Multiscale analysis of soil moisture using satellite and aircraft microwave remote sensing, in situ measurements and numerical modelling

Johanna Therese dall'Amico

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Abstract

Surface soil moisture is located at the interface between the land surface and the atmosphere and thus of great importance for the mass and energy fluxes to and from the atmosphere. However, it is difficult to capture its high spatial and temporal variability. In situ measurements are possible only on the point-scale. Remote sensing and hydrological modelling deliver area-wide information on soil moisture at various scales, but either technique is associated with uncertainties. For accurate soil moisture modelling, input data of high resolution and quality are required, which are available only in few parts of the world. For the remote sensing of soil moisture, brightness temperatures from the lower microwave region of the electromagnetic spectrum show a high sensitivity to soil moisture. Until recently, it was not technically feasible to achieve a reasonable spatial resolution when measuring such brightness temperatures from space. The first satellite mission employing this technology, the Soil Moisture and Ocean Salinity (SMOS) mission, was launched in November 2009 and, since then, delivers global maps of brightness temperatures every 2-3 days with a spatial resolution in the order of 40 km. From these brightness temperatures at various incidence angles, a soil moisture data product is derived using an inverted radiative transfer model. Such procedures require dedicated calibration and validation activities in order to improve the retrieval towards the target accuracy. Thus, several field campaigns were conducted in different parts of the world in order to acquire in situ soil moisture data and airborne brightness temperature data for data product validation and the improvement of the model's parameters.

In this thesis, data sets of in situ soil moisture, airborne brightness temperatures, the SMOS soil moisture data product and hydrological model output are presented and analysed. The considered test site is the Upper Danube Catchment (UDC), located mostly in Southern Germany, with a mid-latitude temperate humid climate and predominantly agricultural land use. In situ soil moisture measurements at five ground stations are compared to multiple soil moisture measurements distributed in their surrounding areas. It turns out that these point-like measurements correctly reproduce the soil moisture dynamics of the area. Further, land cover is found to produce a bias in the in situ soil moisture measurements, with wetter soils under grass. Airborne brightness temperatures from a fully polarimetric radiometer (EMIRAD) show the behaviour expected from theory when compared to in situ soil moisture data. Thus, EMIRAD data are suitable for the validation of other data sets. Two-dimensional brightness temperatures with a high spatial resolution obtained from HUT-2D, a novel airborne interferometric radiometer with a measurement technique similar to SMOS, are validated and found to agree well with EMIRAD data. The analysis of modelled soil moisture fields and their comparison with EMIRAD data show that the model data can be expected to be realistic at the SMOS scale in areas with a high density of meteorological stations delivering the precipitation input data. Thus, modelled soil moisture fields may fill the scale gap between localized in situ measurements and area-wide SMOS data for calibration and validation activities. Finally, SMOS soil moisture data of the vegetation period of the year 2010 show a large dry bias and poor correlations (~ 0.2) with in situ data and modelled soil moisture fields. In contrast, SMOS data of the same period of the year 2011 show a smaller bias and better correlations (~ 0.5). This is likely associated with improvements of the SMOS data product and a reduction of radio frequency interference in Europe. The SMOS mission accuracy target of 0.04 $m^3\ m^{-3}$ (volume of water / volume of soil) is not yet reached in the UDC, but recent improvements are encouraging.

Zusammenfassung

Die Bodenfeuchte ist eine zentrale Größe, da sie im Wasserkreislauf die Schnittstelle zwischen Landoberfläche und Atmosphäre darstellt und dort den Energie- und Massenaustausch maßgeblich steuert. Es ist möglich, den Wassergehalt der obersten Bodenschicht im Gelände am Punkt zu messen, allerdings wird damit nicht die hohe zeitliche und räumliche Variabilität der Bodenfeuchte erfasst. Fernerkundung und hydrologische Modellierung hingegen liefern zwar flächige Information über die Bodenfeuchte auf verschiedenen Skalen, sind aber mit spezifischen Unsicherheiten behaftet. Um die Bodenfeuchte korrekt zu modellieren, werden Eingangsdaten mit hoher Qualität und Auflösung benötigt, die nur in wenigen Teilen der Erde verfügbar sind. Für die Fernerkundung von Bodenfeuchte haben sich Strahlungstemperaturen der niedrigeren Frequenzen im Bereich der Mikrowellen als besonders geeignet erwiesen. Es war jedoch bis vor kurzem technisch nicht möglich, diese vom Satellit aus mit einer annehmbaren räumlichen Auflösung zu messen. Die erste Satellitenmission mit dieser Technologie, die Soil Moisture and Ocean Salinity (SMOS) Mission, wurde im November 2009 gestartet und liefert seither alle 2-3 Tage globale Karten von Strahlungstemperaturen mit einer räumlichen Auflösung in der Größenordnung von 40 km. Von diesen Strahlungstemperaturen mit unterschiedlichen Einfallswinkeln wird mit Hilfe eines invertierten Strahlungstransfermodells ein Bodenfeuchteprodukt abgeleitet. Dieses Verfahren setzt sorgfältige Studien zur Kalibrierung und Validierung voraus, um die gewünschte Genauigkeit des Datenprodukts zu erreichen. Daher wurden weltweit verschiedene Geländekampagnen mit Boden- und Flugzeugmessungen durchgeführt, um das SMOS Datenprodukt zu validieren und die Modellparameter zu verbessern.

In der vorliegenden Arbeit wird ein Datensatz vorgestellt und analysiert, der aus Geländemessungen, flugzeuggetragenen Strahlungstemperaturmessungen, dem SMOS Bodenfeuchteprodukt und modellierten Bodenfeuchtedaten besteht. Das Untersuchungsgebiet ist das Einzugsgebiet der Oberen Donau, das zum größten Teil in Süddeutschland liegt. Es zeichnet sich durch ein gemäßigtes feuchtes Klima der Mittelbreiten und vorwiegend landwirtschaftliche Nutzung aus. Die Bodenfeuchtemessungen an fünf Bodenstationen werden mit umfangreichen Messungen in den umliegenden Gebieten verglichen. Es wird gezeigt, dass die Stationsmessungen die Bodenfeuchtedynamik in ihren Gebieten korrekt wiedergeben. Die gemessene Bodenfeuchte zeigt eine Abhängigkeit von der Landnutzung, mit höheren Werten unter Gras. Die Strahlungstemperaturmessungen des flugzeuggetragenen Radiometers EMIRAD verhalten sich im Vergleich mit den Bodenfeuchtemessungen im Gelände im Einklang mit den theoretischen Beziehungen und sind daher für die Validierung anderer Datensätze geeignet. Die hochaufgelösten, zweidimensionalen Strahlungstemperaturmessungen des flugzeuggetragenen HUT-2D, eines neuartigen interferometrischen Radiometers mit einer Aufnahmetechnik ähnlich der von SMOS, werden erfolgreich mit EMIRAD-Messungen validiert. Die Analyse der Modelldaten und ihr Vergleich mit den EMIRAD-Daten führen zu der Erkenntnis, dass die Modellierung von Bodenfeuchte auf SMOS-Skala überall dort realistische Ergebnisse erwarten lässt, wo eine hohe Dichte an meteorologischen Stationen die nötigen Eingangsdaten liefert. Die SMOS Bodenfeuchtedaten der Vegetationsperiode 2010 zeigen einen ausgeprägten Offset hin zu niedrigeren Bodenfeuchten sowie niedrige Korrelationskoeffizienten (~ 0.2) im Vergleich mit Gelände- und Modelldaten. Für denselben Zeitraum im Jahr 2011 sind die Ergebnisse deutlich besser, mit einem verringerten Offset und höheren Korrelationen (~ 0.5). Diese Verbesserung ist

vermutlich bedingt durch ein verbessertes SMOS Datenprodukt und zusätzlich reduzierten Störsignalen in Europa. Obwohl das Ziel der SMOS-Mission, einen Datensatz mit einer Genauigkeit von mindestens 0.04 m^3 m^{-3} (Wasservolumen / Bodenvolumen) zu produzieren, im Untersuchungsgebiet der Oberen Donau noch nicht erreicht wird, ist die beobachtete Verbesserung sehr vielversprechend.

Preface

This thesis was developed in the framework of the project "*SMOSHYD – Integrative Analyse von SMOS Bodenfeuchtedaten*" (German for integrative analysis of SMOS soil moisture data), funded by the German Federal Ministry of Economics and Technology through the German Aerospace Center (DLR, FKZ 50 EE 0731).

I wish to thank Prof. Wolfram Mauser for giving me the chance of conducting this work, for his guidance and support. His open-mindedness and the support received from the LMUMentoring facilitated the task of conducting this work parallel to the birth and raising of two children. I heartily thank Dr Alexander Loew for his initiative and capable guidance throughout the project. Heartfelt thanks are also due to my colleague Florian Schlenz for sharing the ups and downs of this project, for his flexibility, helpfulness and agreeable manners which made the cooperation so enjoyable.

This work would not have been possible without the support and understanding from my dear husband. I also wish to acknowledge the support received from my children in the form of sharing their mum with the computer and from both sets of grandparents in the form of the occasional childcare. Finally, I am grateful to Luisa for keeping up my morale through the most challenging phases of the last couple of years.

1 Introduction

"What happens to the rain?" Hydrology is defined by (Penman 1961) as the science that attempts to answer this simple question. Fifty years later, quantitative answers to this question are still a challenge. Once precipitation in any form has fallen onto land, atmospheric conditions, topography, vegetation, soil types, water bodies and man-made structures all play a role in the journey of the precipitated water which eventually returns to the atmosphere either through evaporation or through plant transpiration. The land surface part of the hydrologic cycle is indeed a complex system, involving fluxes of mass and energy at various temporal and spatial scales. This thesis comprises studies of soil moisture, which is a key yet hardly measurable variable of the land surface part of the hydrologic cycle. Different data sets of soil moisture at various scales are analysed and compared, with the focus on the validation of a novel soil moisture data product derived from satellite microwave remote sensing. In this Chapter 1, an introduction to the topic of this thesis is given. In Chapter 2, an overview of the publications integrated in this thesis and of recent developments in the validation of the satellite data are presented. Conclusions are drawn and an outlook is given in Chapter 3.

1.1. Soil Moisture and In Situ Measurements

Soil moisture is an important variable in the hydrologic cycle. The water content of the upper soil layer influences the partitioning of precipitation into infiltration and runoff and of solar radiation into sensible and latent heat fluxes. The water content of the root-zone layer is critical for plant transpiration. Therefore, soil moisture affects both the energy balance and the mass balance of the atmosphere and the soil and can also limit plant growth. In this way, soil moisture plays an important role in hydrology as well as in agriculture, meteorology and climate research (e.g. Dirmeyer 2000; Fischer et al. 2007; Jung et al. 2010; Seneviratne et al. 2006; Seneviratne et al. 2010). Soil moisture memory is an important aspect of land-atmosphere interaction, such as the impact of soil moisture on precipitation (Ferranti; Viterbo 2006; Koster; Suarez 2001; Koster et al. 2004; Seneviratne; Koster 2012).

Soil moisture is highly variable both in time and in space (e.g. Brocca et al. 2007; Western et al. 2002). The spatial distribution of soil moisture depends on large scale components (precipitation and evaporation patterns) and small scale components such as vegetation cover, soil texture and topography (Entin et al. 2000; Robock et al. 2000; Teuling; Troch 2005; Vinnikov et al. 1996). Depending on the application, information on soil moisture is needed from the field scale (e.g. for crop yield estimation) up to scales of tens of kilometres (e.g. for global atmospheric modelling). Due to its high temporal variability, a high temporal resolution of soil moisture data is of particular importance but currently available only for a few networks around the globe where automated point-like measurements are conducted.

Direct soil moisture measurements are possible through gravimetric sampling in the unit m^3 m^{-3} (volume of water / volume of soil), i.e. weighing a defined volume of soil before and after drying it in the laboratory. These measurements are costly and difficult from a logistic point of view when a large number of measurements is required. Other measurement techniques include neutron probes, heat dissipation sensors and tensiometers (Robock et al. 2000). The widely used electromagnetic methods exploit the fact that the dielectric constant of water (~ 80) is much higher than that of dry soil (~1-7), so that the water content can be inferred from measurements of the dielectric constant of the wet soil (Topp 2003). There are a number of probes from various manufacturers used for automated in situ measurements (Walker et al. 2004). The International Soil Moisture Network (Dorigo et al. 2011) is an initiative to centralize globally available in situ soil moisture measurements from operational networks and field campaigns.

Point-like in situ measurements of soil moisture are only representative for a very small volume of soil. By performing multiple measurements at many points in an area, it is possible to obtain a representative mean value for that area (Famiglietti et al. 2008), but such distributed measurements are labour intensive and not feasible over longer periods of time. The aim of ongoing research is to improve area-wide information on soil moisture derived from remote sensing or hydrological land surface modelling. These two approaches are introduced in the following subsections.

1.2. Soil Moisture from Space: The SMOS Mission

Although there are approaches to derive information on soil moisture from visible and thermal spaceborne data (Verstraeten et al. 2006), most research is dedicated to the retrieval of soil moisture from remote sensing in the microwave domain of the electromagnetic spectrum (e.g. Loew et al. 2006; Owe et al. 2008; Prigent et al. 2005; Rüdiger et al. 2009; Wagner et al. 2007a; Wagner et al. 2008). Microwave remote sensing delivers area-wide information at day and at night and under almost all atmospheric conditions. The measured signal is linked to the water content of the upper soil layer in a rather direct way through the soil's dielectric constant, similar to the electromagnetic in situ measurement methods. While active sensors measure the backscatter of an emitted signal, passive sensors (radiometers) do not emit themselves but measure the radiation emitted by the Earth's surface. A comprehensive review of microwave remote sensing for hydrological applications is given in Wagner et al. (2007b).

The Soil Moisture and Ocean Salinity (SMOS) mission is the first satellite mission dedicated to deliver global soil moisture maps. It was launched on 2 November 2009 by the European Space Agency (ESA) on a sun-synchronous orbit. The scientific payload onboard the satellite, the Microwave Interferometric Radiometer using Aperture Synthesis (MIRAS), is a 2D interferometric radiometer operating at 1.4 GHz (L-band, wavelength ~ 21 cm). At this low frequency, an antenna of about 8 m length would be required in order to achieve a resolution of 40 km from space, as the spatial resolution is proportional to the antenna diameter and inversely proportional to the wavelength (Kerr et al. 2010). This technical problem is overcome by MIRAS using a novel interferometric technique with 69 antennas which are placed regularly on a Y-shaped platform.

The aim of the SMOS mission is to provide global soil moisture maps at least every 3 days with a nominal spatial resolution of 43 km on average and with an accuracy of at least 0.04 $m^3\ m^{-3}$ (Kerr et al. 2010). Soil moisture is derived from multi-angular, dual polarized brightness temperature measurements using an inverse modelling approach with the tau-omega model as forward model (Wigneron et al. 2007).

Apart from soil moisture, other factors contributing to the measured brightness temperature signal include vegetation cover, soil temperature, snow cover, topography and soil surface roughness (Wigneron et al. 2003). They all need to be accounted for within the radiative transfer model in order to retrieve soil moisture from the measured brightness temperature. Several studies are concerned with the parameter estimation for radiative transfer modelling (e.g. Schlenz et al. 2012b; Schwank et al. 2005; Schwank et al. 2004; Wigneron et al. 2007). Although the frequency band used by SMOS is protected, radio frequency interference (RFI) of man-made signals has been detected in several airborne campaigns (Balling et al. 2011; Skou et al. 2010; Zribi et al. 2011) and is a major issue hampering the use of SMOS data (Parrens et al. 2012). Further information on the complex data processing for SMOS and on first strategies of RFI detection is given e.g. in (Anterrieu 2011; Castro et al. 2012; Kerr et al. 2011). In Europe, about half of the RFI sources have already been localized and switched off since SMOS was launched (Oliva et al. 2012).

The operational availability of global soil moisture maps with such a high temporal resolution is a huge appeal of the SMOS mission. The main drawback is the coarse spatial resolution of the data. For their exploitation in hydrological applications at scales between 1 and 10 km, several disaggregation methods have been proposed (e.g. Loew; Mauser 2008; Merlin et al. 2012; Piles et al. 2011). However, before disaggregation schemes can be attempted and validated, SMOS data themselves need to be validated under different climatic conditions. The coarse spatial resolution of the data creates the need for efficient validation strategies due to the scale mismatch with in situ measurements.

Airborne data are useful to bridge the gap between ground and satellite data and for the improvement of model parameters. However, a direct validation of satellite data using airborne data yields limited insights, as airborne data usually stem from campaigns with a maximum duration of a few weeks. Some examples of such campaigns are the NAFE’05 (Panciera et al. 2008), NAFE’06 (Merlin et al. 2008) and AACES (Peischl et al. 2009) campaigns in Australia and SMOSREX in France (Rosnay et al. 2006). The SMOS Validation Campaign 2010 in Europe included the HOBE site in Denmark (Bircher et al. 2012), the Rur and Erft catchments in the Northwest of Germany (Montzka et al. 2012) and the Upper Danube Catchment.

Several techniques have been proposed for the validation of coarse scale satellite products, including the concept of temporally stable soil moisture patterns (Cosh et al. 2004; Cosh et al. 2006; Cosh et al. 2008; Wagner et al. 2008), upscaling of in situ measurements using land surface modelling (Crow et al. 2005), comparison with other satellite soil moisture products (Brocca et al. 2011; Gruhier et al. 2010; Jackson et al. 2012; Loew; Schlenz 2011) or indirectly by testing their capability of improving a simple surface water balance model (Crow 2007). Several studies compare soil moisture data from in situ measurements, land surface modelling and satellite products (Albergel et al. 2012; Albergel et al. 2010; Parrens et al. 2012; Rüdiger et al. 2009). There are also recent studies using simulated brightness temperature data for the validation of SMOS brightness temperature data products (e.g. Bircher et al. 2012; Montzka et al. 2012; Sabater et al. 2012; Schlenz et al. 2012a).

1.3. Hydrological Land Surface Modelling

Distributed hydrological land surface modelling offers the advantage of delivering area-wide output with the desired spatial and temporal resolution. However, the hydrologic cycle on the land surface is complex, and the heterogeneity of the land surface complicates the task of accurate modelling even more. Most models combine the representation of physical processes with (empirical) parameterizations. Required (static) input usually includes a digital terrain model and maps with information on soil (e.g., soil type, texture and porosity) and vegetation (e.g., land cover) properties. Then, going back to the original question "What happens to the rain?", dynamic information on the precipitation input is needed. Depending on the model physics, further atmospheric variables (e.g., air temperature and humidity, wind speed, radiation, sunshine hours) might be required in order to run the model (Singh; Woolhiser 2002). Hence, uncertainties in the model output may arise from uncertainties in the various input data sets as well as from the model's representation and parameterization of the physical processes. The latter can be verified at the point-scale using in situ measurements, but quantifying the uncertainty due to errors in the input data and how they propagate through the model's components is more difficult.

Some examples of distributed hydrological models are TOPMODEL (Beven; Kirkby 1979), LISFLOOD (Knijff et al. 2010), LISFLOOD-FP (Bates; De Roo 2000), GEOtop (Rigon et al. 2006) and ISBA (Noilhan; Planton 1989; Noilhan; Mahfouf 1996), to name a few. The hydrological land surface model PROMET is used in the studies of this thesis and is described in (Mauser; Schädlich 1998; Mauser; Bach 2009). A review of hydrological models is given by (Singh; Woolhiser 2002).

2 Publications and Recent Developments

The work presented in this thesis contributes to the calibration and validation (cal/val) of novel airborne (HUT-2D) and spaceborne (SMOS) sensors, which employ the innovative technique of interferometric L-band radiometry for the remote sensing of soil moisture. Potential and current limitations of their data products are explored. Furthermore, the suitability of the developed framework for the cal/val activities is demonstrated through the analysis of different data sets of in situ measurements and model simulations. In particular, the suitability of the algorithm used to interpolate precipitation from gauge stations in order to force the hydrological model is demonstrated, modelled soil moisture fields are validated with the measurements of a well-proven airborne radiometer (EMIRAD), and point-like in situ measurements are shown to represent the soil moisture dynamics of their surrounding areas.

2.1 Overview of Publications

This thesis includes three publications in lead authorship (Appendix A) which are all related to the analysis of soil moisture data at different scales. They are numbered according to the context, not chronologically. Paper I deals with the acquisition and validation of in situ and airborne data and is accepted for publication in the journal IEEE Transactions on Geoscience and Remote Sensing (TGRS). Paper II deals with the uncertainties in modelled soil moisture fields due to the precipitation input data. It has been submitted to the journal Hydrology and Earth System Sciences (HESS) and is published as a HESS Discussions (HESSD) paper (doi: 10.5194/hessd-9-1-2012). Paper III deals with the validation of satellite data using in situ measurements and modelled soil moisture and is accepted for publication in TGRS (doi: 10.1109/TGRS.2011.2171496). Furthermore, a co-authored paper (Schlenz et al. 2011) deals with the model's validation with in situ data and is accepted for publication in TGRS (doi: 10.1109/TGRS.2011.2171694). As this is important to justify the use of the model for the validation of satellite data, this co-authored paper has been added (Appendix B). The journals' rankings and impact factors are given in Table 1. In the following sections, a summary of each publication is given.

Table 1: Journal ranking and impact factors according to the 2010 Thomson Reuters Journal Citation Report Science Edition

	IEEE Transactions on Geoscience and Remote Sensing (TGRS)	Hydrology and Earth System Sciences (HESS)
Category	remote sensing	water resources
journal ranking in its category	2/23	5/76
ISI impact factor	2.485	2.463
5-year impact factor	3.013	2.967

Paper I:

The SMOS Validation Campaign 2010 in the Upper Danube Catchment: A Data Set for Studies of Soil Moisture, Brightness Temperature and their Spatial Variability over a Heterogeneous Land Surface

In this paper, the data set obtained during the SMOS Validation Campaign 2010 in the Vils area in southern Germany is presented. The Vils area is part of the Upper Danube Catchment (UDC), which is a major calibration and validation site for SMOS in Europe. In May and June 2010, airborne thermal infrared and L-band passive microwave data were collected together with spatially distributed in situ measurements. Two airborne radiometers, EMIRAD and HUT-2D, were used during the campaign providing two complementary sets of measurements at incidence angles from 0° to 40° and with ground resolutions from roughly 400 m to 2 km. The contemporaneous distributed ground measurements include surface soil moisture, soil texture, a detailed land cover map, vegetation height, phenology and biomass. Furthermore, several ground stations provided continuous measurements of soil moisture and soil temperature as well as of meteorological parameters such as air temperature and humidity, precipitation, wind speed and radiation. All data have undergone thorough post-processing and quality checking. It is shown that the soil moisture measurements of the ground stations agree well with the distributed measurements under different soil moisture conditions. This implies that they give valuable information for the validation of the coarse scale SMOS data. A dependency of measured soil moisture on the land cover type is demonstrated using the distributed measurements. In particular, soil moisture measurements under grass show consistently higher values than under all other vegetation types. Furthermore, EMIRAD data are compared to measured soil moisture, showing the theoretically expected behaviour. This includes decreasing brightness temperatures on wetter soils as well as the relationship between the measurements with different incidence angles and polarizations. Thus, they are suitable for the validation of other data sets. Data of the novel high-resolution interferometric sensor HUT-2D are compared to the EMIRAD data. In general, the radiometers show consistent measurements despite the different measurement techniques and spatial resolutions. However, it is recommended to filter or calibrate HUT-2D data with EMIRAD data in order to remove outliers and to improve the radiometric accuracy of HUT-2D data. It is then shown that even in unfiltered and uncalibrated HUT-2D data, the measurements over areas with high vegetation cover (forests) can be distinguished from those over areas with low vegetation cover (grass, crops). It is concluded that the presented data set is well suited to be used for potential further studies of soil moisture, brightness temperature and their spatial variability.

Paper II:

Precipitation Fields Interpolated from Gauge Stations versus a Merged Radar-Gauge Precipitation Product: Influence on Modeled Soil Moisture at Local Scale and at SMOS Scale

For the validation of coarse resolution soil moisture products from missions such as the SMOS mission, hydrological modelling of soil moisture is an important tool. The spatial distribution of precipitation is among the most crucial input data for such models. Thus, reliable time series of precipitation fields are required, but these often need to be interpolated from data delivered by scarcely distributed gauge station networks. In this study, a commercial precipitation product derived by Meteomedia AG from merging radar and gauge data is introduced as a novel means of adding the promising area-distributed information given by a radar network to the more accurate, but point-like measurements from a gauge station network. This precipitation product is first validated against an independent gauge station network. Further, the novel precipitation product is assimilated into the hydrological model PROMET for the UDC. The modelled soil moisture fields are compared to those obtained when the operational interpolation from gauge station data is used to force the model. The results suggest that the assimilation of the novel precipitation product can lead to deviations of modelled soil moisture in the order of 0.15 m^3 m^{-3} on small spatial (~1 km^2) and short temporal resolutions (~1 day). As expected, after spatial aggregation to the coarser grid on which SMOS data are delivered (~195 km^2), these differences are smaller and of the order of 0.04 m^3 m^{-3}, which is the accuracy benchmark for SMOS. The results of both model runs are compared to brightness temperatures measured by the airborne radiometer EMIRAD during the SMOS Validation Campaign 2010 in the Vils area. Both comparisons yield good correlation coefficients, which are similar to those obtained from a comparison of EMIRAD data with in situ soil moisture measurements in Paper I. This suggests that PROMET is capable of realistically model area-wide soil moisture in the Vils area. It is concluded that the uncertainties in modelled soil moisture associated with the uncertainties in the precipitation input and its interpolation are not crucial for the SMOS validation in the UDC area.

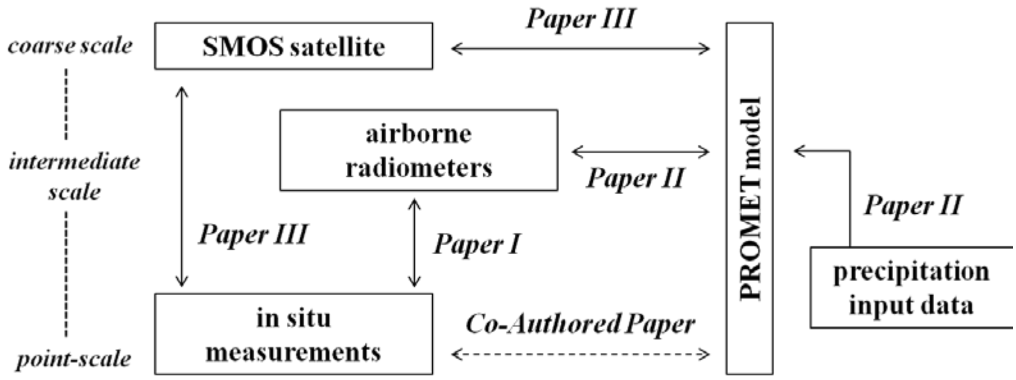

Figure 1: Interrelation of the three publications included in this thesis and of a co-authored paper, together with the various spatial scales of the analyzed data sets

Paper III:

First Results of SMOS Soil Moisture Validation in the Upper Danube Catchment

With SMOS launched in 2009, global measurements of L-band microwave emissions and processed “soil moisture” products at a fine time resolution have become available. After validation, these may lead to quantitative maps of global soil moisture dynamics. This paper presents a first validation of the SMOS “soil moisture” product delivered by ESA in the UDC. Processing of the SMOS “soil moisture” product and the methodology to compare it with in situ and model data are described. The in situ data were taken from May to mid July 2010 in the Vils area (data set described in Paper I), while the modelled time series spans from April to October 2010 for the whole catchment. The comparisons exhibit a dry bias of the SMOS data of about 0.2 m^3 m^{-3} with respect to in situ measurements. Throughout the catchment, the SMOS data product shows a dry bias between 0.11 and 0.3 m^3 m^{-3} when compared to modelled soil moisture. Correlation coefficients between both data were found to be mostly below 0.3. Radio frequency interference (RFI) over Europe appeared to be the main problem in obtaining valuable information from the SMOS soil moisture product over this region. RFI was not adequately captured by the employed methods for filtering and flagging. Nevertheless, some improvements of these results were expected to be achievable through refinements of the soil moisture modelling as well as through improvements to the processors used to generate the SMOS soil moisture product.

Co-Authored Paper: „Uncertainty Assessment of the SMOS Validation in the Upper Danube Catchment”

In this paper, the soil moisture modelling is validated on various scales using in situ measurements. It is shown that the root-mean-squared errors of the modelled soil moisture decrease from 0.094 m^3 m^{-3} on the local scale to 0.040 m^3 m^{-3} on the large scale (~195 km^2). The bias-corrected root-mean-squared error is found to be 0.024 m^3 m^{-3} on the large scale. The results of this co-authored paper are important to justify the validation of SMOS data using PROMET. Therefore, it is included as Appendix B.

2.2 Interrelation of Publications

The studies presented in the three publications are closely linked to each other. Their interrelation and the various spatial scales are illustrated in Figure 1. In Paper I, the in situ measurements are compared with each other and with the airborne radiometers. These consistency checks are the prerequisite for any further use of this data set. Of particular importance is the conclusion that the soil moisture ground station measurements capture the soil moisture dynamics of their surrounding areas. This implies that they give valuable information for the validation of the coarse scale SMOS data, which is presented in Paper III. Also, in Paper I the brightness temperature measurements of the airborne radiometer EMIRAD are compared with ground data, showing the good quality of the radiometer data. This is important for Paper II, in which EMIRAD data are used for an area-wide comparison with the soil moisture fields modelled by PROMET. Modelled soil moisture is validated with in situ soil moisture measurements at or close to meteorological measurement stations in the co-authored paper. However, it is difficult to assess the uncertainties of modelled soil moisture in areas lying between meteorological stations, as there are no in situ soil moisture data available. Therefore, the study presented in Paper II allows examining the uncertainties of modelled soil moisture due to the uncertainties of the precipitation data input and its interpolation. The studies of Paper II and the co-authored paper show that modelled soil moisture maps can be expected to be reliable enough to perform a validation of SMOS data in the UDC. A first validation of SMOS data using in situ measurements and modelled soil moisture fields is presented in Paper III. These comparisons are carried out for the vegetation period of 2010 and show rather poor results. Very recently, the same analyses using data of the vegetation period of 2011 showed an improved agreement of the different data sets. Therefore, these novel results are included in this thesis and are presented in the next section.

2.3 Recent Developments in SMOS Validation

The results of comparing SMOS data with in situ measurements and modeled soil moisture fields for the vegetation period 2010 (presented in Paper III) were not very encouraging. While the SMOS data are being improved, further work has been also undertaken to improve the soil moisture modeling with the hydrological model PROMET. This includes various model improvements, in particular improvements of the parameterization of some soil types (Schlenz et al. 2012a). The improved model leads to a better agreement of modeled soil moisture with in situ measurements. While the comparison of modeled soil moisture with ground station measurements exhibited a root-mean-squared error (RMSE) of 0.094 $m^3\ m^{-3}$, including the bias (see the co-authored paper Schlenz et al. 2011), the same comparison using the improved model shows a decreased RMSE of 0.065 $m^3\ m^{-3}$ (Schlenz et al. 2012a).

The comparison with SMOS data as presented in Paper III was repeated for the time period 1 April 2010 to 31 October 2010 and also carried out over the same period of the year 2011 using the improved model with a consistent configuration. Rowlandson et al. (2012) found a significant difference between SMOS data stemming from morning overpasses and those stemming from evening overpasses over the United States. Therefore, only morning overpasses were used for this analysis. Maps of correlation coefficients and RMSEs of the anomalies (i.e. the deviations from the mean value) for the years 2010 and 2011 are shown in Figure 2. The same colour scales as for the corresponding figures in Paper III (Figures 4 and 5) are used to allow for a direct comparison. The same data for the year 2011 are shown again in the bottom row of Figure 2 with their own color scales in order to better visualize the spatial variability of the two performance metrics. The model improvements clearly lead to a better agreement of SMOS soil moisture and modelled soil moisture in the year 2010 in terms of correlation as well as in terms of RMSEs. One likely reason may be the increased dynamical range of PROMET soil moisture, which is now closer to the dynamical range observed in SMOS data. The comparison of the two data sets for the year 2011 exhibits a considerable increase of correlation coefficients and decrease of RMSEs. Most correlation coefficients are above 0.4, and RMSEs are around 0.055 $m^3 m^{-3}$. Both performance metrics show a more homogeneous spatial distribution for the year 2011 than they do for the 2010 data. The highest deviations in the 2011 data are found in and around the city of Munich, which follows the theoretically expected behaviour as large urban areas may disturb the retrieval of soil moisture from the measured microwave emission.

SMOS soil moisture data were also compared to time series of in situ soil moisture measurements for the same two periods. Measurements of all soil moisture probes in the upper 10 cm of 5 ground stations in the Vils area were averaged (similar to Fig. 2 of Paper III for the period May to mid-July 2010). The time series of both data sets are shown as absolute values and as anomalies in Figure 3 for the period from 1 April to 31 October 2010 and in Figure 4 for the same period in 2011.

Table 2 summarizes the correlation coefficients, RMSEs (bias-corrected) and the bias for 2010 and 2011 for the three ISEA grid nodes in the Vils area for the comparisons of a) SMOS data with in situ data, b) SMOS data with PROMET soil moisture and c) in situ data with PROMET soil moisture. Correlation coefficients and biases for the comparison of SMOS data with in situ data for the year 2010 are in line with the findings of Albergel et al. (2012). They evaluated, amongst other data sets and test sites, SMOS data and in situ data in the Vils area for the whole year 2010 using a slightly different approach and data processing. They found a correlation coefficient of 0.29 and a bias of 0.267 $m^3 m^{-3}$. The comparison with in situ data shows the same improved agreement with SMOS soil moisture data in the year 2011 as was found when comparing SMOS data with PROMET data. The comparison between in situ data and PROMET data in the Vils area performs similarly for both years, confirming that the improvements observed in the other comparisons for the year 2011 are indeed due to improved SMOS data.

There are several possible reasons for this improvement. Firstly, there are ongoing efforts to switch off sources of radio frequency interference (RFI) in Europe, leading to enhanced SMOS data quality. Since SMOS was launched, about half of the RFI sources in Europe have been identified and switched off (Oliva et al. 2012). Secondly, the refinements of the algorithms used to retrieve soil moisture from SMOS brightness temperatures are ongoing and lead to an improved soil moisture data product in the first years after launch, as is also expected by Jackson et al. (2012). Also, it is possible that the signal of the strong drying period in spring 2011 (see Figure 4) exceeded the level of noise otherwise present in the SMOS data, leading to improved correlations.

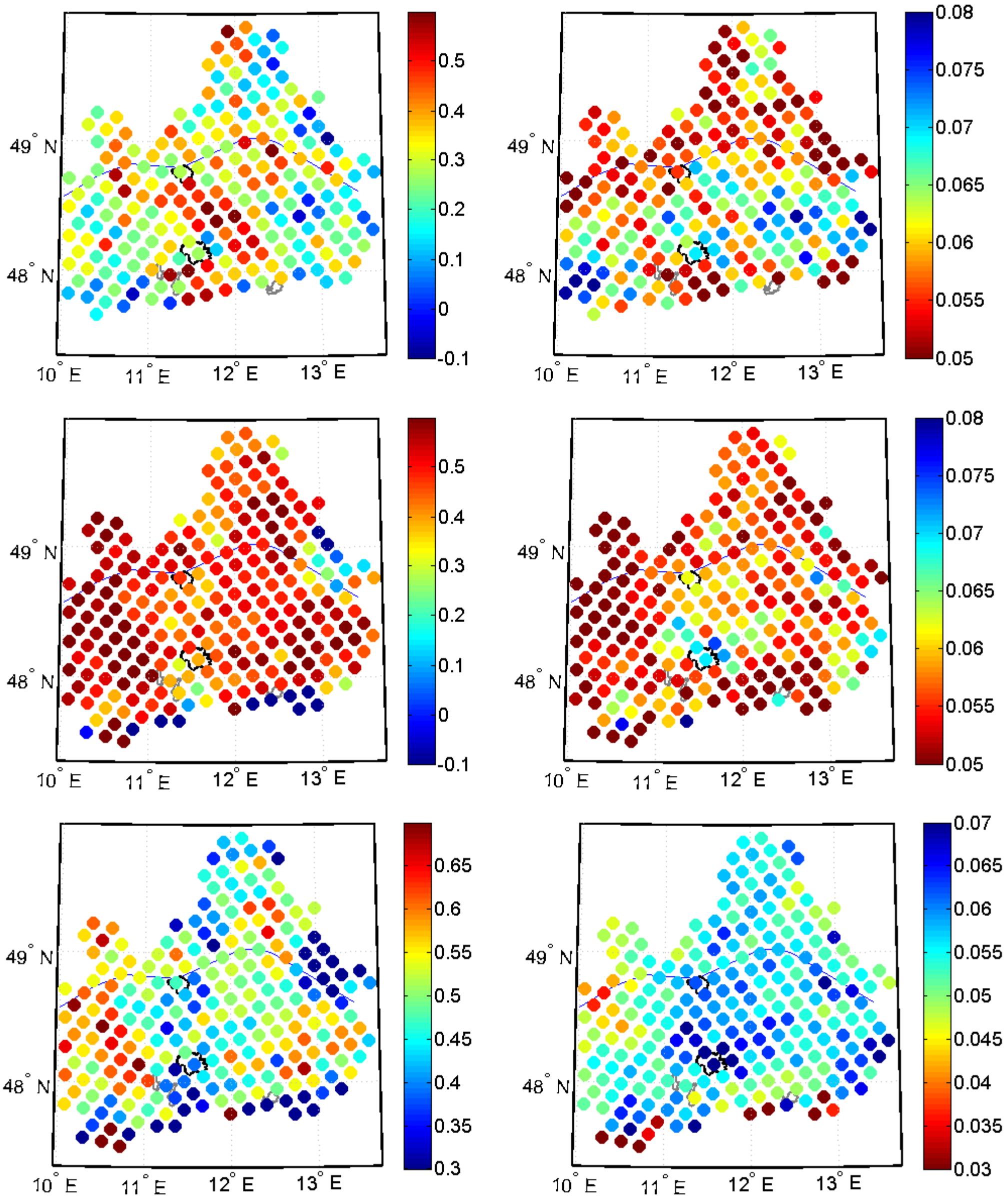

Figure 2: Correlation coefficient (left column) and root-mean-squared error [m^3 m^{-3}] (right column) for SMOS and PROMET data on the ISEA grid for the period from 1 April 2010 to 31 October 2010 (first row) and the period from 1 April 2011 to 31 October 2011 (second row). In the third row, the same data as in the second row are presented, but with a different color scale in order to better visualize the spatial patterns. The cities of Munich (south) and Ingolstadt (north) are shown as black polygons while the three light gray polygons show some lakes in the Alpine foreland. The blue line shows the river Danube.

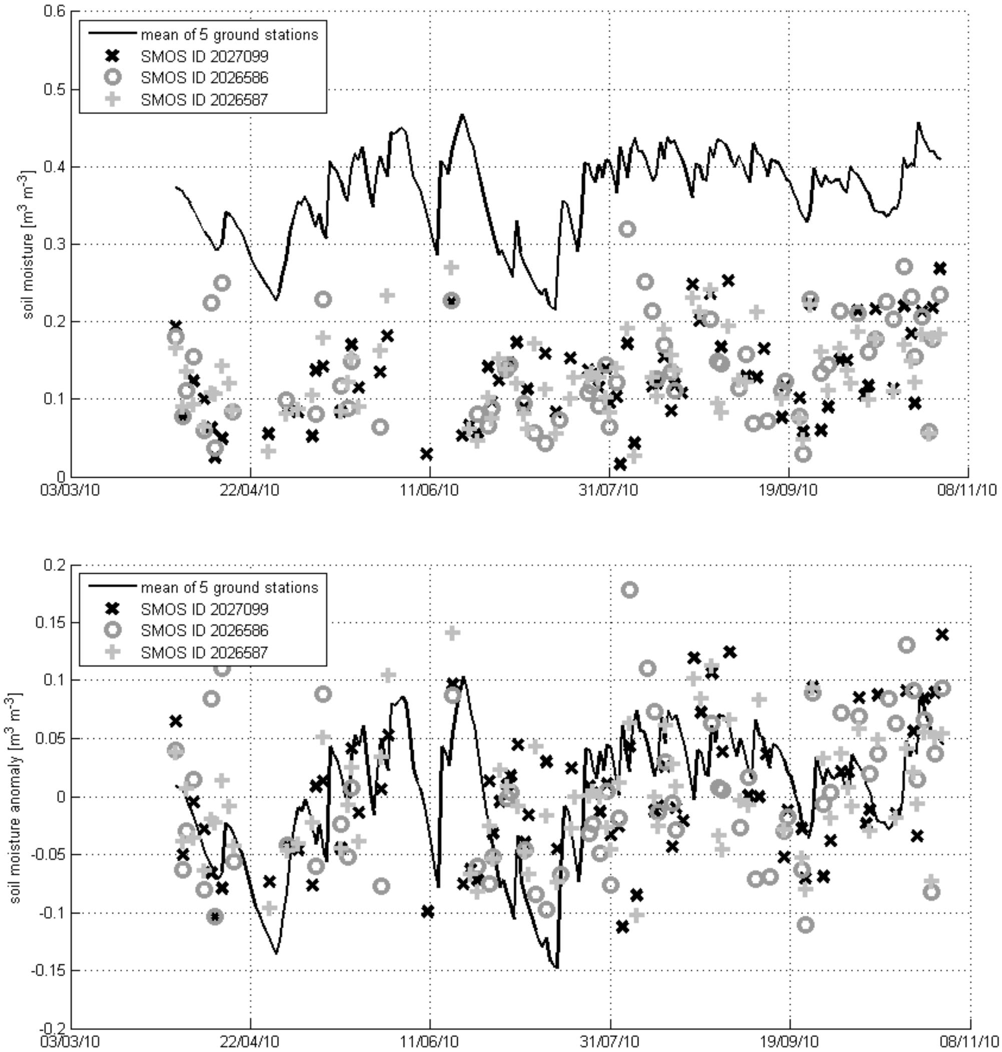

Figure 3: Mean value of the soil moisture measurements recorded at the five ground stations in the Vils area (black line) and SMOS soil moisture data on ISEA grid points ID 2027099, ID 2026586, and ID 2026587. Upper panel: absolute values; lower panel: anomalies, i.e., deviations from the mean value of each data set for the period 1 April to 31 October 2010.

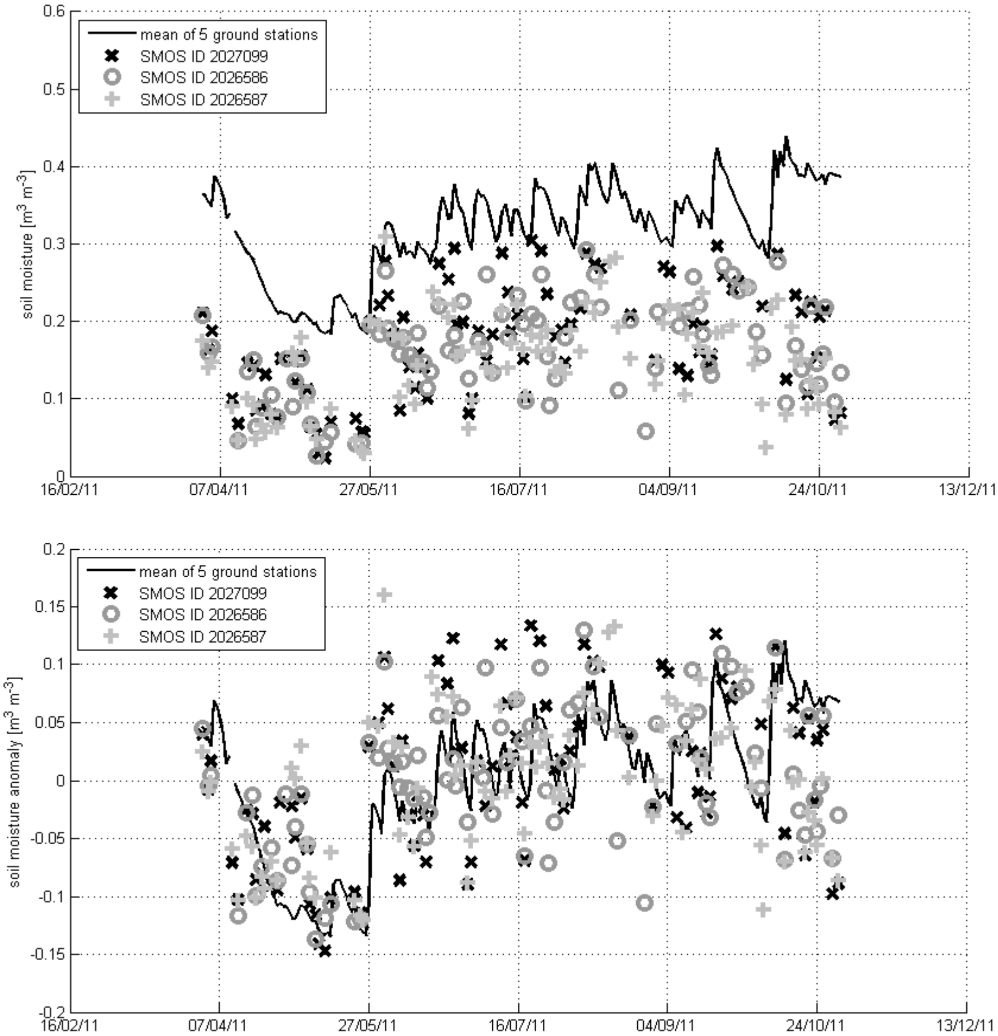

Figure 4: Same as Fig. 3, but for the year 2011.

Table 2: Correlation coefficients (corr), root-mean-squared error (RMSE) of anomalies [m^3 m^{-3}] and bias [m^3 m^{-3}] of the various soil moisture data from 1 April to 31 October of the years 2010 and 2011 on the ISEA grid nodes in the Vils area (1 = ID 2027099, 2 = ID 2026586, 3 = ID 2026587). In situ soil moisture is the mean value of 5 ground stations in the Vils area for all comparisons.

	2010			2011		
	a) in situ / SMOS	*b) PROMET / SMOS*	*c) in situ / PROMET*	*a)*	*b)*	*c)*
corr 1	0.23	-0.05	0.68	0.60	0.57	0.66
corr 2	0.24	0.16	0.76	0.54	0.52	0.78
corr 3	0.29	0.23	0.82	0.43	0.52	0.79
RMSE 1	0.069	0.079	0.045	0.061	0.059	0.046
RMSE 2	0.072	0.071	0.038	0.059	0.054	0.039
RMSE 3	0.063	0.064	0.034	0.065	0.054	0.038
bias 1	0.235	0.192	0.042	0.147	0.123	0.018
bias 2	0.223	0.179	0.045	0.153	0.134	0.022
bias 3	0.235	0.189	0.045	0.169	0.143	0.025

3 Conclusions and Outlook

In the studies presented in this thesis, several data sets of soil moisture in the Upper Danube Catchment (UDC) in southern Germany are analysed and compared to each other at various scales. Dynamics of soil moisture measured at a few ground stations turn out to be representative for the soil moisture dynamics in the areas around them. Land cover is found to produce a bias in the in situ soil moisture measurements, with wetter soils under grass. Airborne radiometer measurements of brightness temperature agree well amongst each other and show the theoretically expected behaviour when compared to in situ soil moisture measurements. Soil moisture modelled by the hydrological land surface model PROMET in the Vils area agrees well with in situ data on the point-scale and also shows a good correlation with airborne data on the scale of 1 km^2. At the SMOS scale (~ 195 km^2), PROMET soil moisture is found to be appropriate for calibration and validation activities and to be rather insensitive to the use of an improved precipitation data set as forcing data. While the comparison of SMOS data for the vegetation period 2010 with in situ measurements and modelled soil moisture leads to rather poor results, the improvement observed in the analysis of SMOS data of the vegetation period 2011 is very encouraging. This improvement is likely associated with the reduction of radio frequency interference in Europe and with ongoing refinements of the SMOS algorithms used to retrieve soil moisture from the brightness temperature measurements. SMOS data of the vegetation period 2011 show bias-corrected RMSEs of 0.055-0.06 $m^3 m^{-3}$ in most parts of the Upper Danube Catchment when compared to modelled soil moisture fields. Hence, the mission target of reaching an accuracy of better than 0.04 $m^3 m^{-3}$ is not yet fulfilled in this area. Although smaller than in 2010, there is still a large dry bias in SMOS data in the UDC area.

The hydrological land surface model PROMET has proven to be a powerful tool for the validation of SMOS data. It delivers area-wide information on soil moisture with a high temporal and spatial resolution. However, detailed input data of high quality are needed for the modelling, in particular maps of soil and vegetation properties and a dense network of meteorological stations. Additionally, modelled soil moisture should be validated under different soil moisture conditions and at various scales using in situ and, possibly, airborne measurements. In many parts of the world, such input and validation data are not available. In such regions, satellite remote sensing provides the only means to monitor area-wide soil moisture. The SMOS mission is a large step in this direction, introducing a new technology for soil moisture monitoring from space.

In several watersheds in the U.S., SMOS data of the year 2010 were found to be very close to the mission target and they also showed only a very small bias (Jackson et al. 2012). There, SMOS data performed equally well or slightly better than the operational soil moisture product from the Advanced Microwave Scanning Radiometer (AMSR-E) when compared to in situ soil moisture measurements. Jackson et al. (2012) also showed that bias and RMSE of AMSR-E data decreased with increasing period of record and concluded that refinements to the SMOS algorithm are likely to further enhance the soil moisture retrievals.

A lot still has to be learnt about measuring soil moisture using spaceborne L-band radiometry, and their coarse spatial resolution limits the range of possible applications for SMOS data. Nevertheless, the experience gained with SMOS data is very valuable for the upcoming Soil Moisture Active Passive (SMAP) mission (Entekhabi et al. 2010) of the U.S. National Aeronautics and Space Administration (NASA). SMAP is currently scheduled for launch in 2014/2015. The instrument includes a radiometer (spatial resolution: 40 km) and a synthetic aperture radar (spatial resolution: 1-3 km) operating at the same frequency as SMOS (L-band). The measurements of the SMAP radiometer and radar will be combined to generate a data product with an intermediate resolution (9 km), thus exploiting both the higher accuracy of passive microwave remote sensing and the higher spatial resolution of active microwave remote sensing. There may well be other ways of combining different measurement techniques, possibly operating at other wavelengths, with spaceborne L-band radiometry in order to obtain a global data set of soil moisture with a high accuracy and a high temporal resolution, but without the drawback of a very coarse resolution. However, a significant amount of research is needed to explore such possibilities. This shows that, although a lot of progress has been made since Penman posed his question, research of what happens to the rain remains a challenge. In order to further understand and, to some extent, predict the hydrologic cycle on various scales, a combination of in situ measurements, remote sensing and modelling techniques is still necessary and very valuable.

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Appendix A: Publications in Lead Authorship

Paper I:

The SMOS Validation Campaign 2010 in the Upper Danube Catchment: A Data Set for Studies of Soil Moisture, Brightness Temperature and their Spatial Variability over a Heterogeneous Land Surface

J. T. dall'Amico[1], F. Schlenz[1], A. Loew[2], W. Mauser[1], J. Kainulainen[3], J. Balling[4], C. Bouzinac[5]

(1) University of Munich, Department of Geography, Munich, Germany
(2) Max-Planck-Institute for Meteorology, KlimaCampus, Hamburg, Germany
(3) Aalto University School of Electrical Engineering, Department of Radio Science and Engineering, Espoo, Finland
(4) National Space Institute, Microwaves and Remote Sensing, Technical University of Denmark, Kongens Lyngby, Denmark
(5) ESA-ESTEC, EOP-SM, Noordwijk, Netherlands

IEEE Transactions on Geoscience and Remote Sensing, accepted.

Paper II:

Precipitation Fields Interpolated from Gauge Stations versus a Merged Radar-Gauge Precipitation Product: Influence on Modeled Soil Moisture at Local Scale and at SMOS Scale

J. T. dall'Amico[1], W. Mauser[1], F. Schlenz[1], H. Bach[2]

(1) University of Munich, Department of Geography, Munich, Germany
(2) VISTA Remote Sensing in Geosciences GmbH, Munich, Germany

Hydrology and Earth System Sciences, submitted.

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Paper III:

First Results of SMOS Soil Moisture Validation in the Upper Danube Catchment

J. T. dall'Amico[1], F. Schlenz[1], A. Loew[2], W. Mauser[1]

(1) University of Munich, Department of Geography, Munich, Germany
(2) Max-Planck-Institute for Meteorology, KlimaCampus, Hamburg, Germany

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The SMOS Validation Campaign 2010 in the Upper Danube Catchment: A Data Set for Studies of Soil Moisture, Brightness Temperature and their Spatial Variability over a Heterogeneous Land Surface

J. T. dall'Amico, F. Schlenz, A. Loew, W. Mauser, J. Kainulainen, J. Balling, C. Bouzinac

***Abstract*— The Soil Moisture and Ocean Salinity (SMOS) mission has been launched by the European Space Agency (ESA) in November 2009. It is the worldwide first satellite dedicated to retrieve soil moisture information at the global scale, with a high temporal resolution, and from spaceborne L-band radiometry. This novel technique requires careful calibration, validation, and an in-depth understanding of the acquired data and the underlying processes. In this light, a measurement campaign was undertaken recently in the river catchment of the Upper Danube in southern Germany. In May and June 2010, airborne thermal infrared and L-band passive microwave data were collected together with spatially distributed in situ measurements. Two airborne radiometers, EMIRAD and HUT-2D, were used during the campaigns providing two complementary sets of measurements at incidence angles from 0° to 40° and with ground resolutions from roughly 400 m to 2 km. The contemporaneous distributed ground measurements include surface soil moisture, soil texture, a detailed land cover map, vegetation height, phenology and biomass. Furthermore, several ground stations provide continuous measurements of soil moisture and soil temperature as well as of meteorological parameters such as air temperature and humidity, precipitation, wind speed and radiation. All data have undergone thorough post-processing and quality checking. Their values and trends fit well among each other and with the theoretically expected behavior. The aim of this paper is to present these data which may contribute to potential further studies of soil moisture, brightness temperature and their spatial variability. The presented data are available to the scientific community upon request to ESA.**

***Index Terms*—soil moisture, passive microwave, SMOS**

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J. T. dall'Amico, F. Schlenz and W. Mauser are with the University of Munich, Department of Geography, Luisenstr. 37, 80333 Munich, Germany (phone: +49 89 21806695; fax: +49 89 2180 6676; e-mail: j.dallamico@iggf.geo.uni-muenchen.de).

A. Loew is with Max-Planck-Institute for Meteorology, KlimaCampus, Hamburg, Germany (e-mail: alexander.loew@zmaw.de).

J. Kainulainen is with the Aalto University School of Electrical Engineering, Department of Radio Science and Engineering, Espoo, Finland (e-mail: juha.kainulainen@aalto.fi).

J. Balling is with the National Space Institute, Microwaves and Remote Sensing, Technical University of Denmark, Kongens Lyngby, Denmark (e-mail: jeb@space.dtu.dk).

C. Bouzinac is with ESA-ESTEC, EOP-SM, Noordwijk, Netherlands (e-mail: Catherine.Bouzinac@esa.int).

I. Introduction

MONITORING and responsible management of the environment require an understanding of the physical processes and of the temporal and spatial variability of its key variables. For disciplines such as hydrology, meteorology and agriculture, one of these key variables is the water content of the upper soil layer: It affects both the mass and energy balance of atmosphere and soil and, if short in supply, limits plant growth. Surface soil moisture affects the energy balance of the atmosphere and the soil through the latent heat flux [1], and the mass balance through the partitioning of rainfall into evaporation and runoff, which in turn is largely controlled by the saturation level of the soil [2].

Both temporal and spatial variability of surface soil moisture are extremely high and difficult to monitor on large scales using conventional measurement techniques, because soil moisture measurement stations require considerable maintenance work and their soil moisture probes only measure the water content of a small volume. With the Soil Moisture and Ocean Salinity (SMOS) mission, the European Space Agency (ESA) launched a satellite carrying the first-ever spaceborne 2-D interferometric radiometer (called MIRAS, for Microwave Interferometric Radiometer using Aperture Synthesis). It is designed to provide global near-surface soil moisture data with a temporal resolution of 2-3 days [3]. Soil moisture is retrieved from the brightness temperature measurements at a range of incidence angles from 0° to 55°. Data gained from this novel technique require careful and thorough calibration and validation. As the use of a radiometer operating at 1.4 GHz (L-band) leads to a coarse spatial resolution of the data in the order of 40 km over land surfaces, airborne data can complement ground measurements to perform the calibration and validation of SMOS data covering large study sites. For that purpose, ESA has chosen a number of validation sites throughout the world where SMOS calibration and validation activities are supported [4, 5]. One of ESA's major validation sites for SMOS soil moisture in Europe is the Upper Danube Catchment (UDC) in southern Germany which was chosen as an example of a subcontinental area in the mid-latitudes with a temperate and humid climate.

Before and after the SMOS launch on 2 November 2009, airborne and ground campaigns were undertaken in a number of calibration and validation sites, both over land and sea [5]. Some examples are the National Airborne Field Experiment 2005 and 2006 (NAFE'05 and NAFE'06), the Campaign for validating the Operation of Soil Moisture and Ocean Salinity (CoSMOS) and the Australian Airborne Cal/Val Experiments for SMOS (AACES) in Australia [6-9], the European Surface Monitoring Of the Soil Reservoir Experiment (SMOSREX) in France [10], CoSMOS-OS-2 2007, Salinity Demonstration 2007 and SEA-ICE 2007 in Finland [11, 12], and the Canadian Experiment for Soil Moisture in 2010 (CanEx-SM10) in Canada (http://pages.usherbrooke.ca/canexsm10/). The SMOS Validation Campaign 2010 in Europe included the Hobe site in Denmark [13], the Rur and Erft Catchments in northwestern Germany [14] and the Upper Danube Catchment in southern Germany. The airborne radiometers used in all of these campaigns include EMIRAD [15], PLMR [7] and HUT-2D [16].

The aim of this paper is to present the data set obtained during the SMOS Validation Campaign carried out in May and June 2010 in the Upper Danube Catchment in southern Germany. During the campaign, the radiometers EMIRAD and HUT-2D were flown over parts of the UDC. The airborne campaign was accompanied by a ground campaign, leading to a comprehensive data set ready for scientific use. Some of its important features are:

- the availability of radiometric data from two L-band sensors with different spatial resolutions, but flown contemporaneously on the same platform together with a thermal infrared camera
- the coverage of a heterogeneous land surface with a variety of land cover types on small spatial scales, documented by a high resolution land cover map
- the availability of data from several ground stations measuring continuously soil moisture profiles and all relevant meteorological data, in addition to the extensive field measurements in larger areas during the campaign days

Besides its contribution to the calibration and validation of SMOS data as done in [17], these features qualify the obtained data set also for the validation of hydrological and radiative transfer models as done in [18] as well as the refinement of soil moisture retrieval algorithms and the analysis of temporal and spatial variability of brightness temperature and soil moisture. Such analyses are a prerequisite for the development and verification of methods for the downscaling of the low-resolution SMOS data in order to exploit it for hydrological applications.

In Section II., the test site is described, while Sections III. and IV. provide a description of the airborne and ground-based measurements, respectively. In Section V., some of the analyses undertaken in order to check data quality and consistency are presented. Section VI. is dedicated to the data request procedures. A summary is given and conclusions are drawn in Section VII.

II. TEST SITE

The Upper Danube Catchment (UDC), located mostly in southern Germany, has been the focus of a wide range of hydrological studies for many years, e.g. [19-25]. The 77000 km2 catchment has climate conditions characteristic for many subcontinental areas in the mid-latitudes, with snow cover over several weeks in winter and hot periods in summer. The UDC is an example of a temperate and humid area, with an average temperature of about -2° C in January and about 17° C in July in Munich. The average annual precipitation is more than 900 mm in Munich, increasing towards the Alps in the South.

The data described in this paper were acquired in a part of the Upper Danube Catchment which has about the size of a SMOS footprint (approximately 40 x 40 km) and lies within the subcatchment of the river Vils in the Northeast of the city of Munich (see Fig. 1). More than 50% of the Vils area are used for intensive agriculture with a variety of crops, mainly wheat and maize, but also rye, rape, sugar beet, potatoes, etc. Roughly 20% are used as grassland, another 20% are occupied by forests. Open water bodies are scarce, occupying about 0.5% of the Vils area. The elevation ranges from about 350 m in the river valley to hills of about 500 m above sea level. The typical soil in the Vils area is silty loam.

Since 2007, an operational network of soil moisture profile stations has been established in the Vils area in preparation for the validation of SMOS data products (for locations see Fig. 1, details are given in [18]). These stations are collocated with micrometeorological stations run by the Bavarian State Research Center for Agriculture (Bayerische Landesanstalt für Landwirtschaft, LfL). From May 2009 until November 2010, a ground based L-band radiometer (ELBARA-II, [26]) was located in the Puch site within the UDC to provide reference brightness temperature data over representative agricultural areas [27]. The ELBARA-II was located outside the Vils area (see Fig. 1), its range of incidence angles does not overlap with those of the airborne radiometers used in this campaign and its footprint is extremely small when compared to a SMOS footprint. Therefore, its properties and data are not discussed further here. A dedicated study using data of this ELBARA-II instrument is presented in [28].

III. AIRBORNE DATA

The remote sensing instruments used in this campaign were two L-band radiometers (EMIRAD and HUT-2D), a thermal infrared sensor and a low-resolution video camera. The complementary features of the two radiometers are summarized in Table I. All remote sensing instruments were mounted on the Skyvan aircraft, owned and operated by the Aalto University in Espoo, Finland. For this campaign, Skyvan was based at the research airport of the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR) in Oberpfaffenhofen. A total of 5 flights were carried out: 17, 22, 25 May and 12 and 17 June 2010. The duration of the flights was approximately 3 hours, with a SMOS morning overpass in the middle of the time frame (about 4:30 am UTC). Coming from DLR airport, four legs were flown over the Vils area, passing over the ground stations as shown in Fig. 1. These four legs had a total length of approximately 208 km. This results in an area covered with airborne radiometer measurements of approximately 305 km^2, which corresponds to almost 20% of a SMOS "pixel" of 40 km x 40 km.

In order to validate the radiometers' internal calibration, the acquisition of measurements with footprints containing only water was needed. As it was not clear whether the long but relatively narrow lake Ammersee (shown in Fig. 1) near DLR would be sufficient and also free of radio frequency interference, it was decided to fly also over the lake Chiemsee on the first of the 5 flight days (17 May), shown as route 1 in Fig. 1. However, the measurements over Ammersee proved to be of good quality, so that the long transit to Chiemsee was omitted on the other days. On 17 June, Munich Airport air traffic control did not grant permission to enter the area over the ELBARA-II radiometer, so that the Skyvan returned directly to DLR airport after the lake measurements (shown as route 2 in Fig. 1). On 22 and 25 May and 12 June, permission was granted and the Skyvan passed additionally over the ELBARA-II radiometer before returning to DLR airport, shown as route 3 in Fig. 1. Table II provides a summary of the radiometer data availability and the time of the SMOS overpass for each flight day. Due to technical problems with the radiometer, no HUT-2D data are available for the flight on 12 June.

For the flights in the Vils area, the flight altitude was approximately 2100 m above ground, which is the maximum manageable without a pressurized aircraft cabin. After the measurements in the Vils area, the aircraft descended to the minimum manageable under the given weather conditions (approximately 600 – 1000 m above ground, depending on the day) in order to achieve a higher resolution of the airborne data over the lake and the ELBARA-II radiometer.

A. EMIRAD

EMIRAD is a fully polarimetric radiometer operating at L-band with the frequencies 1400.5 - 1426.5 MHz (-3 dB beamwidth) and 1392 - 1433 MHz (-60 dB beamwidth). It is owned and operated by the Technical University of Denmark (DTU). EMIRAD was mounted on the back of the Skyvan. The antenna system consists of two Potter horns, one pointed at nadir and the other one at 40° aft with 38° and 31° half-power beamwidth (HPBW), respectively. The instrument's sensitivity is 0.1 K for one second integration time at an input temperature of 300 K. The nadir antenna footprint diameter is around 700 m per 1000 m flight altitude above ground. Hence, for the flights in the Vils area the nadir antenna footprint diameter was about 1500 m and about 400 – 700 m at the Puch site. The nadir antenna footprint has roughly the form of a circle, while the footprint of the aft antenna has the form of an ellipse with the longer axis along-track (about 2 km for the flight altitude in the Vils area). Both footprints and swath are illustrated in Fig. 2. A detailed technical description of the instrument's characteristics is given in [29], while details about the various calibration procedures are given in [15].

Raw data is delivered as calibrated contemporaneous measurements of all Stokes parameters in antenna frame with the two incidence angles 0° and 40° and an integration time of 1 ms. Data are not corrected for aircraft attitude, but the required parameters are given along with the data.

B. HUT-2D

The interferometric radiometer HUT-2D is owned and operated by the Aalto University in Espoo, Finland. Its measurement principle is similar to the MIRAS radiometer mounted on SMOS. While MIRAS consists of 69 receivers on a Y-shaped platform, HUT-2D consists of 36 receivers on a U-shaped platform. This radiometer was mounted below the Skyvan aircraft. HUT-2D is a novel instrument, delivering high resolution (in the order of 400 m for the flights in the Vils area) two-dimensional images of brightness temperatures. The radiometric resolution is 3.5 K, incidence angles vary from 0 to 40 degrees at 7-10 degree intervals. A detailed description of the instrument can be found in [16], a performance assessment is described in [30]. A sketch of HUT-2D swath and resolution cell is shown in Fig. 2.

Raw data is delivered as calibrated and geocoded measurements with alternating polarizations. This nominal data format is similar to the processing stage of the SMOS Level 1c brightness temperature data product.

C. Thermal Infrared Camera

For the SMOS Validation Campaign 2010, an imaging thermal camera (VarioCAM□ hr, InfraTec GmbH) provided by the Max Planck Institute for Meteorology, Hamburg, was installed in the nose cone of the Skyvan. Two-dimensional images were acquired with a field of view (FOV) of 30 x 23°. The instrument's instantaneous field of view (IFOV) was 1.4 mrad which corresponds approximately to a spatial resolution (pixel size) of 4 m at the typical flight heights during the campaign. Thermal images were acquired with a temporal sampling rate of 1 Hz. The measurement accuracy as given by the manufacturer is ± 1.5 K for the temperature range observed during the campaign.

IV. GROUND DATA

A. Ground Station Network

Since 2007, the Vils area has been instrumented with a network of 5 permanent soil moisture profile stations at the locations Lochheim, Engersdorf, Steinbeissen, Neusling and Frieding (shown in Fig. 1). Each station has 5-6 IMKO time domain reflectometer (TDR) probes installed horizontally at depths of about 5 cm (twice), 10 cm (twice) and, depending on the station, at depths between 20 and 40 cm (once or twice). They also have one probe diagonally installed from the surface to about 10 cm depth. Instead of a site-specific probe calibration, the station measurements were compared to additional measurements of soil moisture around the stations using Delta-T Theta frequency domain (FD) probes over various soil moisture conditions. Also, the measurements using FD probes were compared to gravimetric measurements. None of these comparisons showed a systematic bias and both resulted in a root-mean-squared error in the order of 0.05 m^3 m^{-3}, which is a good result given that the standard deviations of the data sets regularly exceed 0.10 m^3 m^{-3} (for details on these comparisons see [18]). For the SMOS Validation Campaign 2010, two additional soil moisture stations with five DECAGON ECH2O frequency domain probes were installed at the locations Erlbach and Harbach (near Frieding and Engersdorf, respectively, which are shown in Fig. 1). Here, two probes each are installed in 5 and 10 cm depth and an additional one in 20 cm depth. All soil moisture measurements at the stations are conducted under grass at one hour intervals.

The five permanent soil moisture stations are collocated with the micrometeorological stations run by the Bavarian State Research Center for Agriculture (Bayerische Landesanstalt für Landwirtschaft, LfL). The data recorded by LfL include precipitation, air temperature (at 2 m and 20 cm above ground) and humidity, wind speed and global radiation as well as soil temperature (at 5 cm and 20 cm depth). All data are recorded hourly and were available in near-real time.

B. Distributed Measurements during the Campaign

The airborne campaign was accompanied by a ground campaign in the period from 17 May to 8 July 2010 in 5 focus areas with an area of about 2-3 km x 7 km each (see Fig. 1). The focus areas were chosen in a way that all of them contained one of the permanent soil moisture stations described in the previous section and are henceforth called by the name of the corresponding station (Lochheim, Engersdorf, Steinbeissen, Neusling and Frieding). The focus areas are spread over the Vils area with a spacing of approximately 20 km such that the heterogeneities in terms of topography, land cover and soil texture occurring in the Vils area are covered by the focus areas. The sand/clay percentages at the stations and the percentages of the main land cover classes of the focus areas are summarized in Table III.

In each focus area, soil moisture measurements were taken on two “grids” using Delta-T’s Theta frequency domain probes. Measurements with these probes are valid for the upper 6 cm of the soil. The coarser “grid” covered the whole focus area with about 60 sampling points. A smaller area of about 1 km^2 per focus area was additionally sampled with about 60-100 points with the exception of Lochheim, where measurements were taken only on the coarse “grid”. Results from previous field campaigns in the area (not published) have shown that it is more important to cover all land cover types with sampling points than to cover the area with sampling points on a strictly regular grid. Therefore, the sampling points for this campaign were chosen close to roads or paths, so that the ground teams could move faster and cover more fields. The coarse “grid” measurements were taken approximately every 500 m and those of the fine “grid” approximately every 50 m along these transects. An example of a focus area with the sampling points and their spacing is shown in Fig. 3. All measurements were taken well in the fields to avoid any boundary effects. The exact location of each sampling point was defined on the first campaign day and the measurements repeated on the same spot on the other days using a hand-held GPS. The ground measurements took place from early morning until the afternoon. During this time window, the ground stations show a drying of 0.01 - 0.025 m^3 m^{-3} of the upper 10 cm of the soil, depending on the day. The magnitude of this drying is considered insignificant and thus no correction has been applied to the data.

The distributed ground measurements were taken on all flight days and also on 28 May, 14 June and 8 July, aligned with SMOS overpasses. However, on 14 June measurements had to be aborted due to rain. On this day, only the focus area Neusling was covered representatively by measurement points. At all sampling points and on all days, five soil moisture measurements were taken and vegetation height was measured (examples of vegetation height shown in Fig. 4). The state of vegetation and soil were documented by photographs. Well before the campaign, soil texture information was determined at the ground stations and other locations in the focus areas by taking soil samples for grain-size analysis in the laboratory. As the soil texture showed little variation within each focus area, the data set described in this paper comprises only the soil texture information at the ground stations. During the campaign period, a detailed land cover map of the focus areas and large parts of the flight track was prepared by the ground teams based on reconnaissance. The land cover map covers more than 192 km^2, corresponding to over 10% of a 40 km x 40 km SMOS “pixel”, and distinguishes more than 50 different land cover classes. An impression of the typical field size in the area can be obtained from Fig. 3. On two days during the campaign (9 and 23 June), phenology and biomass were measured in selected fields. Phenology was identified using the BBCH-scale (Biologische Bundesanstalt, Bundessortenamt and CHemical industry). Wet and dry biomass was determined by cutting plants of a defined area, drying them in the laboratory and weighing them before and after the drying. Mean vegetation water content and dry biomass for winter wheat and maize are shown in Table IV. Each mean value was calculated from 5 measurements within one field.

V. DATA ANALYSIS FOR QUALITY CHECKING

In this section, some of the analyses are presented which were conducted in order to assess the consistency of the measured values and trends amongst each other as well as with the theoretically expected relationships. The soil moisture measurements of the ground stations have been compared to the distributed measurements carried out in the focus areas around them. All airborne data have undergone post-processing in order to prepare them for consistency checks among each other and with ground data. The temperatures measured by the thermal infrared camera above the ground stations have been compared to the temperatures measured by the ground stations. The brightness temperatures measured by EMIRAD have been compared to the in situ measurements in order to check their sensitivity to soil moisture. As HUT-2D is a novel instrument, the consistency of its measurements with the EMIRAD measurements has been analyzed. Finally, a first test of HUT-2D's capability of capturing high resolution heterogeneities of the land surface has been attempted by comparing the measured brightness temperatures to the high resolution land cover map.

A. Analysis of In Situ Measurements

The aim of the analysis described in the following is mainly to check whether the stations measure soil moisture values which are representative for the focus areas around them. This includes the investigation of the correspondence between the distributed soil moisture measurements taken during the course of the day and the soil moisture as measured by the stations in the early morning (5 am UTC) shortly after the SMOS overpass. The effect of the drying in the course of the day is considered insignificant (see Section IV.*B.*).

For this analysis, only measurements from the coarse "grid" have been used to calculate the mean value of distributed measurements in order to equally represent the whole focus area. An impression of the spatial and temporal variability of measured soil moisture can be obtained from the mean values and standard deviations given in Table 5. The mean value of the ground station measurements was calculated by averaging the measurements of all probes of the 5 permanent soil moisture profile stations at the locations Lochheim, Engersdorf, Steinbeissen, Neusling and Frieding (shown in Fig. 1) at 5 and 10 cm depth at 5 am UTC. The results of these comparisons vary slightly from one station to the other (not shown), but the general pattern is very similar. Fig. 5 (upper panel) shows the mean of the 5 am UTC (shortly after the SMOS overpass) soil moisture as measured by the five soil moisture stations together with the mean value of the distributed soil moisture measurements in all focus areas. Although mean values of measurements taken at five points (stations) early in the morning are compared to mean values of measurements taken at hundreds of points (distributed measurements) in the course of several hours, these data sets yield similar results. This applies particularly for the lower panel of Fig. 5 where the time series of anomalies show a very good agreement under different soil moisture conditions. For each data set, the time series of anomalies has been obtained by subtracting the mean value over the period in question from the value at each time step.

The fact that the measured soil moisture at the ground stations was consistently higher than in the focus areas around them is likely associated with the fact that the ground stations were all located under grass whereas the distributed measurements were taken under all types of land cover. The dependency of soil moisture on the land cover type was explored in previous field campaigns in this area (not published) and confirmed using the measurements from this campaign. For the most distinct land cover classes, all of the distributed measurements (of both "grids") have been averaged over each campaign day (see Fig. 6, left panel). This shows that soil moisture under grass is consistently at least 0.06 $m^3 m^{-3}$ higher than under all other land cover classes under all of the observed soil moisture conditions. Once the bias is removed from the data by subtracting the mean value for each land cover class, the obtained anomalies show a similar temporal evolution for all land cover classes (see Fig. 6, right panel) although vegetation height increased significantly in the course of the campaign, especially for maize (see Fig. 4).

In summary, measured ground data appear to be reasonably consistent with each other and with the experience previously gained in this site and thus appropriate for further studies.

B. Processing of Airborne Data

All airborne data have been considerably post-processed and enhanced at the University of Munich. EMIRAD data were filtered using the radio frequency interference (RFI) flag and additional flags provided together with the data by DTU. On all days except the first flight day, the percentage of RFI flagged measurements in the Vils area was about 0.4 % for the nadir antenna and about 0.7 % for the aft antenna. For 17 May, the values are 0.7 % and about 2.0 %, respectively. As RFI cannot be removed completely using the RFI flag, all data above a threshold of 300 K were also discarded, but only a small amount of data were lost through that procedure. To reduce the amount of data and enhance stability, the filtered data were aggregated by averaging 1000 measurements at a time. The resulting data with an approximate integration time of 1 s were then projected from the antenna frame to the ground by geocoding and polarization rotation.

The post-processing of the HUT-2D data in their nominal data format is slightly more complicated, as they are not flagged for RFI, and the brightness temperatures in the two polarizations are measured sequentially and with different incidence angles and polarization rotation angles. As a crude RFI filter, all data above 300 K and below 200 K were discarded, as only the emissions of land surfaces are of interest for studies of soil moisture and vegetation parameters. The closest measurements at X and Y polarizations in terms of location on the ground, incidence angle and polarization rotation angle were chosen for transformation to H and V by polarization rotation.

For the two-dimensional thermal infrared data, an area in the centre of the field of view of the camera was chosen such that it roughly corresponds to the footprint of the EMIRAD nadir antenna. For each snapshot, mean value and standard deviation of all thermal infrared data within this area were calculated.

C. Comparison of EMIRAD Data with Distributed In Situ Measurements

For all focus areas and for all flight days, brightness temperatures as measured by EMIRAD have been compared to the distributed in situ soil moisture measurements. For this comparison, all distributed soil moisture measurements from the coarse “grid” on one day in one focus area have been averaged (values shown in Table V). The mean EMIRAD brightness temperatures per focus area and flight day are obtained by averaging the brightness temperatures of all footprints with centre points falling into that focus area on that day (separately for nadir and aft antenna and for H and V polarization). The results of this comparison are shown in Fig. 7. For all combinations of incidence angles and polarizations, measured brightness temperature decreases with increasing soil moisture, as theoretically expected. Also as expected, H and V polarized measurements are the same at 0° incidence angle, while V-polarized measurements yield higher brightness temperatures at 40° incidence angle. H-polarized measurements at 40° incidence angle are lower and show more variability than the corresponding V-polarized measurements.

In summary, data measured with EMIRAD appear to be reasonably consistent with the theoretically expected behavior and thus appropriate for further studies.

D. Comparison of HUT-2D Measurements with EMIRAD Measurements

As two radiometers measuring at the same frequency were flown contemporaneously on the same platform, an important task of quality control is to check the consistency of the data acquired by the two instruments. As EMIRAD has already been used in previous studies for many years, its values may be assumed to be an appropriate benchmark for assessing the quality of the measurements acquired by the newer and more complex HUT-2D radiometer. This was done for a previous campaign with a similar set-up by [31]. The methodology of the comparison needs to account for the differences of spatial resolution and measurement technique and is described in the following.

As HUT-2D measurements at incidence angles above 30° are scarce, only the measurements of the EMIRAD nadir antenna were considered for the comparison. In order to roughly match the incidence angles covered by the EMIRAD nadir antenna (0° ± 19° because of the 38° opening angle), all HUT-2D measurements with an incidence angle of within ± 20° were selected. The microwave emission of points close to the centre of the EMIRAD footprint contributes more to the measured signal than the emission of points further away from the centre of the footprint. This antenna gain pattern of the EMIRAD antennas has been measured and used to calculate normalized weights with which the HUT-2D measurements are multiplied according to their distance from the centre of the EMIRAD footprint. The resulting weighted mean of the HUT-2D measurements is then subtracted from the corresponding EMIRAD measurement for all EMIRAD footprints along the whole flight track on each of the four days separately.

The statistics of these differences are summarized in Table VI, and an example of the geographical distribution of the observed differences is shown in Fig. 8 for the day with the largest differences (22 May 2010). The overall agreement is good with a mean difference of roughly 2 - 5 K on all days and for both polarizations. On all days, HUT-2D measures higher brightness temperatures than EMIRAD on average. However, for some EMIRAD footprints the differences can reach extreme values of 20 K and more in both directions. As can be seen from Fig. 8, the larger differences usually occur in consecutive footprints. Therefore, they are likely due to either thermal instabilities of the HUT-2D instrument for some minutes during the flight (as discussed in [31]) or to radio frequency interference (RFI) in some areas. Due to its interferometric measurement technique, HUT-2D is more susceptible to RFI than EMIRAD. When all footprints with differences of more than 10 K are classified as outliers and removed from the sample, standard deviations of the differences decrease to 2-3 K for both polarizations on all of the four flight days.

In summary, data measured with HUT-2D appear to be reasonably consistent with the EMIRAD measurements and thus appropriate for further studies. However, depending on the scope of the study, it is recommended to filter and/or calibrate HUT-2D data using the EMIRAD measurements in order to remove outliers and improve the radiometric accuracy of the data.

E. Comparison of TIR Data with Station Measurements

The measurements of the thermal camera do not relate directly to the physical skin temperature of the surface (soil or vegetation) as they have not been corrected for atmospheric effects. Still, for a first check of their credibility, they have been compared to the available ground measurements of temperature. These are the air temperature 20 cm above ground and the soil temperature in 5 cm depth as measured by the five ground stations at 5 am UTC. These values are shown in Table V together with the TIR value at each station (if not covered by clouds).

As expected in the early morning at that time of the year, the soil temperature is higher than the air temperature apart from a few exceptions. The temporal evolution of the TIR measurements is mostly in line with both ground measurements at all stations. The absolute values of the TIR measurements are, with a few exceptions, below the other two values. However, the deviations from the air temperature are all below 3.5 K, in most cases much smaller. Given the lack of atmospheric correction (see above) and the measurement accuracy of the camera of ± 1.5 K (see Section III.*C.*), no further conclusions can be drawn from the comparison of absolute temperature values.

In summary, temperatures measured with TIR appear to be reasonably consistent with the temperatures measured by the ground stations and thus appropriate for further studies. However, depending on the scope of the study, an atmospheric correction could be applied to the TIR measurements in order to improve their accuracy (e.g. using radiosonde data from Munich Airport).

F. Comparison of HUT-2D Data with Land Cover Map

The HUT-2D radiometer has a high spatial resolution in the order of 400 m for the flights in the Vils area. Thus, its measurements may show a dependency on the underlying land cover, despite the usually small field size in the area (see for example field boundaries shown in Fig. 3). The measured brightness temperature depends not only on vegetation parameters, but also on soil moisture, which has been shown to depend on the land cover class (see Section V.*A.* and Fig. 6). The aim of the comparison described in the following is to test whether the HUT-2D measurements are sensitive to the underlying land cover class.

The land cover map acquired during this campaign has been digitized to a series of polygons (one polygon per field) which are each assigned to a land cover class. For a first comparison, all HUT-2D measurements falling into a single polygon are averaged if their incidence angle is below 20° (data used for the consistency check with EMIRAD measurements in Section V.*D.*). Then, the total average for all polygons is calculated for each land cover class. This has been done for each of the four days with available HUT-2D data. The results are shown for V-polarized measurements in Fig. 9 (left panel: absolute values, right panel: anomalies, i.e. deviation from class mean value). On all of the four days, HUT-2D measurements are significantly higher over forested areas than over areas with lower vegetation, with an almost constant difference of about 4 K between forest and open fields. On three of the four days, mean brightness temperatures over grass areas are also higher than those over the other land cover classes, but here the differences vary only between 1-4 K. Neither of these features can be clearly identified considering the brightness temperature anomalies. For more sophisticated analyses, which go beyond the scope of this paper, HUT-2D data could be filtered and/or calibrated with EMIRAD data using the comparison of Section V.*D.* in order to avoid that the discovered outliers may affect the analysis. However, it is encouraging that even without the additional use of EMIRAD data, HUT-2D seems to clearly distinguish between forest and open fields. As the spatial resolution of HUT-2D is coarser than the average field size in the test site, its ability to detect forests better than the other land cover classes probably derives from the fact that forested areas are usually larger than individual fields.

VI. DATA AVAILABILITY

This campaign data set can be obtained by submitting a request to ESA on the website http://earth.esa.int/campaigns/index.htm (listed under CoSMOS campaigns). This includes ground station soil moisture data and meteorological data as described in Section IV.*A.* for the campaign period, the distributed ground data described in Section IV.*B.*, TIR data and all airborne radiometer data in nominal data format as described in Section III. The only exception is the detailed land cover map, which is available from ESA only for the focus areas. The land cover map of the other parts of the flight track is with the University of Munich and available upon request (w.mauser@lmu.de). Furthermore, the meteorological station data are publicly available without registration and can be downloaded directly from LfL (http://www.wetter-by.de/). Due acknowledgement in any publication or presentation arising from the use of these data is required.

VII. SUMMARY AND CONCLUSIONS

In this paper, the data set gained during the SMOS Validation Campaign 2010 in the Upper Danube Catchment has been presented. Five measurement flights were carried out in May and June 2010, producing airborne L-band radiometer data with two radiometers (EMIRAD, HUT-2D) at different incidence angles (0 - 40°) and ground resolutions (approx. 400 m – 2 km). Also, thermal infrared data from a sensor mounted on the same platform are available. The measurements were taken over a mainly agricultural area with approximately the size of a SMOS pixel (40 km x 40 km) and with heterogeneous land cover. The airborne campaign was accompanied by distributed field measurements of soil and vegetation parameters, including soil moisture, soil texture, land cover, vegetation height, phenology and biomass. In addition to those measurements available only on the eight campaign days, five ground stations are distributed in the area, where soil moisture profiles and meteorological variables are measured continuously.

At the University of Munich, all airborne data have been post-processed and all ground data have been digitized and quality checked. The soil moisture measurements on the campaign days show the same temporal evolution as the soil moisture measured at the ground stations, and have also confirmed a previously observed dependency of soil moisture on the land cover class. Brightness temperatures measured by EMIRAD have been compared to the in situ soil moisture measurements and found to behave as theoretically expected. Brightness temperatures measured by the novel high resolution radiometer HUT-2D have been compared to EMIRAD brightness temperatures. The agreement of the measurements has been found to lie in the order of 2-5 K on average, but as there are distinct outliers in some of the footprints, a filtering of HUT-2D data using EMIRAD data is recommended. The temperatures measured by the airborne thermal infrared camera have been found to lie within 3.5 K of the air temperatures measured 20 cm above ground at the ground stations. As a first attempt to relate HUT-2D measurements to the underlying land cover class, a comparison with the land cover map has been conducted. Although HUT-2D data were not previously filtered or calibrated with EMIRAD data for this analysis, a clear difference between measurements over areas with high vegetation (forest) and areas with low vegetation (grass, crops) can be observed.

The presented data set has been used for the validation of modeled soil moisture and brightness temperature by [18] (ground data, EMIRAD data) and for the validation of the SMOS soil moisture product by [17] (ground data). The analyses presented in [17] show that during the campaign period, SMOS soil moisture values in this area have a dry bias of 0.18 m^3 m^{-3} and do not show the same temporal evolution as measured soil moisture. This is explained partly by problems with radio frequency interference (RFI) affecting most of Europe and partly by deficiencies of the algorithm used to retrieve soil moisture from the SMOS brightness temperatures. Similarly, [32] found only correlations in the order of 0.2 between ground station measurements in the UDC area and SMOS soil moisture data for the year 2010.

The data of this campaign do not only contribute to the calibration and validation of SMOS data products, but may also provide a valuable contribution to other studies. Potential applications could be the parameter estimation for soil moisture retrieval models from passive microwave data and studies of the effect of vegetation on the brightness temperature signal as well as studies of subscale variability of soil moisture and vegetation parameters. The presented data are available to the scientific community as described in Section VI.

ACKNOWLEDGMENT

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Johanna T. dall'Amico received the BSc degree in mathematics from the University of Reading, Reading, United Kingdom, in 2007 and the Diplom degree in geography with remote sensing and mathematics from the University of Munich, Munich, Germany, in 2008. She is currently working towards a Ph.D. degree at the Department of Geography of the University of Munich.

In 2005, she was a visiting student at the UK Natural Environment Research Council Environmental Systems Science Centre (ESSC) in Reading, UK, working on remote sensing applications for fluvial flood mapping and modelling. Since 2007, she is at the University of Munich, working on the project SMOSHYD which aims at the calibration and validation of SMOS data in the Upper Danube Catchment as well as at the study of related scaling issues. Her current research interests include airborne and satellite remote sensing of soil moisture and its spatial variability, including the analysis of ground data, model output and ancillary remote sensing data.

Florian Schlenz (M'08) was born in Forchheim, Germany, 1980. He finished his Diplom degree in physical geography with remote sensing and computer science at the Department of Geography, University of Munich, Munich, Germany in 2007.

He is with the Department of Geography, University of Munich since 2007 and works as a researcher on the project SMOSHYD which aims at the calibration and validation of SMOS data in the Upper Danube Catchment as well as at the study of scaling issues. His research interests include hydrological and radiative transfer modeling as well as airborne and satellite based remote sensing of soil moisture, including the analysis of field data and passive microwave radiometer data.

Dipl. Geogr. Schlenz is a member of the European Geosciences Union.

Alexander Loew (M'04) studied geography, computer science, remote sensing, and landscape ecology at the University of Munich (LMU), Munich,
Germany. He received the M.S. degree in geography and the Ph.D. degree from LMU in 2001 and 2004, respectively.

From 2001 to 2008, he was a Postdoctoral Fellow with LMU, working on the retrieval of bio- and geophysical parameters from microwave remote sensing data. In 2007, he was a Visiting Scientist with the Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, MD. In 2009, he joined the Max Planck Institute for Meteorology, Hamburg, Germany, where he is leading a research group on terrestrial global remote sensing, focusing on global-scale remote sensing for climate studies. He is an Editor for Hydrology and Earth System Sciences and acts as a Reviewer for several national and international journals.

His research interests include the quantitative retrieval of geophysical parameters from remote sensing data, the development of image-processing algorithms, coupling of land surface process models with microwave scattering and emission models, and the development of land surface process models and data assimilation techniques.

Wolfram Mauser (M'92) was born in Innsbruck, Austria in 1955. He received the MS degrees in experimental physics ('79) and geography/hydrology ('81) and the Ph.D. ('84) degree in hydrology from the University of Freiburg, Germany. In 1981 he worked with the Univ. of Maryland, College Park and the Goddard Space Flight Center, Greenbelt Md. in the field of remote sensing and hydrology. From 1984-1991 he was assistant professor at the Dept of Hydrology, Institute for Physical Geography, University of Freiburg. In 1991 he was appointed full professor for geography and geographical remote sensing, department of geography, university of Munich, Germany. From 2003-2009 he was chairman of the German National Committee for Global Change Research.

He has been working in the field of remote sensing and hydrology within the major European research programs. He was appointed PI by ESA for its ERS-1, ERS-2 and ENVISAT program and is PI for the SRTM and SMOS mission. He was member of ESA's Mission Advisory Group of the Earth Explorer Surface Processes and Ecosystem Changes Through Response Analysis (SPECTRA) Mission. He took part in the MAC-Europe, E-MAC and DAISEX-campaign. His special research interest is the development and validation of spatially distributed land surface processes models and image processing algorithms as well as model assimilation procedures for microwave and hyperspectral optical data.

Juha Kainulainen was born in Lappajärvi, Finland, in 1979. He received the M.Sc. degree in technology from the Helsinki University of Technology (now part of the Aalto University), Espoo, Finland, in 2004.

Since 2005, he has been Doctoral Student and Project Manager with the Department of Radio Science and Engineering of the Aalto University School of Electrical Engineering, in Espoo, Finland. His duties include development and testing of Department's airborne synthetic aperture radiometer system HUT-2D and managing and working in several projects in the frame of SMOS mission. From 2004 to 2005, he was a Young Graduate Trainee with the European Space Agency. His work was related to signal processing of the payload instrument of the SMOS satellite mission. From 2001 to 2004, he has worked as a Research Assistant with the Laboratory of Space Technology of the Helsinki University of Technology. From 1998 to 1999, he worked as Trainee for Nokia Networks and Nokia Telecommunications. His research interests include radiometry, interferometry, and signal processing.

Jan E. Balling received the M.Sc. degree from the Technical University of Denmark (DTU) in 2002, and is currently employed at the division of Microwaves and Remote Sensing within the DTU Space department. His work has mainly been focused on the development of COTS-based data acquisition and control systems suitable for various remote sensing applications such as the EMIRAD L-band polarimetric radiometer. In preparation for the ESA/SMOS (Soil Moisture and Ocean Salinity) mission, he has participated in several airborne campaigns, and has been involved in the post-campaign data calibration and quality assessment activities. This has led to special interest being taken in the field of detection and mitigation of harmful RF interference.

Catherine Bouzinac received the master degree in fundamental physics in 1992 and the PhD degree in ocean physics in 1997 from the University Pierre et Marie Curie, Paris, France. Since 2002, she is a scientific consultant at RHEA SA for the European Space Agency. Between 2002 and 2005, she supported the development of the interferometric processing chain and the calibration plan for the CRYOSAT project. Between 2006 and 2010, she supported the validation plan and the airborne and in-situ campaign activities for the SMOS project.

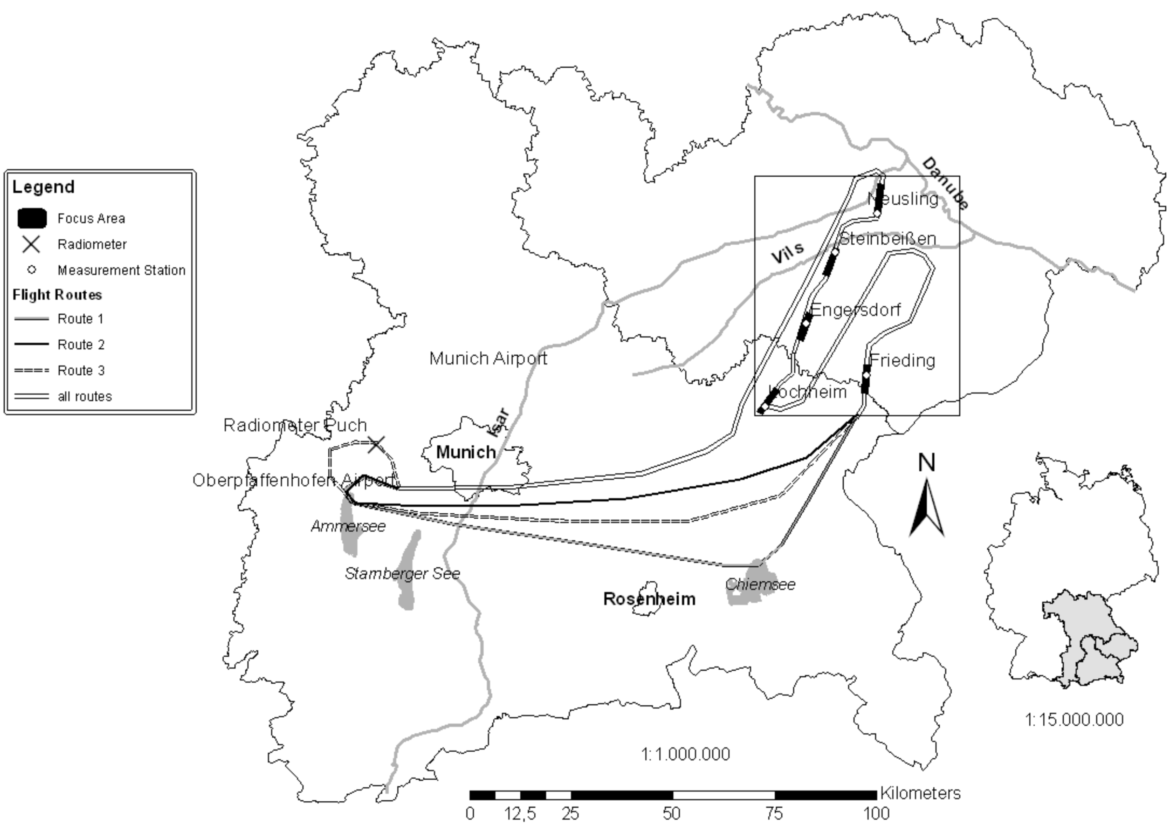

Fig. 1: Sketch of the different flight routes and location of the focus areas containing the ground stations Lochheim, Engersdorf, Steinbeissen, Neusling and Frieding. The black box shows the Vils area test site. Black lines give the boundaries of Upper and Lower Bavaria in the 1 : 1 000 000 map. The gray area in the 1 : 15 000 000 map shows the extent of the federal state Bavaria in Germany.

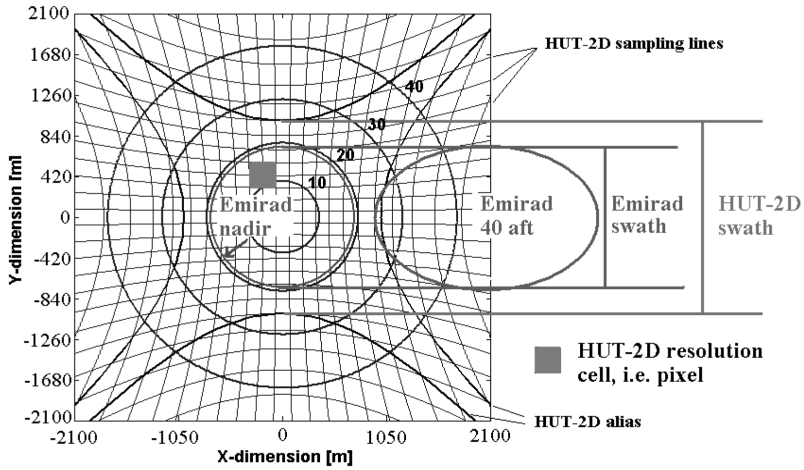

Fig. 2: HUT-2D swath and resolution cells together with the footprints of both EMIRAD antennas for a flight altitude of 2100 m above ground, with X-dimension along-track and Y-dimension across-track.

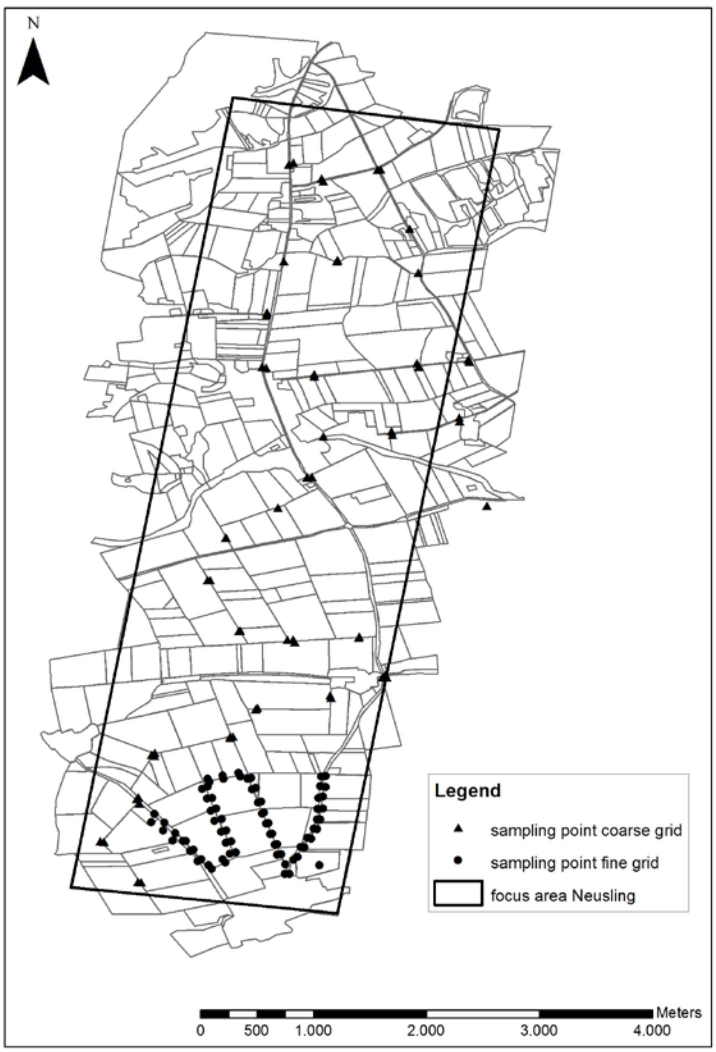

Fig. 3: "Grids" for soil moisture sampling points over a map showing the field boundaries in the Neusling area.

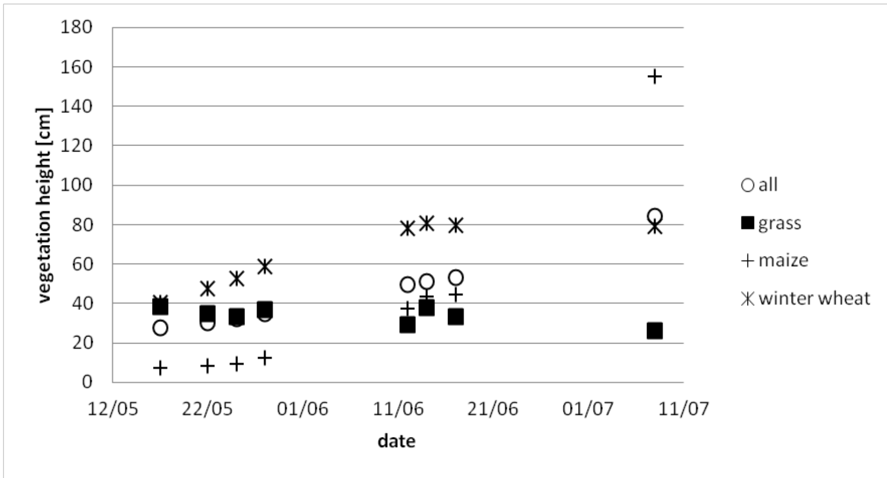

Fig. 4: Mean vegetation height as measured on the ground campaign days in all focus areas for all measurements and for the most distinct land cover classes. The class “all” includes all measurements.

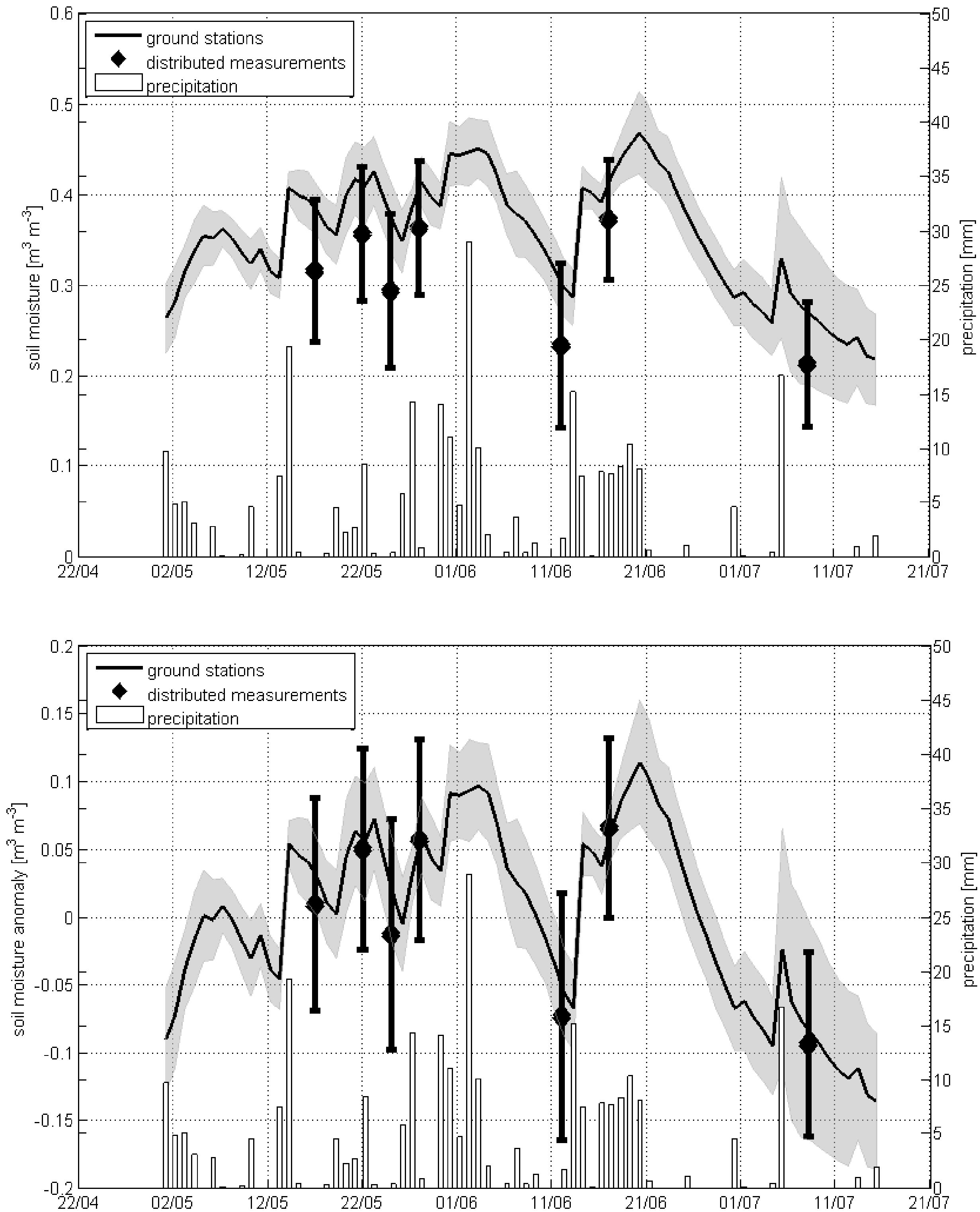

Fig. 5: Mean soil moisture as measured at 5 am UTC by the probes installed horizontally at depths of 5 cm and 10 cm at the five ground stations (black line) and as measured manually (vertically, upper 6 cm) on the campaign days (black diamonds). All mean values are calculated across the five focus areas, the shaded area and black bars indicate the standard deviations. Precipitation is given as mean daily precipitation sums as measured at the five ground stations. Upper: absolute soil moisture values, lower: soil moisture anomalies. For each data set, the time series of anomalies has been obtained by subtracting the mean value over the period in question from the value at each time step.

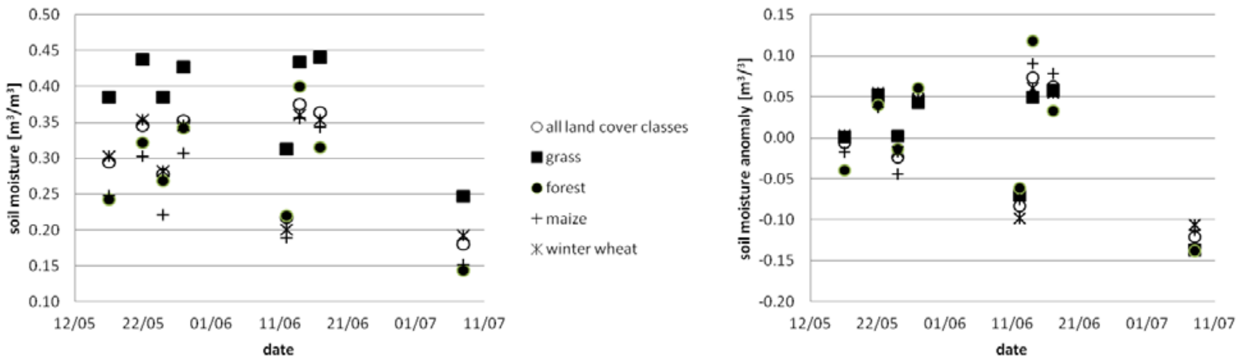

Fig. 6: Mean measured soil moisture per day for all manual measurements and for the most distinct land cover classes. The class "all land cover classes" includes all manual measurements. Left panel: absolute soil moisture values, right panel: soil moisture anomalies. For each data set, the time series of anomalies has been obtained by subtracting the mean value over the period in question from the value at each time step.

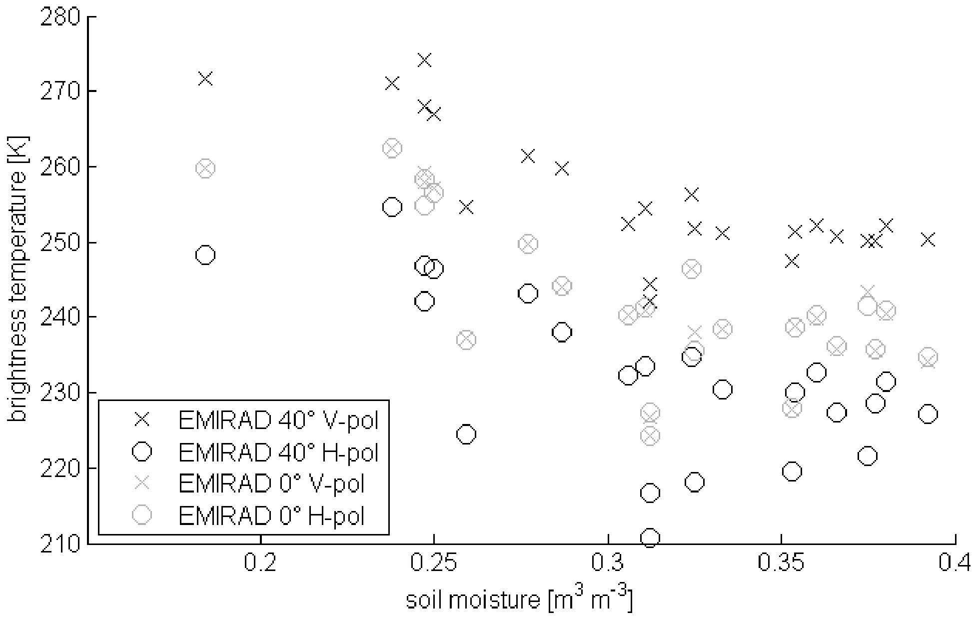

Fig. 7: Comparison of EMIRAD mean brightness temperature with mean measured soil moisture per focus area per day. Correlation coefficients are -0.79 (-0.64) for V-pol (H-pol) of the aft antenna and -0.7 for both polarizations of the nadir antenna.

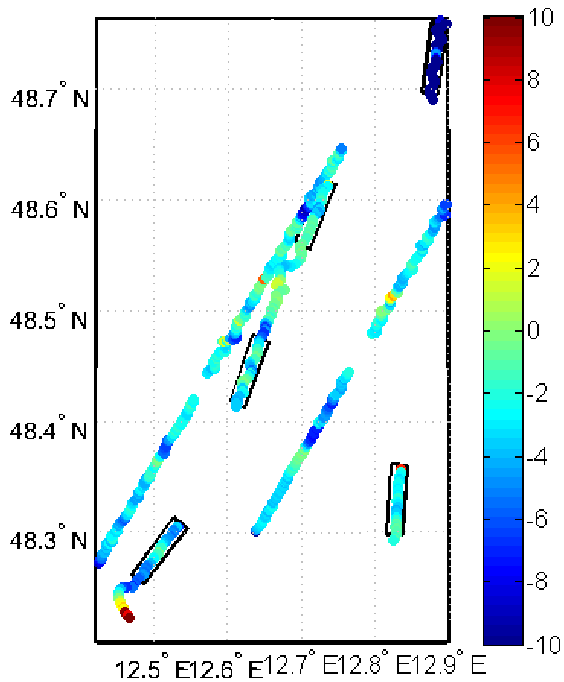

Fig. 8: Difference of EMIRAD and HUT-2D brightness temperature measurements (EMIRAD minus HUT-2D, V-pol) in Kelvin along the flight track on 22 May 2010. The black polygons show the five focus areas.

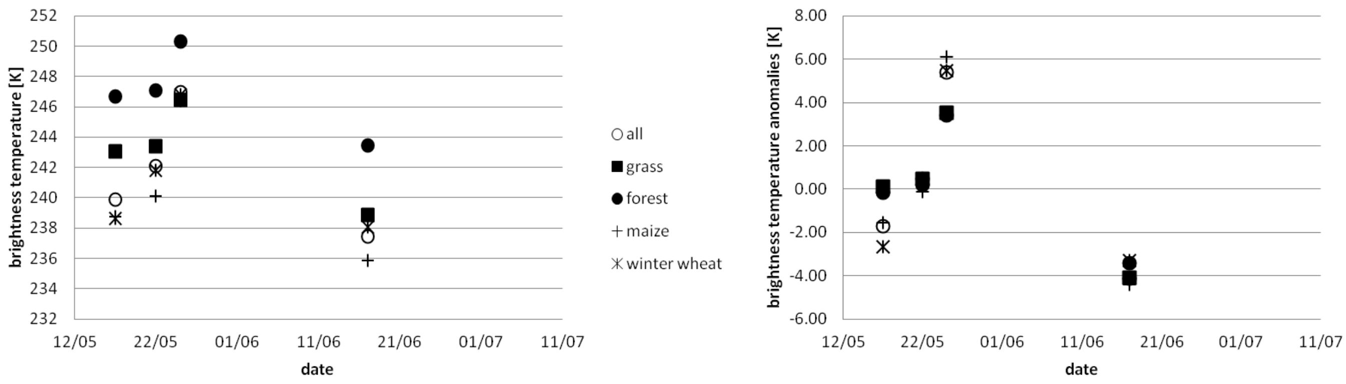

Fig. 9: Mean HUT-2D brightness temperature (V-pol) per day for all measurements and for the most distinct land cover classes. The class "all" includes all measurements. Left panel: Absolute brightness temperature values, right panel: brightness temperature anomalies. For each data set, the time series of anomalies has been obtained by subtracting the mean value over the period in question from the value at each time step.

TABLE I: MAIN CHARACTERISTICS OF THE TWO AIRBORNE L-BAND RADIOMETERS INSTALLED ON THE SAME PLATFORM

	EMIRAD	HUT-2D
Owner	Technical University of Denmark (DTU)	Aalto University (Espoo, Finland)
Instrument type	Fully polarized radiometer	Interferometric radiometer, X and Y polarized
Antennas	Two Potter horns with 38° and 31° half-power beamwidth	36 receivers on a U-shaped platform
Incidence angles	Nadir (0°) antenna and aft (40°) antenna	0° - 40°
Spatial resolution for flights in the Vils area	Nadir antenna: ~ 1.5 km, Aft antenna: ~ 2 km	~ 400 m

TABLE II: AVAILABILITY OF AIRBORNE DATA ON EACH OF THE FLIGHT DAYS

	EMIRAD	HUT-2D	ELBARA-II	SMOS acquisition time (UTC)
17 May 2010	yes	yes	no	4:37
22 May 2010	yes	yes	yes	4:42
25 May 2010	yes	yes	yes	4:26
12 June 2010	yes	no	yes	4:25
17 June 2010	yes	yes	no	4:30

TABLE III: SAND AND CLAY CONTENT AT THE GROUND STATIONS AND PERCENTAGES OF MAIN LAND COVER CLASSES IN THE FOCUS AREAS AROUND THEM

	Lochheim	Engersdorf	Steinbeissen	Neusling	Frieding
sand [%]	27.6	40.3	30.5	19.5	36.6
clay [%]	11.2	6.4	5.5	6.8	5.1
grass [%]	20.1	11.0	5.7	1.8	27.6
winter wheat [%]	18.5	23.3	16.1	26.2	15.2
maize [%]	24.6	27.1	16.5	11.0	20.2
other crops [%]	6.9	8.1	21.0	44.3	7.9
forest [%]	11.4	22.0	28.0	1.7	21.6
water [%]	1.1	0.0	0.0	1.5	0.1
other land use [%]	17.5	8.6	12.7	13.4	7.5

TABLE IV: MEAN VEGETATION WATER CONTENT AND DRY BIOMASS FOR WINTER WHEAT AND MAIZE AS MEASURED ON 9 AND 23 JUNE 2010 AT 5 POINTS IN EACH FIELD

	vegetation water content [g/m^2] 9 June	**vegetation water content [g/m^2] 23 June**	**dry biomass [g/m^2] 9 June**	**dry biomass [g/m^2] 23 June**
winter wheat	2597.4	3312.7	583.0	977.7
maize	59.6	365.7	3.9	27.7

TABLE V: MEAN AND STANDARD DEVIATION OF DISTRIBUTED SOIL MOISTURE MEASUREMENTS (SM) [M^3 M^{-3}] FROM THE COARSE "GRID", SOIL TEMPERATURE AT 5 CM DEPTH [K] AND AIR TEMPERATURE AT 20 CM ABOVE GROUND [K] AT THE GROUND STATIONS TOGETHER WITH TEMPERATURE MEASURED BY THE THERMAL INFRARED CAMERA [K] OVER THE STATION FOR EACH FOCUS AREA AND FLIGHT DAY

	Parameter	**17 May**	**22 May**	**25 May**	**12 June**	**17 June**
Lochheim	mean sm	-	0.375	0.325	0.247	-
	stddev sm	-	0.085	0.094	0.091	-
	soil temperature	282.6	283.7	285.8	292.3	288.0
	air temperature	280.6	280.6	283.0	290.1	286.4
	TIR measurement	-	280.2	282.7	290.5	-
Engersdorf	mean sm	0.311	0.36	0.287	0.247	0.392
	stddev sm	0.085	0.083	0.089	0.091	0.069
	soil temperature	282.0	283.2	287.1	292.8	288.5
	air temperature	279.5	281.9	286.4	-	-
	TIR measurement	276.5	280.3	284.5	290.0	-

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Precipitation fields interpolated from gauge stations versus a merged radar-gauge precipitation product: influence on modelled soil moisture at local scale and at SMOS scale

J. T. dall'Amico[1], W. Mauser[1], F. Schlenz[1], and H. Bach[2]

[1]University of Munich, Department of Geography, Munich, Germany
[2]VISTA Remote Sensing in Geosciences GmbH, Munich, Germany

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Correspondence to: J. T. dall'Amico (j.dallamico@iggf.geo.uni-muenchen.de)

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Abstract

For the validation of coarse resolution soil moisture products from missions such as the Soil Moisture and Ocean Salinity (SMOS) mission, hydrological modelling of soil moisture is an important tool. The spatial distribution of precipitation is among the most crucial input data for such models. Thus, reliable time series of precipitation fields are required, but these often need to be interpolated from data delivered by scarcely distributed gauge station networks. In this study, a commercial precipitation product derived by Meteomedia AG from merging radar and gauge data is introduced as a novel means of adding the promising area-distributed information given by a radar network to the more accurate, but point-like measurements from a gauge station network. This precipitation product is first validated against an independent gauge station network. Further, the novel precipitation product is assimilated into the hydrological land surface model PROMET for the Upper Danube Catchment in southern Germany, one of the major SMOS calibration and validation sites in Europe. The modelled soil moisture fields are compared to those obtained when the operational interpolation from gauge station data is used to force the model. The results suggest that the assimilation of the novel precipitation product can lead to deviations of modelled soil moisture in the order of 0.15 $m^3\,m^{-3}$ on small spatial (~1 km^2) and short temporal resolutions (~1 day). As expected, after spatial aggregation to the coarser grid on which SMOS data are delivered (~195 km^2), these differences are reduced to the order of 0.04 $m^3\,m^{-3}$, which is the accuracy benchmark for SMOS. The results of both model runs are compared to brightness temperatures measured by the airborne L-band radiometer EMIRAD during the SMOS Validation Campaign 2010. Both comparisons yield equally good correlations, confirming the model's ability to realistically model soil moisture fields in the test site. The fact that the two model runs perform similarly in the comparison is likely associated with the lack of substantial rain events before the days on which EMIRAD was flown.

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1 Introduction

Knowledge of temporal and spatial soil moisture patterns on different scales is important for a number of disciplines. In agriculture, the water content of the root-zone soil layer is an important factor limiting plant growth, while the water content of the soil surface is of great importance for applications in meteorology and hydrology. This is especially true for the modelling and forecasting of extreme events (e.g. Seneviratne et al., 2006; Fischer et al., 2007; Loew et al., 2009), but also for studies of climate (Dirmeyer, 2000; Timbal et al., 2002). For the various applications, area-wide information on soil moisture dynamics is needed on a variety of scales up to scales in the order of tens of kilometers (Entekhabi et al., 1999). Indeed these scales are bound to decrease as the resolution of numerical models increases. Nevertheless, direct measurement techniques like gravimetric samples provide only point-like information of soil moisture.

The derivation of soil moisture maps from remote sensing data has been dealt with in a number of studies. In particular, data from sensors operating at wavelengths in the microwave region have been found useful, either active (e.g. Loew et al., 2006; Wagner et al., 2007; Demircan et al., 1993; Rombach and Mauser, 1997) or passive (e.g. Jackson et al., 1995, 1999; Wigneron et al., 2003). While a number of algorithms yield promising results, they all rely on a sound knowledge of the contributing soil moisture fields in different areas for the calibration of model parameters. In particular, microwave remote sensing at low frequencies has proven promising for the derivation of surface soil moisture (Kerr, 2007), but with the drawback of a low spatial resolution.

The Soil Moisture and Ocean Salinity (SMOS) mission was launched in November 2009 by the European Space Agency (ESA) and carries the first spaceborne interferometric L-band radiometer. The mission is designed to produce global maps of surface soil moisture with an accuracy better than 0.04 $m^3 m^{-3}$, a temporal resolution of 2–3 days and a spatial resolution of about 40–50 km (Kerr et al., 2010). This spatial resolution is rather low when compared to the available in situ measurements. Thus,

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the calibration and validation (henceforth cal/val) of SMOS soil moisture products is a difficult task. For this purpose, numerical modelling of soil moisture fields is a useful tool to fill the gap between point-like measurements and the coarse-scale remote sensing data (Rüdiger et al., 2009; Albergel et al., 2010; Juglea et al., 2010b).

If modelled soil moisture fields are to be used for cal/val purposes, a firm knowledge of the uncertainties associated with the soil moisture modelling itself is required. The quality of hydrological model output crucially depends on the quality of the input data, in particular on the spatial variability of rainfall (Syed et al., 2003; Wilk et al., 2006). Juglea et al. (2010a) suggested that, at SMOS scale, soil moisture variability is mostly driven by atmospheric forcing effects. Their study focused on how the use of the PERSIANN-CCS (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Cloud Classification System) database instead of sparsely distributed rain gauge measurements affects soil moisture modelling. Their study site was the Valencia Anchor Station experimental site in Spain, one of the main cal/val sites for SMOS in Europe.

This study aims at analysing the potential of using a merged radar-gauge precipitation input dataset for the modelling of soil moisture fields in the Upper Danube Catchment (UDC). The UDC is a major cal/val site for SMOS in Europe. Thus, an understanding can be gained of the uncertainties in the SMOS cal/val activities in the UDC area that are associated with the precipitation input. Two different sources of rainfall information are compared as input to the hydrological land surface model: a high resolution merged radar-gauge precipitation data set vs. interpolated station recordings from a high density precipitation network.

For SMOS cal/val purposes, continuous soil moisture measurements at several ground stations are complemented by airborne and ground campaigns in parts of the UDC and by numerical modelling of the entire catchment (dall'Amico et al., 2012; Schlenz et al., 2011). Output from the Process Oriented Multiscale EvapoTranspiration (PROMET) model (Mauser and Bach, 2009) was compared to SMOS soil moisture data for the vegetation period of 2010 by (dall'Amico et al., 2011). PROMET has been

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validated on different scales in a variety of studies (Ludwig and Mauser, 2000; Strasser and Mauser, 2001; Ludwig et al., 2003a; Bach et al., 2003). In particular, the soil water model has been validated by Loew et al. (2006) and Pauwels et al. (2008) with good results. Schlenz et al. (2011) studied explicitly the uncertainties of the SMOS validation in the UDC by comparing modelled soil moisture to ground station measurements and to distributed field measurements with satisfying results. However, the uncertainties related to the interpolation of gauge station measurements could not be assessed in that study, because all in situ soil moisture measurements were close to the meteorological stations whose data were used for the interpolation. Hence, the interpolated precipitation fields are expected to be realistic in the areas for which in situ soil moisture data are available.

Several studies, e.g. Tetzlaff and Uhlenbrook (2005); Goudenhoofdt and Delobbe (2009), have shown the high potential of the combination of radar data and ground station data for determining quantitative precipitation fields. In this study, a commercial precipitation data product for Germany, established by Meteomedia AG, is used to force the PROMET model. The data product is derived from radar data calibrated with measured precipitation data from a Meteomedia owned precipitation network. This combines the area-wide information from the radar with the more accurate quantitative information delivered by the point-wise gauge station measurements. All used data and the PROMET model are described in Sect. 2. Section 3 is dedicated to the validation of the precipitation data product and to assessing its influence on modelled soil moisture fields. In particular, in Sect. 3.1 the data product is validated using independent gauge station data from the Bavarian agrometeorological service. Sections 3.2 and 3.3 focus on the influence of this data product on modelled soil moisture both on the local scale and on SMOS scale, respectively. As an attempt to validate the modelled soil moisture fields, these are compared in Sect. 3.4 to airborne data acquired with the EMIRAD radiometer during the SMOS Validation Campaign 2010 (dall'Amico et al., 2012). Conclusions are drawn in Sect. 4.

2 Data

2.1 Meteomedia data product

The precipitation data product used in this study has been developed by Meteomedia AG (Meteomedia, 2012) using their radar data calibrated with gauge data from their own meteorological station network. Access to this commercial data set has been granted to the University of Munich for the purpose of the presented analyses.

The Meteomedia data set used in this study covers the Federal Republic of Germany with a spatial resolution of 500 m. Data were available to this study from 8 April 2010 to 31 August 2010 with hourly resolution. The full spatial resolution is reached from 1 May 2010 onwards, while the April data have a reduced spatial resolution of 1 km.

In this study, the original data product provided by Meteomedia AG is used for comparison with an independent gauge station network. For the forcing of the PROMET model, the original data are mapped to the 1 km × 1 km model grid using a nearest-neighbour approach, hence reducing the spatial resolution of the data product.

2.2 Gauge station network

The gauge station network used in this study is owned and operated by the Bavarian State Research Center for Agriculture (Bayerische Landesanstalt für Landwirtschaft, henceforth LfL). It consists of 130 micrometeorological stations spread over Bavaria as shown in Fig. 1. The average station density of the network amounts to 1 station per approximately 500 km^2. This means that on the average ~3 stations are contained in one SMOS footprint. Precipitation is measured hourly using a Hellmann rain gauge installed at 1 m above ground. Other measurements include air temperature and humidity, wind speed and radiation. All measured data are publicly available (http://www.wetter-by.de/).

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2.3 Study area

The Upper Danube Catchment (UDC), shown in Fig. 1, is located mostly in southern Germany and hence characterized by a temperate humid climate with precipitation maxima in summer and snow cover in winter. It covers an area of approximately 77 000 km^2. The largest settlement in the area is the city of Munich, capital of the federal state Bavaria. Here, the average temperature is about −2 °C in January and about 17 °C in July. The average annual precipitation is more than 900 mm and increases to more than 2000 mm towards the Alps in the South of the catchment.

The UDC has been the focus of many studies in the past (Mauser and Schädlich, 1998; Ludwig and Mauser, 2000; Ludwig et al., 2003b; Probeck et al., 2005; Loew et al., 2006; Mauser and Marke, 2009). More recently, it has been used as one of the major test sites in Europe for the calibration and validation of SMOS data products (dall'Amico et al., 2011). In this context, an area of about the size of a SMOS footprint (roughly 40 km × 40 km) of the Vils area in the Northeast of Munich was selected as a reference area for detailed studies. It is shown in Fig. 1 and was chosen because a synthetic study by Loew (2008) suggested that the SMOS retrieval algorithm should work well in this region. Airborne and ground campaigns were conducted in the Vils area for studies of soil moisture and L-band brightness temperature. Airborne data of the most recent campaign, the SMOS Validation Campaign 2010 (dall'Amico et al., 2012), are used in this study for comparison with the modelled soil moisture fields.

2.4 EMIRAD brightness temperature measurements

EMIRAD is a radiometer owned and operated by the Technical University of Denmark, operating at the same frequency as used for the SMOS mission (L-band, 1.4 GHz). The radiometer consists of two Potter horns which are pointed at nadir (0°) and aft (40°). A detailed technical description of the instrument is given in Skou et al. (2010).

During the SMOS Validation Campaign 2010, EMIRAD was mounted on an aircraft, which flew four legs over the Vils area on 17, 22 and 25 May and 12 and 17 June 2010.

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Flights took place in the early morning hours, with the SMOS overpass (~04:30 UTC) in the middle of the three-hour flight. The nadir antenna ground resolution for the given flight altitude is approximately 1.5 km. The footprint of the aft antenna has the form of an ellipse with the longer axis (~2 km on the ground) along-track. Details on the flight pattern, the radiometric accuracy and a comparison with ground data are given in dall'Amico et al. (2012).

For this study, EMIRAD data were gridded on the model grid (1 km × 1 km) by averaging all footprints with their centre point falling into the same grid cell. This was done for both antennas separately. Although EMIRAD is a fully polarimetric radiometer, i.e. data are available as V-polarized and H-polarized measurements, only the total amount of emitted energy is used in this study for simplicity. This quantity is the First Stokes Parameter, which is the sum of V-polarized and H-polarized measurements.

2.5 The hydrological land surface model PROMET

PROMET is a spatially distributed, physically based hydrological land surface model, originally developed by Mauser and Schädlich (1998). In its current release, it consists of eight coupled components: meteorology, land surface energy and mass balance, vegetation, snow and ice, 4-layer soil hydraulic and soil temperature, ground water, channel flow and man-made hydraulic structures. For this study, calculations are performed on a 1 km × 1 km grid with hourly resolution. The soil hydraulic and soil temperature component models soil water content and soil temperature of 4 layers, which for this study are situated at 0–2, 2–15, 15–50 and 50–150 cm depth, as well as vertical and lateral flows of water in unsaturated soil. The meteorology component delivers the meteorological forcing data for each pixel to the other components. This includes air temperature, rainfall, air humidity, wind speed and incoming short and longwave radiation fluxes. These meteorological input data can be derived from remote sensing or from station data, in which case they are spatially interpolated. Static, but spatially distributed input data for the PROMET model include a digital terrain model, a soil map

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and a land cover map. All model components and static input data are described in detail in Mauser and Bach (2009).

The meteorology component as implemented in PROMET for this study spatially interpolates meteorological data from the hourly measurements of the LfL stations and delivers them to the other components. For the spatial interpolation of precipitation, an altitudinal gradient is calculated from the measured station data in order to generate a precipitation field which takes into account the influence of topography. The deviations at the measurement station from this averaged altitudinal field are interpolated and superimposed on the altitudinal field to account for regional differences in the meteorological variables. As this procedure is not able to reproduce the complex, small-scale, stationary rainfall patterns which are present especially in the hilly terrain of the Alps, an additional small-scale correction based on a 10-yr analysis of the monthly rainfall is applied. This procedure spatially re-distributes hourly rainfall, but preserves the total amount of annual rainfall in the catchment. More details on the interpolation procedures are given in Mauser and Bach (2009). In the first model run in this study the interpolated meteorological drivers are delivered to the other model components without change.

PROMET allows for substitution of meteorological fields, which were internally interpolated from station data as described above, with timeseries of measured fields at runtime. This option was used for the precipitation fields in the second model run in this study. For each model time step, precipitation fields from Meteomedia were used to overwrite the interpolated precipitation fields. The other meteorological variables (e.g. air temperature) are interpolated from station data as described above. Finally, all meteorological forcing data are delivered to the other model components.

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3 Results and discussion

3.1 Validation of Meteomedia data product with LfL station data

Meteomedia data were first validated using the independent gauge data from the LfL station network. Since no position of the Meteomedia rain gauge network coincides with the LfL station network, the quality of the Meteomedia rainfall data between their gauging stations is tested. First, the total precipitation sum of the 5 months from 8 April to 31 August 2010 was compared for all 130 pixels of the Meteomedia data set, which contain an LfL station (resolution: 500 m). The root-mean-squared error of this comparison is 51.24 mm, which is roughly 10 % of the mean precipitation sum of 523.2 mm in this time period. As a next step, the time series of daily precipitation sums measured at the stations were compared to the time series of daily sums of the corresponding pixel (resolution 500 m) of the Meteomedia data. The data pairs are shown in Fig. 2 for the LfL Station Engersdorf, which is located in the Vils area. Figure 3 shows the correlation coefficients and root-mean-squared errors (RMSE) for all LfL stations. At only 11 stations, the correlation coefficient is below 0.9, showing an excellent agreement between the two data sets. RMSEs are largely between 1.5 and 2.5 mm, with 5 stations exceeding 4 mm. The mean daily precipitation measured by the stations in this period varies from 4.4 mm to 10.8 mm, with a mean value of 6.5 mm. Hence, relative RMSEs are mostly between 23 % and 38 %. The main sources of disagreement are likely uncertainties of timing and amount of short but intense precipitation events. This is confirmed when the same comparison is done for the hourly data, which shows increased uncertainties but still correlation coefficients above 0.6 at all stations (with 4 exceptions) and most RMSEs between 0.3 and 0.6 mm (results not shown).

3.2 Influence on modelled soil moisture at local scale (1 km)

In order to study the influence of the two different precipitation inputs on modelled soil moisture, two model runs were conducted for the period from 1 May 2010 to

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26 August 2010. For the first run, LfL station precipitation data were used and interpolated as described in Sect. 2.5. For the second run, the Meteomedia data precipitation fields were used directly to force the model (see Sect. 2.5). All remaining model configurations, initializations and input data were the same for the two runs. Although calculations are performed hourly, the soil moisture output is given daily at 05:00 UTC which corresponds to the SMOS overpass time. As SMOS soil moisture is expected to be representative for the upper ~5 cm of the soil (Kerr et al., 2010), the arithmetic mean of modelled soil moisture of the upper two model layers is considered in this study.

As shown in Fig. 4, the modelled soil moisture fields of both runs are in general very similar. In large parts of the catchment, correlation coefficients are 0.8 or above and RMSEs are below 0.02 $m^3 m^{-3}$. The larger deviations in the most western part of the catchment are most likely due to the larger uncertainties in the interpolation of precipitation from the LfL network, as there are no stations outside Bavaria (see Fig. 1). In the South of the catchment, the border of Bavaria is the border of Germany as well (see Fig. 1), so that neither station data nor Meteomedia data are available. Here, the pattern reflects the digital elevation model due to the elevation-based interpolation of the station data implemented in PROMET. However, these Alpine regions are not considered in the SMOS cal/val activities, as no SMOS soil moisture data are available there (dall'Amico et al., 2011).

Even though the modelled soil moisture fields are, in general, very similar for the two runs, noticeable differences can occur on small temporal and spatial scales. An example of soil moisture time series of both model runs is shown in Fig. 5 for a 1 km × 1 km grid cell in the Vils area. Although almost equal on almost all days, differences of up to 0.15 $m^3 m^{-3}$ occur in the first half of July. Figure 6 shows the difference of the two runs (modelled soil moisture using Meteomedia data minus modelled soil moisture using LfL data) for the Vils area on 5 July 2010. Results are almost the same at the pixels with LfL stations (black crosses). However, there apparently was a small precipitation cell between the stations, seen only by the radar, leading to larger differences in the modelled soil moisture fields.

3.3 Influence on modelled soil moisture at SMOS scale (ISEA grid)

For the comparison of modelled soil moisture fields at SMOS scale, the icosahedrons Snyder equal area (ISEA) grid on which SMOS data are delivered is used. The spacing between two ISEA nodes is about 12.5 km. Each model grid cell was assigned to the nearest ISEA grid node. For each ISEA grid node, all soil moisture values of the model cells assigned to it were averaged. This procedure was carried out for the two model runs described in the previous section.

Figure 7 shows correlation coefficients and RMSEs for the time series of the two model runs on the ISEA grid. Results are similar to those of the comparison on the 1 km grid, showing a very good agreement of the modelled soil moisture fields with correlation coefficients mostly above 0.8 and RMSEs mostly below 0.015 $m^3 m^{-3}$. As on the local scale, deviations increase towards the West of the catchment due to the lack of LfL stations and in the South of the catchment due to the lack of LfL stations as well as Meteomedia data.

In the previous section, larger differences were observed for some 1 km grid cells in the Vils area in the first half of July. In Fig. 8, the time series of both model runs are shown for the ISEA node in this area (node ID 2026587, location shown in Fig. 1). While most of the few detectable differences indeed occur in the month of July, their magnitude is much smaller (maximum of 0.047 $m^3 m^{-3}$). Apparently, the effect of the small scale precipitation events on modelled soil moisture is reduced through the spatial averaging. For many ISEA nodes, the maximum differences in the modelled period are even much smaller than for the example shown here.

3.4 Comparison of both model runs with measured brightness temperatures

For each 1 km^2 cell in the Vils area, the brightness temperatures measured by EMIRAD on the five flight days were paired with the modelled soil moisture on the same days. This was done for both EMIRAD antennas (0° and 40° incidence angle) and both model runs separately.

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The scatter plots of these data pairs are shown in Fig. 9 (left panel: LfL run, right panel: Meteomedia run). Both model runs result in equally good negative correlations between modelled soil moisture and measured brightness temperature, with correlation coefficients of about −0.7.

This robust correlation confirms the ability of the model to produce realistic soil moisture fields in the Vils area. Certainly, measured brightness temperature is also influenced by other factors, mainly vegetation cover and surface temperature (Wigneron et al., 2003). Surface temperature can be assumed to be a relatively homogeneous field because flights were conducted in the early morning hours. In contrast, different vegetation cover is expected to have a strong influence on the signal measured by EMIRAD and may likely be responsible for most of the spread observed in Fig. 9.

During the 24 h before the flights, Meteomedia data show almost no precipitation in the Vils area on three of the five days. On 22 May, the mean 24h-sum of precipitation in the Vils area was 1.4 mm (minimum 0.3 mm, maximum 4.7 mm). On 17 June, the precipitation events before the flight were more intense (24h-sums: maximum 10.3 mm, minimum 4.7 mm, mean 7.7 mm), but still not very heavy. Therefore, it is not surprising that the model run using Meteomedia data does not lead to an improved correlation of modelled soil moisture with EMIRAD data. However, we expect that the correlation would have substantially improved if there had been small but intense convective precipitation events before the flights since the Meteomedia data product has shown to better capture those events.

4 Conclusions

In this study, an operational precipitation data product derived from merging radar data with gauge station data was validated and assimilated into a hydrological land surface model for the Upper Danube Catchment. The effect on modelled soil moisture fields of using this data product (Meteomedia data) instead of a state-of-the-art interpolation of precipitation data from gauge stations (LfL stations) has been studied at local scale (1 km^2) as well as at SMOS scale (~195 km^2).

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The precipitation sums over a period of five months as given in the Meteomedia data fit very well with those observed at the LfL stations. The RMSE of roughly 10 % is within the measurement accuracy of rain gauge station measurements in Germany (Baumgartner and Liebscher, 1996). The comparison of daily precipitation sums at the stations shows good agreement between the two data sets in terms of correlation (0.9 or above) as well as in terms of absolute errors (1.5–2.5 mm d^{-1}). Uncertainties increase for hourly precipitation data, especially concerning the exact timing and amount of short but intense precipitation events. The agreement of the two time series is still very good for most of the 130 stations. Therefore, the data set provided by Meteomedia AG seems to be very well suited to force the hydrological land surface model of the UDC, especially after spatial aggregation from 500 m to the 1 km model grid, which is expected to further decrease the deviations.

Soil moisture modelled using the Meteomedia data as precipitation input is compared to soil moisture modelled using an interpolation of the precipitation measured at the LfL meteorological stations. Both model configurations are run from 1 May 2010 to 26 August 2010 on the 1 km × 1 km model grid and the two model runs yield very similar soil moisture fields. Larger differences occur only in those parts of the catchment where either the LfL station data or the Meteomedia data are not available. At the local scale, a comparison of the two time series suggests that differences between the two model runs are mainly associated with small but intense convective precipitation cells, which fall through the mesh of the LfL station network but can still be captured by the radar data. If, on the other hand, a small precipitation cell happens to be above a station, the interpolation most likely results in an overestimation of precipitation in the pixels towards neighboring stations.

At the SMOS scale, the above mentioned differences associated with small precipitation cells reduce to small amounts. In the time series of modelled soil moisture, only small differences (0.047 $m^3 m^{-3}$) can be seen in an area where clear differences (0.15 $m^3 m^{-3}$) could be observed at the local scale.

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A comparison of modelled soil moisture of both model runs with brightness temperatures measured on five days by the airborne radiometer EMIRAD shows an equally good negative correlation (−0.7) for both model runs. This correlation is similar to the correlation found between EMIRAD data and in situ soil moisture measurements (dall'Amico et al., 2012). While this confirms the model's ability to realistically simulate soil moisture in the Vils area, it also shows that the use of the Meteomedia data does not result in improved modelled soil moisture field on these days. This similarity in the quality of the output is likely associated with the lack of substantial precipitation events before the flights which could have reduced the quality of the model run with interpolated gauge station data.

From this study, it can be concluded that the interpolation of precipitation from gauge station measurements as currently implemented in the PROMET model is appropriate to realistically simulate soil moisture fields in the Vils area on the spatial scale of SMOS observations. This is most likely also the case for the other parts of the Upper Danube Catchment where gauge station data are available. The main sources of uncertainties in the interpolation seem to be small-scale precipitation events. Therefore, if high spatial resolution is required together with high temporal resolution, the use of a data product combining gauge data with information from radar is recommended. This is especially important for studies including the summer months because of the higher frequency of occurrence of small-scale convective precipitation cells. This is in line with the findings of Goudenhoofdt and Delobbe (2009), who evaluated several radar-gauge merging methods in the Walloon region of Belgium and concluded that the benefit of using radar observations in addition to gauge station measurements is particularly significant during summer.

At the SMOS scale, hardly any differences can be detected in the soil moisture output of the two model runs with the different precipitation input data. The root-mean-squared errors of the two time series are below 0.015 $m^3 m^{-3}$ for most of the ISEA grid nodes. These uncertainties are of the order of the theoretical accuracies of the handheld soil moisture probes used for the model validation at the point scale (Schlenz et al., 2012).

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Even on days with differences of up to 0.15 $m^3 m^{-3}$ in some 1 km^2 cells within the area associated with an ISEA grid node, the spatial aggregation to the ISEA grid reduces these differences to the magnitude of the accuracy benchmark of the SMOS mission (∼0.04 $m^3 m^{-3}$). Therefore, from a SMOS point of view, the uncertainties of modelled soil moisture due to different precipitation input are not relevant in the UDC area. Nevertheless, the use of a merged precipitation product may be of substantial advantage in regions where small-scale precipitation cells occur more frequently or where there are large distances between gauge stations.

Acknowledgements. This work was funded by the German Federal Ministry of Economics and Technology through the German Aerospace Center (DLR, 50 EE 0731). The merged radar-gauge precipitation product was made available by Meteomedia AG, which is gratefully acknowledged. The Authors wish to thank Timo Gebhardt for the implementation of the systematic handling of LfL station data and Alexander Loew for the effort he put into the post-processing of EMIRAD data.

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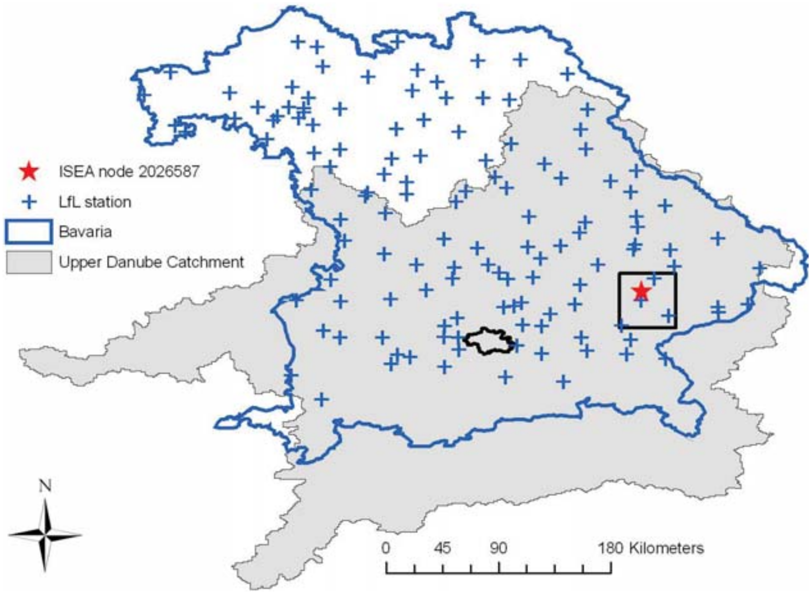

Fig. 1. Upper Danube Catchment with LfL meteorological station network. The black box shows the Vils area, the black polygon represents Munich, the capital of the federal state Bavaria. The red star marks the position of one of the nodes of the ISEA grid in the Vils area on which SMOS data are delivered.

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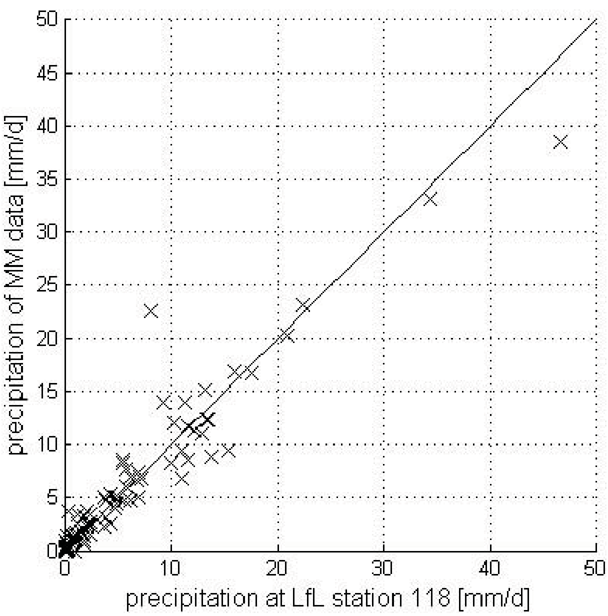

Fig. 2. Scatter plot of daily rainfall of the Meteomedia data set ("MM data") and the measurements of LfL station 118 (Engersdorf, located in the Vils area) for the period from 8 April 2010 to 31 August 2010.

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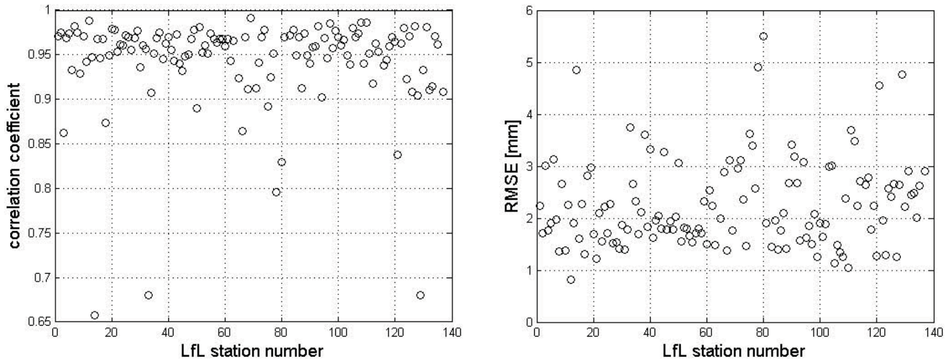

Fig. 3. Correlation coefficients (left panel) and root-mean-squared errors (right panel) for the comparison of daily rainfall of the Meteomedia data set with the measurements of the LfL stations for the period from 8 April 2010 to 31 August 2010.

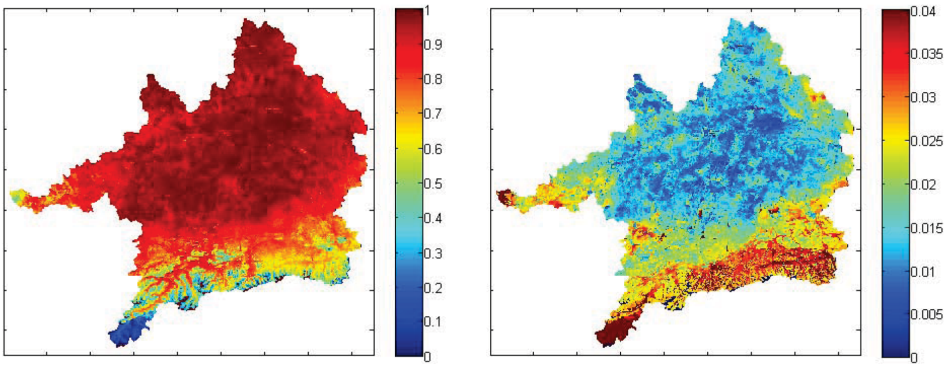

Fig. 4. Maps of correlation coefficients (left panel) and root-mean-squared errors (right panel) of soil moisture from the two model runs on the 1 km model grid for the period from 1 May to 26 August 2010.

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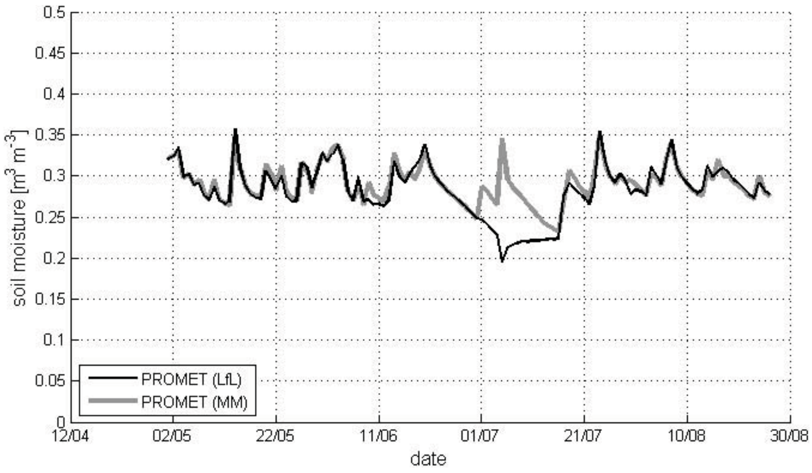

Fig. 5. Time series of modelled soil moisture at a 1 km grid cell in the Vils area (location shown in Fig. 6). The black line shows the modelled soil moisture with precipitation input from interpolated LfL station data, the grey line shows the modelled soil moisture with precipitation input from Meteomedia data ("MM").

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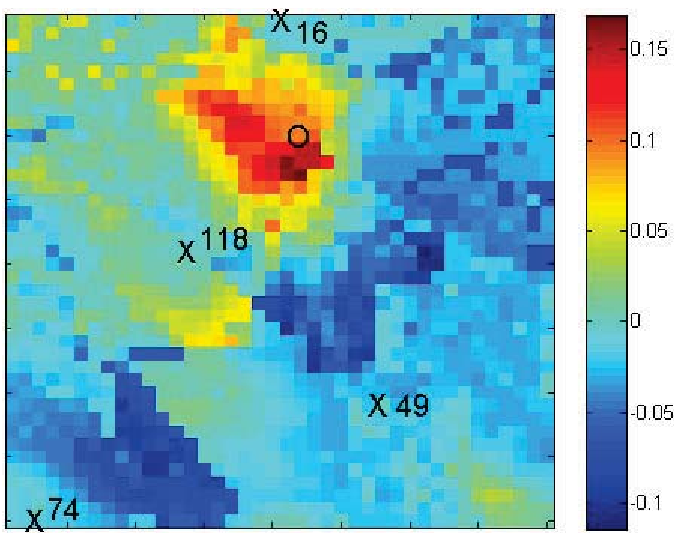

Fig. 6. Difference of modelled soil moisture fields [$m^3 m^{-3}$] from the two model runs (Meteomedia run minus LfL run) in the Vils area on 5 July 2010. Black crosses are the LfL stations with their numbers. The circle marks the location of the pixel for which the time series are shown in Fig. 5. Axes ticks mark distances of 5 km (model grid is 1 km × 1 km).

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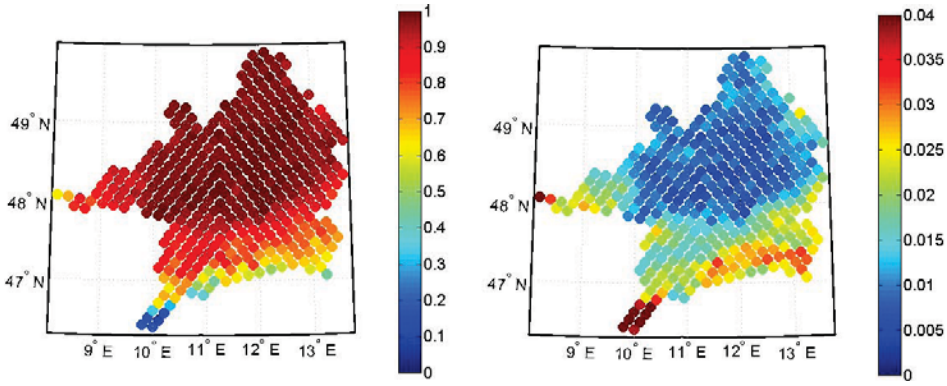

Fig. 7. Maps of correlation coefficients (left panel) and root-mean-squared errors (right panel) of the two model runs (for the period from 1 May to 26 August 2010) after aggregating modelled soil moisture to the ISEA grid.

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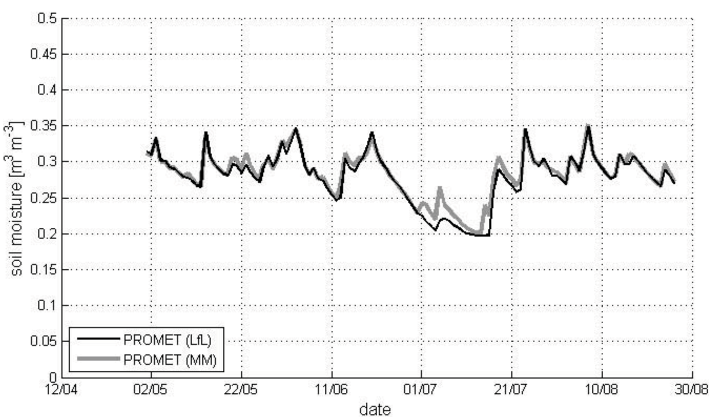

Fig. 8. Time series of modelled soil moisture for the ISEA node ID 2026587, located in the Vils area. The black line shows the modelled soil moisture with precipitation input from interpolated LfL station data, the grey line shows the modelled soil moisture with precipitation input from Meteomedia data ("MM").

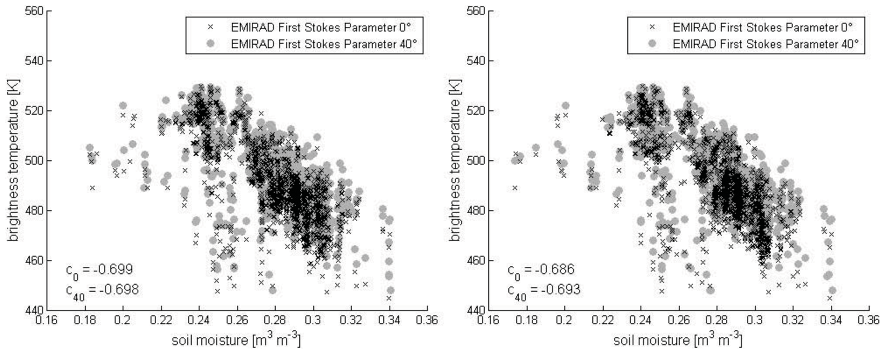

Fig. 9. Scatter plot of modelled soil moisture versus measured brightness temperature; left panel: model run using LfL data, right panel: model run using Meteomedia data. c_0 denotes the correlation coefficient between modelled soil moisture and brightness temperatures as measured by the EMIRAD nadir antenna (0° incidence angle), c_{40} the same for the EMIRAD aft antenna (40° incidence angle).

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First Results of SMOS Soil Moisture Validation in the Upper Danube Catchment

Johanna T. dall'Amico, Florian Schlenz, *Member, IEEE*, Alexander Loew, and Wolfram Mauser, *Member, IEEE*

***Abstract*—With the Soil Moisture and Ocean Salinity (SMOS) satellite launched in 2009, global measurements of L-band microwave emissions and processed "soil moisture" products at a fine time resolution are available. They may, after validation, lead to quantitative maps of global soil moisture dynamics. This paper presents a first validation of the SMOS "soil moisture" product delivered by the European Space Agency in the upper Danube catchment (southern Germany). Processing of the SMOS "soil moisture" product and the methodology to compare it with *in situ* and model data are described. The *in situ* data were taken from May to mid-July 2010 in a small and homogeneous area within the catchment, while the modeled time series spans from April to October 2010 for the whole catchment. The comparisons exhibit a dry bias of the SMOS data of about 0.2 $m^3 \cdot m^{-3}$ with respect to *in situ* measurements. Throughout the catchment, the SMOS data product shows a dry bias between 0.11 and 0.3 $m^3 \cdot m^{-3}$ when compared to modeled soil moisture. Correlation coefficients between both data were found to be mostly below 0.3. Radio-frequency interference (RFI) over Europe appears to be the main problem in obtaining valuable information from the SMOS soil moisture product over this region. RFI is not adequately captured by current methods for filtering and flagging. Nevertheless, some improvements of these results might be achievable through refinements of the soil moisture modeling as well as through improvements to the processors used to generate the SMOS soil moisture product.**

***Index Terms*—Passive microwave remote sensing, soil moisture.**

I. Introduction

SOIL Moisture and Ocean Salinity (SMOS), the European Space Agency (ESA)'s recent satellite for the observation of soil moisture and ocean salinity, was launched on November 2, 2009. It carries an interferometric L-band radiometer (1.4 GHz) with multiangular viewing capabilities [1]. SMOS' novel technique is used to provide global near-surface soil moisture maps with a temporal resolution of about two to three days, a spatial resolution on the order of 40 km, and an accuracy target of 0.04 $m^3 \cdot m^{-3}$ [2], [3]. The soil moisture is obtained from multiangular L-band microwave brightness temperatures using an inverse modeling approach with the tau–omega radiative transfer model as forward model [4]. This involves uncertainties about the representation of several effects, e.g., surface roughness and vegetation opacity [5], [6]. As the microwave brightness temperature is largely affected by the spatial heterogeneity of the land surface at scales of tens of kilometers, an appropriate consideration of the subscale variability of land surface properties needs to be taken into account during the soil moisture retrieval. The spatial heterogeneity might introduce biases and uncertainties in the soil moisture product [7].

For the validation of the SMOS soil moisture product and for adjustments to the retrieval algorithms used in its processor, test sites in different climatic zones of the Earth were established [8]. These test sites should be large enough to contain at least several SMOS pixels, but they should also be well characterized in terms of meteorological and soil moisture conditions, as well as soil and vegetation properties.

Some examples of such calibration and validation (henceforth cal/val) sites for SMOS are in Antarctica [9], West Africa [10], and Australia [11]. In Europe, cal/val activities are being undertaken, among others, at the Valencia Anchor Station in Spain [12], the Surface Monitoring of Soil Reservoir Experiment (SMOSREX) site in France [13], the Hobe site in Denmark [14], [15], the Rur catchment in northwestern Germany [16], and the upper Danube catchment (UDC) in southern Germany [17]. The insights gained through the SMOS data validation at such sites can be useful feedback to adjust and calibrate the algorithms used in the data processors in order to produce more accurate data products. An overview of the cal/val activities is given in [18].

The aim of this paper is to present the validation of SMOS soil moisture data during the first Northern Hemisphere growing season after launch (April to October 2010) in the UDC by making use of *in situ* data as well as model simulations. In Section II, the test site, all data sets used, and the methodology are described. Section III contains the comparison of the SMOS soil moisture product with *in situ* and model data. In Section IV, the results are discussed, and conclusions are drawn.

II. Data and Methodology

The cal/val activities for SMOS in the UDC use a multiscale framework of *in situ* data and soil moisture maps produced by the hydrological land surface model called the Process Oriented

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J. T. dall'Amico, F. Schlenz, and W. Mauser are with the Department of Geography, University of Munich, 80333 Munich, Germany (e-mail: j.dallamico@iggf.geo.uni-muenchen.de; f.schlenz@iggf.geo.uni-muenchen.de; w.mauser@lmu.de).

A. Loew is with the Max Planck Institute for Meteorology, 20146 Hamburg, Germany (e-mail: alexander.loew@zmaw.de).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

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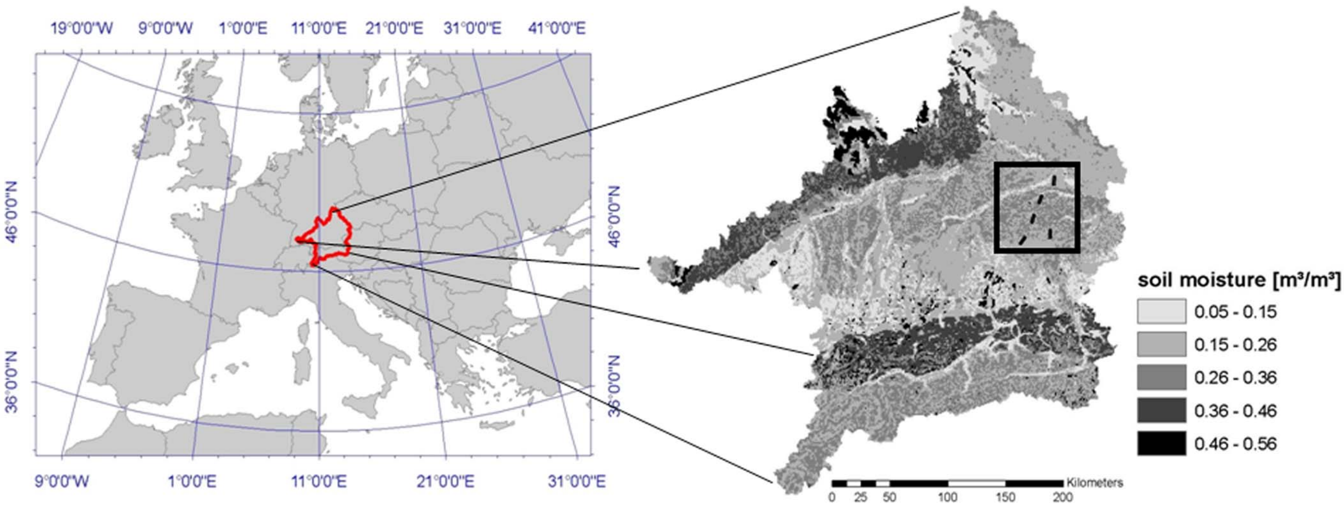

Fig. 1. (Left panel) Location of the UDC in Europe. (Right panel) Example of a soil moisture map of the UDC as modeled by PROMET. The black box shows the Vils area containing (black patches) the five focus areas where distributed soil moisture measurements were taken during the SMOS Validation Campaign 2010.

Multiscale EvapoTranspiration (PROMET) model [19], [20]. Soil moisture data are recorded continuously at several ground stations and used to validate PROMET on the point scale [21]. In addition to these ground stations, distributed soil moisture measurements were taken during the SMOS Validation Campaign 2010 during the growing season between May and July [22]. These distributed *in situ* data can be used to validate the 2-D model output as done in [21] and also for a direct comparison with SMOS soil moisture data on selected dates in a limited area. In order to perform an area-wide comparison over a longer period of time, the time series of soil moisture maps produced by PROMET are compared to the SMOS soil moisture data product in the parts of the catchment where both data sets are available, containing about 230 grid points with SMOS soil moisture data.

A. Test Site

The UDC covers an area of about 77 000 km^2 and is located mostly in southern Germany. It is characterized by a temperate humid climate and, in the north and center, mostly agricultural land use. In the south of the catchment, arable crops give way to grasslands and eventually the Alps. Other features include the cities of Munich and Ingolstadt and a few lakes just North of the Alps.

The UDC has been the focus of many remote sensing and global change studies, e.g., [19], [20], and [23]–[26]. In 2007, an area of about the size of a SMOS footprint (with a diameter of roughly 50 km) was equipped with soil moisture stations. This so-called Vils area is located in the Northeast of Munich and is used for intensive agriculture on undulating terrain. In this area, SMOS retrieval errors are expected to be small due to the absence of large urban areas and water bodies [7]. The Vils area was also the focus of field campaigns in spring 2008, summer 2009, and late spring/early summer 2010. The campaigns in 2008 and 2010 were connected to airborne campaigns organized and funded by ESA. A subset of the *in situ* data collected during the campaign in 2010, which is called SMOS Validation Campaign 2010, is used in this study. Both the UDC and the Vils area are shown in Fig. 1.

B. Ground Data

During the SMOS Validation Campaign 2010 in the UDC, ground teams recorded, among other parameters, the soil moisture of the upper 6 cm in the five focus areas spread throughout the Vils area using Delta-T's Theta frequency-domain probes. In each of the focus areas, there was also a ground station where soil moisture was recorded continuously at depths ranging from 5 to 40 cm using IMKO time-domain reflectometer probes.

Each focus area was about 7 km long and 3 km wide, containing about 60 measurement points on fields with a variety of land uses, predominantly wheat, maize, and grass. The spatial distribution of the focus areas can be seen in Fig. 1. At each measurement point, five soil moisture measurements were taken. The ground teams took measurements on May 17, May 22, May 25, May 28, June 12, June 17, and July 8, 2010, aligned with SMOS morning overpasses. The decision to use only the days with morning overpasses for ground measurements was taken due to ESA's decision to perform airborne L-band measurements only on those days. Some ground measurements were also taken on June 14 but had to be aborted due to rain before full coverage of the focus areas was achieved. They are not used in this study.

Throughout the campaign period, a detailed land cover map was prepared by ground teams not only for the focus areas but also for large parts of the flight track. A total of more than 192 km^2, corresponding to roughly 10% of an SMOS footprint, is covered by this land cover map, which is henceforth called land cover map 2010. More details on the campaign data sets are given in [22].

C. Hydrological Model: PROMET

The PROMET model is a spatially distributed physically based hydrologic land surface model. Meteorological data from

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about 130 stations run by the Bavarian State Research Center for Agriculture are available in near-real time. They are interpolated to the model grid by combining information on altitudinal gradients with various corrections, including information on monthly mean precipitation [20]. The interpolated precipitation fields are used to force the model. The stations are spread over the German federal state of Bavaria to which the main part of UDC belongs. No other measurements are used to force or calibrate the model, but of course, other spatially distributed input is needed. This includes a high-resolution land cover map which was composed from satellite imagery and statistical information on community level. The calculations and the model output (e.g., soil moisture and temperature, runoff, and evaporation) use a regular 1 km × 1 km grid. Fig. 1 (right panel) shows an example of a modeled soil moisture map of the entire UDC. The wetter band in the south of the catchment corresponds to the Alpine foreland with its typical orographically enhanced precipitation. The wetter band in the north of the catchment is associated with the Swabian mountains.

For the comparison with SMOS data, the southern part of the catchment and the most western corner are excluded. In the south, no SMOS soil moisture data are available due to the strong topography of the Alps, and for the most western corner, there are no meteorological data available in near-real time to force the model, as this part of the catchment lies outside of the German federal state of Bavaria.

The PROMET output has been validated on different spatial scales in different test sites with good results [19], [20], [26], [27]. The soil water model, in particular, has been validated in different test sites using *in situ* soil moisture measurements of soil moisture profiles and remote sensing observations with good results [23], [28]. For the Vils area, [21] studied the uncertainties of the soil water model on the point scale, an intermediate scale, and the scale of the grid used for SMOS data. On the point scale, modeled soil moisture was compared to the measurements of the same soil moisture stations described in the previous section for the period of 2008–2010. Reference [21] found the root-mean-square error [(rmse); including bias and random error] to vary between 0.041 and 0.153 $m^3 \cdot m^{-3}$, the rmse of the bias-corrected model output to vary between 0.033 and 0.067 $m^3 \cdot m^{-3}$, and correlation coefficients (R^2) to vary between 0.45 and 0.79. The analysis on the point scale was also conducted for two soil moisture stations outside the Vils area with slightly better results. The performance improved on the intermediate scale, for which the distributed *in situ* measurements acquired on eight days during the SMOS Validation Campaign 2010 were used. This comparison showed an rmse of 0.045 $m^3 \cdot m^{-3}$ (0.040 $m^3 \cdot m^{-3}$ for the bias-corrected data) and an R^2 of 0.75. Large-scale uncertainties are of particular importance for using PROMET simulations for a comparison with SMOS data. At the large scale, [21] averaged all modeled soil moisture values within an SMOS grid cell (195 km^2) and compared those to the mean value of all distributed *in situ* measurements per campaign day. This resulted in an rmse of 0.040 $m^3 \cdot m^{-3}$, corresponding to 13.7% of the modeled mean value of 0.2917 $m^3 \cdot m^{-3}$. The modeled soil moisture range in the considered time period was 0.22–0.32 $m^3 \cdot m^{-3}$. The rmse of the bias-corrected model output was 0.023 $m^3 \cdot m^{-3}$. This is in line with the findings in [29], which used the triple collocation method on a similar data set of the years 2008 and 2009 and showed that the large-scale random error of the PROMET simulations is better than 0.025 $m^3 \cdot m^{-3}$ at the SMOS grid scale in the Vils test site. This corresponds to 8.5% of the modeled mean value in the considered time period (May to October of the years 2008 and 2009). The modeled soil moisture range in that period was 0.25–0.39 $m^3 \cdot m^{-3}$.

D. SMOS L2 Data

For this study, SMOS data from the period April to October 2010 were used. During this period, which includes also the last part of the commissioning phase, the algorithms used in the Level 1 (L1) and Level 2 (L2) processors have been improved, so that the originally delivered time series of SMOS L2 data was not consistently processed. In early 2011, the whole data of 2010 were reprocessed using a consistent combination of L1 and L2 processors. In this study, this reprocessed data set is used. The processing of SMOS brightness temperature data and the retrieval of soil moisture from these brightness temperatures are described in [30]. Only a few features of the used SMOS L2 data product are described here, because they are considered necessary to understand the rationale of the methodology adopted for this study.

SMOS soil moisture data are delivered on the icosahedron Snyder equal area (ISEA) grid [31], [32] with a spacing of about 12.5 km between two nodes. However, the SMOS soil moisture product is derived from multiangular brightness temperature measurements which cover an area on the order of tens of kilometers. The SMOS L2 product has a nominal spatial resolution of 43 km on average. This oversampling should be taken into account when working with SMOS data. Also, the soil moisture given in the L2 data product for a nominal retrieval configuration is only valid for the nominal land use classes, which are the classes with low vegetation (grass and crops). Hence, in the retrieval configuration of the data product used in this study, no information is given on soil moisture of other land use classes. The contributions of the fractions of nonnominal land use classes (e.g., forests and lakes) to the overall brightness temperature of the footprint are estimated and subtracted from the measured brightness temperature. Only the remaining part of the measured brightness temperature is used for the retrieval of soil moisture (and vegetation optical thickness) of the nominal land use classes. Hence, the retrieved values are only valid for the part of the footprint with nominal land use classes.

Data degradation due to radio-frequency interference (RFI) has been shown to be a major issue in the UDC cal/val site. Sources of RFI can include various emitters as radars from airports and military bases, telecommunication facilities, etc. Due to these signals traveling long distances and SMOS' large field of view and interferometric technique, RFI can be expected to be a problem not only in the UDC but also on larger scales. Some of the corrupted data are identified and eliminated in the data processing before the L2 product is delivered, but the detection and elimination of the different types of RFI are still a major research task [33]. Thus, an appropriate prefiltering of the data is crucial before analyzing the L2 data products. The applied preprocessing steps are discussed in the following.

The SMOS User Data Product used in this study contains a number of variables. In addition to soil moisture, important information is given in the soil moisture Data Quality indeX (DQX) and in both the confidence flags and the science flags. The soil moisture DQX is the "theoretical retrieval *a posteriori* standard deviation" (see [34, p. 77] and [30, p. 92] for details) obtained during the soil moisture retrieval in unit $m^3 \cdot m^{-3}$. In this study, all data with a DQX of −999 are discarded as this means that the given soil moisture did not result from a successful retrieval. In addition to that, excluding data with a DQX value above a threshold of 0.06 $m^3 \cdot m^{-3}$ led to the filtering of obvious outliers while still roughly 80% of the data were kept. Some of the flags have been found to be useful for filtering the data while others did not seem to be associated with poor data quality. The usefulness of the flags may depend on the study area. The confidence flag FL_NO_PROD is set whenever no product is provided for many possible reasons (e.g., retrieval failed or results out of range) and should therefore be used for filtering. Although rarely set, the confidence flags FL_RFI_Prone_H and FL_RFI_Prone_V (set when the probability of RFI is high for H and V polarizations, respectively) and the science flag FL_RAIN (set when heavy rain is expected according to auxiliary data) were also used for filtering. For more information on flags, please refer to [30] and [34]. No clear difference between morning and evening overpasses could be detected in the data over the UDC, so both of them are included in the analysis.

E. Methodology of Comparisons

The distributed *in situ* soil moisture measurements are mainly used for the validation of the PROMET model as in [21]. However, a direct comparison of *in situ* and SMOS soil moisture data has also been attempted. For each of the seven campaign days, all soil moisture measurements taken on grass or crops in all five focus areas in the Vils area were averaged. This gives one soil moisture value for each of the seven days. These mean values stem from about 1500 single soil moisture measurements for each campaign day. Thus, a comparison is made between the averaged measured distributed soil moisture and the SMOS soil moisture for seven campaign days. In order to check the soil moisture evolution with time, SMOS soil moisture data have also been compared with the soil moisture continuously measured at the five ground stations. For this comparison, the measurements at 5- and 10-cm depths of all stations were averaged to give one time series.

To compare the time series of model simulations with SMOS data throughout the catchment, each PROMET grid cell (grid size of 1 km) is assigned to the closest ISEA grid node (approximately, a spacing of 12.5 km). For each ISEA grid node, all PROMET soil moisture values assigned to it are averaged if they belong to one of the nominal land use classes for which the SMOS soil moisture is valid (see Section II-D). The PROMET soil moisture simulations used are sampled twice daily (at 5 A.M. and 5 P.M. UTC, roughly corresponding to SMOS overpass times) in the period from April 1 to October 31, 2010.

F. Representativeness of Measurements and Model Output

In the Vils area, there are three ISEA grid points on which SMOS data are delivered: ID 2027099, ID 2026586, and ID 2026587. Grid point ID 2027099 is in the center of the area, so the area contributing to most of the SMOS signal measured at this grid point lies almost entirely within the Vils area. This footprint has a diameter on the order of 50 km, so the question arises whether the *in situ* soil moisture measurements taken in that footprint are representative of the soil moisture in the whole footprint. The same needs to be considered for the modeled soil moisture. Although the model output is area wide, i.e., it does not have missing locations, the model consequently relies on area-wide input. The input data used in the model stem from a variety of sources and do not necessarily match exactly the reality as seen by SMOS at the time of the overpass. These uncertainties might degrade the model output. As for the factors influencing the modeled soil moisture distribution, in the UDC area, the main factors have been found to be precipitation and land cover (i.e., vegetation). Therefore, in the following is discussed how realistically these two factors are represented in the measurements and in the model output on the scale of the ISEA grid cells.

The five focus areas with the distributed *in situ* measurements are spread over the Vils area with a spacing of about 20 km as shown in Fig. 1. They also contain one meteorological station each, the data from which are interpolated and used to force the model PROMET. It can therefore be expected that variability due to precipitation is represented well in both *in situ* measurements and model output. Only some very local thunderstorms could lead to increased precipitation between the focus areas without affecting the focus areas themselves and, with them, the meteorological stations. However, if there were such very small thunderstorms, they would probably not lead to a significant increase of soil moisture of the whole SMOS footprint. This hypothesis is difficult to verify without area-wide precipitation measurements. Precipitation fields derived from rain radar and calibrated with gauging stations could lead to new insights on these uncertainties. Currently, such fields are being fed to PROMET, and the resulting soil moisture output will be compared to the standard case when PROMET interpolates the precipitation given by the gauging stations. However, as the spacing between the gauging stations used in this study is on the order of 20 km, i.e., well below the resolution of SMOS, the interpolation of their measurements is expected to give realistic results within Bavaria on the SMOS scale.

Similarly, the true land cover distribution of the year 2010 in the whole Vils area should be known in order to check how well it is represented in the *in situ* measurements and in the modeled soil moisture. The best available ground truth data for this are the land cover map 2010 produced during the SMOS Validation Campaign 2010 by ground teams, covering roughly 10% of the whole Vils area. Table I shows the distribution of the main land cover types for the focus areas ($\sim$105 km^2), for

TABLE I
PERCENTAGE OF LAND COVER CLASSES OF THE FOCUS AREAS, OF THE WHOLE LAND COVER MAP AS MAPPED DURING THE SMOS VALIDATION CAMPAIGN 2010, AND OF THE LAND COVER MAP USED IN THE PROMET MODEL FOR ALL 1-km PIXELS MAPPED TO THE CENTRAL ISEA GRID POINT IN THE VILS AREA (ID 2027099)

land cover	% of all focus areas	% of land cover map 2010	% of land cover map used in PROMET
grass	13.6	22.9	15.4
maize	26.5	28.1	39.5
other crops	30.6	24.5	22.6
forest	16.9	21.9	19.5
water	0.5	0.5	0.0
other	11.9	2.6	3.1

the whole land cover map 2010 (192 km^2), and for the land cover map used as input for the PROMET model for the central ISEA ID 2027099 (195 km^2). The nominal land use classes, i.e., grass and all crops, occupy roughly 75% of the area in all three cases (focus areas: 70.7%; land cover map 2010: 75.5%; PROMET land cover map: 77.5%). However, the class grass is underrepresented in the focus areas and the PROMET land cover map when compared to the land cover map 2010. As in this area, soil moisture under grass has been usually found to be at least 0.06 $m^3 \cdot m^{-3}$ higher on average than that under the class "other crops"; the true mean soil moisture of the nominal land use classes within the central ISEA grid point might be slightly underestimated by the *in situ* measurements and the modeled soil moisture.

It should be noted that the comparison between PROMET and SMOS on the basis of the ISEA grid is straightforward but neglects the fact that the SMOS footprint is indeed much larger than an ISEA grid cell. As land cover fractions are not expected to change abruptly from one grid cell to the next in the UDC area, this will, in most cases, not affect the comparison. In the Vils area, the differences between PROMET simulations on the three ISEA grid points are less than 0.001 $m^3 \cdot m^{-3}$ on average, with a maximal difference on a few dates of 0.05 $m^3 \cdot m^{-3}$. However, in regions with large water bodies (e.g., some lakes in the south of Munich) or strong topography, a disturbance of the signal in neighboring ISEA grid cells can be expected.

III. DATA ANALYSIS/SMOS VALIDATION

A. Comparison of SMOS L2 Data With In Situ Measurements

For the period of the SMOS Validation Campaign 2010, SMOS L2 data on the ISEA grid points in the Vils area (ID 2027099, ID 2026586, and ID 2026587) were compared to the mean soil moisture as measured continuously by the five ground stations and to the mean soil moisture as measured throughout the focus areas on the seven campaign days by the ground teams (Fig. 2, upper panel). It is clear that the level of soil moisture is too low in the SMOS data. Over this campaign period (May until mid-July 2010), the mean soil moisture values are 0.35 $m^3 \cdot m^{-3}$ for the automated ground stations, 0.31 $m^3 \cdot m^{-3}$ for the distributed manual measurements during the campaign, and 0.12 $m^3 \cdot m^{-3}$ for SMOS. An SMOS "soil moisture" value of around and below 0.1 $m^3 \cdot m^{-3}$ can be considered to be unrealistic for the temperate humid climate of the UDC with a rainfall event every 2.4 days, an average rainfall of 900 mm/a, and an average evapotranspiration of 500 mm/a. The Global Soil Moisture Data Bank [35] for similar conditions in Russia gives average soil water contents in the top 1 m of approximately 0.25–0.35 $m^3 \cdot m^{-3}$. Since there is no dry season in the UDC and rainfall peaks during summer, the top soil is not drying significantly, and thereby, top soil moisture is similar to root zone soil moisture in the UDC. Although the soil moisture stations overestimate soil moisture as measured by the ground teams on the campaign days, this seems to be a bias which is the same under various soil moisture conditions. This bias is due to the fact that the stations are located on grassland which is typically wetter than the surrounding cropland areas. Once the mean values are subtracted from their respective time series to obtain anomalies (Fig. 2, lower panel), the soil moisture stations agree very well with the distributed measurements. SMOS data, however, in their current state do not seem to be able to capture the soil moisture evolution over time as measured by the ground stations. The variability of the SMOS data is similar to that of the *in situ* measurements with standard deviations of 0.05 (SMOS) and 0.06 $m^3 \cdot m^{-3}$ (stations, distributed measurements).

B. Comparison of SMOS L2 Data With Model Simulations

Time Series in the Vils Area: The Vils area is a part of the UDC where soil moisture retrieval is expected to work well and is well known through ground measurements. Thus, the first step in comparing modeled soil moisture to SMOS L2 data is to consider ISEA grid point 2027099 (located in the center of the Vils area; latitude/longitude: 48.425°/12.748°). Both PROMET and SMOS time series are shown in the upper panel of Fig. 3. Again, the overall soil moisture level of the SMOS data is too low. The mean values over the shown time period are 0.29 $m^3 \cdot m^{-3}$ for PROMET and 0.13 $m^3 \cdot m^{-3}$ for SMOS. The anomalies obtained by subtracting these mean values from their respective time series are shown in the lower panel of Fig. 3. It is difficult to see a common soil moisture evolution in the two data sets, although some precipitation events and drying phases between these events as modeled by PROMET seem to be captured by SMOS as well (e.g., in August). There is also a noticeable difference in the variability of the two data sets, with the standard deviations being 0.03 $m^3 \cdot m^{-3}$ for PROMET and 0.06 $m^3 \cdot m^{-3}$ for SMOS.

Area-Wide Comparison in the UDC: For an area-wide comparison, the same comparison between SMOS and PROMET as shown in the previous section has been conducted for a total of 232 suitable ISEA grid points in the UDC. Excluded were the region of the Alps, where no SMOS L2 data are available due to strong topography, and the most western corner of the catchment, where no meteorological data are available in near-real time in order to force the model. The correlation coefficient and the rmse of the anomalies (i.e., deviations from the mean value of the time series) have been computed for each grid

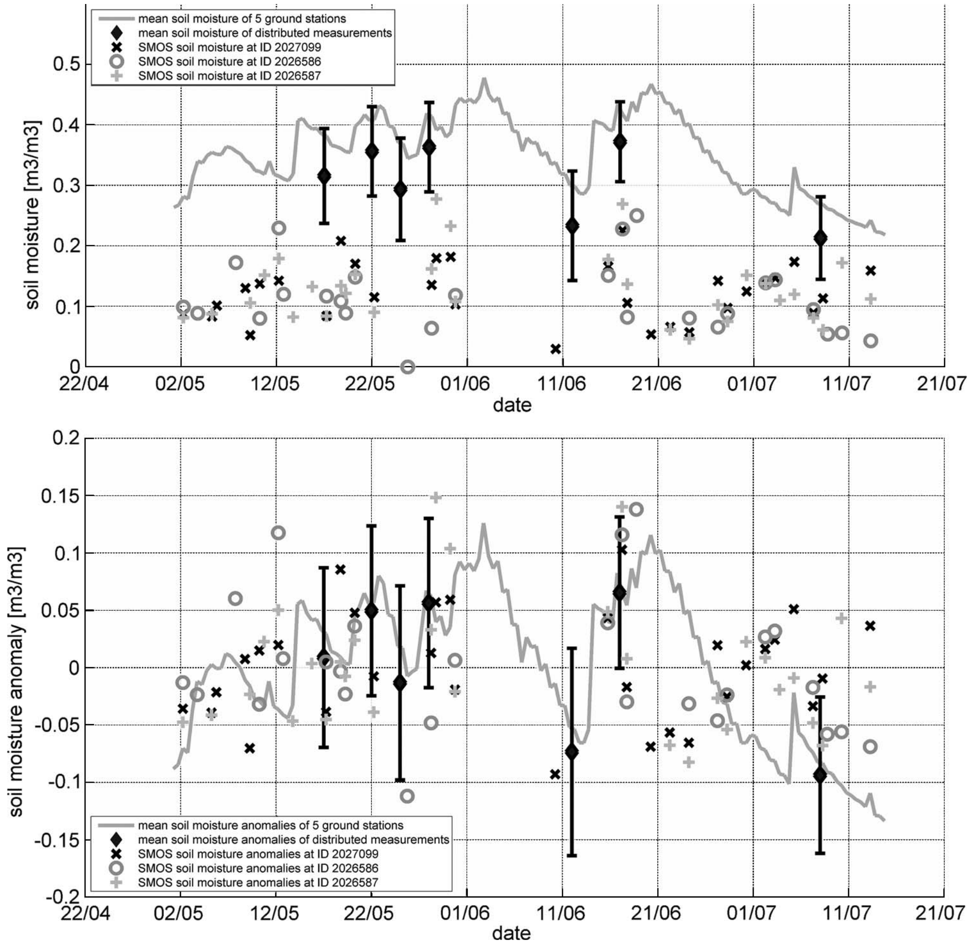

Fig. 2. (Gray line) Mean value of the soil moisture measurements taken at the five ground stations in the Vils area, (black diamonds) mean value of the distributed *in situ* soil moisture measurements taken during the SMOS Validation Campaign 2010 (with bars indicating standard deviations), and SMOS soil moisture data on ISEA grid points ID 2027099, ID 2026586, and ID 2026587. (Upper panel) Absolute values. (Lower panel) Anomalies, i.e., deviations from the mean value of each data set for the period May to mid-July 2010.

point separately using the whole time series from April 1 to October 31, 2010.

The correlation coefficients are shown in Fig. 4. They have been found to be fairly low (between 0 and 0.5 and even negative at some points) with better correlations in the center of the catchment and worse correlations toward the east and the west. The rmse of the anomalies, shown in Fig. 5, varies between 0.05 and 0.08 $m^3 \cdot m^{-3}$. The largest rmse values are found in the southwest of the catchment, while some of the lowest values are found between the two cities of Munich and Ingolstadt.

In order to see whether spatial patterns of soil moisture and its variability are similar, maps of mean soil moisture and standard deviation (both for the whole time series) have been produced for both data sets, shown in Fig. 6 for SMOS and Fig. 7 for PROMET. While the mean soil moisture field simulated by PROMET exhibits an almost zonal pattern, this is not the case for SMOS. Consequently, differences can be very large. The dry bias in the SMOS data with respect to the PROMET data varies from about 0.11 to as much as 0.3 $m^3 \cdot m^{-3}$. The most striking feature in the mean soil moisture field as produced by SMOS is the very dry stripe reaching from the Alps to the north of the city of Munich. Also, standard deviations are much higher in the SMOS data than in the model simulations [note the different color scales in Figs. 6(b) and 7(b)].

IV. Discussion and Conclusion

In this paper, the approach and framework used to validate SMOS soil moisture data in the UDC have been presented. Modeled soil moisture is available as time series on a 1-km grid throughout the catchment. Detailed ground data on soil moisture (time series of five ground stations and distributed *in situ* data on seven days) and land cover have been collected in a smaller area (called the Vils area) of about the size of an SMOS footprint. SMOS data of the first Northern Hemisphere vegetation growth period after launch have been compared with ground stations and distributed *in situ* data on three grid points in the Vils area (between May and mid-July 2010) and with model simulations for almost the whole UDC (April 1 to October 31, 2010).

The comparison with ground data shows a dry bias in the SMOS data of 0.18 $m^3 \cdot m^{-3}$ with respect to the distributed measurements (on grass and all types of crops) and of 0.23 $m^3 \cdot m^{-3}$ with respect to the mean measurements of the ground stations (on grass only). No clear agreement in the

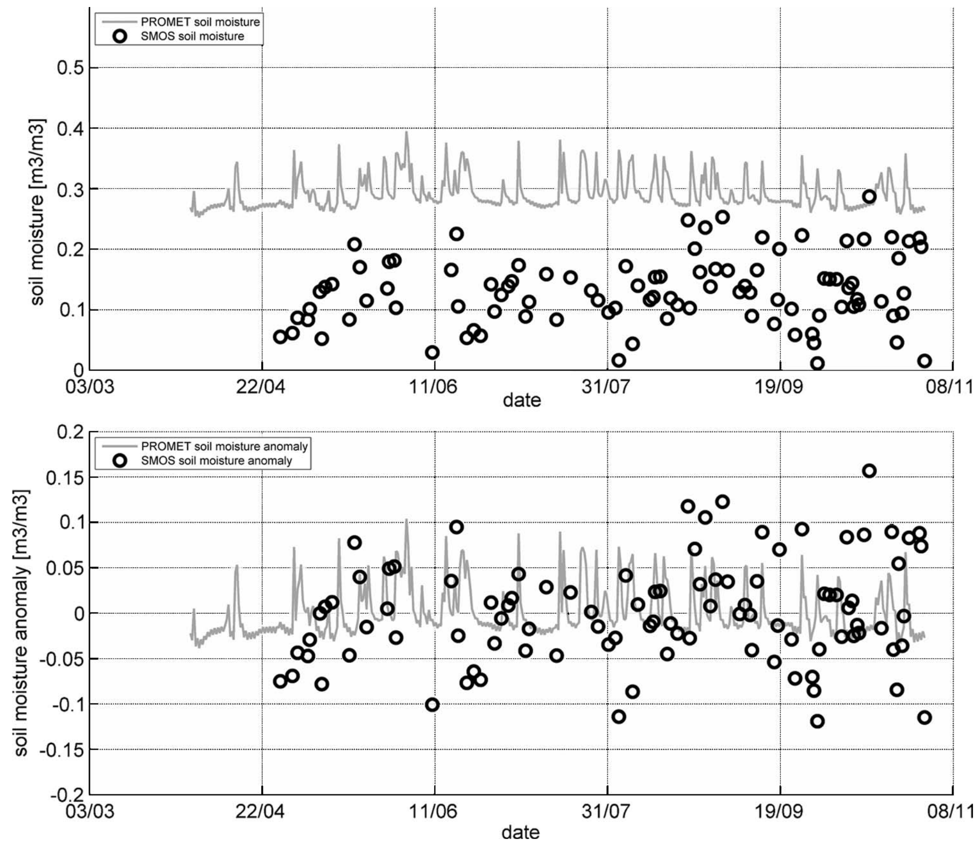

Fig. 3. Time series of modeled soil moisture (PROMET) and SMOS soil moisture data at the central ISEA grid point in the Vils area (ID 2027099). (Upper panel) Absolute values. (Lower panel) Anomalies, i.e., deviations from the mean value of each data set for the period April to October 2010.

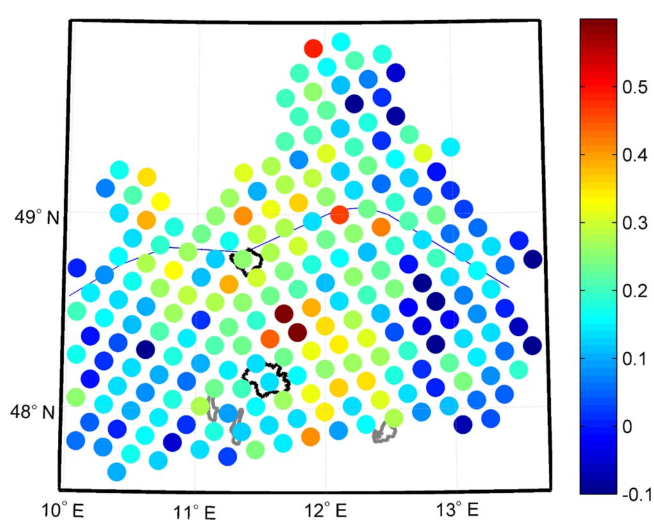

Fig. 4. Map of the correlation coefficients between modeled soil moisture (PROMET) and SMOS L2 soil moisture for the time period of April 1 to October 31, 2010 [(blue) low correlation; (red) high correlation]. The cities of Munich (south) and Ingolstadt (north) are shown as black polygons while the three gray polygons show some lakes in the Alpine foreland. The blue line shows the river Danube.

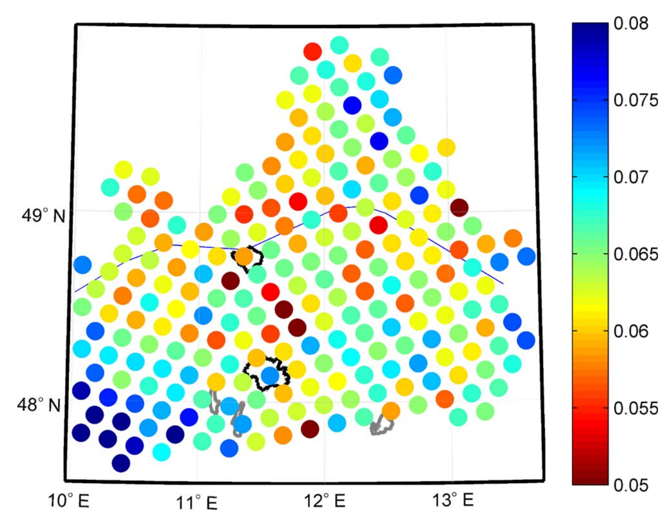

Fig. 5. Map of rmses between modeled (PROMET) and SMOS L2 soil moisture anomalies (in $m^3 \cdot m^{-3}$) for the time period of April 1 to October 31, 2010 [(red) low rmse; (blue) high rmse]. The polygons and lines are as in Fig. 4.

soil moisture evolution has been found between the time series of SMOS data and station measurements in the time period considered.

Despite the mismatch of resolution, the variability of the SMOS data at one grid point with time (standard deviations on the order of 0.06 $m^3 \cdot m^{-3}$) seems to be more similar to the temporal variability of the ground measurements (standard deviations of 0.06 $m^3 \cdot m^{-3}$) than to the temporal variability produced by the model simulations (standard deviations on the order of 0.04 $m^3 \cdot m^{-3}$). The high variability of SMOS data despite its coarse resolution could indicate that the data are affected by the interference of man-made signals (e.g., radars)

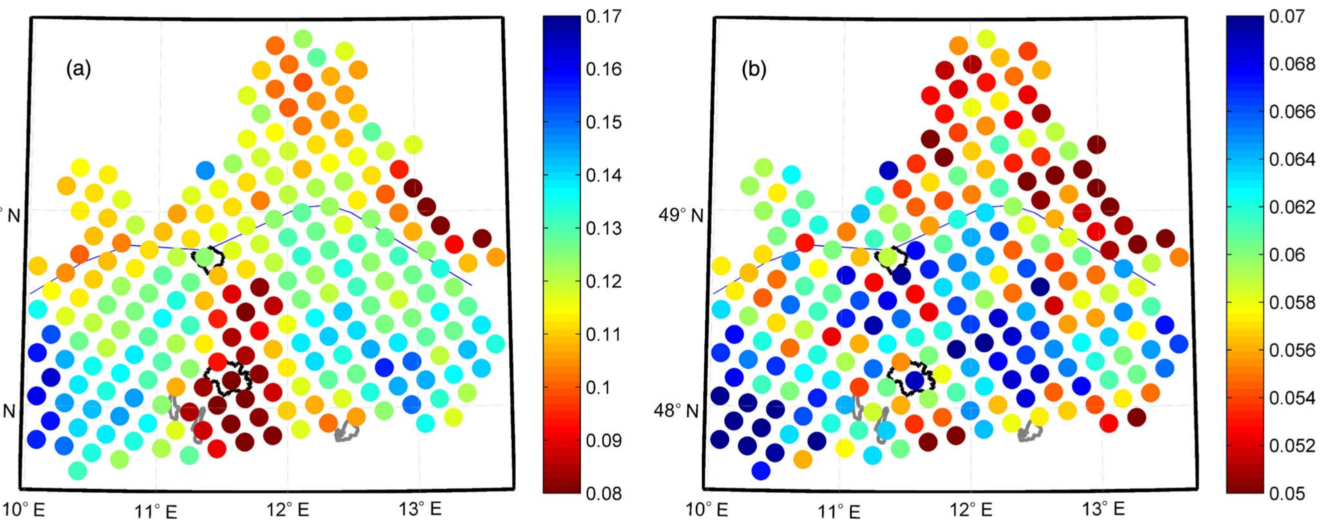

Fig. 6. (a) Mean value of SMOS L2 data (in $m^3 \cdot m^{-3}$) for the time period of April 1 to October 31, 2010 [(red) low mean value; (blue) high mean value]. (b) Standard deviation with respect to this mean value [(red) low standard deviation; (blue) high standard deviation]. The polygons and lines are as in Fig. 4.

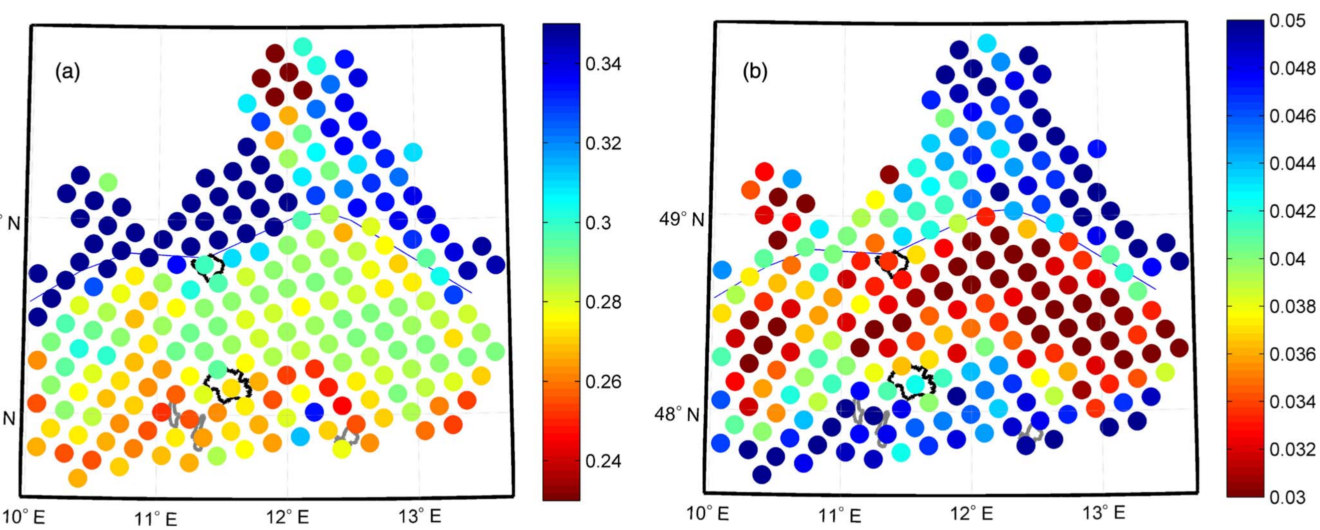

Fig. 7. (a) Mean value of modeled (PROMET) soil moisture (in $m^3 \cdot m^{-3}$) for the time period of April 1 to October 31, 2010 [(red) low mean value; (blue) high mean value]. (b) Standard deviation with respect to this mean value [(red) low standard deviation; (blue) high standard deviation]. The polygons and lines are as in Fig. 4.

or that some parameters in the algorithms used to retrieve soil moisture from the brightness temperatures need to be adjusted.

Similar to the results from the comparison with *in situ* data in the Vils area, a strong dry bias in the SMOS data with respect to the modeled soil moisture is observed in the whole catchment, varying from 0.11 to 0.3 $m^3 \cdot m^{-3}$. The correlation coefficients are mostly below 0.3, and neither the spatial pattern of the mean soil moisture fields nor that of the soil moisture variability matches for the two data sets. There are many possible reasons for this disagreement; some of them are associated with the PROMET simulations, and some of them are associated with the SMOS data.

The uncertainties of the soil moisture output of the model PROMET are not known everywhere in the catchment. The fact that the southwestern part of the area exhibits larger rmse values of the anomalies could be associated with uncertainties in the meteorological data used to force the model, as there are only two meteorological stations in that corner. Also, there could be unknown errors in the maps of soil texture and/or land cover which are used as input. However, in the regions where PROMET has been validated with *in situ* measurements, errors with an rmse of 0.2 $m^3 \cdot m^{-3}$ or correlation coefficients of 0.3 and below have never been found.

The uncertainties associated with SMOS L2 data are manifold [30, p. 101]. First, it is known that SMOS data in most of Europe are affected by RFI. Care has been taken to use flags and error estimates provided with the L2 data product in order to filter corrupted data, but most likely, more sophisticated methods for RFI mitigation and flagging are needed in the processing from the L1 to the L2 data product. Second, a lot still has to be learnt about soil moisture retrieval from brightness temperatures measured at L-band at such a large scale. Possible error sources in the retrieval mechanism include model parameters (such as roughness), static input (such as soil texture and land cover), and time-variant input (such as surface temperature fields). It is very likely that the overall observed dry bias in the SMOS L2 data in this area can be reduced through improvements to the retrieval algorithm. More research in this field is needed to gain experience and develop a more sophisticated data product, but in order to do this in areas like the UDC, the problems caused by RFI need to be tackled first.

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Johanna T. dall'Amico received the B.Sc. degree in mathematics from the University of Reading, Reading, U.K., in 2007 and the Diploma degree in geography with remote sensing and mathematics from the University of Munich, Munich, Germany, in 2008, where she is currently working toward the Ph.D. degree in the Department of Geography.

In 2005, she was a Visiting Student at the U.K. Natural Environment Research Council Environmental Systems Science Centre, Reading, working on remote sensing applications for fluvial flood mapping and modeling. Since 2007, she has been with the University of Munich, working on the project Integrative analysis of SMOS soil moisture data (SMOSHYD) which aims at the calibration and validation of Soil Moisture and Ocean Salinity data in the upper Danube catchment as well as at the study of related scaling issues. Her current research interests include airborne and satellite remote sensing of soil moisture and its spatial variability, including the analysis of ground data, model output, and ancillary remote sensing data.

Florian Schlenz (M'08) was born in Forchheim, Germany, in 1980. He received the Diploma degree in physical geography with remote sensing and computer science from the University of Munich, Munich, Germany, in 2007.

Since 2007, he has been with the Department of Geography, University of Munich, where he works as a Researcher on the project Integrative analysis of SMOS soil moisture data (SMOSHYD) which aims at the calibration and validation of Soil Moisture and Ocean Salinity data in the upper Danube catchment as well as at the study of scaling issues. His research interests include hydrological and radiative transfer modeling, as well as airborne and satellite-based remote sensing of soil moisture, including the analysis of field data and passive microwave radiometer data.

Mr. Schlenz is a member of the European Geosciences Union.

Alexander Loew (M'04) studied geography, computer science, remote sensing, and landscape ecology at the University of Munich (LMU), Munich, Germany. He received the M.S. degree in geography and the Ph.D. degree from LMU in 2001 and 2004, respectively.

From 2001 to 2008, he was a Postdoctoral Fellow with LMU, working on the retrieval of bio- and geophysical parameters from microwave remote sensing data. In 2007, he was a Visiting Scientist with the Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, MD. In 2009, he joined the Max Planck Institute for Meteorology, Hamburg, Germany, where he is leading a research group on terrestrial global remote sensing, focusing on global-scale remote sensing for climate studies. He is an Editor for *Hydrology and Earth System Sciences* and acts as a Reviewer for several national and international journals. His research interests include the quantitative retrieval of geophysical parameters from remote sensing data, the development of image-processing algorithms, coupling of land surface process models with microwave scattering and emission models, and the development of land surface process models and data assimilation techniques.

Wolfram Mauser (M'92) was born in Innsbruck, Austria, in 1955. He received the M.S. degrees in experimental physics and geography/hydrology and the Ph.D. degree in hydrology from the University of Freiburg, Freiburg im Breisgau, Germany, in 1979, 1981, and 1984, respectively.

In 1981, he worked with the University of Maryland, College Park, and the Goddard Space Flight Center, Greenbelt, MD, in the field of remote sensing and hydrology. From 1984 to 1991, he was an Assistant Professor with the Department of Hydrology, Institute of Physical Geography, University of Freiburg. Since 1991, he has been a Full Professor for geography and geographical remote sensing with the Department of Geography, University of Munich, Munich, Germany. From 2003 to 2009, he was the Chairman of the German National Committee on Global Change Research. He has been working in the field of remote sensing and hydrology within the major European research programs. He was appointed Principal Investigator (PI) by the European Space Agency (ESA) for its ERS-1, ERS-2, and Envisat programs and is PI for the Shuttle Radar Topography Mission and Soil Moisture and Ocean Salinity mission. He was a Member of ESA's Mission Advisory Group of the Earth Explorer Surface Processes and Ecosystem Changes Through Response Analysis mission. He took part in the Multi-Sensor Airborne Campaign (MAC Europe), the European Multisensor Airborne Campaign (EMAC) and the Digital Airborne Imaging Spectrometer Experiment (DAISEX). His special research interest is the development and validation of spatially distributed land surface process models and image processing algorithms, as well as model assimilation procedures for microwave and hyperspectral optical data.

Appendix B: Co-Authored Publication

Uncertainty Assessment of the SMOS Validation in the Upper Danube Catchment

F. Schlenz[1], J. T. dall'Amico[1], A. Loew[2], W. Mauser[1]

(1) University of Munich, Department of Geography, Munich, Germany
(2) Max-Planck-Institute for Meteorology, KlimaCampus, Hamburg, Germany

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Uncertainty Assessment of the SMOS Validation in the Upper Danube Catchment

Florian Schlenz, *Member, IEEE*, Johanna T. dall'Amico, Alexander Loew, *Member, IEEE*, and Wolfram Mauser, *Member, IEEE*

***Abstract*—The validation of coarse-scale remote sensing products like SMOS (ESA's Soil Moisture and Ocean Salinity mission) L2 soil moisture or L1c brightness temperature data requires the maintenance of long-term soil moisture monitoring sites like the Upper Danube Catchment SMOS validation site situated in Southern Germany. An automatic framework has been built up to compare SMOS data against *in situ* measurements, land surface model simulations, and ancillary satellite data. The uncertainties of the different data sets used for SMOS validation are being assessed in this paper by comparing different microwave radiative transfer and land surface model results to measured soil moisture and brightness temperature data from local scale to SMOS scale. The mean observed uncertainties of the modeled soil moisture decrease from 0.094 m^3 m^{-3} on the local scale to 0.040 m^3 m^{-3} root mean squared error (RMSE) on the large scale. The RMSE of anomalies is 0.023 m^3 m^{-3} on the large scale. The mean R^2 increases from 0.6 on the local scale to 0.75 on the medium scale. The land surface model tends to underestimate soil moisture under wet conditions and has a smaller dynamical range than the measurements. The brightness temperature comparison leads to a RMSE around 12–16 K between microwave radiative transfer model and airborne measurements under varying soil moisture and vegetation conditions. The assessed data sets are considered reliable and robust enough to be able to provide a valuable contribution to SMOS validation activities.**

***Index Terms*—Brightness temperature, measurement, model, passive microwave remote sensing, soil moisture.**

I. Introduction

THE WATER content of the soil layer is one of the key variables controlling the mass and energy exchanges between the Earth's surface and the atmosphere [1], [2]. It has an impact on the partitioning of rainfall into runoff and infiltration, affects the partitioning of available energy into sensible and latent heat flux by conditioning plant transpiration and soil evaporation, and can influence regional weather and vegetation development [2]. The development of extreme events like floods and droughts can be influenced considerably by soil moisture [3]–[6]. In this context, soil moisture plays an important role in numerical weather forecasting, land surface hydrology, agricultural applications, and in climate research [1], [7]. As soil moisture is very variable in time and space, it is complicated to measure over large areas and long time spans with appropriate spatial and temporal resolution. Therefore, the knowledge about soil moisture still needs considerable improvement [6]. Microwave remote sensing of soil moisture is a promising technique for that purpose as it can provide soil moisture information on large scales in a timely fashion [8]–[12]. The European Space Agency's (ESA) Soil Moisture and Ocean Salinity (SMOS) mission launched in November 2009 is designed to provide global near-surface soil moisture maps every 2–3 days with an accuracy target of 0.04 m^3 m^{-3} random error [13]–[15]. The unique SMOS 2-D interferometric L-band radiometer (1.4 GHz) allows to disentangle vegetation and soil moisture dynamics from multiangular (0° to 55°) brightness temperature measurements [13], [14]. The spatial resolution of the soil moisture data products is of the order of 40 km; they are delivered on the ISEA (icosahedral Snyder equal area projection) grid which has a spacing of 12.5 km between grid points [13], [14].

Validation of passive microwave remote sensing soil moisture products is difficult because a direct comparison with local soil moisture measurements, which serve as a reference, is hampered by the large size of the footprints [16]. Only if a large number of continuous soil moisture measurements were available, it would be possible to determine the soil moisture dynamics at the footprint scale with an accuracy better than 0.04 m^3 m^{-3} [17], which is the accuracy requirement for SMOS and other satellite soil moisture missions [14]. As dense sampling is very costly and labor intensive and therefore only possible during short-term field campaigns, often in conjunction with airborne measurements (e.g., SMEX02, SMEX03 [17], the SMOS validation campaigns in Europe [18]–[21] and Australia [22]), a lot of long-term satellite soil moisture validation activities rely on data of few point measurements or sparse networks scattered around the globe [9], [11], [23].

To avoid this problem, different approaches are proposed for validating satellite soil moisture products.

The analysis of temporally stable soil moisture patterns has been used to develop concepts for the upscaling of local soil moisture measurements to larger scales to be used for satellite soil moisture product validation [24]–[26].

The potential synergies of combining *in situ* soil moisture information with distributed land surface modeling for the

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F. Schlenz, J. T. dall'Amico, and W. Mauser are with the University of Munich, Department of Geography, 80333 Munich, Germany (e-mail: f.schlenz@iggf.geo.uni-muenchen.de; j.dallamico@iggf.geo.uni-muenchen.de; w.mauser@lmu.de).

A. Loew is with the Max-Planck-Institute for Meteorology, KlimaCampus, 20146 Hamburg, Germany (e-mail: alexander.loew@zmaw.de).

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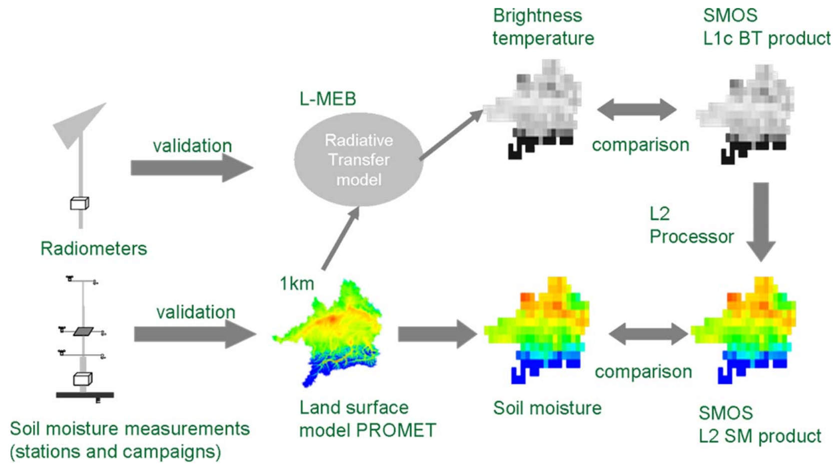

Fig. 1. SMOS cal/val approach in the UDC.

validation of satellite products is a promising technique. It is being evaluated by [27]–[29] and is used for SMOS validation in the Valencia SMOS validation site [30] and in the Upper Danube Catchment (UDC), which is described in the present paper.

A new approach for the error estimation of satellite soil moisture products was investigated by [31]. They used the so-called triple collocation analysis, to quantify the uncertainty of three independent soil moisture data sets, namely a passive microwave soil moisture product, and data from a land surface model and sparse ground-based observations. Loew and Schlenz 2011 [32] adopted the triple collocation approach to compare coarse-scale satellite soil moisture products with modeled soil moisture fields and soil moisture measurements in a temporally dynamic way that applies the triple collocation method to monthly temporal slices. They used a similar data set in the same area as the present study to quantify the soil moisture anomalies related to the three different data sets. The soil moisture anomalies are computed by subtracting the mean value of each data set and calculating the root mean squared deviation of those two unbiased data sets afterward.

One of the long-term soil moisture monitoring test sites that are needed for calibration and validation purposes of a satellite like SMOS is situated in the UDC in Southern Germany [18], [33]. Since 2007, based on previous studies [34], [35], an automatic framework has been built up to compare SMOS products against *in situ* measurements, land surface model simulations, and ancillary satellite data. During the SMOS validation campaign that took place in the UDC in May and June 2010, airborne measurements with two L-band radiometers (EMIRAD and HUT-2D) were performed in five days together with extensive ground measurements. This data set forms an interesting extension to the other measurements and modeled data sets that are being used for SMOS validation in the UDC. Fig. 1 gives an overview about the SMOS cal/val approach in the UDC. As measurements and model results always have specific uncertainties that are related, e.g., to their scale, measurement principle or algorithm used, it is necessary to assess the accuracy of the data used for SMOS validation, which is the scope of this paper. No SMOS data are shown in this paper as this would require a detailed discussion of the postprocessing that has been applied to the SMOS data which is beyond the scope of this paper. In addition, the SMOS L2 soil moisture products are not directly comparable to the data sets presented here as the SMOS L2 soil moisture product is valid only for low vegetation. A detailed comparison of SMOS data and the earlier mentioned validation data sets is performed in a companion paper [36] and discussed thoroughly. There, it is concluded that the SMOS soil moisture product exhibits a considerable dry bias in the order of -0.11 to $0.3\ \mathrm{m}^3/\mathrm{m}^3$ when compared to *in situ* measurements and land surface model simulations. A major issue hampering SMOS data analysis in the test site is radio-frequency interference (RFI) [36].

In Section II of this paper, the test site and the different data sets used in this study are introduced. They comprise different field measurements of soil moisture and other parameters as well as airborne data sets from the EMIRAD radiometer. The HUT-2D radiometer is not being used in this study. The following section gives an overview about the coupled land surface and radiative transfer models used. Section IV describes the model validation and uncertainty assessment. This is being done by comparing the model results on different scales to field measurements of soil moisture. Different field data sets of soil moisture are compared against each other to assess their specific uncertainties. After that, the brightness temperature simulations are being compared against airborne measurements from EMIRAD to assess the uncertainties related to the radiative transfer modeling. In Section V, the results from the previous sections are discussed considering scaling issues and the characteristics of the different measured and modeled data sets. In the following Section VI, conclusions are drawn to relate the results of this study to the SMOS validation being performed in the UDC.

II. Test Site and Data Sets

A. Cal/Val Approach

The SMOS validation in the UDC is being done by comparing the SMOS soil moisture products (Level 2 data) to land surface model simulations in the whole UDC. *In situ* measurements taken at soil moisture measuring stations and during

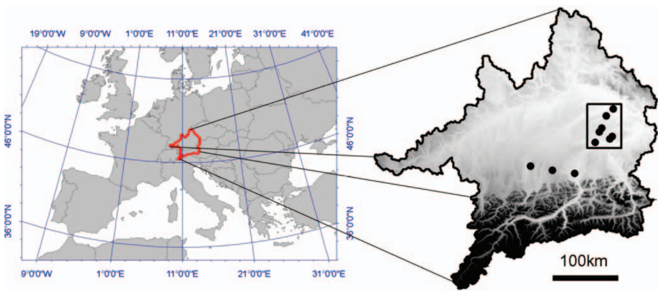

Fig. 2. Upper Danube Catchment, located in Central Europe, with an area of 77 000 km^2 The black rectangle defines the Vils test site (approximately 50 × 60 km), the black dots represent the soil moisture stations. The background of the catchment is a digital elevation model with 1-km resolution (white: 312 m. a.s.l.; black: 3630 m.a.s.l.).

ground campaigns are used for model validation. In addition to that, SMOS L1c products (brightness temperatures) are being compared to modeled brightness temperatures obtained from a radiative transfer model coupled to the PROMET land surface model. The algorithms used in the radiative transfer model for retrieving soil moisture from SMOS observations are being validated with airborne radiometers during campaigns and the ground-based ETH L-Band Radiometer (ELBARA) 2 [37].

B. Upper Danube Catchment

The UDC is located mostly in Southern Germany and the Northern Alps (Fig. 2, [33]). It has been the focus of a wide range of hydrological, remote sensing, and global change studies for many years (e.g., [38]–[44]). Being situated in Central Europe, the climate is temperate and humid which is characteristic for many subcontinental regions in the midlatitudes. The average temperatures range from about −2 °C in January to about 17 °C in July, and the mean annual precipitation sum is about 900 mm in Munich, in the center of the catchment. Snow cover typically lasts for several weeks in winter. The test site is dominated by the alpine foreland with heterogeneous land cover and soil types, while the Alps form the southern border. The annual precipitation sum decreases from the Alps northwards, while the mean temperature increases.

Best soil moisture retrieval performance is expected in the Vils test site which is located in the catchment of the river Vils, situated in the Northeast of the city of Munich [45]. It has about the size of a SMOS footprint. The reason for expected good soil moisture retrieval performance is the lack of substantial open water bodies or large urban areas which could considerably affect the passive microwave signal in that area. The terrain is undulating with elevations varying between about 320 and 470 m a.s.l. The soils are fairly homogeneous and consist mainly of loam with high percentages of silt, particularly in areas where Loess can be found. The area is being used intensively by agriculture. The three most important agricultural land cover types in the Vils test site, grass, maize, and winter wheat, cover more than 60% of the area.

Since 2007, a total of ten soil moisture stations have been built up at different locations in and around the Vils Catchment.

For validation purposes, the study of scaling issues related to SMOS and the verification of model parameters, two airborne

TABLE I
OVERVIEW ABOUT THE SOIL MOISTURE STATIONS IN THE UPPER DANUBE CATCHMENT

Station number	Name	Lat/lon [deg]	Elev. [m]	sand/clay content [%]	TDR / FD	Operation period	In Vils test site
14	Neusling	12.87/ 48.69	345	19.5/6.8	TDR	11/2007 -	X
16	Steinbeissen	12.73/ 48.60	380	30.5/5.5	TDR	3/2008 -	X
49	Frieding	12.83/ 48.33	480	36.6/5.1	TDR	3/2008 -	X
74	Lochheim	12.49/ 48.27	410	27.6/11.2	TDR	3/2008 -	X
80	Rothenfeld	11.22/ 47.97	690	67.1/3.1	FD	3/2008 – 3/2010	-
115	Wettlkam	11.64/ 47.91	675	65.4/3.5	FD	3/2008 – 10/2008	-
118	Engersdorf	12.63/ 48.45	460	40.3/6.4	TDR	11/2007 -	X
125	Karolinenfeld	12.07/ 47.86	468	41.9/3.9	FD	3/2008 – 3/2010	-
500	Erlbach	12.82/ 48.30	426	62.4/5.6	FD	5/2010 -	X
501	Harbach	12.61/ 48.42	467	32.8/9.6	FD	5/2010 -	X

campaigns have been conducted in 2008 and 2010, respectively [20], [33]. Focus of both campaigns was the Vils test site.

C. Continuous Soil Moisture Measurements

From the ten soil moisture measuring stations, an hourly data record of measured soil moisture exists starting in November 2007. Some of the stations were moved to different locations during their lifetime, some had to be removed for technical or logistical reasons. At all stations, soil moisture was measured in 5-cm depth with at least two probes installed horizontally. At most stations, additional probes are installed in different depths. Table I gives an overview of these stations including the surface sand and clay contents, the operation period and an indication whether the station is situated inside the Vils test site. The measurement devices used are IMKO Trime-ES time domain reflectometer (TDR) probes (theoretical accuracy $\pm 0.01 - \pm 0.03$ m^3 m^{-3} [46]) and Decagon ECHO-TE and EC-5 frequency domain (FD) probes (theoretical accuracy ± 0.03 m^3 m^{-3} [47], [48]). To monitor the quality of the stations, independent handheld soil moisture measurements were conducted regularly (typically every 2–4 weeks) starting in March 2008 at the stations with Delta-T Theta FD probes (theoretical accuracy ± 0.05 m^3 m^{-3} [49]) and gravimetric samples (theoretical accuracy ± 0.02 m^3 m^{-3} [50]). These handheld measurements were conducted in such a manner that 20 FD measurements were taken inside a circle with a diameter of 3 m around the station and three gravimetric samples taken within 1 m of the station. Station 125 is not used in this analysis as it is situated in a moor and not representative for a considerable area.

D. SMOS Validation Campaign Data Set

In spring and early summer 2010, the SMOS validation campaign took place in the UDC on eight days from 17 May to 8 July 2010. On five of those days two L-band radiometers, EMIRAD (owned by the Technical University of Denmark) and HUT-2-D (owned by the Aalto University, Finland) and a thermal camera (supplied by the Max-Planck Institute for Meteorology, Hamburg), were flown on the Skyvan aircraft. Soil moisture, land use, and vegetation status were recorded by several ground teams on all eight days in five focus areas spread over the Vils test site. All focus areas were located around one or two of the soil moisture stations and had a size of about 3 km by 7 km. In each of the focus areas, soil moisture was measured on two grids with different resolution using Delta-T Theta FD probes. The coarser grid covered the whole focus area with 60 sampling points along transects, while the finer grid covered an area with a size of about 1 km^2 with 60–100 sampling points. The coarse-grid data will be used in the present study. At all sampling points, multiple soil moisture measurements were taken to decrease uncertainty resulting in more than 9000 samples in the course of the campaign.

The resolution of sampling points was chosen in such a way to best represent the different land cover classes while being coarse enough to allow an efficient sampling of a large area. In preparation of the SMOS validation campaign 2010, two extensive field campaigns were used to assess the soil moisture variability across different scales and the number of samples needed to be able to calculate the soil moisture mean of the focus areas in the Vils test site with an appropriate accuracy. [17] have developed an empirical model to study the number of samples necessary to measure the area-averaged soil moisture mean of a certain area to a certain degree of accuracy during field campaigns. They state that a number of 18 point samples is sufficient to measure the area-averaged soil moisture mean of an area of 800×800 m^2 and 30 samples for an area of 50×50 km^2 with an accuracy better than 0.03 m^3 m^{-3} with 95% confidence [17]. As this model was developed with data from the Central U.S., it may only be transferable to areas with similar climatic, topographic, and land surface features to the study area. Also, the empirical model may underestimate the amount of samples needed if some assumptions made may not hold [17]. Still, these numbers provide an indication about the order of magnitude of the amount of samples needed for a representative mean value of soil moisture.

Therefore, the means of measured soil moisture in the focus areas are considered representative for the sampled area. As the location of the focus areas has been chosen carefully in such a manner to best represent the heterogeneity of the Vils test site and the Vils test site is relatively homogeneous related to land cover, topography, soils, and climate, it is assumed that the soil moisture mean of all focus areas is representative for the Vils test site. Destructive biomass sampling was performed in selected areas. Due to the long duration of the campaign and different weather conditions, vegetation and soil moisture changed significantly in the course of the campaign. A more detailed overview of the airborne campaign is given in [20]. To study the conditions during the campaign in more depth, Figs. 3 and 4 show the temperature, precipitation, and soil moisture conditions during the campaign. An area of more than 192 km^2 was land cover mapped in the course of the campaign.

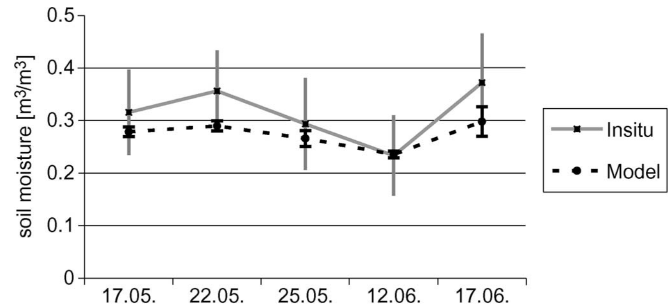

Fig. 3. Large-scale comparison of measured and modeled soil moisture means for the Vils test site for the flight days during the SMOS validation campaign 2010.

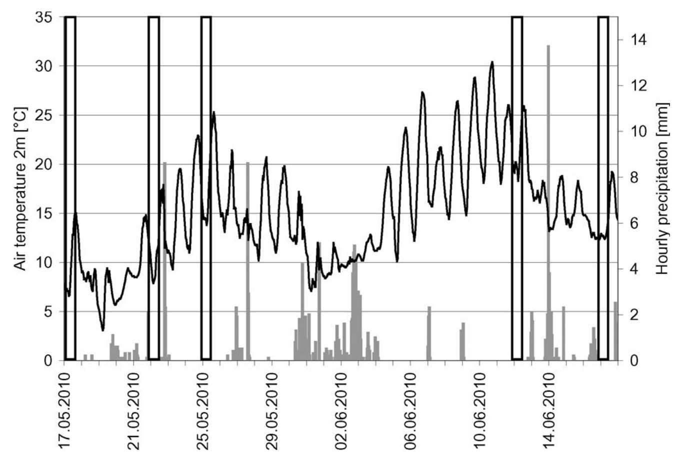

Fig. 4. Hourly temperature (black line) and precipitation (grey bars) measured at the meteorological station Engersdorf (118) during the SMOS validation campaign 2010. Black bars indicate the flight days.

E. Airborne Data

The EMIRAD data are used in this study as reference for the validation of the radiative transfer modeling. The aircraft flight track with four flight lines inside the Vils test site is shown in Fig. 5 for one campaign day. A similar pattern was flown on all campaign days. EMIRAD is a fully polarimetric radiometer operating at L-band with an antenna system consisting of two Potter horns, one pointed nadir and the other one 40° aft. A detailed technical description of the instrument's characteristics is given in [51]. The EMIRAD footprint size is of the order of 2 km for the nadir antenna and about 4 km for the 40° looking antenna for an average flight altitude of 2 km above ground. Raw data were delivered as calibrated contemporaneous measurements in antenna geometry and were postprocessed before usage. This included temporal aggregation of the data, geocoding, and the geometric rotation from X/Y plane to H/V plane around the polarization rotation angle at boresight. During the geolocation, the 3-dB EMIRAD footprints were projected on the ground using a high-resolution digital elevation model and information on aircraft speed and orientation. In addition to that, RFI filtering was performed using RFI flags provided together with the data. The RFI flagging is being done with the kurtosis method, which is a widely used approach [51], [52]. As RFI cannot be removed completely using this flag, all data above a threshold of 300 K are discarded afterward. The RFI filtering is necessary as RFI is present in the EMIRAD

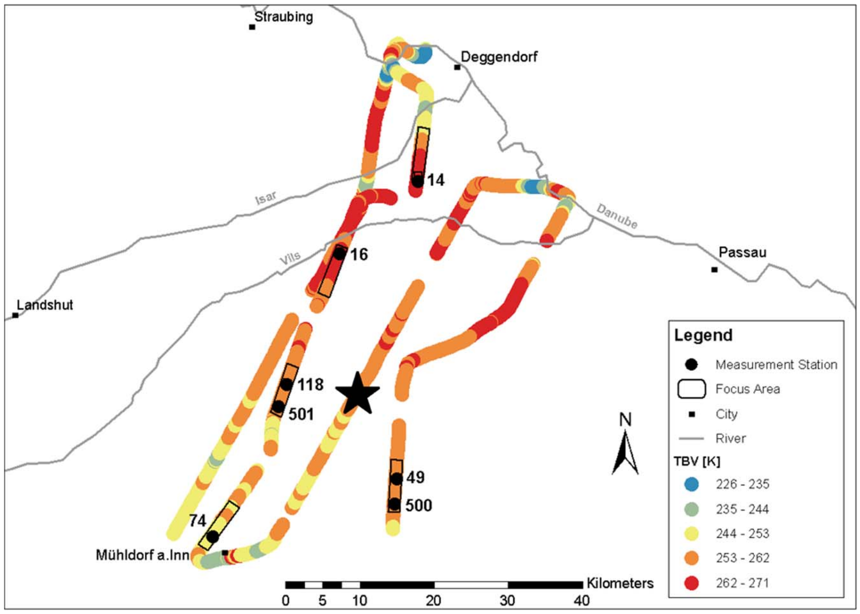

Fig. 5. Flight line with EMIRAD brightness temperature data (vertical polarization) for the SMOS validation campaign flights inside Vils test site on June 12, 2010. The Vils test site soil moisture stations are marked with black dots, the focus areas with black rectangles, the central ISEA grid point 2027099 with a star.

data measured in the UDC and makes part of the radiometer data unusable [51]. After processing, the data is available for the two incidence angles 0° and 40° for vertical and horizontal polarizations.

III. Coupled Land Surface and Radiative Transfer Model

For the present study, the land surface model PROMET (process-oriented multiscale evapotranspiration model) [44] was coupled with the microwave emission model L-MEB (L-band emission of the biosphere) [53] to be able to model the soil moisture and temperature fields as well as the resulting microwave emissions in the L-band for the entire UDC.

A. PROMET

The PROMET hydrologic land surface model is used to simulate fields of land surface states on a 1-km grid with hourly resolution in the UDC. It is spatially distributed and describes all relevant water and energy fluxes [38] related to the radiation balance, vegetation, soil, snow, and aerodynamic processes. The soil moisture dynamics are simulated with a modified version of the Richards equation for flow in unsaturated media [54]. The soil water retention model of [55] is used to relate soil suction head to soil moisture content. A detailed description of the model physics is given in [44]. The model is based on high-resolution spatial input data like soil and land cover maps and meteorological forcing data as input for the calculations. The meteorological station network providing the meteorological forcing is collocated with the *in situ* soil moisture network and consists of more than 130 stations. The land cover map has been derived from high-resolution satellite imagery and statistical information on community level.

The model has been validated in different test sites on different scales with good results [38], [39], [44], [56]. The soil water model in particular has been validated in different test sites using *in situ* soil moisture measurements of soil moisture profiles and remote sensing observations with good results [43], [57]. Very good agreements between soil moisture profile measurements and simulations were found ($\mathrm{RMSE} = 0.016\ \mathrm{m}^3\ \mathrm{m}^{-3}$) by [57]. Model simulations are available for the period from 1st November 2008 until the end of 2010. For these model runs, we renounced to specifically tune the soil information used by PROMET with soil parameterizations derived from field studies at the measurement sites and intentionally used standard soil maps, which are part of the Global Soil Data Base. This allows to generalize the results of the uncertainty analysis beyond the UDC.

B. L-MEB

The land surface microwave emission results from the continuous soil vegetation layer and is affected by soil temperature, soil moisture, and vegetation opacity.

A microwave emission model coupled to PROMET is used to simulate brightness temperatures for the whole UDC. The zero-order τ–ω radiative transfer model [58] is used for that purpose. In this paper, the model utilized is L-MEB, which is also a part of ESA's SMOS Level 2 soil moisture processor [53]. It is used to simulate high-resolution (1 km) microwave L-band brightness temperatures using, among others, the soil moisture fields, temperatures, and vegetation parameters simulated by PROMET. Wigneron *et al.* [53] give a comprehensive overview about that model; therefore, it is only introduced here briefly.

The effects of soil and vegetation on the brightness temperature with horizontal and vertical polarization $(P = h, v)$ are considered through [53], [59]

$$T_{BP} = T_a + \gamma_a \left[e_{GP} \cdot T_G \cdot \gamma_P + T_C(1-\omega_P)(1-\gamma_P) + TC(1-\omega_P)(1-\gamma_P)(1-e_{GP})\gamma_P \right] \quad (1)$$

TABLE II
THE MODEL PARAMETERS USED FOR L-MEB

	h	QR	NRh/ NRv	tth/ ttv	ωh/ωv	b'	b''
Bare soil	0.1	0	0/-1	1/1	0/0	0	0
Crops general	0.15	0	0/-1	1/1	0/0	0.05	0
Wheat	0.1	0	0/-1	1/8	0/0	0.035	0
Corn	0.6	0	0/-1	2/1	0.05/ 0.05	0.05	0
Grass	1.3-1.13*SM	0	1/0	1/1	0/0.05	0.04	0.03
Coniferous	1.2	0	1.8/2	0.9/ 0.8	0.07/ 0.07	τNAD= 0.65	0.
Deciduous	1.	0	1/2	0.6/ 0.5	0.07/ 0.07	τNAD=1.	0

where T_{BP} is the brightness temperature [K]; T_{a} is the upwelling atmospheric emission [K]; ω_{P} is the single scattering albedo of the canopy $[-]$; γ_{a} and γ_{P} are the transmissivity of the atmosphere and canopy, respectively, $[-]$ and T_{G} and T_{C} are the temperature of the ground and the canopy [K] , respectively. e_{GP} is the emissivity of the soil surface $[-]$.

The reflectivity $(1 - e_{\mathrm{GP}})$ of a rough soil is typically described as a function of the Fresnel reflectivities of a smooth surface, modified by a surface roughness component. The vegetation parameters are the vegetation single scattering albedo ω_{P} and the vegetation transmissivity γ_{P}. The latter is described as a function of the vegetation optical thickness τ at nadir and the observation angle (Beer's law). The atmospheric effects are being neglected in this study as no spaceborne brightness temperature data is being used.

The effective temperature of the ground, T_{G}, is calculated after the approach of [53] from the soil surface temperature and the temperature of a deeper soil layer, both provided by PROMET. T_{C} is approximated with the temperature of the vegetation surface as modeled by PROMET. The vegetation optical depth is calculated using modeled leaf area index values with the approach of [53]. The optical depth of forests is fixed to a defined value. The roughness parameter h over grass is soil moisture dependent [60], [61]. Table II gives an overview about the vegetation-dependant model parameters used for L-MEB. They are in line with the parameters used for [53], [62], and [63] (J.-P- Wigneron, personal communication).

IV. MODEL VALIDATION AND UNCERTAINTY ASSESSMENT

A. Soil Moisture

1) Local Scale Soil Moisture: To verify the accuracy of the continuous soil moisture measurements from the stations, the 5-cm means of the continuous surface soil moisture measurements (TDR, FD) have been compared to the means of the handheld measured FD surface soil moisture that has been measured regularly at all stations. Fig. 6 shows that comparison. The station measurements seem to slightly overestimate the handheld measurements during very dry conditions. R^2 is 0.63, and the root mean squared error (RMSE) is 0.052 m^3 m^{-3}. There is no systematic bias but as indicated by the standard

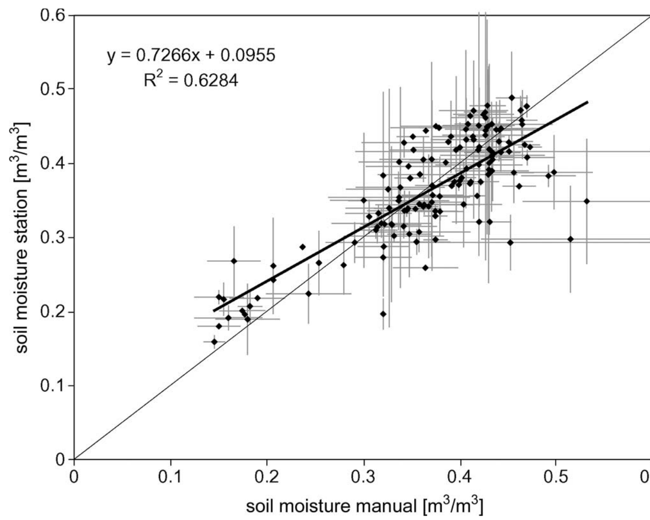

Fig. 6. Local comparison of continuously measured surface soil moisture at the stations with handheld and simultaneously measured surface soil moisture.

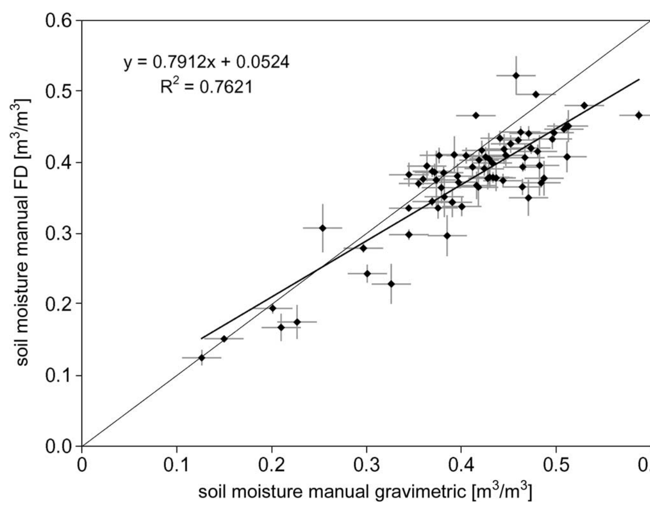

Fig. 7. Local comparison of manually measured surface soil moisture with handheld FD probes and gravimetric samples.

deviation bars and some outliers, the soil moisture variability within those measurements can be quite high even within a few meters around the station. The standard deviations of both data sets regularly exceed 0.10 m^3 m^{-3}.

To validate the handheld FD measurements, they were taken simultaneously with gravimetric samples. The comparison of the latter two data sets is shown in Fig. 7. The handheld FD measurements seem to slightly underestimate soil moisture under very wet conditions. R^2 is 0.76, and the RMSE is 0.053 m^3 m^{-3}. There does not seem to be a systematic bias.

To validate PROMET on the local scale and estimate the uncertainties related to the soil moisture modeling, PROMET has been used to model point-scale surface soil moisture at all stations which then was compared to the station measurements. The results of the comparison for the months April to October are summarized in Table III. The R^2 for five stations is above 0.6, the RMSE is below 0.05 m^3 m^{-3} for three stations and above 0.10 m^3 m^{-3} for five stations. The gains and offsets of the regression lines and the mean values of the data sets are also given in the table. It is obvious that a bias leads to

TABLE III
STATISTICS OF THE COMPARISON BETWEEN MODELED AND MEASURED SOIL MOISTURE AT THE MEASURING STATIONS

No.	Name	RMSE / RMSE of anomalies [$m^3\ m^{-3}$]	Gain / Offset	Mean PROMET [$m^3\ m^{-3}$]	Mean station [$m^3\ m^{-3}$]	R^2
14	Neusling	0.041 / 0.033	0.881 /0.011	0.284	0.307	0.64
16	Steinbeissen	0.076 / 0.036	0.626 /0.067	0.288	0.359	0.79
49	Frieding	0.111 / 0.056	0.365 /0.142	0.277	0.374	0.55
74	Lochheim	0.153 / 0.067	0.299 /0.113	0.220	0.357	0.45
80	Rothenfeld	0.039 / 0.035	0.553 /0.100	0.245	0.260	0.77
115	Wettlkam	0.047 / 0.038	0.536 /0.163	0.317	0.294	0.64
118	Engersdorf	0.111 / 0.043	0.474 /0.095	0.275	0.376	0.66
500	Erlbach	0.119 / 0.060	0.289 /0.176	0.278	0.393	0.27
501	Harbach	0.149 / 0.053	0.428 /0.101	0.275	0.420	0.59

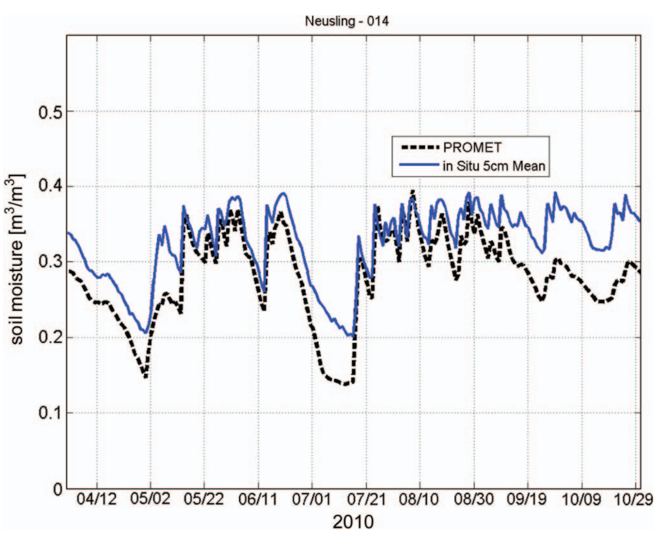

Fig. 8. Local comparison of measured and modeled 5-cm soil moisture for station Neusling for April to October 2010.

high RMSE values at some stations. At the stations with high RMSE values, the deviation of the mean values of the two data sets compared are in the order of the RMSE value. The RMSE of anomalies is below 0.07 $m^3\ m^{-3}$ for all stations. PROMET tends to underestimate the soil moisture under wet conditions that occur mainly in spring and fall. This leads to an underestimation of the seasonal soil moisture dynamics by PROMET. The time series of the comparison with daily data for station 14 for the year 2010 is shown in Fig. 8.

2) Medium-Scale Soil Moisture: To see how well the model reproduces the medium-scale soil moisture dynamics, simulated soil moisture fields were compared with the distributed medium-scale measurements made during the 2010 field campaign. For that purpose, the mean value of all field measurements made on the coarse grid in one focus area was calculated for each campaign day and compared to the mean value of all model grid cells covering the same focus area.

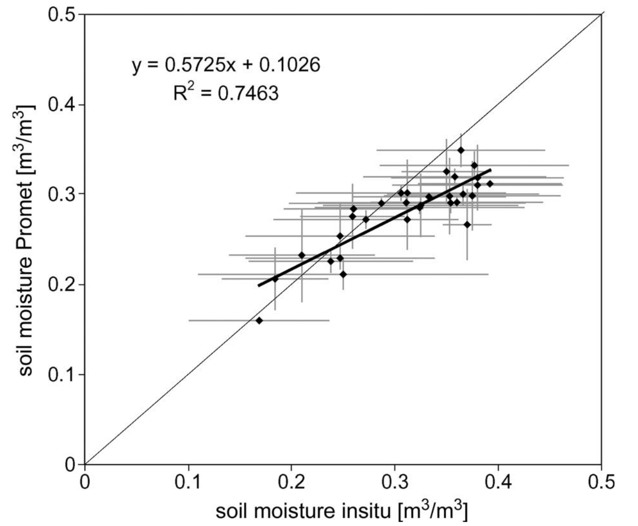

Fig. 9. Medium-scale comparison of area mean values of modeled and measured soil moisture in the five focus areas on the eight campaign dates of the SMOS validation campaign 2010.

The measurements used for this study are only the coarse-grid measurements to weight the whole focus area uniformly. Fig. 9 shows the comparison, each dot represents one focus area mean value which corresponds to about 300 independent soil moisture measurements. The model standard deviations are considerably smaller than the standard deviations of the measurements which are of the order of 0.07–0.08 $m^3\ m^{-3}$, on some days in some focus areas also exceed 0.1 $m^3\ m^{-3}$. The model tends to underestimate soil moisture under wet conditions which leads to an underestimation of soil moisture dynamics. The RMSE is 0.045 $m^3\ m^{-3}$ for that comparison and R^2 is 0.75. The RMSE of anomalies is 0.040 $m^3\ m^{-3}$.

3) Large-Scale Soil Moisture: To estimate how well the model is able to simulate soil moisture in extended areas on a SMOS-like scale, a comparison of measured and modeled mean soil moisture in the whole Vils test site was performed on basis of the ISEA grid. It is shown in Fig. 3. The mean values of the focus area means of measured soil moisture were compared to the mean values of simulated soil moisture for the central ISEA grid point in the Vils test site, ID 2027099. For this purpose, all model grid cells in the Vils test site were mapped to the ISEA grid with the nearest neighbor approach. For each day, all data mapped on a grid point were averaged. As the Vils test site is very homogeneous on that scale, it is assumed that the area mapped to one ISEA grid point is representative for a considerably larger area. For this analysis, only campaign days were used on which at least four out of the five focus areas had been sampled sufficiently. The days June 14 and July 8 had to be excluded because only one and three focus areas had been sampled, respectively, because of rain events starting in the course of the day. The RMSE of this analysis is 0.040 $m^3\ m^{-3}$, the RMSE of anomalies is 0.023 $m^3\ m^{-3}$.

B. Brightness Temperature

To assess the quality of the radiative transfer modeling with the coupled models PROMET and L-MEB, modeled brightness temperatures are compared to L-band radiometer measurements. Apart from the point-like scale (e.g., with measurements from a ground-based radiometer), this can be done on a SMOS-like scale with airborne radiometer data. The latter approach is subject of this chapter. All 1-km brightness temperature data available from the coupled models and all airborne EMIRAD radiometer data were mapped to the same geometry based on SMOS's ISEA grid. This was done with the nearest neighbor approach for the five SMOS validation campaign days with airborne L-band radiometer measurements. During the mapping of EMIRAD footprints to the ISEA grid, the center coordinates of the EMIRAD footprints were used for the decision whether an EMIRAD footprint lied inside the area being mapped to an ISEA grid point. The central ISEA grid point in the Vils test site, ID 2027099, was used as comparison reference. For each day, all data mapped on that grid point were averaged. It is assumed that the results are valid for larger areas as the Vils test site is very homogeneous. This comparison includes some approximations. The defined look angles (0°, 40°) of the radiometer are only valid in the center of the elliptical radiometer footprint. Near the edges of the footprint, the look angle deviates from the defined one. As the signal from the center has a larger influence on the overall measurement than the signal near the edges of the footprint due to the antenna diagram, the modeled brightness temperatures have only been produced for the center angle (0°, 40°).

This comparison was performed for the 40° look angle brightness temperatures as well as the 0° look angle brightness temperature. Fig. 10 shows the result of that comparison for vertical and horizontal polarizations for 40° incidence angle; Fig. 11 shows the comparison for the 0° brightness temperature in vertical polarization. Horizontal polarization data are not shown here, as for an incidence angle of 0°, both polarizations show essentially the same behavior. For 40° on three of the five campaign days, the simulated and observed brightness temperatures show a good agreement, while larger discrepancies are observed on days 22 May and 17 June, resulting in an RMSE of 16.52 K for H polarization and 13.14 K for V polarization. The model tends to simulate higher brightness temperatures than EMIRAD measurements, particularly for vertical polarization, and particularly for the two days mentioned above. For the vertical polarization in 0°, the picture is very similar. The two days that show the largest deviation between model and measurement lead to an RMSE of 12.09 K (12.97 K for horizontal polarization). The reasons for these discrepancies will be discussed below. Fig. 4 shows that there are precipitation events between all five EMIRAD overflight days, even though one has to bear in mind that the data shown are only representative for one meteorological station that is close to the center of SMOS grid point 2027099. This emphasizes that both the environmental conditions and the brightness temperatures are very dynamic, and their variability is much larger than what can be seen in the measurements of the five campaign days. The surface temperature during the EMIRAD overflights varies between about 7 and 18 °C in the course of the campaign and the focus area means of soil moisture between 0.169 and 0.392 $m^3\ m^{-3}$.

The vegetation conditions change significantly in the course of the campaign. The mean vegetation height of maize for example varies between 7.2 and 44.5 cm, that of winter wheat between 40.2 and 79.5 cm. The measured vegetation heights during the campaign have been used to improve the vegetation parameterization in L-MEB.

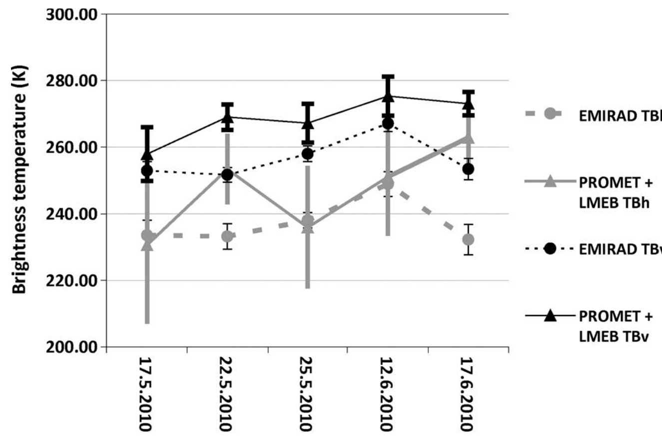

Fig. 10. Large-scale comparison of modeled and measured (EMIRAD) 40° brightness temperatures (V and H polarization) on the five flight days during the SMOS validation campaign 2010 based on the ISEA grid.

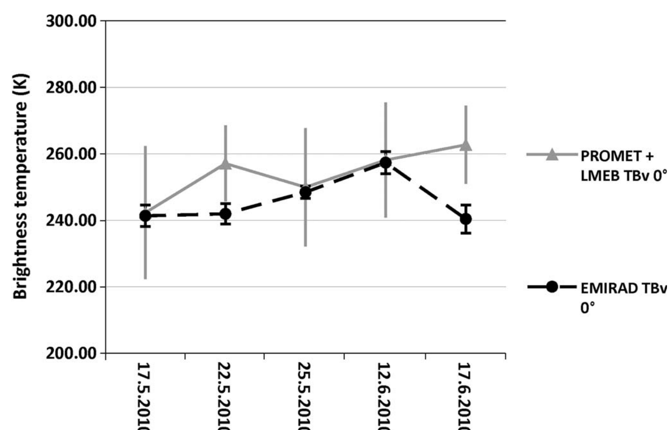

Fig. 11. Large-scale comparison of modeled and measured (EMIRAD) NADIR (0°) brightness temperatures (V polarization) on the five flight days during the SMOS validation campaign 2010 based on the ISEA grid.

V. Discussion

A. Soil Moisture Measurements

Comparisons of different *in situ* data sets have been made to assess the accuracy of the data sets that will be used as reference data in the further analysis.

By looking at the comparisons shown above, one has to bear in mind several issues related to the different measurement techniques. Each technique has its own unique measurement principle and sampling volume resulting in different representations of the natural soil heterogeneities (e.g., soil type variations, air bubbles, stones, vegetation material, etc.) or soil moisture gradients in the soil profile in the measurements. Care has been taken to minimize those effects. The different measurements sample different soil volumes which results in the data sets compared being valid for slightly different soil layers. While the continuously measuring probes are installed horizontally in 5-cm depth and measure an integrated signal of a varying soil volume depending on soil moisture content, the vertical handheld FD measurements are valid for the upper 6 cm and the gravimetric samples are valid for the upper 4 cm of the soil. In addition, the measurements were not taken at exactly the same locations in order not to disturb the soil around the installed probes. Instead, the locations for the different measurements can be situated up to about 3 m apart from each other. As soil moisture variability can be quite high even on that scale, which is shown by the sometimes considerable standard deviations in Figs. 6 and 7, a sufficient amount of samples has been taken at all sampling days to minimize the effects of soil heterogeneity.

Considering all mentioned obstacles in determining representative soil moisture values for extended areas, the comparisons shown above seem to support the thesis that the soil moisture measured at the stations and with handheld FD probes shows the expected variability and is therefore reliable enough to be used in further analysis. However, the uncertainties of the measurements should be kept in mind when using them as reference data set.

B. Soil Moisture Modeling at the Local Scale

The local scale soil moisture comparison between model and measurements show that the model is able to capture the temporal and spatial dynamics of the soil moisture reasonably well, but at some stations has a considerable offset when it comes to absolute values, particularly under wet conditions, which reduces the dynamic range of the model. These offsets are due to discrepancies between the soil parameters derived from the large-scale soil maps used to parameterize PROMET and the individual soil properties at the specific location chosen for the soil moisture measurements. We decided to not tune the PROMET simulations to the soil properties of the specific measurement locations to determine the range of uncertainty that is introduced into the soil moisture simulations by the underlying soil map.

When looking at this, one has to keep in mind the uncertainties related to the soil moisture measurements. The standard deviation of the mean of the 5 cm *in situ* measurements indicate for example that different probes in the same depth sometimes have considerable deviations in their measurements. At station Frieding, for example, where the RMSE between model and measurement is relatively high, the mean standard deviation of the 5 cm means of the *in situ* measurements is 0.097 $m^3\ m^{-3}$ and regularly exceeds 0.1 $m^3\ m^{-3}$, while in Neusling and Steinbeissen, where the RMSE is relatively low, the mean standard deviations of the measurements are below 0.01 $m^3\ m^{-3}$. In Harbach and Lochheim, standard deviations exceed 0.05 $m^3\ m^{-3}$ regularly. In addition, Frieding is an example of a station, where the station *in situ* soil moisture is regularly higher than the soil moisture of the handheld FD measurements. This is particularly true during wet periods. As the FD measurements are validated with gravimetric samples, this is an indicator for less reliable measurements.

Stations Erlbach and Harbach are the only ones not situated next to a meteorological station. Even though they are less than 4 km away from the next meteorological station, it is obvious in the data that the meteorological forcing data used for modeling at those stations are inaccurate as some precipitation events that occurred at the meteorological station were not registered at the soil moisture stations. Therefore, the modeled soil moisture values at those stations are less reliable. On a larger scale, however, this should become insignificant.

C. Soil Moisture Modeling on the Medium Scale

The comparison of measured and modeled focus area means of soil moisture during SMOS validation campaign 2010 seems to perform better than the local scale soil moisture comparisons. They may be valid mainly for spring and summer, but they represent a considerable area of more than 100 km^2 of very heterogeneous land cover due to very small field sizes in the Vils test site. Both temporal and spatial variability of soil moisture are high during the campaign and are captured quite well.

The comparison of measured and modeled focus area means of soil moisture is affected considerably by the different scales of the two data sets. The high natural soil moisture variability of an area sized about 3 km $\times$ 7 km with heterogeneous land cover (e.g., forest, bare soil, wheat, grassland) leads to high standard deviations as seen in Fig. 9. The standard deviations of the modeled values are often smaller due to the model resolution of 1 km which leads to a strongly reduced variety of land covers and natural conditions appearing in a focus area. In fact, the land cover map used for the model could introduce substantial errors when differing substantially from the actual land cover in the field. A comparison of mapped land cover with the land cover map used for modeling shows that the shares of the three main agricultural land cover types, grassland, winter wheat, and maize, which cover more than 58% (model map: 61) of the Vils test site, are very similar in both maps: Winter wheat: 16% (14), grassland: 23% (28), maize: 19% (19). This means that the error due to the land cover map used in the model is expected to be small if the mean value of several pixels is considered. However, when looking at smaller areas with only a few pixels of model output, the statistical nature of the land cover distribution in the model can introduce considerable deviations. For this reason, mean values per focus area are used for the comparison rather than looking at *in situ* measurements located in a single PROMET pixel.

As mentioned earlier, deviations between modeled and measured soil moisture may always result from inaccurate forcing data. At this time of year, convective precipitation events are quite common in the area, and it is obvious in the data of measurement stations Harbach and Erlbach that some rain events that occurred in a focus area were missed by the meteorological stations delivering the forcing data as input for soil moisture modeling.

D. Soil Moisture Modelling on the Large Scale

As shown in Section IV, the large-scale comparison between measured and modeled soil moisture on basis of the ISEA grid for the Vils test site produces a smaller RMSE than that on the medium and local scale. This may be due to deviations between measurement and model resulting from small-scale heterogeneity getting more and more insignificant when the scale increases. Measurement errors, land cover distribution, and small-scale precipitation events play a less significant role here. Of course, the sample size of six days is not very large, hampering a more detailed analysis, but for distributed measurements in an area as large as the Vils test site, it is hardly possible to get substantially larger data sets.

E. Brightness Temperature Modeling

Considering all the highly temporally and spatially variable parameters needed for the L-band emission modeling and the heterogeneity and small field size of the area, the results of the brightness temperature modeling look very promising.

The L-band emission of a surface depends mainly on surface temperature, surface soil moisture, vegetation properties, and soil properties like roughness. Therefore, the brightness temperature simulation is very sensitive to the soil moisture and temperature simulations that are used as input as well as the vegetation and soil properties used for the parameterization of the model. The overestimation of modeled brightness temperature can partly be explained by the underestimation of modeled soil moisture. It is obvious that on the two days, 22 May and 17 June, the deviation between both data sets is larger than on the other days. This is in line with the soil moisture estimate for those two days being less accurate than for the others when compared to soil moisture measurements in the field as can be seen in Fig. 3. The larger standard deviations of the model, when compared to the radiometer measurements, can be explained with the relatively large footprint of EMIRAD (approximately 4×4 km for 40° incidence angle), which leads to an integration over a variety of land cover types within every footprint. Therefore, the brightness temperature from one footprint to the next will not change considerably, leading to very small standard deviations when averaged. PROMET, on the other hand, models pure pixels containing only one land cover type per pixel (e.g., water, forest, bare soil, barren, grass) which have certain physical parameters related to them (e.g., surface temperature, soil moisture, vegetation parameters, roughness) leading to a high variability of brightness temperatures from one pixel to the next. As these pure pixels are then mapped and averaged on the ISEA grid, they produce the observed high standard deviations.

F. Implications for the SMOS Validation

1) Soil Moisture: For the SMOS validation, it will be important to know the dimension of the uncertainties related to the data sets used for validation. In the case of soil moisture, the uncertainties seem to reduce from local to medium to large scale. While having a mean RMSE value in the range of 0.09 $m^3\ m^{-3}$ for the soil moisture comparisons on the local scale and 0.045 $m^3\ m^{-3}$ on the medium scale, the RMSE value for the SMOS-like scale is in the order of 0.040 $m^3\ m^{-3}$. The RMSE of anomalies on that scale is 0.023 $m^3\ m^{-3}$ which is better than the accuracy target of the SMOS soil moisture product, 0.04 $m^3\ m^{-3}$ random error [14], [15]. It is important to mention that all model runs, regardless of scale or area, have been performed with the same set of soil parameters to make comparisons across scales and different areas possible. Therefore, these results are also transferable to other areas inside the UDC, even though the data sets used for the modeling (e.g., soil map, forcing data) may introduce different errors in different parts of the catchment. Due to the extensive data collected in the Vils test site and most of the comparisons being done here, the uncertainty analysis in this paper is most reliable in the Vils test site. Going from local to large scale, the time series of soil moisture measurements reduces to a few sampled days, while the spatial distribution of samples increases substantially. Therefore, the significance of the results on the large scale may be limited when it comes to long-term soil moisture dynamics, while the significance of the local scale results may be limited in terms of spatial distribution. As all results, regardless of scale and area used, point in the same direction, the results related to soil moisture uncertainty seem quite robust.

On the local scale, it is obvious that the RMSE values are not sufficient to describe model quality as simple offsets result in high RMSE values while the soil moisture dynamics may still be captured quite well by the model. Concerning SMOS validation, this means that in addition to comparing absolute values, it is necessary to also study how well specific soil moisture dynamics are captured. Considering soil moisture anomalies instead of using only absolute values might prove valuable for the SMOS validation [36].

Using a very similar data set of modeled soil moisture and station measurements for 2008 and 2009 in the Vils test site using the triple collocation method, [32] found that PROMET is commonly underestimating the soil moisture dynamical range at large scales (gain around 0.5). The correlation coefficients were of the order of 0.7 and the mean offsets about 0.09 $m^3 m^{-3}$. Similar relationships between PROMET and measured soil moisture on different scales were found in this study (Fig. 9, Table I). Loew and Schlenz [32] concluded that the large-scale random error of PROMET soil moisture is better than 0.025 $m^3\ m^{-3}$, which is in line with the findings of the current study.

2) Brightness Temperatures: The results of the brightness temperature simulations indicate that a validation of SMOS brightness temperature products is possible with an uncertainty in the range of 12–16 K RMSE for the period, area, and the incidence angles studied. As the data used in this study is only from five campaign days and the comparison was only performed on the large scale, the results are less robust than the soil moisture results. In addition, the model complexity of the coupled models makes it difficult to estimate wether the results in other areas or during other seasons would be similar. Still, considering the complexity of the approach, the results seem very promising. As the influence of soil moisture errors on the modeling seems to explain most of the observed deviations in brightness temperatures, the radiative transfer model does not seem to introduce large errors here.

VI. Conclusion

It was shown in this paper how soil moisture and L-band passive microwave emission can be modeled in different regions of the UDC under varying soil and vegetation conditions with a coupled land surface and radiative transfer model.

Soil moisture modeling results have been compared to measurements on a local scale over three years and in the course of the SMOS validation campaign 2010 in an area about the size of a SMOS footprint with spatially distributed measurements. The soil moisture behavior has been captured with satisfying results in time as well as in space (R^2 mostly between 0.5–0.7). The absolute soil moisture deviations between model and measurement have a mean RMSE in the order of 0.09 m^3 m^{-3} for local measurements and 0.040 m^3 m^{-3} for large-scale values. The RMSE of anomalies is 0.023 m^3 m^{-3} on the large scale.

As the model tends to underestimate soil moisture under wet conditions, which leads to a reduced soil moisture dynamical range, a rescaling of land surface model soil moisture data might reduce the uncertainty of the SMOS validation.

The brightness temperature simulations have been compared with airborne radiometer measurements based on the SMOS ISEA grid for the Vils test site for five days of measurements under varying soil moisture and vegetation conditions. The overall performance is very promising (RMSE around 12–16 K). Uncertainties related to such a complex modeling approach and the measurements are manifold and have been discussed.

Approaches to improve brightness temperature modeling will have to take into account the possibility that the L-MEB parameters that have been used so far will have to be adapted to local conditions and new findings concerning brightness temperature modeling. The roughness parameter h for example plays an important role in L-band emission modeling [64]–[66] but has not been altered in the course of this study. To further improve the brightness temperature modeling, it would be possible to use the relationships found between modeled and measured soil moisture to rescale soil moisture before using it as input to the radiative transfer model.

The modeled soil moisture and brightness temperature maps in the UDC can be used for the validation of data products from SMOS and other remote sensing instruments. As the uncertainties assessed in this study lie well in the margin of uncertainty that SMOS has shown so far (e.g., dry bias of -0.11 to 0.3 m^3/m^3 when compared to *in situ* measurements and model simulations [36]) and all data sets described in the current paper point in the same direction, this study can provide a valuable contribution to SMOS validation activities.

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Florian Schlenz (M'08) was born in Forchheim, Germany, 1980. He received the Diplom degree in physical geography with remote sensing and computer science from the University of Munich, Munich, Germany, in 2007.

He has been with the Department of Geography, University of Munich, since 2007, and works as a researcher on the project SMOSHYD (Integrative analysis of SMOS soil moisture data) which aims at the calibration and validation of SMOS data in the Upper Danube Catchment as well as at the study of scaling issues. His research interests include hydrological and radiative transfer modeling as well as airborne and satellite-based remote sensing of soil moisture, including the analysis of field data and passive microwave radiometer data.

Mr. Schlenz is a member of the European Geosciences Union.

Johanna T. dall'Amico received the B.Sc. degree in mathematics from the University of Reading, Reading, U.K., in 2007 and the Diplom degree in geography with remote sensing and mathematics from the University of Munich, Munich, Germany, in 2008. She is currently working toward the Ph.D. degree at the Department of Geography, University of Munich. In 2005, she was a visiting student at the Natural Environment Research Council Environmental Systems Science Centre in Reading, U.K., working on remote sensing applications for fluvial flood mapping and modeling.

Since 2007, she has been with the University of Munich, working on the project SMOSHYD (Integrative analysis of SMOS soil moisture data) which aims at the calibration and validation of SMOS data in the Upper Danube Catchment as well as at the study of scaling issues. Therefore, her current research interests include airborne and satellite remote sensing of soil moisture and its spatial variability, including the analysis of ground data as well as ancillary remote sensing data.

Alexander Loew (M'04) received the M.S. and the Ph.D. degrees in geography from University of Munich (LMU), Munich, Germany in 2001 and 2004, respectively.

From 2001 to 2008, he was a PostDoc with the LMU, working on the retrieval of bio- and geophysical parameters from microwave remote sensing data. In 2007, he was a Visiting Scientist with the NASA Goddard Space Flight Center, Greenbelt, MD. In 2009, he joined the Max Planck Institute for Meteorology, Hamburg, Germany. Currently, he is leading a research group on Terrestrial Global Remote Sensing, focusing on global-scale remote sensing for climate studies. His research interests include the quantitative retrieval of geophysical parameters from remote sensing data, the development of image processing algorithms, coupling of land surface process models with microwave scattering and emission models, and the development of land surface process models and data assimilation techniques. He is an editor for *Hydrology and Earth System Science* and acts as a Reviewer for several national and international journals.

Wolfram Mauser (M'92) was born in Innsbruck, Austria, in 1955. He received the M.S. degrees in experimental physics and geography/hydrology and the Ph.D. degree in hydrology from the University of Freiburg, Freiburg, Germany, in 1979, 1981, and 1984, respectively.

In 1981, he worked with the University of Maryland, College Park and the Goddard Space Flight Center, Greenbelt, MD, in the field of remote sensing and hydrology. From 1984 to 1991, he was an Assistant Professor with the Department of Hydrology, Institute for Physical Geography, University of Freiburg. In 1991, he was appointed Full Professor for geography and geographical remote sensing, Department of Geography, University of Munich, Germany. From 2003 to 2009, he was Chairman of the German National Committee for Global Change Research. He has been working in the field of remote sensing and hydrology within the major European research programs. He was appointed Principal Investigator (PI) by the European Space Agency (ESA) for its ERS-1, ERS-2, and ENVISAT program and is PI for the Shuttle Radar Topography Mission and Soil Moisture and Ocean Salinity mission. He was member of ESA's Mission Advisory Group of the Earth Explorer Surface Processes and Ecosystem Changes Through Response Analysis Mission. He took part in the MAC-Europe, E-MAC, and DAISEX-campaign. His special research interest is the development and validation of spatially distributed land surface processes models and image processing algorithms as well as model assimilation procedures for microwave and hyperspectral optical data.

Curriculum Vitae

Personal information

Name	Johanna Therese dall'Amico, née Elsässer
Date of Birth	08 Feb 1983
Place of Birth	Munich, Germany
Nationality	German
Marital status	married, two children

Work experience

since 11/2007	Researcher at the University of Munich (LMU), Germany
	working for the project "*SMOSHYD: Integrative Analyse von SMOS Bodenfeuchtedaten*" (Integrative analysis of SMOS soil moisture data) funded by the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR)
03/2006 - 08/2006	Intern at the Environmental Systems Science Centre (ESSC), Reading, United Kingdom
09/2004 - 10/2004	Intern at the Remote Sensing Technology Institute (IMF) at the German Aerospace Center (DLR), Oberpfaffenhofen, Germany

Education

10/2002 - 02/2008	Diplom (4.5-year degree) Geography with Remote Sensing and Mathematics, University of Munich (LMU), Germany
	Thesis: “Automatic river flood extent delineation using SAR and LiDAR data“
10/2006 - 07/2007	BSc Mathematics, University of Reading, United Kingdom
06/2001	Abitur (German university-entrance diploma) in Bochum, Germany