PLURI-ANNUAL COMPARISON OF LAND SURFACE MODELLED AND ERS REMOTE SENSED SURFACE SOIL MOISTURE

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Abstract

As homogeneous long time series are becoming available, satellite products will be more and more used to monitor climate and to improve our understanding of climate processes.
The EUMETSAT Satellite Application Facility on Land Surface Analysis (LSA-SAF) has the objective to provide output fields able to characterize continental land surfaces by using information obtained from MSG and METOP satellites. In this framework, RMI's contribution to the LSA-SAF is to develop an evapotranspiration (ET) product. For this purpose, a model based on the ECMWF TESSEL Soil Vegetation Atmosphere Transfer (SVAT) scheme forced with MSG derived data, is currently used and continuously improved. The current version of the algorithm is running in near real-time at the Portuguese Meteorological Institute, host of the LSA-SAF. On the other side, the Hydrology and water management SAF (H-SAF) is deriving a superficial soil moisture index from the scatterometer on board ERS and METOP satellites. In this context, an inter-SAF activity has started between the LSA-SAF and the H-SAF in order to develop a coherent methodology for assimilating the satellite derived surface soil moisture data in the LSA-SAF ET model. The main objective is to increase LSA-SAF ET accuracy over water-stressed regions. A subset of uniformly distributed points over Europe has been selected as well as a first set of points in Africa. A 10 year time period is considered as well as a new version of the LSA-SAF surface model based on the ECMWF H-TESSEL land surface scheme. Results of the validation of this new model against flux stations observations are first illustrated. Then, investigations about transfer functions linking these datasets following Drush et al. (2005) approach are presented in the perspective of a future assimilation of METOP ASCAT data into the LSA-SAF model.
The three soil moisture datasets, from LSA-SAF, ECMWF-ERA Interim and ERS SCAT, are inter-compared over the 1992-2001 period. Finally the impact of satellite data on model outputs is qualitatively investigated.

INTRODUCTION

Both the large scale atmospheric circulation and local surface energy and water fluxes determine local meteorological conditions close to the Earth surface. They need to be correctly evaluated by weather and climate models. A good assessment of the partition between surface energy fluxes is thus important in meteorological models and in several applications fields. Evapotranspiration (ET) is one of the variables estimated by the EUMETSAT's SAF on Land Surface Analysis (LSA-SAF; see http://landsaf.meteo.pt). The Royal Meteorological Institute of Belgium (RMI) is responsible of the ET product within the LSA-SAF. ET is obtained by modeling the energy exchange between the surface (soil and vegetation) and the atmosphere. A simplified Soil-Vegetation-Atmosphere Transfer (SVAT) scheme is used and and produces results in near real time. This initial model version called RMI-1 is driven by input data ('forcing') derived by the LSA-SAF from Meteosat Second Generation (MSG). It uses as input soil moisture (SM) estimated operationally at ECMWF.

During the last decade, many investigators have searched how microwave remote sensing can be used for the SM retrieval. Passive microwave radiometers will be used by the nearing SMOS mission. In the active microwave range, the ASCAT instrument is available on the METOP satellites. In the Satellite Application Facility on support to Operational Hydrology and Water Management (H-SAF), the derivation is coordinated by the Austrian Meteorological Service (ZAMG) and includes both (1) a product based on ERS/SCAT or METOP/ASCAT for superficial SM produced by TU Wien and (2) the retrieval of SM profiles by ECMWF. The method based on ERS scatterometer data (SCAT) has been developed by Wagner (1998) and Wagner et al. (1999) and subsequent works (Wagner and Scipal, 2000; Scipal, 2002; Wagner et al., 2003; Wagner et al., 2007). A database has been set up at the Technical University of Vienna (http://www.ipf.tuwien.ac.at/radar/).

In the SVAT schemes, SM modelling impacts on both ET and runoff simulations (Koster and Milly, 1997). In order to use a remote sensing estimate for soil moisture, one needs first a matching of the model climatology soil moisture and the observations climatology; this matching is often designated as a transfer function, or observation operator, encapsulating deficiencies in both observations and model (Reichle and Koster, 2004). The need for model SM climatology requires a fully-fledged SVAT with thermal and hydrological budgets. A water budget component needs to be added to RMI-1; two successive new resulting model versions will be called RMI-2 and RMI-3.

In the present paper we will investigate the possibility of combining model and satellite soil moisture estimates to improve the LSA-SAF ET algorithm.

RMI-3 MODEL DESCRIPTION AND VALIDATION

Description

The evapotranspiration (ET) and the related energy flux, the latent heat flux, are involved to both water and energy budgets. The initial version of the model, that will be called RMI-1, consists in a simplified Soil-Vegetation-Atmosphere Transfer (SVAT) scheme (Gellens-Meulenberghs et al., 2008).

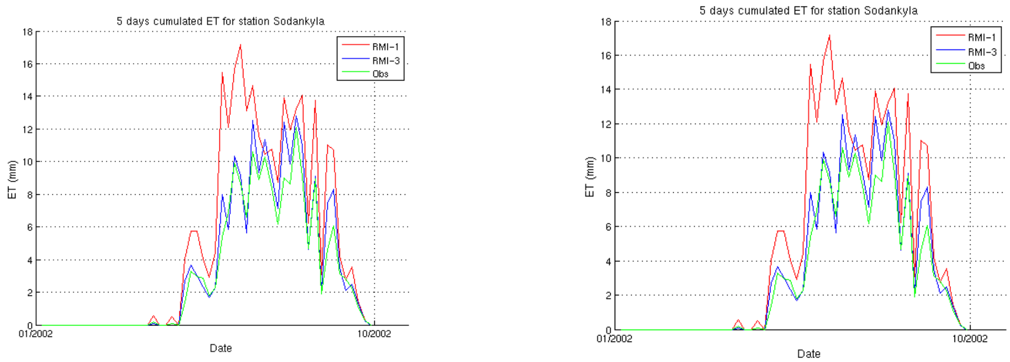
The model used in this paper will be a new version. It has been obtained by adding an interception and a soil module to RMI-1, by changing the model from diagnostic to prognostic and by calculating the 4-layer soil moistures and soil temperatures instead of using ECMWF's values. Both TESSEL (van den Hurk et al. 2000) and H-TESSEL (Balsamo et al. 2008) formulations have been considered with the resulting versions being called RMI-2 and RMI-3 respectively. A one-dimensional, or "point" version of the algorithm is applied in this study. Local observations or pluri-annual series extracted from ERA-Interim ECMWF MARS are used as forcing.

Validation

In order to investigate RMI-3 capabilities compared to RMI-1, we first check RMI-3 algorithm ability to reproduce flux observations at different flux stations. Data from 17 stations mainly selected from FLUXNET (see http://www.fluxnet.ornl.gov/fluxnet/index.cfm) is used for this purpose. RMI-3 was forced with local values, i.e. with observed meteorological and vegetation data from the stations. In such conditions, the algorithm is expected to reproduce observed ET fluxes in a satisfactory way. As RMI-2 and RMI-3 shows similar ET results we will focus on comparison between RMI-1 and RMI-3 versions in the following of this text.

ET agreement with observations is improved in most cases by adding the soil module to RMI-1, as illustrated in Figure 1 and Figure 2, Results at most of the 17 stations show similar or increased Nash indices. For most of the comparisons, RMI-3 algorithm is able to reproduce the temporal evolution of evapotranspiration with values comparable with observations. No evident systematic bias has been discovered for the different vegetation classes. A very good agreement is found for stations made of deciduous or evergreen broadleaf trees. H-TESSEL based version (RMI-3) seems also more promising for the future because of the more realistic physical modelling used. Additionally, RMI-3 is independent of ECMWF soil moistures and temperatures thanks to the soil module contrary to RMI-1.

Figure 1. Evapotranspiration comparison of RMI-1 (red), RMI-3 (blue) outputs with observations (green) for CarboEurope-IP station Sodankyla, located in Finland and covered by Pinus trees. The models were forced both with local data (left-hand) and ECMWF/ECOCLIMAP data (right-hand).



In a second step, the model is forced like in the grid conditions, i.e. using ECMWF meteorological data and ECOCLIMAP vegetation parameters. As MSG data were not yet available for the 10 years period considered in the following of this study, radiative forcing used as input are also extracted from ERA-Interim.

Figure 2. Same as Figure 1 but for CarboEurope-IP station Tojal (PT) covered by tall grass.

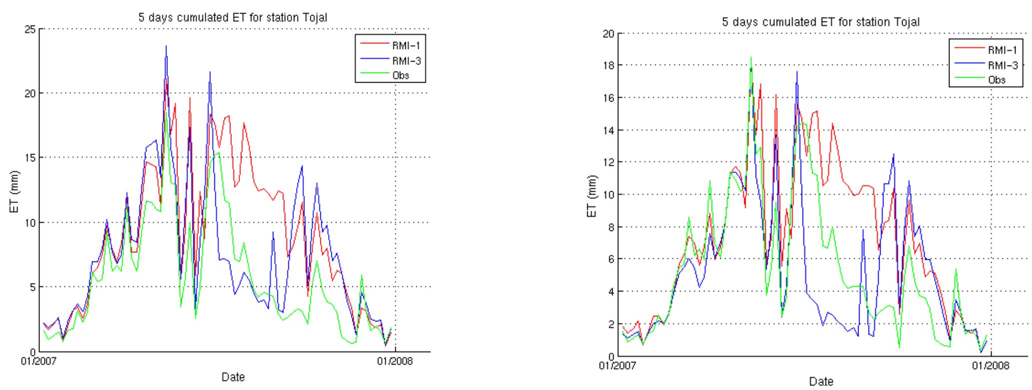
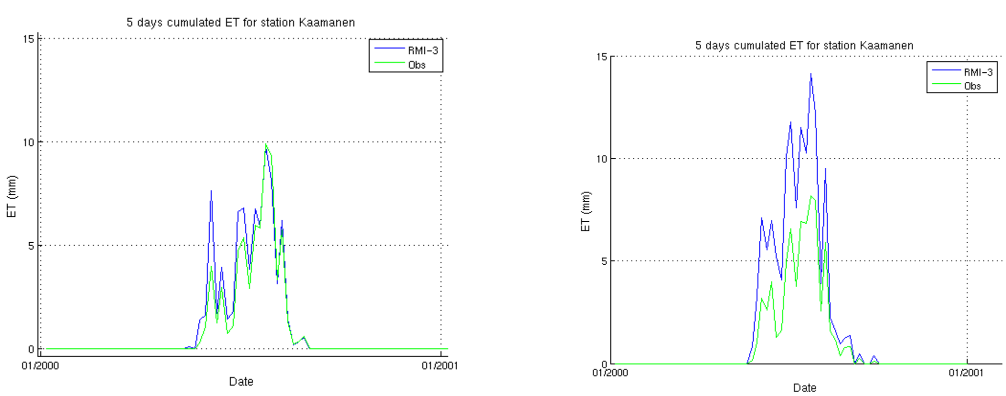
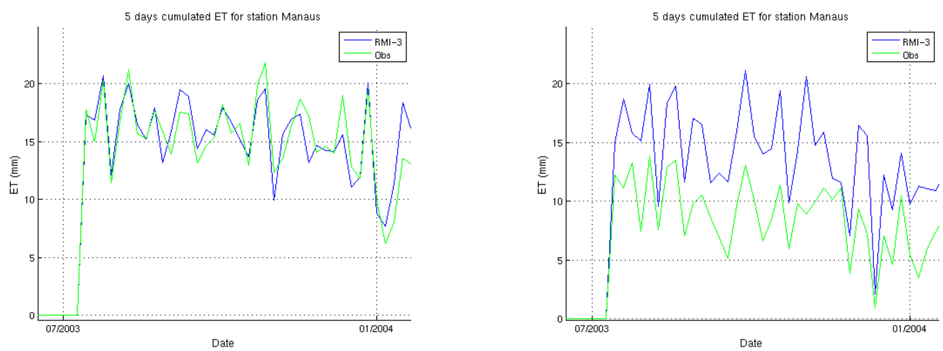


Figure 3. Evapotranspiration outputs of RMI-3 (blue) compared to observations (green) when forced with local (left-hand side) and ECMWF/ECOCLIMAP (right-hand side) forcing at CarboEurope-IP station Kaamanen. Vegetation description is mainly responsible of the agreement degradation of model estimates with measurements when ECOCLIMAP database is used.



As we expected, the Nash indices are degraded when we use grid-version data to force the models instead of local observations. Different explanations can be found for the differences that we observe between simulation and measurements. Errors can be caused by differences between ERA-Interim and observed global solar radiation, which is a main driver of RMI ET algorithm. It can also be caused by differences in vegetation description. Either when the ECOCLIMAP/MSG tile does not correspond to the vegetation type of the station, or when vegetation characteristics, i.e. leaf are index (LAI), fraction of vegetation cover (FVC) and roughness length for momentum (z0), do not correspond. Indeed, due to the spatial heterogeneity and difference of scales, the in-situ measurements will often not be representative of the same vegetation types than the MSG pixel estimates. The grid-version of RMI-3 will for example consider 46% of bogs and marshes and 44% of deciduous needle-leaf trees at Kaamanen ground station while it is only covered by bogs and marshes (Figure 3).

Figure 4. Evapotranspiration outputs of RMI-3 (blue) compared to observations (green) when forced with local (top left) and ECMWF/ECOCLIMAP (top right) forcing at CarboEurope-IP station Kaamanen. Observed precipitation data used in the local conditions (blue) compared to ECMWF values (red) used in the grid conditions (bottom right) are given underneath.



Finally, differences can occur because of differences in meteorological forcing data (Figure 4). Huge differences can exist between observed precipitation data and values extracted from the ECMWF ERA-Interim database. Indeed, for tropical forest station Manaus, ECMWF rains are less intense but more frequent than the observed estimates used as forcing, resulting in doubled cumulated rains that degrade the modelled ET values compared to observations.

However, RMI-1 and RMI-3 show globally similar skills and RMI-3 has been selected for the following of this study.

SOIL MOISTURE INTERCOMPARISON

Datasets

In the framework of this comparison work, 86 points have been chosen over Europe, as well as 20 points over Africa, separated by approximately 5 degrees in longitude and 4 degrees in. Three soil moisture datasets are compared, two model-derived one's, RMI-3 and ECMWF, and one satellite derived. The considered time period starts the 1^{st} January 1992 12UTC and ends the 31^{st} December 2001 12 UTC.

The modelled datasets were available in time-intervals of 30 minutes during this period whereas the scatterometer data were only available 1-3 times per week, depending on location. In order to make comparisons possible, only common dataset pairs were taken into account. RMI-3 has been forced with ERA-Interim data with a 0.5° horizontal resolution. The temporal resolution from the original data is 3 hours but has been interpolated to 30 minutes values. Original ECOCLIMAP vegetation parameters have been re-projected to the MSG grid to be used by the model. It will be termed SM_{RMI3}.

As for RMI-3 meteorological forcing, ECMWF soil moisture dataset is extracted from the ERA-Interim database with a 0.5°and 3h resolution, interpolated to 30 minutes values and termed SM_{EINT}.

Scatterometer data are checked with their available quality flags, as defined in the WARP5 software. For this study, the data were limited to the one where the noise percentage is below or equal to 6%. Scatterometer data represent the relative saturation of the first few centimetres of soil, ranging between 0 and 100%, whereas both the modelled data represent the volumetric soil water content given in m^3/m^3. Before comparison is possible, SM_{ESCA} values are scaled to the modelled data following a linear transformation between wilting point and saturation. For the ERA-Interim data, the soil textures are fixed for the whole area with values of 0.171 for permanent wilting point and 0.470 for saturation. For the RMI-3 data, the soil textures are varying in six classes (coarse, medium, medium-fine, fine, very-fine and organic) with individual parameters, according to the FAO soil texture database.

CDF matching of satellite data

An approach to reduce the systematic bias is by matching the cumulative distribution functions (CDF) of both distributions according to Drush et al. 2005. This can be done in two ways: either by matching mean and standard deviation only, referred to as linear CDF matching; or by matching also higher moments of the distribution (skewness, kurtosis), which is referred to as polynomial CDF matching. Linear matching is nevertheless sufficient for the bias reduction.

In the case of linear matching beween ERA-Interim ('EINT') and ERS SCAT ('ESCA') SM, the approach is to match the mean and standard deviation according the following equations:

$$p_1 = \overline{\Theta}_{EINT} - p_2 \overline{\Theta}_{ESCA} \quad (1)$$

$$p_2 = \frac{stddev(\Theta_{EINT})}{stddev(\Theta_{ESCA})} \quad (2)$$

The parameters from Equations 1 and 2 are then used for a linear transformation of the input data:

$$\Theta_{ESCA\_LIN\_EINT} = p_1 + p_2 \Theta_{ESCA} \quad (3)$$

Figure 5. ERA-Interim and ERS time series for the same point in Niger. ERS data are matched linearly to have the same mean and standard deviation.

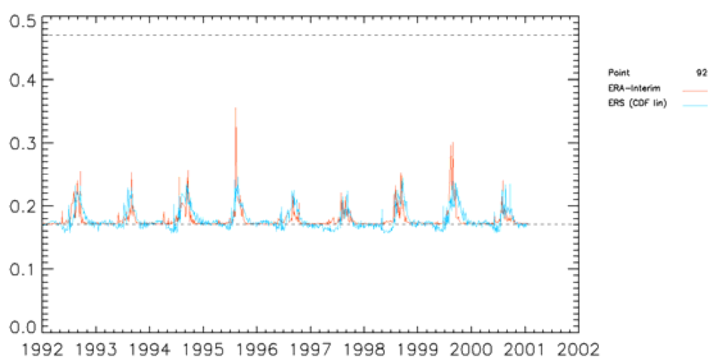


Figure 5 gives an example for the same point as shown above. The systematic bias is reduced by applying Formula 3 and the time series follow a similar temporal pattern. A fact worth noting is that because of the matching technique the lowest values can drop below the wilting point.

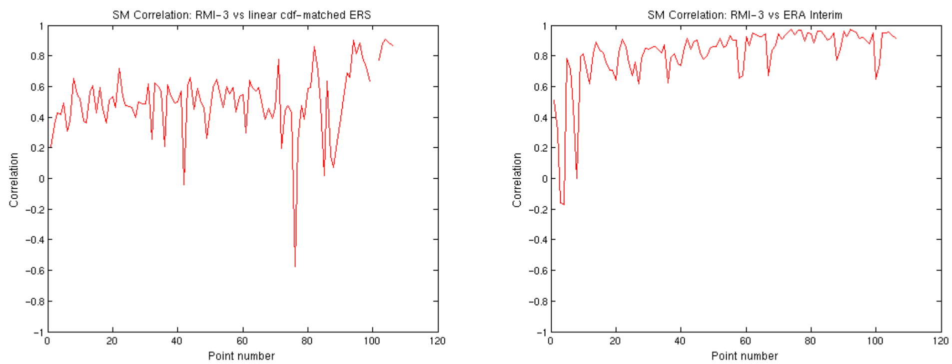
Correlation

To determine if satellite SM, model SM_{RMI3} and SM_{EINT} capture the same processes, the correlations between the different datasets have been calculated (Figure 6). Comparing datasets does not provide any quantitative information about the quality of the data. However, considering that datasets are fully independent we assume that a high correlation indicates that the same processes are captured. Correlation values above 40% are generally obtained over Europe with maximum values around 80%. For Africa, high correlations are obtained, except for the northern points located between the Mediterranean and the Red Sea.

When comparing ERS and ERA-Interim datasets, correlation values above 40% are generally obtained over Europe with maximum values around 80%. These values are lower than the 60% correlation obtained when comparing ERS SM to 6h ECMWF ERA-40 re-analysis dataset (Scipal et al. 2008).

As expected, high correlations between RMI-3 and ECMWF datasets are obtained. Indeed, the land surface scheme used in ECMWF, TESSEL is very similar to the one used in H-TESSEL based one used in RMI-3.

Figure 6. Correlation values for the 106 points over Europe and Africa between RMI-3's first layer soil moisture and respectively linearly CDF-matched scatterometer derived soil moisture (left) and ERA-Interim first layer soil moisture (right) for the 1991-2001 period.



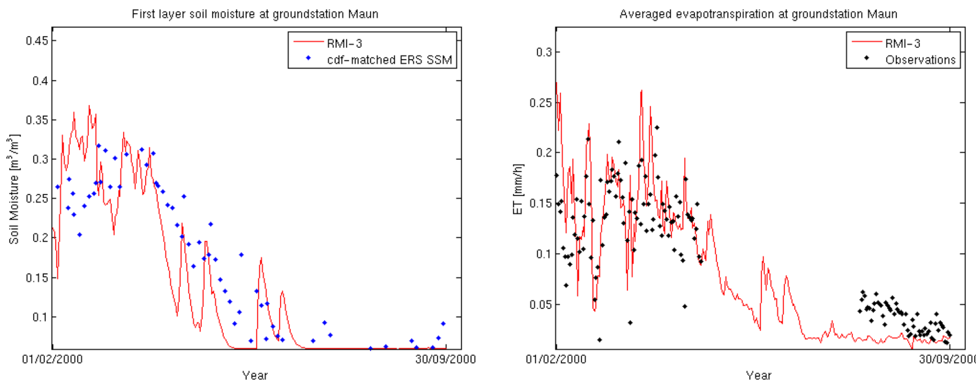
ERS SSM IMPACT ON MODELED ET

The next step is to investigate the impact on the RMI-1 and RMI-3 ET results of assimilated scatterometer soil moisture scaled by the transfer functions. Comparisons can be done at flux stations with both observations and initial output of the RMI-1 and RMI-3 models. From available observed data sets, only a few refers to the 1992-2001 period investigated in this study.

Simple assimilation process of the satellite data have been tested but abandoned because of the pour temporal resolution of the scatterometer data. Indeed, the soil moisture correction effect on modelled ET was only visible for a tiny number of time steps after the nudging. Nevertheless, using data derived from METOP ASCAT, available with a highest frequency than ERS/SCAT seems more promising. At the time of doing this research METOP ASCAT data prior to May 2008 was not available in the EUMETSAT archives and this comparison was left for the future.

We examine hereafter qualitatively the impact of a correction assumed to be done on RMI-3 SM to reduce difference with ERS derived SM. ET from RMI-3 drops with decreasing SM. Therefore, if satellite soil moisture is lower than modelled one, assimilation of scatterometer data will decrease the modelled soil moisture value, which will decrease the modelled evapotranspiration output of RMI-3. If modelled flux before assimilation is higher than the measured ET, it will bring model estimates closer to the observations. In the same way, assimilation of scatterometer data will have a positive impact on ET estimations, if satellite soil moisture is higher than modelled one and modelled ET underestimates the in-situ measurement

Figure 7. Left-hand side figure displays in red the modeled first layer soil moisture for spring+ summer of the year 2000 at CarboAfrica station Maun, blue dots represent ERS-derived superficial soil moisture values after matching its cumulative distribution function on RMI-3 one's. On the right-hand side figure, the black dots represent observed evapotranspiration values while the red curve gives the modeled ET flux.



The impact of using satellite derived data on RMI-3 model has been estimated for African station Maun (Figure 7) and European stations Tharandt, Roccarespampini, Tadham Moor and Collelongo (not shown). Satellite observations, when replacing model soil moisture, will correct model evapotranspiration estimates in the good direction compared to observations in respectively 66, 55, 67, 94 and 66 % of the cases. These percentages are above 50% but the degradation cases are still important. We should therefore explore the possibility to define a criterion allowing exploiting SCAT satellite data with positive impact on the model.

CONCLUSIONS

An extensive validation has been done over Europe and shows satisfactory results. Added value and consistency of RMI-3 has been assessed at 17 FLUXNET stations located within the MSG disk. Furthermore, the impact of fitting the cumulative distribution functions on satellite data has been illustrated which shows the need of a climatological dataset, like the 10 year dataset used here, for computing accurate CDF matching parameters. The potential positive impact of using scatterometer derived data for correcting model outputs has also been showed but putting the stress on the need of an use criterion.

Further work should be done using METOP ASCAT data instead of ERS SCAT soil moisture data. The higher time-resolution as well as the more recent time coverage should respectively improve the assimilation investigation and the validation process.

Research is also on-going to improve ET modeling by using a better representation of vegetation characteristics through a combination of LSA-SAF vegetation products and the ECOCLIMAP database (Ghilain et al. 2008).

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