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Evaluation of the predicted error of the soil moisture retrieval from C-band SAR by comparison against modelled soil moisture estimates over Australia

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ABSTRACT

The Sentinel-1 will carry onboard a C-band radar instrument that will map the European continent once every four days and the global land surface at least once every twelve days with finest 5 × 20 m spatial resolution. The high temporal sampling rate and operational configuration make Sentinel-1 of interest for operational soil moisture monitoring. Currently, updated soil moisture data are made available at 1 km spatial resolution as a demonstration service using Global Mode (GM) measurements from the Advanced Synthetic Aperture Radar (ASAR) onboard ENVISAT. The service demonstrates the potential of the C-band observations to monitor variations in soil moisture. Importantly, a retrieval error estimate is also available; these are needed to assimilate observations into models. The retrieval error is estimated by propagating sensor errors through the retrieval model.

In this work, the existing ASAR GM retrieval error product is evaluated using independent top soil moisture estimates produced by the grid-based landscape hydrological model (AWRA-L) developed within the Australian Water Resources Assessment system (AWRA). The ASAR GM retrieval error estimate, an assumed prior AWRA-L error estimate and the variance in the respective datasets were used to spatially predict the root mean square error (RMSE) and the Pearson's correlation coefficient *R* between the two datasets. These were compared with the RMSE calculated directly from the two datasets. The predicted and computed RMSE showed a very high level of agreement in spatial patterns as well as good quantitative agreement; the RMSE was predicted within accuracy of 4% of saturated soil moisture over 89% of the Australian land mass. Predicted and calculated *R* maps corresponded within accuracy of 10% over 61% of the continent. The strong correspondence between the predicted and calculated RMSE and *R* builds confidence in the retrieval error model and derived ASAR GM error estimates.

The ASAR GM and Sentinel-1 have the same basic physical measurement characteristics, and therefore very similar retrieval error estimation method can be applied. Because of the expected improvements in radiometric resolution of the Sentinel-1 backscatter measurements, soil moisture estimation errors can be expected to be an order of magnitude less than those for ASAR GM. This opens the possibility for operationally available medium resolution soil moisture estimates with very well-specified errors that can be assimilated into hydrological or crop yield models, with potentially large benefits for land-atmosphere fluxes, crop growth, and water balance monitoring and modelling.

1. Introduction

To support the operational use of Synthetic Aperture Radar (SAR) earth observation systems, the European Space Agency (ESA) is developing Sentinel-1, a constellation of two polar-orbiting C-band radar satellites. Much like its SAR predecessors (Earth Resource Satellite, ENVISAT and RADARSAT) the Sentinel-1 will operate at a medium spatial resolution, but with a greatly improved revisit period. Each of the Sentinel-1 satellites is expected to provide coverage over Europe and Canada once every four days and global coverage in twelve days or less. Given the high temporal sampling and the operational configuration Sentinel-1 is expected to be beneficial for operational monitoring of dynamic processes in hydrology and phenology.

The benefit of a C-band SAR monitoring service in hydrology has already been demonstrated within the scope of the Soil Moisture for Hydrometeorologic Applications (SHARE) project (http://www.ipf.tuwien.ac.at/radar/share/) (Bartsch, 2008; Doubkova et al., 2009). SHARE is one of the ESA's Data User Element (DUE) Tiger Innovator

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projects. Within the project a soil moisture dataset at medium resolution was retrieved from the Global Mode (GM) of the Advanced Synthetic Aperture Radar (ASAR) onboard ENVISAT (Pathe et al., 2009). Existing coarse resolution soil moisture data from active and passive sensors (Kerr et al., 2010; Naeimi et al., 2009; Njoku et al., 2003; Wagner, 1998; Wagner et al., 1999b) were found beneficial for weather prediction, climate monitoring or flood forecasting (Brocca et al., 2010; Liu et al., 2010) at global to regional scale. It can be anticipated that further applications would become feasible with medium resolution datasets. These include crop yield and soil moisture monitoring over heterogeneous landscapes and river runoff prediction at areas with local precipitation patterns (Komma et al., 2008; Meier et al., 2011; Osborne et al., 2009; Parajka et al., 2009).

The SHARE project demonstrated the potential of C-band observations at high temporal and moderate spatial resolution to monitor variations in soil moisture on a quasi-operational basis (Pathe et al., 2009). Since the start of the project in 2005, the retrieved soil moisture estimates have been requested by more than 80 organisations worldwide, the main application domains being hydrology, agriculture and comparison with other soil moisture datasets. A published validation study demonstrated a good correspondence of ASAR GM soil moisture with in-situ data and airborne SAR systems (Mladenova et al., 2010). Possible applications of the ASAR GM data included bias identification in the precipitation datasets (Milzow et al., 2010) and support for runoff monitoring (Bartsch et al., 2007). It was nevertheless concluded that the usability of the dataset is compromised by the intermittent coverage and poor radiometric resolution of the sensor in global mode (Wagner et al., 2010). Sentinel-1 will improve revisit period and radiometric resolution and so overcome the major limitations of the ASAR GM sensor. Given the otherwise similar sensor characteristics (Attema et al., 2007), the transfer of the ASAR GM soil moisture service to Sentinel-1 seems an obvious opportunity.

A common approach for demonstrating the benefit of satellite-derived data relies on their assimilation into existing models. Assimilation techniques require accurate estimates of observational errors (Liu et al., 2010; Scipal et al., 2008). Pathe et al. (2009) developed an ASAR GM error propagation model. This model predicts the ASAR GM soil moisture error using the Gaussian error propagation scheme.

In this study the ASAR GM soil moisture error estimates produced following Pathe et al. (2009) are evaluated using independent surface soil moisture estimates from the grid-based landscape hydrological model (AWRA-L) developed within the Australian Water Resource Assessment modelling system (AWRA; Van Dijk, 2010). In particular, the RMSE and *R* computed between the satellite and modelled data are predicted using the ASAR GM error estimates and compared to the observed RMSE and *R* between the two soil moisture datasets.

This paper is organised as follows. The theory, methodology and data sections introduce the models used for the RMSE and *R* computation, processing steps and the data. The discussion and result sections present: a) an evaluation of the correlation between the satellite (ASAR GM) and modelled (AWRA-L) soil moisture datasets to determine if these capture the same processes; and b) an assessment of the ASAR GM error estimate using the models for the RMSE and *R* prediction. The implications for a possible future Sentinel-1 soil moisture product are also discussed. Conclusions and future recommendations are summarized in the final section.

2. Theory

The RMSE and *R* between two datasets can be calculated directly from the variance and covariance statistics; these will be refereed to as the observed values. In addition, if the error (ε) and variance (σ^2) of the respective datasets are known, the RMSE and *R* values can be predicted; these will be refereed as the predicted values.

Although the AWRA-L and ASAR GM soil moisture estimates are assumed to represent the same phenomenon, they are expressed in different units. This may induce a bias in the mean and dynamic range that opposes the model assumption (Dee & Todling, 2000). To correct for possible biases the AWRA-L dataset was adjusted to the ASAR GM dataset using Cumulative Distribution Function (CDF) matching techniques.

Because the goal of this study was to evaluate the quality of the existing satellite error estimate, the modelled data were scaled with respect to the satellite data (for data assimilation studies, an inverse approach is more logical; Reichle & Koster, 2004). The transformation of the AWRA-L soil moisture estimates used in this study is a CDF matching technique simplified to a linear transformation that effectively removes the differences in the first two moments (i.e. mean and variance):

$$\theta_M = \frac{\left(\theta_{M,or} - \bar{\theta}_{M,or}\right)}{stdev_{M,or}} * stdev_S + \bar{\theta}_S, \tag{1}$$

where θ represents the soil moisture observations, and *stdev* and $\bar{\theta}$ the temporal standard deviation and the temporal mean of these observations, respectively. The subscript *S* and *M* symbolize the satellite and modelled dataset, respectively. Finally, the subscript *or* indicates the original dataset before normalisation. In all subsequent computations the normalized AWRA-L soil moisture estimates (θ_M) were used.

2.1. Observed RMSE and R

The RMSE is a straightforward measure of estimation accuracy between two datasets. The RMSE$_a$ between modelled and satellite-derived soil moisture can be defined through the variance of residual errors. If θ_S is the satellite-derived soil moisture and θ_M the normalised modelled soil moisture then the RMSE$_a$ is defined as

$$RMSE_a = \sqrt{\left\langle (\theta_M - \theta_S)^2 \right\rangle}, \tag{2}$$

where the angle brackets represent the mean over time.

The RMSE$_a$ in combination with the variances of the satellite and modelled data can be used to calculate the correlation coefficient R_a (Barnston, 1992; Murphy, 1995):

$$R_a = \frac{stdev_M^2 + stdev_S^2 - RMSE_a^2}{2 stdev_M stdev_S}, \tag{3}$$

where $stdev_M$ and $stdev_S$ stand for the temporal standard deviation of the normalized modelled and satellite derived soil moisture, respectively.

2.2. Predicted RMSE and R

The RMSE can be predicted from the error characteristics of the satellite (ε_S) and the modelled (ε_M) data using error propagation model of (Taylor, 1997):

$$RMSE_b = \sqrt{\langle \varepsilon_M \rangle^2 + \langle \varepsilon_S \rangle^2}. \tag{4}$$

The assumptions of the error propagation model are that the respective error characteristics are independent and follow a Gaussian normal distribution. The assumption on error characteristics is realistic as the main input data to the AWRA-L, daily precipitation, incoming shortwave radiation and temperature, are independent of the ASAR GM backscatter. Moreover, the Gaussian normal distribution