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Editorial

Satellite soil moisture for advancing our understanding of earth system processes and climate change

1. Introduction

Soil moisture products obtained from active and passive microwave satellites have reached maturity during the last decade (De Jeu and Dorigo, 2016): On the one hand, research algorithms that were initially applied to sensors designed for other purposes, e.g., for measuring wind speed (e.g. the Advanced Scatterometer (ASCAT)), sea ice, or atmospheric parameters (e.g. the TRMM Microwave Imager (TMI) and the Advanced Microwave Scanning Radiometer – Earth Observing System AMSR-E), have developed into fully operational products. On the other hand, dedicated soil moisture satellite missions were designed and launched by ESA (the Soil Moisture Ocean Salinity (SMOS) mission) and NASA (the Soil Moisture Active Passive (SMAP) mission).

The development of new products and satellite missions was not only driven by new technological possibilities but possibly even more by the widespread user recognition of satellite soil moisture products for a wide range of applications. In the end, the user requirements have driven the design of the SMOS and SMAP soil moisture missions as well as the specifications of soil moisture Earth Observation programmes, e.g., ESA's Climate Change Initiative for soil moisture, EUMETSAT's Satellite Application Facilities Support to Operational Hydrology and Water Management (H-SAF), and the GMES/Copernicus land services of the European Commission.

Throughout the years, the potential of satellite soil moisture products has been explored for a wide range of applications, ranging from model validation to improving our understanding of climate variability and change. A selection of applications including references is given in Table 1. Traditionally, satellite soil moisture is vastly used for validating soil moisture states for a variety of models, including hydrological, land surface, dynamic global vegetation, and drought models (Table 1). As a result of their recognised quality and their increasing operational and near-real-time availability, remotely sensed soil moisture products are increasingly being assimilated into numerical weather models, e.g. at the UK MetOffice, into reanalysis products, e.g. at ECMWF, and into hydrological models to update the model soil moisture states and ultimately to improve related analysis products such as air temperature and humidity. But apart from updating model states, the assimilation of satellite soil moisture into hydrological and biogeochemical models has also has allowed for calibrating the parameterisations of the models themselves.

Through its central role in the water balance, satellite-observed soil moisture has proven value in improving satellite-based estimates of evaporation and precipitation and in increasing our understanding of complex land-atmosphere feedbacks. As plant available water is the main driver of vegetation growth, soil moisture from satellites is also increasingly being used to improve our understanding of the link between the water and biogeochemical cycles and to assess the impact of drought on plant productivity and agricultural yield.

A big leap forward in soil moisture research was made with the release of the first multi-satellite soil moisture dataset released within the ESA's WACMOS and CCI projects (Liu et al., 2012, 2011b; Wagner et al., 2012). The combination of various soil moisture products from active and passive microwave sensors into a consistent multi-decadal record (currently from 1978 to 2014) allowed to look at long-term variability and change in observed soil moisture at the global scale and to confront long-term soil moisture dynamics with the variability observed in other Essential Climate Variables (ECVs). Over the last years the ESA CCI soil moisture dataset has become integrative part of the yearly State of the Climate reports issued by NOAA (e.g. Dorigo et al., 2015).

Even though the applications of remotely sensed soil moisture may seem unlimited, a successful use of the dataset hinges on the correct use of the data. Users need to be aware of the error characteristics and limitations of the datasets in order to make optimal use of them. The increasing number of available products may even further confuse the user in choosing a soil moisture dataset fit for purpose. The aim of this special issue is to assist the user in this choice by giving a comprehensive state-of-the-art on the potential and limitations of the various new satellite products, in particular with respect to the various application areas. The special issue is linked to the "Satellite soil moisture validation and application workshop 2014" which was held in July 2014 in Amsterdam, the Netherlands, but also contains several studies from non-workshop participants. Because of the large number of submissions, we decided to split the special issue into two parts, each with a different thematic focus. Part 1, which was published as Volume 45, part B in the International Journal of Applied Earth Observation and Geoinformation in January 2016 (http://www.sciencedirect.com/science/journal/03032434/45/part/PB), primarily focused on recent advances in single sensor soil moisture retrievals and validation, while this part (Part 2) mainly focuses on novel applications in which satellite-based soil moisture products play a crucial role.

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Table 1
Selected applications where satellite-observed soil moisture has had a significant added value.

Application area	Main purpose	References
Hydrology	Benchmarking land surface model (LSM) states and processes	Albergel et al. (2012b), Du et al. (2016), Fang et al. (2016), Loew et al. (2013)
	Characterising errors in LSMs	Dorigo et al. (2010), Liu et al. (2011a)
	Improving runoff/discharge predictions	Beck et al. (2009), Ciabatta et al. (2016), Laiolo et al. (2016)
	Improving flood modelling	Massari et al. (2014), Tramblay et al. (2012), Wanders et al. (2014)
	Improves estimation of future flood risk	Tramblay et al. (2014)
	Improving groundwater recharge modelling	Sutanudjaja et al. (2014)
	Improved modelling of land evaporation	Martens et al. (2016), Miralles et al. (2011)
	Assessing irrigation practices	Qiu et al. (2016)
Numerical weather prediction	Improved 2 meter air temperature prediction	Bisselink et al. (2011)
	Improving NWP land surface scheme	Albergel et al. (2012a)
	Improving screen temperature and humidity forecasts by soil moisture assimilation	Dharssi et al. (2011), Scipal et al. (2008)
Precipitation	Correcting satellite-based rainfall estimates	Crow et al. (2011), Pellarin et al. (2013)
	Computing cumulative precipitation amounts	Brocca et al. (2014), Ciabatta et al. (2016)
Land atmosphere interactions	Improved understanding of soil moisture feedbacks on convective precipitation	Taylor et al. (2012)
	Identifying role of soil moisture on the persistence of heatwaves	Miralles et al. (2014a)
	Impact of surface and root-zone soil moisture on hot days	Hirschi et al. (2014)
Drought	Validating drought indices	van der Schrier et al. (2013)
	Improved detection of agricultural droughts	Carrão et al. (2016), Yuan et al. (2015)
	Soil moisture for integrated drought monitoring	Anderson et al. (2012), McNally et al. (2016), Rahmani et al. (2016)
Global biogeochemical cycles	Benchmarking of dynamic global vegetation models (DGVMs)	Rebel et al. (2012), Szczypta et al. (2014), Traore et al. (2014)
	Calibrating DGVMs (through assimilation)	Kaminski et al. (2013)
	Role of soil moisture as a driver of vegetation photosynthetic activity	Barichivich et al. (2014)
	Impact of soil moisture on vegetation productivity	Chen et al. (2014), Muñoz et al. (2014)
	Soil moisture for improved crop modelling	Sakai et al. (2016), Wang et al. (2016)
	Predicting fire occurrence	Forkel et al. (2012)
Climate variability and change	Soil moisture as driver of trends in land evaporation	Jung et al. (2010)
	Long-term trends in soil moisture	An et al. (2016), Dorigo et al. (2012), Qiu et al. (2016), Wang et al. (2016)
	Impact of climate oscillations on soil moisture	Bauer-Marschallinger et al. (2013), Miralles et al. (2014b), van Dijk et al. (2013)

Modified from De Jeu et al. (2014).

A central role in Part 2 play long-term soil moisture records from multi-sensor observations as provided by the ESA Climate Change Initiative for Soil Moisture (ESA CCI SM).

2. Overview of part 2 of the special issue

Part 2 contains 14 contributions where satellite soil moisture plays a central role in several applications (Table 1) related to land surface model (LSM) and hydrological model evaluation (Du et al., 2016; Fang et al., 2016; McNally et al., 2016; Qiu et al., 2016; Rahmani et al., 2016; Sakai et al., 2016), drought monitoring (Carrão et al., 2016; McNally et al., 2016; Rahmani et al., 2016), trend analysis (An et al., 2016; Qiu et al., 2016; Rahmani et al., 2016; Su et al., 2016; Wang et al., 2016), and hydrological modelling (Ciabatta et al., 2016; Laiolo et al., 2016; Martens et al., 2016; Sakai et al., 2016). Notably, most of the contributions focus on data-poor regions or on regions with difficult access to ground-based data, including China, Iran, Africa and South America (An et al., 2016; Carrão et al., 2016; McNally et al., 2016; Qiu et al., 2016; Rahmani et al., 2016; Sakai et al., 2016; Su et al., 2016; Wang et al., 2016), which emphasizes the global outreach of satellite-based soil moisture observations. The applications presented in this special issue are based on data from various sensors, including the radiometers SMOS, AMSR-E, and AMSR-2, the Synthetic Aperture Radars ASAR and Cosmo-SkyMed and the real aperture radar ASCAT. But the majority of applications is driven by the ESA CCI soil moisture dataset (An et al., 2016; Carrão et al., 2016; Du et al., 2016; Fang et al., 2016; McNally et al., 2016; Qiu et al., 2016; Rahmani et al., 2016; Sakai et al., 2016; Su et al., 2016; Wang et al., 2016), which is in the first place motivated by the long time period spanned by this product, which makes it a core dataset for evaluating water cycle changes related to climate change or anthropogenic use.

In more detail, Du et al. (2016) use ESA CCI SM to evaluate the soil moisture fields in the Community Climate System Model along with 8 other models from the Coupled Model Intercomparison Project (CMIP5). Deficiencies observed for model estimates may guide future improvements of these models and may come in time to be implemented in CMIP6 simulations. Other studies use satellite soil moisture in combination with additional datasets to make a comprehensive assessment of the respective suitability of the datasets for various purposes. For example, Qiu et al. (2016) compare ESA CCI SM with soil moisture estimates from ERA-Interim, ERA-Land, and ground stations. Deviations between LSM and satellite estimates are explained by heavy irrigation in the area, which is not accounted for in the LSMs. Based on their results, the authors advocate the inclusion of irrigation modules in LSMs. An et al. (2016) evaluate the ESA CCI SM over China using ground-based observations and show that particularly over grassland correspondence is good but for other land cover types the agreement is weaker for various reasons. Fang et al. (2016) compare the soil moisture fields of three ESA CCI SM products (active, passive, and combined) with those of SM product based on thermal remote sensing (ALEXI), a land surface model and in-situ observations. All products show a similar average performance, but different products outstand for different land cover types. Sakai et al. (2016) assess the potential of two different AMSR-E products and two different versions of the ESA CCI SM product for global crop modelling. Despite the large identified potential they also point at the importance of a good temporal coverage and the importance of higher resolution products for small-scale irrigated crops like rice. The latter may in the future