5 YEARS OF ENVISAT ASAR SOIL MOISTURE OBSERVATIONS IN SOUTHERN GERMAN

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ABSTRACT

Soil moisture is a key variable for the water and energy exchanges at the land surface. The determination of soil moisture dynamics from space is one of the most prominent, but also most challenging applications for recent active microwave sensor systems. Since the launch of ENVISAT ASAR, more than 4 years of data is available for the retrieval of soil moisture information. The wide area coverage of ASAR allows for soil moisture retrievals for large areas. The present study investigates a long term time series of ASAR soil moisture products. The ENVISAT soil moisture data is compared against a soil moisture climatology, simulated by a land surface model within a mesoscale watershed in Southern Germany. The relationship between the simulated and observed soil moisture is quantified and the potential for the integration of ASAR information into the LSM is outlined.

1   INTRODUCTION

There is ample evidence that atmospheric and hydrological processes are significantly influenced by the local and regional availability of soil moisture [1]. It is conditioning the partitioning of the available energy into latent and sensible heat flux and of the rainfall into infiltration and surface runoff [2],[3].

Soil moisture is spatially and temporal highly variable. Soil moisture patterns show spatial and temporal coherent patterns at different scales. Large soil moisture differences may be observed within a distance of a few meters as well as within a distance of several kilometres [4]. Estimating this variable with high temporal resolution and at the global scale has potential applications in meteorology, hydrology and climate research [5].

Active and passive remote sensing methods utilising the microwave region of the electromagnetic spectrum are considered to hold a large potential for soil moisture retrieval because of the pronounced effect of the soil dielectric properties on the microwave signal. Numerous theoretical and empirical models have been developed to retrieve surface soil moisture information from active [6]-[8] and passive [9],[10] microwave data. Nevertheless, surface roughness and vegetation effect might perturbate the retrieval of soil moisture information from microwave remote sensing data, especially at higher frequencies. Different strategies are applied to compensate for vegetation effects on the measured backscattering coefficient. These comprise theoretical, semi-empirical and empirical approaches.

Since it's launch in 2002, the ENVISAT Advanced Synthetic Aperture Radar (ASAR) is used to retrieve soil moisture related information. The sensor offers different imaging modes with varying spatial resolutions and polarization channels.

Land surface models (LSM) are widely used to describe processes at the interface layer within the soil-vegetation-atmosphere continuum. They provide time series of spatially distributed simulations of land surface variables as e.g. soil moisture, evapotranspiration, surface runoff, vegetation biomass or leaf area index. Simulations are based on different kinds of input parameters, as soil texture, land use pattern, meteorological data, which are highly variable in space and time and are available with different accuracies at different scales. The applicability of land surface process models might be limited due to the availability of necessary input data sets, the quality of these datasets and the level of complexity and accuracy of the process description within the model.

Remote sensing derived information about geophysical parameters as e.g. soil moisture might be therefore used to identify uncertainties in LSM simulations and to improve the LSM model performance by assimilating the remote sensing information into the LSM [11]. This might be achieved by either updating the surface state of the LSM or by helping to improve the model parameterization. An intercomparison of LSM simulations and corresponding soil moisture observations is required to evaluate the potential to improve LSM simulations by ENVISAT information.

The present study aims at a long term comparison of ENVISAT ASAR derived soil moisture information with simulations by a state of the art land surface model (LSM). ENVISAT ASAR soil moisture products from four years are compared against the surface soil moisture simulations by the LSM. The comparison is

based on a pixel by pixel comparison between both data sets at the 1-km scale. The used data sets and models are introduced in section 2. The soil moisture retrieval from ASAR is briefly outline in section 3 and the variability of the soil moisture data sets is analysed in section 4. The intercomparison between both data sources is made in section 5 and conclusions are given in section 6.

2 MODELS AND DATA SETS

2.1 PROMET model

The Process Oriented Multiscale EvapoTranspiration model (PROMET) is a family of land-surface-process-models which describe the actual evapotranspiration and water balance at different scales, ranging from point scale, to microscale and mesoscale modelling [12]. The model consists of a kernel model which is based on five sub-modules (radiation balance, soil model, vegetation model, aerodynamic model, snow model) to simulate the actual water and energy fluxes and a spatial data modeller, which provides and organizes the spatial input data on the field-, micro and macroscale. The simulations are made on an hourly basis. For a detailed description of the model see [12].

2.2 Upper Danube test site

The test site for the present study is situated in Southern Germany). The Upper Danube catchment is characterized by large natural gradients. The elevation ranges between 300 and 4000 m.a.s.l. Yearly precipitation ranges from < 500 to > 2000 mm/a. The land cover information for the LSM simulations are based on a 30 m land cover map. This high resolution land cover information was aggregated on a 1 km grid and the fractions for each land cover were estimated for each grid cell. The catchment is dominated by cropland in the northern and grassland areas in the southern areas close to the mountains of the Alps.
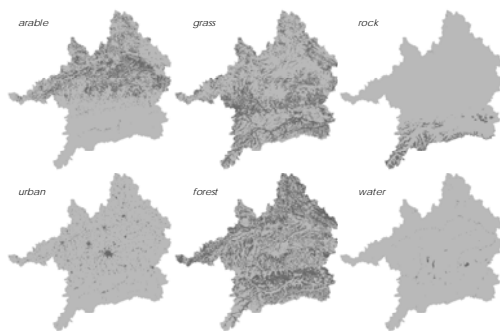

Figure 1: Land cover distribution in the Upper Danube catchment

2.3 Soil moisture simulations

A three layer soil model is used within PROMET to represent the soil water fluxes. The layer thickness is chosen as 10/20/120 cm for the first, second and third soil layer within this study respectively. The infiltration into the soil layer is described using Philip equation. The soil water balance, soil suction and soil moisture are determined through a simplified solution of the Richards-equation, taken from [13]. A mean root depth is specified for each land cover type, which may vary throughout the year as function of the julian day (JD). The soil suction, together with a root-resistance term, determines, whether a lack in soil moisture limits the canopy transpiration.

Figure 2 shows the soil moisture simulated by PROMET in comparison with in situ measurements. The ground data was collected during the ESA AGRISAR 2006 campaign [14]. The simulations and measurements show considerable agreement. The rms error is 1.7 vol.% and 2.0 vol.% for the first and second soil layer (0-10cm,10-30cm) respectively. Very detailed (10 minute) meteorological data and detailed soil information was available in that case.
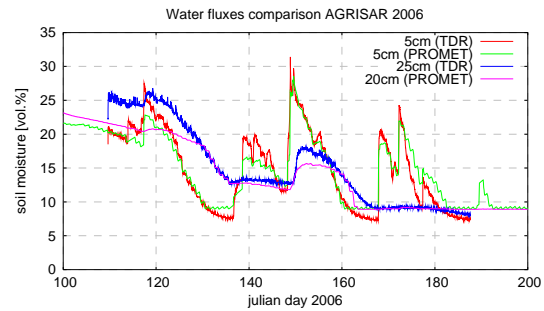

Figure 2: Intercomparison of PROMET simulated soil moisture and TDR measurements

For large area simulations, detailed meteorological and soil data is often not available in the same quality as for field studies. Simulations are then based on generalized soil maps and interpolated meteorological data. This might introduce uncertainties in the simulations of the land surface variables by the LSM.

PROMET simulations are made from 2002 to 2005, whereas the first three months of the first year are used for model spin up. Figure 3 shows the soil moisture evolution throughout the simulation period, as averaged over the entire catchment. The greyed area indicate the variance within the catchment. The mean simulated soil moisture varies between 18 and 33 vol.% throughout the years in the average. Soil moisture dynamics for individual grid cells might be nevertheless much higher, as indicated by the standard deviation, which ranges in between 4.5 and 7.5 vol.% within the catchment.
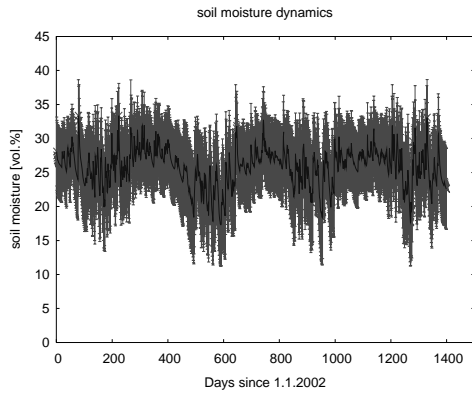
Figure 3: Mean (line) and standard deviation (area) soil moisture for the Upper Danube

3 ENVISAT ASAR SOIL MOISTURE

Within the present study, soil moisture data is retrieved from data of the active microwave ASAR sensor on board of the ENVISAT platform. It provides multiple acquisition modes, including wide area coverage modes as the so called Wide Swath and Global Monitoring mode, which have spatial resolutions of 150 m and 1000 m respectively and a swath width of approximately 400 km. In the present investigation, the medium resolution Wide Swath Mode (WSM) is used.

3.1 SAR data processing

All image data is automatically calibrated and geocoded. In order to compensate the terrain induced local geometric and radiometric distortions, the SAR image is rectified using a digital elevation model and the backscattering coefficient is corrected for the terrain induced effect on the backscattering coefficient [15]. This allows for the quantitative analysis of the image data in rugged terrain.

Large parts of the test site are affected by temporary snow cover. As snow is known to have a considerable effect on the backscatter signature at C-band, snow covered areas are excluded from the investigations. The snow covered area is determined by a) masking all areas, where the LSM predicts snow cover and b) areas, where the backscattering coefficient in winter periods decreases by more than 3 dB with respect to a reference scene, which delineates wet snow areas [16].

SAR acquisitions on days with precipitation are excluded from the analysis as well, as the intercepted water within the canopy and surface soil might detoriate the relationship between the soil moisture and microwave backscatter. The precipitation patterns are obtained from interpolated meteo station data.

3.2 Soil moisture retrieval

The soil moisture products from ENVISAT ASAR are based on the retrieval algorithm, developed by [8]. In contrast to theoretical models, it requires a limited number of necessary ancillary data to retrieve the surface soil moisture information. In addition, it explicitly considers land cover heterogeneities within the image resolution cell and compensates for their effect to improve the soil moisture retrievals. The approach empirically relates the microwave backscattering coefficient to the soil dielectric constant based on land cover information. Intense comparisons of the algorithm have been made within different test sites in Europe. It has been found that the accuracy of the soil moisture retrievals ranges between 3.0 and 6.0 vol.% rms error.

Soil moisture is retrieved only for areas with short vegetation (arable land, grassland), while a retrieval for forested areas or urban areas is not possible due to low soil moisture sensitivity of the signal in those areas. The soil moisture retrieval is therefore based on a high (150 m) resolution land cover classification of the test site. Temporal dynamics of vegetation is taken into account, by assuming a characteristic vegetation development. As the penetration depth into the soil is low, the soil moisture retrieved soil moisture values are related to the surface soil water content (0 … 2 cm).

A total number of 156 ENVISAT ASAR images covering parts of the Upper Danube test site within the period from 2002 to 2005 was processed. Soil moisture information was derived at a scale of 150m and then aggregated to 1 km to reduce the noise of the retrievals. The data set comprises 430 x 425 grid cells at the 1 km resolution. Figure 4 shows an example of a soil moisture product, derived from a wide area covering ASAR WSM data set.
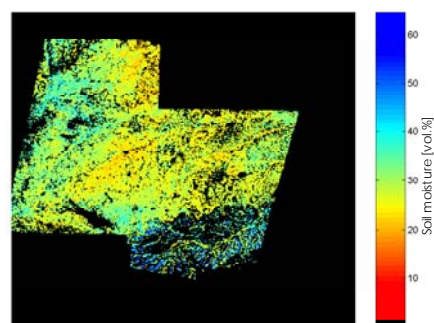

Figure 4: Soil moisture product based on ENVISAT ASAR Wide Swath mode data

Figure 5 shows a comparison between ground measurements of soil moisture and the ENVISAT retrievals for two different imaging modes. The rms error between in situ measured and ENVISAT ASAR

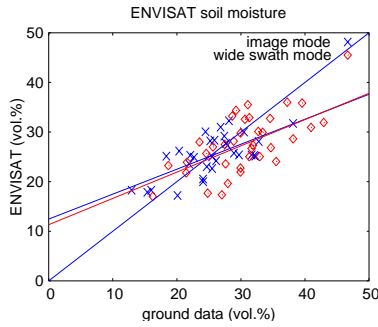derived soil moisture is 4.0 and 5.8 vol.% for the image mode and wide swath mode respectively.

Figure 5: Comparison of ENVISAT ASAR soil moisture against ground measurements

4   SOIL MOISTURE VARIABILITY

Soil moisture is a highly variable surface parameter. It is influenced at the local scale e.g. by soil characteristics and/or small topography variations, while the large scale patterns are basically a function of meteorological conditions and general terrain characteristics, as well as land cover patterns [17].

Field observations by the authors in various test sites indicate a soil moisture variability in the order of 2-6 vol.% (standard deviation) at the local scale.

4.1   Comparison of soil moisture variability

The soil moisture variability might be different for each grid cell, due to different land cover (fractions) and soil types as well as changing mean meteorological conditions (e.g. change of precipitation patterns). The soil moisture variability is estimated from the entire ASAR image database with 156 images.

The spatial coverage of the images varies, resulting in different numbers of image acquisitions for different grid cells. The number of image data used for the analysis therefore varies between 16 and 90 images per grid cell. The simulations of a LSM might show their own climatology as function of model parameterization and model physics. The soil moisture variability is estimated from the PROMET simulations for the same dates as the ENVISAT data is available.

Figure 6 shows the frequency distributions of the soil moisture variability, as derived from ASAR and PROMET results on the 1 km scale. The ASAR soil moisture shows a higher dynamic than the corresponding PROMET results. While the variability of PROMET ends at 6 vol.%, approximately 15% of the grid cells in the test site show a higher variability than 6 vol.% (std.dev.) as derived from the ENVISAT data. This might be explained by the different observation depths of the data sets. While the ENVISAT soil moisture is expected to represent surface soil moisture

content, which shows a high temporal dynamic, the PROMET simulations are taken from the first of a three-layer soil model, which has a depth of 10 cm. Thus, the simulated soil moisture values are attenuated and show a lower dynamic.
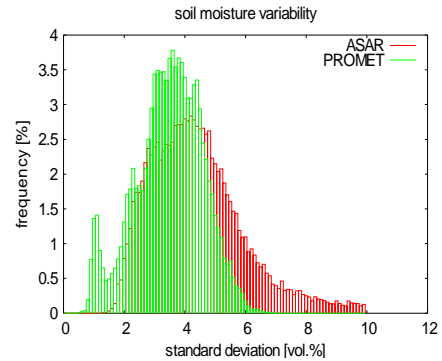

Figure 6: Frequency distribution of soil moisture variability within the Upper Danube area, as derived from ASAR data and PROMET simulations

5   ANALYSIS OF MULTITEMPORAL SOIL MOISTURE DYNAMICS

The soil moisture dynamics as derived from the ENVISAT products and PROMET simulations is compared in the following for a 4-year period (2002-2005). A comparison of the soil moisture climatology from the ASAR and PROMET data is made for the entire test site. All comparisons are made for the soil moisture data sets with 1 km resolution.

The long term time-series of ASAR soil moisture is used to make a comparison between the remote sensing based surface soil moisture and the corresponding PROMET simulations from 2002 to 2005. The time series for each grid cell has a different number of observations, due to the different imaging geometries and the preprocessing of the data sets as said before. The number of images used for the comparison ranges between 16 and 90 data sets. Pairs of soil moisture (ASAR, PROMET) are extracted from the data base for each grid cell individually. A linear regression is then calculated for each grid cell with PROMET being the dependant variable. The coefficient of determination and rms error is estimated for each grid cell. Figure 7 shows examples of the comparison for three different 1-km pixels. A positive relationship is observed in all cases. The gain is 0.25, 0.50 and 0.64 for the red, blue and green data set respectively. The dynamic range of the PROMET simulations is lower than that of the ASAR observations, which might be explained by the difference between the surface soil moisture data (ASAR) and the 20cm soil layer of PROMET.
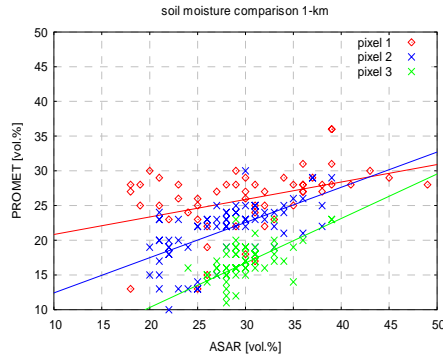
Figure 7: Comparison of ASAR WSM and PROMET soil moisture at the 1 km scale

Figure 8 shows the resulting map of the coefficient of determination. The irregular shape results from a) the mask of the Upper Danube area and b) from the coverage of the ASAR data used for the processing. It is observed, that the coefficient of determination is higher in the Northern and Western part of the catchment, while lower values are observed in the Southern, grassland dominated areas. In general, the coefficient of determination is rather low. It ranges in between 0.1 and 0.4, while the gain of the linear regression ranges from 0.1 to 0.8, with the majority around 0.3. Higher correlations are observed basically in areas, dominated by agricultural crops, situated basically in the Northern and Western part of the test site.
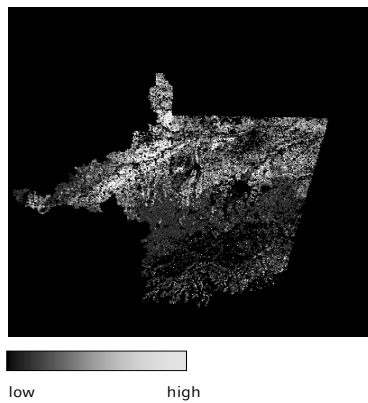

Figure 8:Coefficient of determination

The rms difference between the PROMET and ASAR soil moisture is estimated for each grid node. Figure 9 shows the frequency distribution of the rms difference. It is seen, that for large parts (80%) of the area, the rms difference is smaller than 4 vol.%.
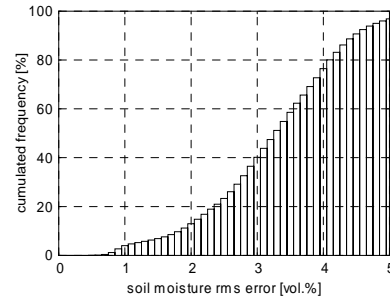

Figure 9:Cumulated frequency distribution of rms error between PROMET and ASAR soil moisture at the 1-km scale

6   SUMMARY AND CONCLUSIONS

The present study has shown for the first time a long term intercomparison of LSM simulations with ENVISAT ASAR based soil moisture estimations for a large area. The ENVISAT ASAR based soil moisture has been evaluated by comparison with ground measurements. The rms difference of the ENVISAT soil moisture products was found to be in the order of 3.5-6 vol.% in case of the Wide Swath mode data. Positive correlations between ASAR and LSM soil moisture were found, based on a data base with 156 ENVISAT ASAR images. The observed deviations between the LSM and ASAR data sets are below 4 vol.% (rms error) for the non-alpine areas of the catchment, which is considered as a typical benchmark for soil moisture retrievals. The ASAR soil moisture products provides reliable estimates of the (relative) soil moisture changes for a given location, when compared against ground measurements. The accuracy of the LSM simulations is highly dependant on the availability of accurate meteorological forcing data (e.g. precipitation) and soil type information. Both are available with limited spatial resolution for larger areas. The ENVISAT ASAR data might be therefore used to improve the LSM simulations, by assimilating the remote sensing based information into the LSM. Appropriate integration approaches will have to be developed, to take into account the different observed soil moisture dynamics of the data sets. This will be subject of further investigations.

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