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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

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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.

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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 $-2\,^{\circ}C$ in January and about $17\,^{\circ}C$ 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 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

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.

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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.

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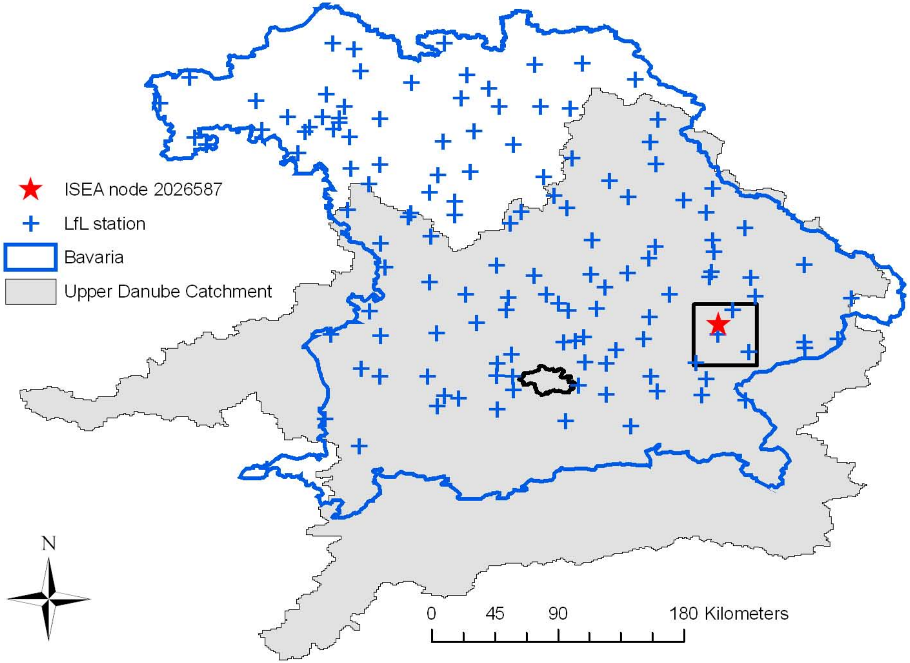

Fig. 1. Upper Danube Catchment with LfL meteorological station network. The black box shows the Vils area, the black polygon represents Munich, the capital of the federal state Bavaria. The red star marks the position of one of the nodes of the ISEA grid in the Vils area on which SMOS data are delivered.

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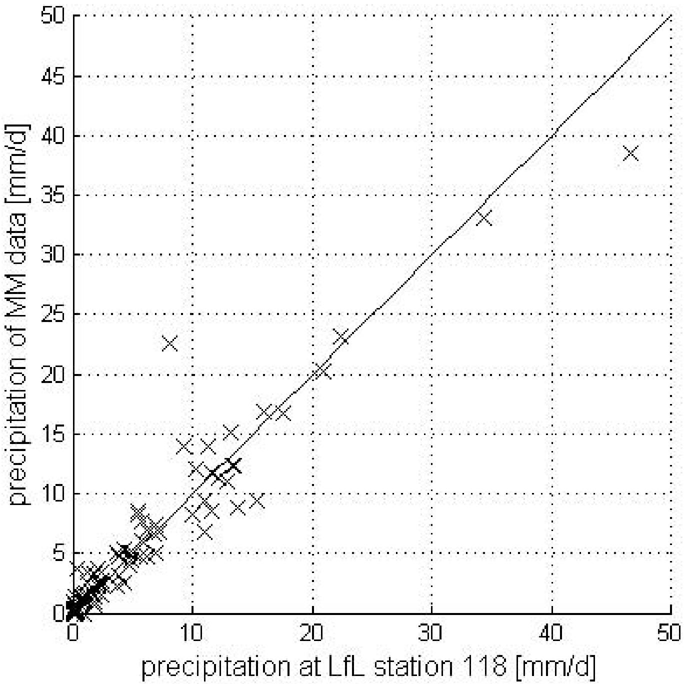

Fig. 2. Scatter plot of daily rainfall of the Meteomedia data set ("MM data") and the measurements of LfL station 118 (Engersdorf, located in the Vils area) for the period from 8 April 2010 to 31 August 2010.

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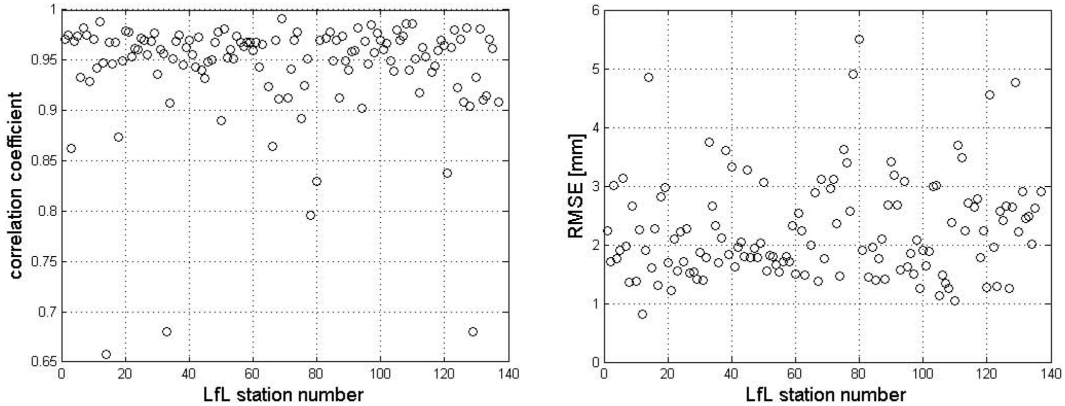

Fig. 3. Correlation coefficients (left panel) and root-mean-squared errors (right panel) for the comparison of daily rainfall of the Meteomedia data set with the measurements of the LfL stations for the period from 8 April 2010 to 31 August 2010.

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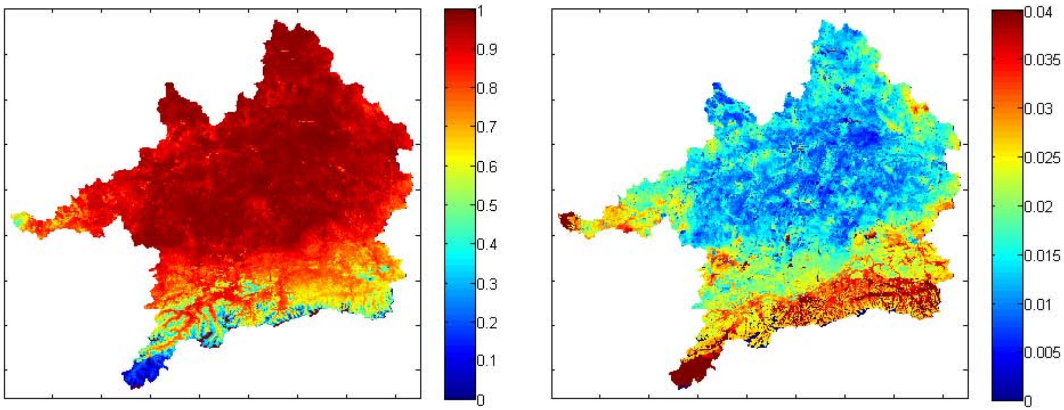

Fig. 4. Maps of correlation coefficients (left panel) and root-mean-squared errors (right panel) of soil moisture from the two model runs on the 1 km model grid for the period from 1 May to 26 August 2010.

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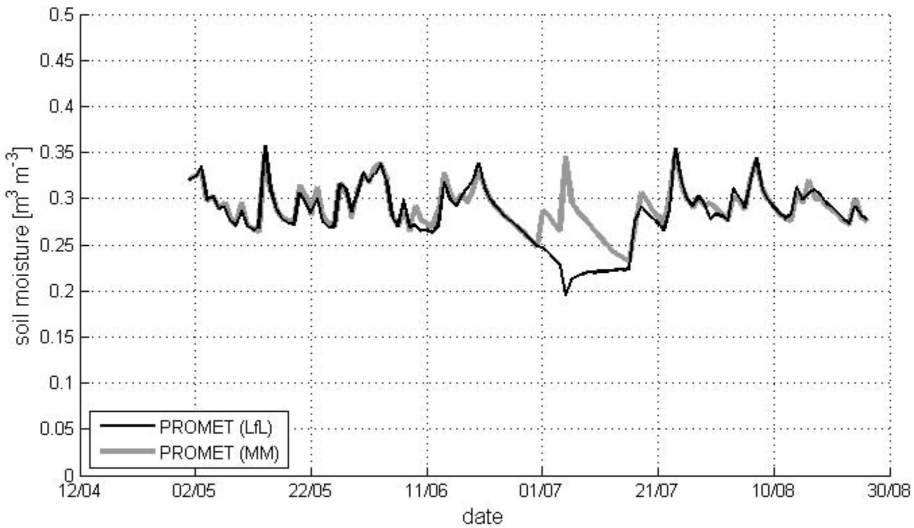

Fig. 5. Time series of modelled soil moisture at a 1 km grid cell in the Vils area (location shown in Fig. 6). The black line shows the modelled soil moisture with precipitation input from interpolated LfL station data, the grey line shows the modelled soil moisture with precipitation input from Meteomedia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

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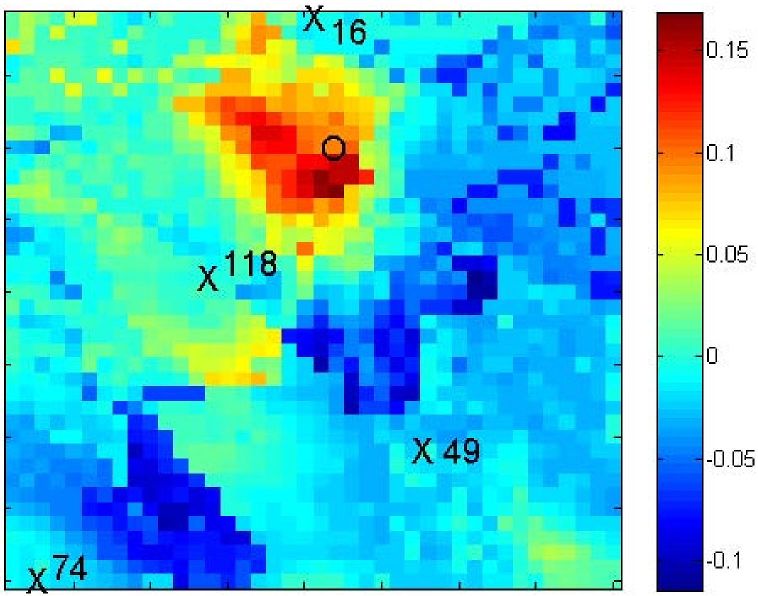

Fig. 6. Difference of modelled soil moisture fields [$m^3 m^{-3}$] from the two model runs (Meteomedia run minus LfL run) in the Vils area on 5 July 2010. Black crosses are the LfL stations with their numbers. The circle marks the location of the pixel for which the time series are shown in Fig. 5. Axes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

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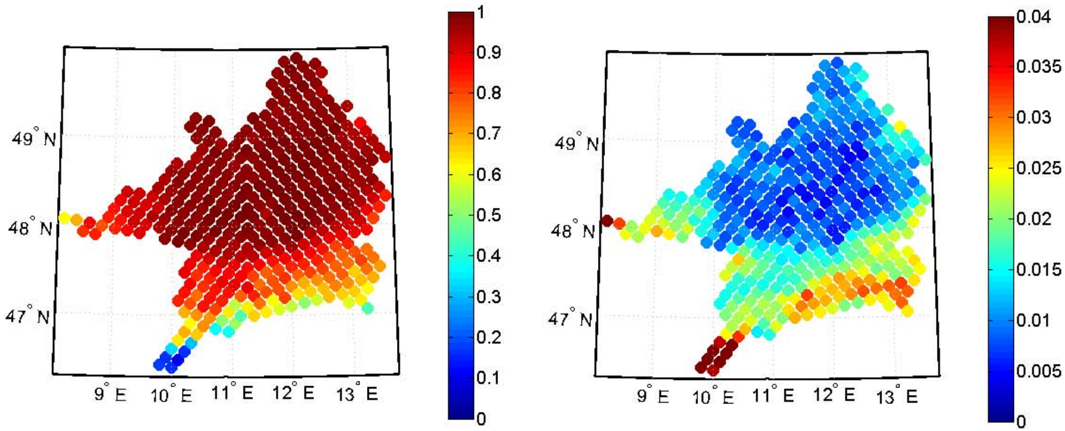

Fig. 7. Maps of correlation coefficients (left panel) and root-mean-squared errors (right panel) of the two model runs (for the period from 1 May to 26 August 2010) after aggregating modelled soil moisture to the ISEA grid.

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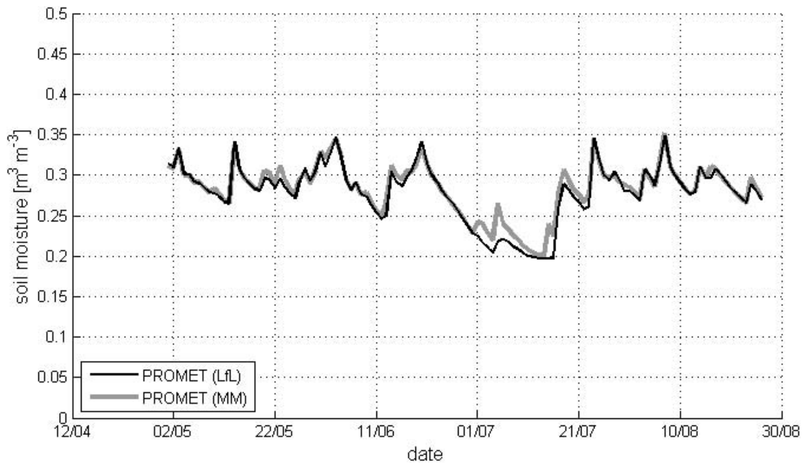

Fig. 8. Time series of modelled soil moisture for the ISEA node ID 2026587, located in the Vils area. The black line shows the modelled soil moisture with precipitation input from interpolated LfL station data, the grey line shows the modelled soil moisture with precipitation input from Meteomedia data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

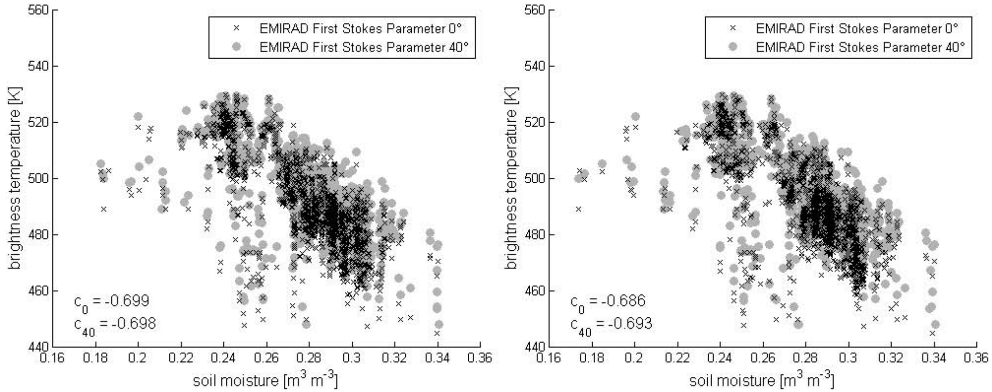

Fig. 9. Scatter plot of modelled soil moisture versus measured brightness temperature; left panel: model run using LfL data, right panel: model run using Meteomedia data. c_0 denotes the correlation coefficient between modelled soil moisture and brightness temperatures as measured by the EMIRAD nadir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

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