Remote Sensing of Environment 184 (2016) 1–14

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

# A combination of DISPATCH downscaling algorithm with CLASS land surface scheme for soil moisture estimation at fine scale during cloudy days

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ARTICLE INFO

*Article history:*
Received 26 June 2015
Received in revised form 31 May 2016
Accepted 5 June 2016
Available online 14 June 2016

*Keywords:*
Soil moisture
SMOS
Downscaling
DISPATCH
CLASS
SMAPVEX12
Cloudy and cloud-free days

ABSTRACT

The main objective of this study is to propose and evaluate a new approach to overcome the major limitation of downscaling methods based on optical/thermal data, particularly the DISaggregation based on Physical And Theoretical scale Change (DISPATCH) algorithm. Data collected over an agricultural site located in Winnipeg (Manitoba, Canada) during the SMAP Validation Experiments 2012 (SMAPVEX12) field campaign were used. At this site, SMOS soil moisture estimates showed a relatively good correlation for both AM and PM overpasses ($R \geq 0.67$), but with a significant underestimation (bias $\approx -0.10$ m$^3$/m$^3$), when compared to ground data. SMOS soil moisture data also showed a significant sensitivity to rainfall events. The DISPATCH algorithm was used to downscale bias-corrected SMOS soil moisture data over the study area for the cloud-free days during SMAPVEX12. Compared to ground data, DISPATCH performed well, especially with the soil evaporative efficiency (SEE) linear model ($R = 0.81$, bias $= -0.01$ m$^3$/m$^3$, RMSE $= 0.05$ m$^3$/m$^3$), which slightly outperformed the SEE non-linear model ($R = 0.72$, bias $= -0.01$ m$^3$/m$^3$, RMSE $= 0.06$ m$^3$/m$^3$). For both models, the accuracy of the downscaling soil moisture is inversely proportional to the absolute value of soil moisture. For cloudy days, a new operational downscaling approach was proposed. It consists of combining the soil moisture simulations of the Canadian Land Surface Scheme (CLASS) with DISPATCH-downscaled soil moisture during cloud-free days in order to provide estimates of temporally continuous series of soil moisture at 1 km resolution. Compared to ground soil moisture data, the results indicated the high potential of our approach to retrieve soil moisture at 1 km resolution during cloudy days ($R = 0.80$, bias $= -0.01$ m$^3$/m$^3$, RMSE $= 0.07$ m$^3$/m$^3$).


## 1. Introduction

The fine scale distribution of soil moisture (SM) is needed for several applications, such as meteorology to improve weather prediction (Koster et al., 2011), hydrology to better describe the water cycle and predict flooding (Elbialy, Mahmoud, Pradhan, & Buchroithner, 2014), and agriculture for irrigation scheduling, site-specific management against diseases and pests, and improved crop yield prediction (Dursun & Ozden, 2011). The spatial and temporal dynamics of soil moisture are very complex since they depend on several factors (atmospheric forcing, topography, texture, and land cover). One way of monitoring this variability is through a dense network of continuous soil moisture observations, but this is costly to operate over large areas and long periods. By contrast, spaceborne sensors allow the frequent mapping of the top layer soil moisture for spatial scales that are inaccessible with direct methods.

Soil moisture estimates from space-based microwave measurements began with the launch of the Scanning Multichannel Microwave Radiometer in 1978 (Choudhury & Golus, 1988). Since then, numerous algorithms based on the inversion of a radiative transfer model have been developed to retrieve soil moisture (Njoku, Jackson, Lakshmi, & Chan, 2003; Draper, Walker, Steinle, De Jeu, & Holmes, 2009). Active microwave sensors, such as the synthetic aperture radars, provide data at fine spatial resolution (for example, up to 3 m for RADARSAT-2). While these data meet the spatial resolution required for applications at a local scale, they are significantly affected by the surface roughness and vegetation cover, thus making soil moisture retrieval difficult. Passive microwaves have a higher sensitivity to surface soil moisture, especially in the L-band (Njoku & Entekhabi, 1996; Kerr, 2007). The Soil Moisture and Ocean Salinity (SMOS) satellite of the European Space Agency (ESA), in orbit since November 2nd, 2009, is the first ever L-band passive microwave satellite with one of its objectives being the cartography of surface soil moisture at global scale with an accuracy better than 0.04 m$^3$/m$^3$ (Kerr et al., 2010). SMOS provides global soil moisture in the top 5 cm of soil on average and at a repeat cycle less than

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http://dx.doi.org/10.1016/j.rse.2016.06.010

3 days. However, its coarse spatial resolution (~40 km) is not suitable for applications at local scale. The new Soil Moisture Active/Passive (SMAP) mission, launched in January 2015, also has a coarse resolution passive microwave sensor (~40 km). Thus, downscaling algorithms are needed to improve the spatial resolution of passive microwave soil moisture products, in order to address the mismatch in the spatial resolution between the available spaceborne soil moisture data (several tens of kilometers) and local scale applications' (e.g., agriculture, water resources) requirements (from 1 to 10 km, Entekhabi et al., 2010).

SMAP was designed to combine active and passive microwave measurements at L-band in order to provide soil moisture data at 9 km resolution (Das, Entekhabi, & Njoku, 2011). Unfortunately, the radar sensor failed, and can no longer return data. Other downscaling approaches are based on a combination of coarse resolution passive microwave data with moderate resolution optical/thermal sensors data (1 km) (Chauhan, Miller, & Ardanuy, 2003; Merlin, Chehbouni, Kerr, Njoku, & Entekhabi, 2005; Merlin, Walker, Chehbouni, & Kerr, 2008; Piles et al., 2011; Merlin, Jacob, et al., 2012; Merlin, Rüdiger, et al., 2012; Merlin et al., 2013; Rahimzadeh-Bajgiran, Berg, Champagne, & Omasa, 2013), which have better temporal resolution than operational radar sensors. Moreover, they are cheaper and easier to obtain. The relationship between soil moisture, surface temperature, and vegetation index is known since the nineties through the "universal triangle" concept (Carlson, Gillies, & Perry, 1994). Since then, efforts have been made to derive fine scale soil moisture by introducing optical/thermal data. Chauhan et al. (2003) used the "universal triangle" concept to empirically infer high-resolution soil moisture from coarse resolution Special Sensor Microwave Imager (SSM/I) and Advanced Very High Resolution Radiometer (AVHRR) data. Later, the approach was improved by using a semi-empirical model for the relationship between the Soil Evaporative Efficiency (SEE), which is considered as a soil moisture index at local scale, and the near-surface soil moisture (Merlin et al., 2008).

Since the launch of SMOS in 2009, efforts to downscale soil moisture estimates were multiplied. Indeed, Piles et al. (2011) and Sánchez-Ruiz et al. (2014) suggested the incorporation of coarse resolution SMOS brightness temperature with SMOS soil moisture estimates, MODIS land surface temperature and Normalized Difference Vegetation Index (NDVI) to estimate soil moisture at MODIS scale based on an empirical model. To downscale the coarse resolution AMSR-E soil moisture estimates, in a weighting parameters approach, Kim and Hogue (2012) considered various key factors about the relative variations in surface wetness conditions derived from MODIS (i.e., surface temperature, vegetation indices, and albedo). Rahimzadeh-Bajgiran et al. (2013) replaced the surface temperature axis in the "universal triangle" space by the difference between the surface and air temperatures. The DISaggregation based on Physical And Theoretical scale Change (DISPATCH) algorithm developed by Merlin et al. (2012a) is an improved version of the former algorithm of Merlin et al. (2008). It used a "trapezoidal model" instead of the "universal triangle" to account for the effect of vegetation water stress at high resolution (Moran, Clarke, Inoue, & Vidal, 1994) for the derivation of SEE from optical/thermal data. DISPATCH has shown good results for different surface conditions in Australia (Merlin et al., 2012b), Spain (Merlin et al., 2013), the United States (Molero et al., submitted for publication) and the Canadian prairies in Saskatchewan (Djamai et al., 2015b).

One major limitation of DISPATCH, like any other downscaling algorithm using optical/thermal data, is the requirement for cloud free conditions, which limits its relevance in areas where clouds are frequent. Extending downscaling to cloudy days is necessary for the establishment of consistent and continuous spatial–temporal datasets at fine scale.

The main objective of this research is to propose and evaluate a new approach, based on a combination of DISPATCH and the Canadian Land Surface Scheme (CLASS, Verseghy, 1991; Verseghy, McFarlane, & Lazare, 1993; Verseghy, 2011), to estimate soil moisture at fine scale for cloudy days. Land surface models, such as CLASS, have the advantage of providing temporally continuous soil moisture simulations on hourly, daily, or monthly time steps and at different spatial scales. However, their accuracy depends on the model complexity and the accuracy of the input data, particularly at fine scale for which accurate input data are difficult to obtain (Overgaard, Rosbjerg, & Butts, 2006). In fact, Dumedah and Berg (2011) showed that CLASS overestimates the soil moisture over the Canadian Prairies (Saskatchewan), particularly at the 5 cm top soil layer. In the approach proposed, DISPATCH provides downscaled soil moisture at fine scale (1 km) for cloud-free days, while CLASS simulates the soil moisture profile for cloudy days at the same scale. The results obtained from DISPATCH for cloud-free days allow the calibration of CLASS-derived soil moisture. This study offered the opportunity to further evaluate SMOS soil moisture data and validate the DISPATCH algorithm with the dataset from the SMAP Validation Experiment 2012 (SMAPVEX12) field campaign (McNairn et al., 2015), which is characterized by a large spatial and temporal variability of soil moisture conditions.

## 2. Study area

The study site (49.4–50 N; 97.6–98.56 W) is the site of the SMAPVEX12 field campaign (McNairn et al., 2015). It is mostly an agricultural area of about 15 km × 70 km located south of Winnipeg (Manitoba, Canada). Grassland and pasture cover approximately 16% of the site. In addition, the site contains wetlands and forest cover. The Assiniboine River crosses the north end of the site. Fig. 1 shows the geographic position and the crop map of the study site. Agricultural fields as well as SMOS grid centers used for the study are also shown. It should be noted that the forested area was masked in the study, due to the low sensitivity of MODIS land surface temperature to the surface soil moisture.

## 3. Data description

### 3.1. Ground measurements of soil moisture

The ground measurements of soil moisture were collected during the SMAPVEX12 field campaign from June 6 to July 17, 2012 (between 6 a.m. and mid-day). They are available for 55 agricultural fields at a depth of 0–5 cm for 17 days (Table 1). For each field, the measurements were taken every 75 m at 16 points distributed along two transects 200 m apart, using Steven's Water Hydra and Delta-T Theta probes (McNairn et al., 2015). To ensure the representativeness of the field data, at each point, three measurements of soil moisture were collected. Then, the field average soil moisture is computed using a simple spatial average of discrete measurements. More details on the SMAPVEX12 protocols and dataset can be found in McNairn et al. (2015), the dedicated websites (https://smapvex12.espaceweb.usherbrooke.ca/) and the NSIDC repository (http://nsidc.org/data/smap/validation/val-data.html#smapvex12).

Fig. 2 presents the temporal variation of the in situ average soil moisture over the SMAPVEX12 site during the campaign. The average and standard deviation were calculated with the measurements of the 55 fields for each day considered. A high variability in soil moisture conditions can be seen, with mean values ranging from dry (around 0.15 $m^3/m^3$) to wet (around 0.35 $m^3/m^3$) conditions. This allowed the evaluation of the SMOS data, DISPATCH and the CLASS/DISPATCH combination for a wide range of soil moisture conditions (Fig. 2).

### 3.2. Satellite measurements

#### 3.2.1. SMOS soil moisture data

We used version 5.51 of the SMOS soil moisture data (L2 product). Details on the SMOS soil moisture algorithm are available in the Algorithm Theoretical Baseline Document (ATBD), version 3.6 (Kerr et al.,