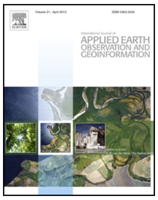
International Journal of Applied Earth Observation and Geoinformation xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

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



Spatio-temporal evaluation of resolution enhancement for passive microwave soil moisture and vegetation optical depth

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ARTICLE INFO

Article history:
Received 9 January 2015
Received in revised form 3 August 2015
Accepted 14 August 2015
Available online xxx

Keywords:
Soil moisture
Vegetation optical depth
Resolution enhancement
Passive microwave radiometry
Remote sensing

ABSTRACT

Space-borne passive microwave radiometers are used to derive land surface parameters such as surface soil moisture and vegetation optical depth (VOD). However, the value of such products in regional hydrology is limited by their coarse resolution. In this study, the land parameter retrieval model (LPRM) is used to derive enhanced resolution (~10 km) soil moisture and VOD from advanced microwave scanning radiometer (AMSR-E) brightness temperatures sharpened by a modulation technique based on high-frequency observations. A precipitation mask based on brightness temperatures was applied to remove precipitation artefacts in the sharpened LPRM products. The spatial and temporal patterns in the resulting products are evaluated against field-measured and modeled soil moisture as well as the normalized difference vegetation index (NDVI) over mainland Australia. Results show that resolution enhancement accurately sharpens the boundaries of different vegetation types, lakes and wetlands. Significant changes in temporal agreement between LPRM products and related datasets are limited to specific areas, such as lakes and coastal areas. Spatial correlations, on the other hand, increase over most of Australia. In addition, hydrological signals from irrigation and water bodies that were absent in the low-resolution soil moisture product become clearly visible after resolution enhancement. The increased information detail in the high-resolution LPRM products should benefit hydrological studies at regional scales.

1. Introduction

Soil moisture plays an important role in the water and energy cycles, e.g., by controlling the partitioning of rainfall into evapotranspiration, runoff and percolation (Seneviratne et al., 2010). Information on the spatial distribution of soil moisture is therefore crucial to improve understanding of hydrological processes. Passive microwave sensors make it possible to estimate soil moisture at global scale as retrievals are mostly independent of weather and have a near-daily revisit time. However, the coarse resolution of these sensors limits their suitability for regional and local hydrological applications. There are satellite soil moisture products with a higher spatial resolution, such as synthetic aperture radar (SAR) products, but these in turn have a low temporal resolution. The need for soil moisture datasets with both high temporal and spatial resolutions has prompted the development of several methods to increase the spatial resolution of passive microwave soil moisture products (i.e., Das et al., 2011; Kim and Hogue, 2012).

Soil moisture downscaling methods rely on the combination of low-resolution data with other products of higher resolutions based on the assumption that the higher resolution products contain information on the variable of interest at a finer spatial scale. A first approach combines passive microwave data with field-measured data, such as in situ soil moisture measurements (Kaheil et al., 2008), or topography and soil depth (Pellenq et al., 2003). A second approach is to combine passive microwave data with high-resolution land surface temperature retrievals and satellite-derived vegetation indices (Chauhan et al., 2003; Piles et al., 2011). Another approach has been to combine these data with estimates from models of varying complexity (Merlin et al., 2005; Merlin et al., 2008). Recently, a method has been developed that uses satellite-derived evaporative fraction to increase the resolution of passive microwave soil moisture datasets, called DISPATCH (Merlin et al., 2013). Finally, passive and higher-resolution active microwave

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http://dx.doi.org/10.1016/j.jag.2015.08.006

Please cite this article in press as: Gevaert, A.I., et al., Spatio-temporal evaluation of resolution enhancement for passive microwave soil moisture and vegetation optical depth. Int. J. Appl. Earth Observ. Geoinf. (2015), http://dx.doi.org/10.1016/j.jag.2015.08.006

observations can be combined (Das et al., 2011; Zhan et al., 2006), which is the goal of the recently launched NASA soil moisture active passive (SMAP) mission (Entekhabi et al., 2010). Note that while the Japan Aerospace Exploration Agency (JAXA) provides a passive soil moisture product at relatively high resolution, no downscaling technique is involved in the generation of this product. Instead, the coarse resolution (~50 km) swath data are aggregated to a 0.10° grid rather than the more typical 0.25° grid.

The downscaling methods described above require data from different sensors, such microwave radiometers and an optical/infrared spectroradiometer (Kim and Hogue, 2012; Piles et al., 2011) or radar and radiometer systems (Das et al., 2011). An alternative approach that is based on the smoothing filter-based modulation (SFIM) technique (Liu, 2000) uses the high-resolution brightness temperature data to sharpen the low-resolution bands from the same instrument (Santi, 2010). Soil moisture retrieval algorithms, such as the Land Parameter Retrieval Model (LPRM, Owe et al., 2008), can then use the sharpened brightness temperatures to derive soil moisture products at an enhanced spatial resolution (de Jeu et al., 2014). The advantage of this technique is that all observations not only made from the same platform, avoiding issues regarding observation times and processes occurring during inter-observational time periods, but also by the same sensor.

The objective of this study is to evaluate LPRM soil moisture and vegetation optical depth (VOD) retrievals based on sharpened microwave brightness temperatures derived using the SFIM technique. We use remotely-sensed vegetation indices and specifically modeled moisture fields, and examine changes in the spatial and temporal agreement with soil moisture and VOD retrievals before and after the sharpening of brightness temperature for the period 2002–2011. Our investigations focus on mainland Australia because previous studies have shown that the LPRM has a relatively good performance in this region (Draper et al., 2009; Su et al., 2013). While areas that LPRM performs poorly have the most potential for improvement, the main challenge for LPRM and passive remote sensing in general is masking of the soil signal by vegetation. Since the SFIM technique uses only passive microwave data and thus does not avoid this issue, we chose to study an area where vegetation is relatively sparse.

2. Materials and methods

2.1. Resolution enhancement

The sharpening technique and retrieval model were applied to data from the Advanced Microwave Scanning Radiometer (AMSR-E) onboard the Aqua satellite. We used Level 2A V12 Global Swath Spatially Resampled AMSR-E brightness temperatures (http://nsidc.org/data; Ashcroft and Wentz, 2013) and focused on the descending overpasses only. The differences between soil and vegetation temperature are relatively small during the nighttime descending overpass compared to those during the daytime ascending overpass (de Jeu, 2003; Liu et al., 2011). Since the LPRM assumes that soil and vegetation are the same temperature, this means that conditions are better suited to soil moisture retrieval during the descending overpass. Our study period is determined by the operating period of AMSR-E, which was from June 2002 to October 2011. AMSR-E has six different frequencies, of which the 6.9 GHz (C-band) and 36.5 GHz (Ka-band) at both horizontal and vertical polarizations are used in the LPRM. The footprint sizes of these frequencies are 75 × 43 and 14 × 8 km^2, respectively.

First, we enhanced the resolution of the C-band brightness temperatures to the resolution of the Ka band by applying the SFIM method (Parinussa et al., 2013; Santi, 2010), which was originally developed as a pan-sharpening technique (Liu, 2000). In this technique, the Ka-band brightness temperatures are aggregated to the resolution of the C band using a low pass filter. Subsequently, the ratio between the high- and low-resolution Ka-band brightness temperatures is used to modulate the low-resolution C-band brightness temperatures of both polarizations by the following equation:

$$\mathrm{Tb}_{\mathrm{C-high}} = \frac{\mathrm{Tb}_{\mathrm{Ka-high}}}{\mathrm{Tb}_{\mathrm{Ka-low}}} \times \mathrm{Tb}_{\mathrm{C-low}} \tag{1}$$

where the subscripts in Eq. (1) refer to the frequency bands and resolutions, respectively. This technique assumes that the variability within a C-band footprint is linked to the variability in the Ka band. The Ka band is not used directly for soil moisture retrievals because the signal is more sensitive to attenuation by vegetation and thus less sensitive to soil moisture than longer wavelengths such as the C band. Even so, this enhanced sensitivity to vegetation could potentially impact the quality of sharpened LPRM products over densely vegetated areas. For more information about this technique, see Santi (2010) or Parinussa et al. (2013).

Next, the LPRM used the C-band and Ka-band brightness temperatures to derive soil moisture and VOD. The LPRM models a range of plausible brightness temperatures from a set of soil moisture and VOD values, and then uses an optimization routine to choose the values that best fit the observation; see Owe et al. (2008) for a full description of the model. Previous studies have shown that LPRM performs well when compared to other soil moisture products, though the performance tends to decrease over densely vegetated areas (Brocca et al., 2011; Draper et al., 2009; Su et al., 2013). For convenience, we will refer to the LPRM products based on C-band brightness temperatures with, and without applying the SFIM technique as low- and high-resolution products, respectively.

In this study, we use gridded LPRM data for the temporal analyses (0.25° and 0.10° at the low and high resolutions, respectively), but swath data for the spatial analyses. The advantage of using swath data in the spatial analysis is that we use the actual values derived from AMSR-E observations and thus avoid averaging effects due to the gridding process. Swath data is provided at a resolution of approximately 10 km, meaning that measurements overlap significantly at low resolution, but are nearly independent at high resolution.

2.2. Precipitation mask

LPRM soil moisture sharpened by the SFIM technique has previously been analyzed in studies over the Iberian Peninsula (Parinussa et al., 2013) and the Fitzroy catchment in Australia (de Jeu et al., 2014). These studies showed that unfavorable atmospheric conditions such as heavy precipitation events could lead to errors in the sharpened soil moisture product. This can occur because higher microwave frequencies are more sensitive to precipitation than lower microwave frequencies. This sensitivity affects the ratio used for modulating the low resolution C-band brightness temperatures in Eq. (1), propagates into the sharpened C-band brightness temperatures and subsequently into the LPRM products. We therefore applied a precipitation mask based on AMSR-E brightness temperatures. The mask is derived from the scattering index of Kummerow et al. (2001) and the desert and semi-arid screening methods of NSIDC (1996) and Ferraro et al. (1994), respectively. As a final step, a buffer equivalent to the radius of the C-band footprint was added to the mask to prevent the precipitation signal in the Ka band propagating through the aggregated Ka band and into the high-resolution products.

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