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Combining SMOS with visible and near/shortwave/thermal infrared satellite data for high resolution soil moisture estimates

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SUMMARY

Sensors in the range of visible and near–shortwave–thermal infrared regions can be used in combination with passive microwave observations to provide soil moisture maps at much higher spatial resolution than the original resolution of current radiometers. To do so, a new downscaling algorithm ultimately based on the land surface temperature (*LST*) – Normalized Difference Vegetation Index (NDVI) – Brightness Temperature (T_B) relationship is used, in which shortwave infrared indices are used as vegetation descriptors, instead of the more common near infrared ones. The theoretical basis of those indices, calculated as the normalized ratio of the 1240, 1640 and 2130 nm shortwave infrared (SWIR) bands and the 858 nm near infrared (NIR) band indicate that they are able to provide estimates of the vegetation water content. These so-called water indices extracted from MODIS products, have been used together with MODIS *LST*, and SMOS T_B to improve the spatial resolution of ~40 km SMOS soil moisture estimates. The aim was to retrieve soil moisture maps with the same accuracy as SMOS, but at the same resolution of the MODIS dataset, i.e., 500 m, which were then compared against *in situ* measurements from the REMEDHUS network in Spain. Results using two years of SMOS and MODIS data showed a similar performance for the four indices, with slightly better results when using the index derived from the first SWIR band. For the areal-average, a coefficient of correlation (*R*) of ~0.61 and ~0.72 for the morning and afternoon orbits, respectively, and a centered root mean square difference (cRMSD) of ~0.04 $m^3 m^{-3}$ for both orbits was obtained. A twofold improvement of the current versions of this downscaling approach has been achieved by using more frequent and higher spatial resolution water indexes as vegetation descriptors: (1) the spatial resolution of the resulting soil moisture maps can be enhanced from ~40 km up to 500 m, and (2) more accurate soil moisture maps (in terms of *R* and cRMSD) can be obtained, especially in periods of high vegetation activity. The results of this study support the use of high resolution *LST* and SWIR-based vegetation indices to disaggregate SMOS observations down to 500 m soil moisture maps, meeting the needs of fine-scale hydrological applications.

1. Introduction

The knowledge of soil moisture plays a determinant role in several hydrologic and atmospheric processes. In fact, soil moisture content controls the exchange of latent and sensible heat between land and atmosphere across the surface, which are the triggers of feedback mechanisms in land–atmosphere interactions (Entekhabi et al., 1996). Soil moisture also affects surface thermal inertia, surface temperature, surface shortwave albedo and precipitation. It provides key information about evaporation, infiltration and runoff (Kerr et al., 2001), and it is also used in Soil Vegetation Atmosphere Transfer models (Kerr et al., 2010a). Soil moisture could even potentially serve to better predict extreme events like storms, floods, droughts or landslides (Kerr et al., 2010a).

Microwave sensors have been largely used in the retrieval of soil moisture due to the direct relationship between soil moisture and the soil dielectric constant. Low microwave frequencies are generally preferred for soil moisture estimation than higher frequencies, because long wavelengths penetrate deeper in soil and vegetation, and are less affected by atmospheric conditions. Since late 1970s, data from microwave radiometers like the Scanning Multichannel Microwave Radiometer (SMMR) or the Advanced Microwave Scanning Radiometer (AMSR-E) have been utilized for the estimation of soil moisture from passive microwaves above 6.6 GHz achieving spatial resolutions between 148 km × 95 km

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(SMMR 6.6 GHz channel) and 74 km × 43 km (AMSR-E 6.9 GHz channel). Also active sensors can be used for soil moisture estimations. Nevertheless, although synthetic aperture radars can achieve spatial resolutions of meters, their temporal resolution needs to be considerably improved and its signal is significantly affected by soil roughness and vegetation, which hampers the accuracy of soil moisture retrievals. On the other hand, the scatterometers of, for example, the European Remote Sensing missions (radars operating in a 5.3 GHz channel) have been operating and distributing data between 50 and 25 km spatial resolution and 1–2 days of temporal resolution (Wagner et al. (2007) since the early 1990s (ERS and ASCAT). Altogether, passive microwave has to deal with low spatial resolutions and active microwave has to deal with low temporal resolutions and the effects of vegetation and roughness (Sobrino et al., 2012).

The first sensor dedicated specifically to globally remote sensing the soil moisture was launched in 2009: the Soil Moisture and Ocean Salinity (SMOS) mission (Kerr et al., 2010a) from the European Space Agency (ESA). Its unique payload is a radiometer which operates at L-band (1.4 GHz) and produces daily brightness temperature products with about 40–50 km of spatial resolution and daily soil moisture products resampled into 15 km-equally spaced grid. The expected accuracy of the soil moisture is 0.04 $m^3\,m^{-3}$. On the other hand, the National Aeronautics and Space Administration (NASA) plans to launch the Soil Moisture Active Passive mission (Entekhabi et al., 2010) in 2014, with the goal of retrieving soil moisture and freeze/thaw state. In this case, the measurements registered by an L-band radiometer will be combined with radar measurements to improve the spatial resolution of the estimations and it is expected to provide soil moisture maps of 36, 9 and 3 km spatial resolutions.

An indirect way to retrieve soil moisture from remote sensors is based on the plants reflectance measurements (Hardy et al., 2012). In this context, some studies have demonstrated that a direct and significant relationship exists between soil moisture and the spectral response in the visible and near infrared (VNIR) region. Products such as the Normalized Difference Vegetation Index (NDVI), reflectances, derivatives or other vegetation indices in the VNIR region have been compared against *in situ* or modeled soil moisture (Adegoke and Carleton, 2002; Farrar et al., 1994; Khanna et al., 2006; Schnur et al., 2010; Wang et al., 2007). However, some research evidenced that the shortwave infrared (SWIR) region could provide better results in order to detect soil water content (Finn et al., 2011; Lobell and Asner, 2002; Whiting et al., 2004). Moreover, the SWIR band presents regions of water absorption by plant leaves, and it is well known that SWIR reflectance is negatively related to leaf water content (Fensholt and Sandholt, 2003). Hence, vegetation water content (VWC) has been retrieved using different operational satellite data (Ceccato et al., 2002; Chen et al., 2005; Hunt and Rock, 1989; Jackson et al., 2004; Zarco-Tejada et al., 2003). The spectral signature of vegetation in NIR and SWIR bands can thus be associated to the plant water status. Furthermore, there are few studies linking this status, described by the NIR–SWIR indices, to soil moisture in the root zone (Fensholt and Sandholt, 2003; Lobell and Asner, 2002; Ridder et al., 1983). This link can be particularly traced in grasses, where volumetric soil moisture content measured at 10–20 cm depth is regarded as a proxy of the water availability for the plant photosynthetic activity (Fensholt and Sandholt, 2003), due to their shallow root depth. Conversely, VWC and plant's water status must be hardly related to soil moisture conditions and can be used as indirect estimators. The hypothesis suggested in the present research is that SWIR–NIR indices that represent plant's water conditions can improve the current soil moisture downscaling approaches based in the synergy between visible, infrared and microwave observations. Indeed, many disaggregation methods using VNIR data as inputs have been applied to improve the retrieval of soil moisture (Chauhan et al., 2003; Choi and Hur, 2012; Kim and Hogue, 2012; Merlin et al., 2010, 2005, 2013; Piles et al., 2011; Ray et al., 2010; Yu et al., 2008), but little research has been done applying the SWIR-based indices. Most of these downscaling methods are based on the relationship between land surface temperature (*LST*) and NDVI to soil moisture (Carlson, 2007; Carlson et al., 1994). That research assumed and demonstrated that soil moisture and evapotranspiration can be obtained from NDVI and *LST* by means of regression equations, established for each region and scene. Some of the studies mentioned above have included other inputs in the polynomial equations in order to improve the regression. Chauhan et al. (2003) included the surface albedo, and this idea was followed by Choi and Hur (2012) for downscaling the AMSR-E soil moisture. Piles et al. (2011) included the SMOS brightness temperatures to disaggregate SMOS level 2 soil moisture products. Later, they showed that including SMOS brightness temperatures at different incidence angles and polarizations resulted in a more robust relationship (Piles et al., 2013). Sobrino et al. (2012) included the surface emissivity centered in 9.17 μm, although in this study only soil moisture estimation was performed, but not disaggregation. For SMOS, combination with kilometric optical data seems to be the most promising strategy (Merlin et al., 2010; Piles et al., 2013). In the present work, the aim is to study the prospect of improvements of using the 8-day 500 m land surface reflectance MODIS product in the current downscaling methods for SMOS. Besides, the objective is also to evaluate the performance of the water indices as inputs in the disaggregation model, together with the comparison with the performance of the NDVI. The study period comprises two years, from April 2010 to April 2012.

2. Satellite imagery data

2.1. SMOS soil moisture and brightness temperature

SMOS L1C version 504 brightness temperatures (T_B) are used to derive horizontal and vertically polarized T_B maps at incidence angles θ_i of 32.5°, 42.5° and 52.5°. These maps are estimated through chi squared linear fit of all T_B values included in the $\theta_i \pm 5°$ interval, which is the methodology used to generate the SMOS L1C browse product (McMullan et al., 2008). Surface level T_B maps are then obtained by correcting ionospheric (geometric and Faraday rotations) and atmospheric effects.

Although the SMOS L2 version 551 is already available nowadays, the version 500 Soil Moisture data is used as benchmark soil moisture in this study. Retrieved values outside acceptable range or with poor fit quality were filtered out (confidence flags FL_RANGE and FL_CHI2_P). The global quality index DQX has not been used in order to keep the number of soil moisture retrievals to a maximum (Kerr et al., 2010b).

The resolution of SMOS observations varies from 30 km at nadir to ∼90 km at the upper borders of the field-of-view. SMOS brightness temperatures and soil moisture estimates are remapped from ISEA4H9 to a regular latitude-longitude grid using linear averaging and ensuring there is no loss of statistical significance of the average value at high latitudes.

Since its launch in November 2009, SMOS images have been strongly impacted by Radio Frequency Interference (RFI). Although L-band is protected, data are contaminated from on-ground manmade sources of RFIs, which operate close to this band or whose spurious signals fill in this band. The areas affected by RFI experience either an underestimation in the retrieved geophysical parameters or data loss. Approximately 500 RFI sources distributed worldwide have been detected, most of them located in Asia and Europe. A lot of effort has been put in place in order to reduce

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