. The decomposition of spatial variance into temporal variant and invariant components exhibits high dependence on the retrieval methods of the respective products. The change detection retrieval method causes higher influence of temporal variant factors (e.g. precipitation, evaporation) on the ASCAT product, while SMOS and ERA products are stronger determined by temporal invariant factors (e.g. topography, soil characteristics). The investigation of the effect of changing scales on spatial variance in three different areas indicates that the variance does not vary with increasing support scale. Increasing extent scales from 250 to 3000 km raise spatial variance of all products and all study areas according to a power law, which is varying seasonally. ERA shows a consistent scaling behavior with a constant power scale factor and similar intercepts across all study regions. In general, the investigated products show overall different spatial and temporal statistics which are induced by their different estimation methods and which are important to be aware of for the selection of a product for application and for their up- or downscaling.

1. Introduction

Impacting surface and subsurface runoff as well as evaporation and transpiration, soil moisture is an essential variable in energy and water balance (Seneviratne et al., 2010). Thus, information about soil moisture and its spatial and temporal dynamics is crucial for improvements in climate and hydrological modeling and in numerical weather prediction. These applications require representative soil moisture time series for large regions or even global coverage.

Remote sensing techniques showed to be able to provide soil moisture with high coverage and in reasonable temporal and spatial resolution (Kerr, 2006). Several sensors differing in sensing technique (active/passive), frequency, and retrieval methods are currently used for monitoring soil moisture, resulting in soil moisture products with different characteristics and spatial resolution. Sensors used for retrieving soil moisture at present are the Advanced Scatterometer (ASCAT) onboard the meteorological

---

* Corresponding author. Tel.: +49 246161 5309.
E-mail addresses: k.roetzer@fz-juelich.de (K. Rötzer), c.montzka@fz-juelich.de (C. Montzka), h.vereecken@fz-juelich.de (H. Vereecken).

http://dx.doi.org/10.1016/j.jhydrol.2014.12.038
0022-1694/

satellite MetOp-A (Bartalis et al., 2007), the Advanced Microwave Scanning Radiometer (AMSR-2) on the GCOM-W1 (Global Change Observation Mission – Water) (Su et al., 2013), the Soil Moisture and Ocean Salinity (SMOS) satellite (Kerr et al., 2010), and the combined active and passive instrument Aquarius (Luo et al., 2013). The Soil Moisture Active Passive (SMAP) satellite, whose launch is planned for winter 2014/2015, will also provide soil moisture products (Entekhabi et al., 2010).

Another way to provide soil moisture with high spatial coverage is modeling. Products from different models are available, for example from the Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004) or from the Integrated Forecast Model (IFS) of the European Centre for Medium Range Weather Forecast (ECMWF). They provide operational analyses for which the model is constantly improved, but also reanalyses, that use only one model and thus give consistent data (Albergel et al., 2012), for example the ERA Interim (Dee et al., 2011).

Modeled, but also remotely sensed products show a large range of spatial resolutions. While for models spatial resolution is chosen mainly on consideration about computational and storage costs, remotely sensed products are dependent on the technical possibilities of antennas. Currently, C-band active microwave systems provide higher spatial resolutions than passive microwave systems operating at lower frequencies, such as L-band (Wang and Qu, 2009). Nevertheless, theory says that L-band radiometry has several advantages for the estimation of soil moisture compared to higher frequencies (Kerr et al., 2012; Vittucci et al., 2013), especially the higher vegetation penetration depth (Njoku and Entekhabi, 1996) and the higher soil penetration depth, which is between 0.5 and 2 cm for C-band systems like ASCAT and AMSR-E and about 3–5 cm for L-band systems (Escorihuela et al., 2010), like SMOS, Aquarius, and SMAP.

These differences, as well as diverse modeling and retrieval approaches are the main sources of deviations between different modeled and remotely sensed soil moisture products. The validation of these products is challenging due to their rather coarse resolution compared to in situ data and the lack of extensive in situ measurements. Additionally, the products and in situ data have different scaling characteristics. According to Western and Blöschl (1999) "scale" can be defined as a triplet consisting of spacing, extent and support. Spacing refers to the distance between samplings or neighboring pixels, support to the integrated volume or area of one measurement, and extent to the covered area (Vereecken et al., 2014). However, in situ data differs from the global products in these three components. Therefore, to estimate the spatial and temporal validity of validation studies, it is important to know the spatio-temporal characteristics of the soil moisture products.

In this study we evaluate these characteristics to exhibit statistical and structural differences and similarities between the products, and also between different regions. The influence of sensor and retrieval methods on the statistical patterns is analyzed. This knowledge is also important in case that several products should be used in one application. The ESA Climate Change Initiative (CCI) soil moisture product (Dorigo et al., 2012; Liu et al., 2011, 2012), for example, combines products from different sensors. But also if only one product is used in a designated region, it is important to be aware of these characteristics. Applications for soil moisture products are for example usage in runoff forecasting (Brocca et al., 2012), vegetation monitoring (Gouveia et al., 2009), and natural risk assessment, especially drought (Bolten et al., 2010) and flood monitoring (Wanders et al., 2014). Furthermore, the knowledge of systematic differences between soil moisture products is essential for usage in hydrological data assimilation (Yilmaz and Crow, 2013). As global soil moisture products may not always meet the spatial requirements of the respective applications due to their rather coarse resolution, up- and downscaling of soil moisture is of importance. For this task, information about spatial variability of soil moisture is crucial (Manfreda et al., 2007).

On larger extent scales, precipitation patterns and climatic influences are the dominant factors on spatial soil moisture distribution (Famiglietti et al., 2008). Nevertheless, its impact is controlled by evaporation, soil type, irradiation, vegetation and topography (Dorigo et al., 2012).

The influence of these factors should be reflected in the soil moisture products. If their spatial and temporal patterns are different, these differences will be introduced by the respective estimation method.

To examine spatial and temporal patterns in the different soil moisture products, we apply several frequently used methods on three different soil moisture products in this study: First, a rank stability analysis is performed. This is traditionally used for the minimization of sampling locations for soil moisture measurements on field scale through the determination of locations that are representative for the whole area (Vachaud et al., 1985; Cosh et al., 2004; Brocca et al., 2009; Zhao et al., 2013). In Rötzer et al. (2014) it was introduced as a method for the validation of soil moisture products through the correlation of their ranks. Vanderlinden et al. (2012) give an overview on methodologies and applications of temporal stability.

Then we analyze the relationship of spatial mean and spatial variance of soil moisture. This relationship was often investigated on small extent scale and it was found to be quite variable: Bell et al. (1980) and Famiglietti et al. (1998) found decreasing variance with decreasing mean, while for example Famiglietti et al. (1999), Hupet and Vanclooster (2002) and Brocca et al. (2007) found increasing variance with decreasing mean. Others, like Famiglietti et al. (2008) and Rosenbaum et al. (2012) observed a convex upward relationship. The different shapes of relationships are caused by a variety of factors like topography, radiation, soil characteristics, vegetation and land use, with different strength of influence in the respective study areas. Li and Rodell (2013) analyzed the same relationship on the continental extent scale for in situ measurements, modeled and remotely sensed soil moisture from AMSR-E and found a convex relationship for in situ measurements over different climate zones. For modeled and remotely sensed soil moisture this relationship was less pronounced.

The third analysis is the examination of influencing factors on the spatial variance of soil moisture through its decomposition in temporal variant and temporal invariant parts (Mittelbach and Seneviratne, 2012).The analysis considers not only absolute values, but the temporal mean of a site and its anomalies and provides information wether differences between sites are due to temporal mean or anomaly (Brocca et al., 2014). The comparison of the single contributors to the different products can give added value for improved downscaling algorithms (e.g. Das et al., 2014; Merlin et al., 2006, 2013) and for matching different soil moisture products to generate long-term time series (Dorigo et al., 2012; Liu et al., 2011, 2012). For the latter, it is important that all products have a similar temporal mean on one study site. Through these analyses, we will access the statistical and structural relative differences of the soil moisture products.

We also analyze the soil moisture products on their behavior on different scales following the definition of Western and Blöschl (1999). Changes of one of the three components spacing, support, and extent impact the spatial variance of soil moisture. Rodriguez-Iturbe et al. (1995) found a power law decay of spatial variance of soil moisture with increasing support for areas up to 1 km^2, while Ryu and Famiglietti (2006) did not find this behavior for larger support areas of 1–140 km^2. The increase of extent was found to increase spatial variance according to a power law func-