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# Evapotranspiration modelling at large scale using near-real time MSG SEVIRI derived data

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## Abstract

We present an evapotranspiration (ET) model developed in the framework of the EU-METSAT “Satellite Application Facility” (SAF) on Land Surface Analysis (LSA). The model is a simplified Soil-Vegetation-Atmosphere Transfer (SVAT) scheme that uses as input a combination of remote sensed data and atmospheric model outputs. The inputs based on remote sensing are LSA-SAF products: the Albedo (AL), the Downwelling Surface Shortwave Flux (DSSF) and the Downwelling Surface Longwave Flux (DSLFL). They are available with the spatial resolution of the MSG SEVIRI instrument. ET maps covering the whole MSG field of view are produced by the model every 30 min, in near-real-time, for all weather conditions. This paper presents the adopted methodology and a set of validation results. The model quality is evaluated in two ways. First, ET results are compared with ground observations (from CarboEurope and national weather services), for different land cover types, over a full vegetation cycle in the Northern Hemisphere in 2007. This validation shows that the model is able to reproduce the observed ET temporal evolution from the diurnal to annual time scales for the temperate climate zones: the mean bias is less than  $0.02 \text{ mm h}^{-1}$  and the root-mean square error is between  $0.06$  and  $0.10 \text{ mm h}^{-1}$ . Then, ET model outputs are compared with those from the European Centre for Medium-Range Weather Forecasts (ECMWF) and the Global Land Data Assimilation System (GLDAS). From this comparison, a high spatial correlation is noted, between 80 to 90%, around midday time frame. Nevertheless, some discrepancies are also observed and are due to the different input variables and parameterisations used.

## 1 Introduction

Evapotranspiration (ET) is an important component of the water cycle, and is directly connected to the surface energy budget. However, as ET cannot be observed directly at large (regional to continental) scale, it is still poorly known today. A correct

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quantification of ET would contribute to a better knowledge of the water cycle and to an improved ability to quantify future changes in water cycle variables. Therefore, in order to palliate the lack of observations, ET models are developed. However, large uncertainties remain on the temporal evolution and spatial repartition of ET, and especially over land surface (see for example Boone et al., 2009). The Global Energy and Water Experiment (GEWEX) of the World Climate Research Program has been concentrating its efforts for many years on this issue. In particular LandFlux (Wood, 2010), a recent initiative of the GEWEX Radiation Panel, is tasked to set up global data sets of multi-decadal surface turbulent fluxes.

Although ET cannot be observed directly at large scale, remote sensing techniques offer increasing possibilities to characterise land surfaces at the regional scale and are able to provide useful input to a variety of ET models. Different techniques to assess ET using remote sensing (see Courault et al., 2005; Kalma et al., 2008, Li et al., 2009), from simple empirical relationships (e.g. Wang et al., 2007) to the most complex models (e.g. Rodell et al., 2004; Alberghel et al., 2010) have been investigated and applied to a variety of spatial scales, from local and regional (Bastiaanssen et al., 1997; Stisen et al., 2008; Miglietta et al., 2009) to global scales (Jiménez et al., 2009). Most of these studies are made for research purposes and use only selected datasets.

Recently, new developments have been made in order to obtain operationally ET estimates based on remote sensing, both at continental scale and global scales. These new monitoring tools exploit either polar or geostationary satellite data. The MODIS instrument, on-board Terra and Aqua is used to provide 8-days ET estimates at the global scale (Mu et al., 2007). WACMOS (Fernández Prieto, 2010; <http://wacmos.itc.nl/>), a recent initiative of ESA in collaboration with GEWEX, is currently developing a new global ET product (Timmermans, 2010) based on SEBS model (Su, 2002; Su et al., 2007) and on AATSR and MERIS sensors, both on-board the ENVISAT satellite. These new monitoring tools make use of polar orbiting satellite data. These satellites provide images with a high spatial resolution, but have the disadvantage of a low observation frequency (of the order of one observation per day, or less, for a given site). Consequently, these

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studies have to rely on interpolations in order to fill observation gaps and on the hypothesis of a constant evaporation fraction during the day, an approximation as, in practice, a diurnal variation exists (Lhomme and Elguero, 1999; Gentine et al., 2007). On the other hand, geostationary satellites provide images at continental scale with lower spatial resolution but a very high observation rates (with one observation every 30 min, or even 15 min, in the case of METEOSAT satellites). This high observation frequency is particularly interesting to monitor quickly evolving variables as a function of diurnal cycle and cloudiness. Precursor work has been made by Rosema (1993) to assess ET with METEOSAT satellite. Over the United States, GOES thermal sensor is exploited to provide hourly and daily ET estimates (Anderson et al., 2007). Other works in the same direction are on-going in Europe in the framework of the Global Monitoring for Environment and Security (GMES), in particular through the Geoland project.

The purpose of the present work is to present an ET operational model, relying on geostationary satellite data, which provides half-hourly ET in near-real time, over Europe, Africa and a part of South America. This work is developed in the framework of the EUMETSAT's "Land Surface Analysis – Satellite Application Facility" (LSA-SAF) (Trigo et al., 2010; <http://landsaf.meteo.pt/>), of which the objective is to develop algorithms for the estimation of operational land products using meteorological satellites. Its source of information is the SEVIRI instrument, on-board Meteosat Second Generation (MSG) satellites. This satellite has a 3 km spatial resolution at sub-satellite point, located at 0° latitude above the equator, and has a high observation repetition rate (15 min).

An important characteristic of our study is that we propose ET estimates for all weather conditions. Therefore, the model provides continuous ET times series, useful for further applications. Contrarily to most studies (Kalma et al., 2008), we do not use Land Surface Temperature (LST) as a mandatory input of the model for an all-weather evaluation of ET, because model evaluation would be restricted to cloud free sky conditions. Alternatively, the methodology developed here follows as a baseline the parametrizations used in Soil-Vegetation-Atmosphere Transfer (SVAT) schemes.

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Validation is an important activity for models targeting an offer of operational products. Therefore, an important part of this paper focuses on the model validation. Comparison with in-situ observations at local scale is a direct way to assess the quality of the ET model outputs. We therefore compare our model results with observations from CarboEurope and European stations from national weather services in Europe. Investigations of model behaviour at regional scale are beneficial to ensure good spatial estimation. However, validation at larger scale is still hardly possible, because of the lack of observations at this scale. Consequently, we compare our results with two operational models that provide ET at global scale, ECMWF and GLDAS (Rodell et al., 2004). This comparison is carried on over the whole MSG field of view.

This paper is organised as follows. The model formulation and its use in the context of LSA-SAF are presented (Sect. 2) and are followed by a short description of the LSA-SAF ET product (Sect. 3). Comparison with in-situ observations at local scale in Europe is the subject of Sect. 4. We present in Sect. 5 the results of the comparison with ECMWF and GLDAS. We finally discuss the results and draw conclusions and guidelines for future research directions (Sects. 6 and 7).

## 2 Methodology

In this section, we consider successively the model formulation, the used forcing data, as well as the operational implementation of the model in the context of LSA-SAF.

### 2.1 Model

The proposed model includes relationships classically used in SVAT models. We choose specific parameterizations from the TESSEL SVAT scheme (van den Hurk et al., 2000; Balsamo et al., 2009) as a baseline for model development, with a few variants in the formulation (see description below). The algorithm is then adapted to accept real-time data from meteorological satellites as forcing (Gellens-Meulenberghs et al., 2007).

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The basic spatial unit for the model is called hereafter pixel, in reference to the elementary unit of the sensor onboard the meteorological satellites. The model provides output directly at this scale. However, depending on the location of the pixel, different types of vegetation can share the area. In practice, the set of equations of the model is solved for different vegetation types composing the pixel, before spatially averaging at the pixel level. The pixel is therefore decomposed for the model calculation into smaller entities, homogeneous in term of vegetation type. The latter ones are called tiles hereafter.

The sensible  $H_i$  and latent  $LE_i$  heat fluxes are computed for each tile  $i$  using the classical bulk relationships

$$H_i = \frac{\rho}{r_{ai}} [c_p(T_{sk,i} - T_a) - g z_a] \quad (1)$$

and

$$LE_i = \frac{L_v \rho}{(r_{ai} + r_{si})} [q_{sat}(T_{sk,i}) - q_a(T_a)] \quad (2)$$

with  $\rho$  the air density,  $r_{ai}$  the aerodynamic resistance,  $c_p$  the heat capacity at constant pressure,  $T_{sk,i}$  the surface “skin” temperature,  $T_a$  the air temperature at level  $z_a$  above the location,  $g$  the acceleration due to gravity,  $L_v$  the latent heat of vaporisation,  $r_{si}$  the stomatal resistance,  $q_a$  the air specific humidity at height  $z_a$  and  $q_{sat}$  the value of the surface specific humidity at saturation. The aerodynamic resistance  $r_{ai}$  is computed as a function of the atmospheric stability following Monin-Obukhov similarity theory (Brutsaert, 1982)

$$\frac{1}{r_{ai}} = \frac{k u_{*i}}{\ln\left(\frac{z_a - d_i}{z_{0hi}}\right) - \Psi_h\left(\frac{z_a - d_i}{L_i}\right) + \Psi_h\left(\frac{z_{0hi}}{L_i}\right)} \quad (3)$$

with friction velocity given by

$$u_{*,i} = \frac{k u}{\ln\left(\frac{z - d_i}{z_{0mi}}\right) - \Psi_m\left(\frac{z - d_i}{L_i}\right) + \Psi_m\left(\frac{z_{0mi}}{L_i}\right)} \quad (4)$$

and Monin-Obukhov stability parameter computed as

$$L_i = \frac{\rho u_{*i}^3}{kg \left( \frac{H_i}{c_p T_a} + 0.608 \frac{LE_i}{L_v} \right)} \quad (5)$$

In Eqs. (3) to (5),  $k$  is the von Kármán constant ( $k = 0.40$ ),  $u_a$  is the wind speed at height  $z$  above the surface,  $\Psi_h$  and  $\Psi_m$  are respectively the sensible heat and momentum stability functions (Beljaars and Viterbo, 1994),  $d_i$  is the displacement height,  $z_{ohi}$  and  $z_{omi}$  are respectively the roughness lengths related to sensible and momentum fluxes. The stomatal resistance is obtained following the Jarvis (1976) approach adopted in ECMWF TESSEL SVAT scheme (Viterbo and Beljaars, 1995; van den Hurk et al., 2000). For vegetation, the general formulation is given by

$$r_{s,i} = \frac{r_{s,\min,i}}{LAI_i} f_1(S \downarrow) f_2(\bar{w}) f_3(\delta q_a) \quad (6)$$

where  $r_{s,\min,i}$  is the minimum stomatal resistance,  $\bar{w}$  is the average unfrozen soil water content,  $\delta q_a$  is atmospheric air moisture deficit and  $f_1$  to  $f_3$  are the Jarvis functions.

For the particular case of bare ground, a simplified formulation is used

$$r_{s,i} = r_{s,\min,i} \cdot f_2(w_1) \quad (7)$$

with  $w_1$  being the unfrozen soil water content in first soil layer. In Eqs. (6) and (7) TESSEL parameterizations and parameters values are adopted, excepted  $r_{s,\min,i}$  and  $LAI_i$ . Monthly  $LAI_i$  values are used as well as related parameterizations for displacement height ( $d_i$ ) and roughness lengths ( $z_{omi}$ ,  $z_{ohi}$ ) according to Masson et al. (2003). Adopted values for  $r_{s,\min,i}$  are listed in Table 1.

At tile level  $i$ , the surface energy budget, acting as a constraint on surface heat fluxes, is expressed by

$$Rn_i - H_i - LE_i - G_i = 0 \quad (8)$$

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where  $Rn_i$  is the net radiation at the surface and  $G_i$  is the ground heat flux. In Eq. (8) all fluxes, excepted  $Rn_i$ , are computed positively upward.

Net radiation is given by

$$Rn_i = (1 - \alpha)S \downarrow + \varepsilon(L \downarrow - \sigma T_{sk,i}^4) \quad (9)$$

5 where  $\alpha$  is the albedo,  $S \downarrow$  is the downwelling short wave surface flux (DSSF),  $\varepsilon$  is the emissivity,  $L \downarrow$  is the downwelling surface longwave flux (DSLFL),  $\sigma$  is the Stefan-Boltzmann constant and  $T_{sk,i}$  is the skin temperature. In the above expression,  $Rn_i$ ,  $S \downarrow$ ,  $L \downarrow$ , are counted positively downward.

As a second constraint, the ground heat flux is approximated by

$$10 \quad G_i = \beta_i \cdot Rn_i \quad (10)$$

the method of Chehbouni et al. (1996) being adopted to derive  $\beta_i$  from the Leaf Area Index ( $LAI_i$ ) at the tile level.

Given the non-linear interdependency between variables  $H_i$ ,  $LE_i$ ,  $T_{sk,i}$  and  $u_{*,i}$ , an iterative procedure is used to solve the Eqs. (1), (2), (4) and (8) taking relationships  
 15 (3), (5) to (7), (9) and (10) into account. Neutral stability is assumed as initial condition. Iteration is stopped when pixel estimates of latent and sensible heat fluxes are numerically stabilized.

The averaged  $LE$  flux at pixel level is given by

$$LE = \sum \zeta_i LE_i \quad (11)$$

20 where  $\zeta_i$  and  $LE_i$  are respectively the coverage fraction and the latent heat flux of tile  $i$  in the considered pixel. The land cover types associated to tiles (grassland, crops, forests, bare soil, etc.), the respective coverage fraction  $\zeta_i$  and associated parameters are deduced from the ECOCLIMAP land cover database (Masson et al., 2003).

25 The evapotranspiration flux  $E$  [ $\text{kg m}^{-2} \text{s}^{-1}$ ] at pixel level is associated to the latent heat flux  $LE$  [ $\text{W m}^{-2}$ ] through

$$E = LE/L_v \quad (12)$$

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with  $L_v$  the latent heat of vaporisation [ $\text{J kg}^{-1}$ ] computed as

$$L_v = [2.501 - 0.00234 (T_a - 273.15)] 10^6 \quad (13)$$

$T_a$  being the air temperature [ $\text{K}$ ] at the height  $z_a$  above the surface.

In the above expressions, all fluxes are expressed in  $\text{W m}^{-2}$ .

The model presented here can be seen as a simplified SVAT scheme, because soil moisture variation is not explicitly modelled but is provided by an external source. This version of the ET model is currently running in near real time at the LSA-SAF host institute producing ET results over the full MSG disk with a time step of 30 min.

The model described in this section is referred by the acronym “MET” (for “MSG ET”) in the text. To check ability of the model to reproduce ET observations in a variety of biomes under different climatic conditions, the model has been first forced in off-line mode with local observations. Results of this verification are presented in Appendix A.

## 2.2 Forcing data and practical algorithm implementation

In the context of EUMETSAT LSA-SAF, the evapotranspiration model is forced with the available input derived from remote sensing, and especially from SEVIRI. The daily albedo (Geiger et al., 2008a, Carrer et al., 2010),  $\alpha$ , and the half-hourly short and long-wave surface radiative fluxes (Geiger et al., 2008b; Ineichen et al., 2009),  $S \downarrow$  and  $L \downarrow$ , available in the LSA-SAF are ET model forcing. In this way, we insure that short term fluctuations related to cloudiness variations as well as diurnal and annual radiation cycles are taken into account.

ECOCLIMAP (Masson et al., 2003) provides the model with the land cover at 1 km resolution and vegetation parameters required in SVAT models. In addition to the land cover classification in 215 ecosystems, the database provides a decomposition of each ecosystem into vegetation types, or tiles listed in Table 1. The tiles are the usual elementary units of most SVAT models. We adapted ECOCLIMAP, such as it could be used by our model. First, ECOCLIMAP is projected onto the grid defined by SEVIRI.

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ECOCLIMAP must then be obtained at a coarser spatial resolution. The number of tiles that one pixel can sustain is constrained to be three at maximum. For each pixel, monthly vegetation parameters are used for the three dominant tiles.

In operational mode, meteorological variables are pre-processed by the LSA-SAF computer system. Forecasts fields corresponding to 12 h–24 h term  $0.5^\circ \times 0.5^\circ$  are projected and spatially interpolated onto the MSG grid. Air and dew point temperatures at 2 m, 10 m wind speed, surface atmospheric pressure, soil moisture and temperature in the 4 soil layers are retrieved. Nearest neighbour is used as interpolation scheme except for temperatures for which a bicubic interpolation is implemented. Dew point temperature, air temperature and air pressure are used to calculate air specific humidity needed in Eq. (2). Soil moisture and soil temperature allow computing the liquid fraction of soil water content  $\bar{w}$  in the root-zone and in the superficial soil layer  $w_1$  in Eqs. (6) and (7), following van den Hurk et al. (2000). The meteorological fields are then linearly interpolated to 30 min time steps from their original tri-hourly values.

In the same way, MET adopts soil moisture and soil temperature with 4 soil layers from ECMWF forecasts, reinitialized twice a day by the ECMWF 4DVAR analysis process.

### 3 LSA-SAF ET product

The presented model is used to produce data files corresponding to land surface evapotranspiration estimates over the areas covered by MSG. The evapotranspiration product, ET, is generated in near-real-time every 30 min in the LSA-SAF system, using the latest information available from MSG SEVIRI instrument and ECMWF forecasts. Data files and quality flags are produced for the full MSG grid divided in 4 sub regions: Europe, North Africa, South Africa and South America. Figure 1 provides an example for the 19 August 2009 at 12:00 UTC for Europe and North Africa. A full ET product description is detailed in LSA-SAF Product User Manual (LSA-SAF, 2010).

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Registered users have free access to LSA-SAF ET results over full disk through LSA-SAF web site (see <http://landsaf.meteo.pt/>) or via EUMETCast (<http://www.eumetsat.int/Home/Main/DataAccess/EUMETCast/index.htm>) dissemination. Registered beta-

- 5 By interacting with the development team, users can contribute to improve the results or better adapt the proposed products to their specific needs.

#### 4 In-situ validation

The MET model is validated over Europe. We present here the results obtained from the comparison of the model with in-situ surface flux data from ground measurement stations. The surface fluxes have been provided by the CarboEurope network (Baldocchi et al., 2001), and local networks of national weather services (Table 2). Five measurement stations are situated in temperate climate zones, while another is located in a Mediterranean environment. Three types of temperate forest are represented in this validation, as well as Mediterranean and temperate grasslands. Lack in energy balance closure can lead to uncertainty on fluxes measurement around 20% (Wilson et al., 2002). However, FLUXNET data is obtained by state-of-the art eddy correlation technique applied uniformly over the full network. Possible accuracy limitation will be considered by comparison to a quality criterion defined at the end of this section.

We consider the period spanning from 1 March to 31 December 2007. This period is particularly relevant for Europe, because it includes a vegetation cycle and, in the same time, the periods for which the evaporation demands are the largest, due to the solar forcing. However, comparison at Hesse was not possible for 2007. Instead, data are available from 1 May to 30 June 2006, which, at least, includes the entire period of development of the canopy.

25 We focus on the comparison of the ET variable, since model aims at providing that output. However, the direct result of the model, corresponding to the pixel level estimation, is not used. Indeed, the pixel ET estimate could be very different from in-situ

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measurements if the pixel encompasses other vegetation types than the measurement target. In Europe, in particular, landscapes are fragmented a lot, and one MSG pixel is usually composed of various patches of vegetation. An example for March to May 2007 obtained from the Belgian measurement station over a forest in Vielsalm (Fig. 2) shows that the pixel mean seasonal diurnal cycle of ET is larger than observed. However, the MET tile level estimate, corresponding to the targeted vegetation type, reproduces the right diurnal cycle. This is explained by the occurrence in the MSG pixel of large grassland patches that are exposed to higher evaporation demand during that period. Therefore, to allow a meaningful comparison with ground measurements, we systematically force the model to output the ET estimate at the tile level for validation stations location. We select then ET for the tile that corresponds to the vegetation type representative of the local measurements.

In Table 3, we present the statistical results obtained from the comparison with the half-hourly measurements for the selected stations. All ET estimates are expressed in  $\text{mm h}^{-1}$ . Four statistical indices are tabulated for each dataset: the global bias, the root mean square error (RMS), the Nash index (Nash and Sutcliffe, 1970) and the global correlation coefficient. As well, a density scatter plot is shown in Fig. 3 for Vielsalm and Tojal, allowing an eased visualization of the statistical results. Bias is low, not exceeding  $0.2 \text{ mm h}^{-1}$  excepted for Tojal, indicating that on the long term, the mean ET computed is consistent with in-situ measurements. The RMS shows a fairly good capture of the short temporal scale dynamics by the model. At last, the correlation coefficient indicates that the model used in the context of remote sensing is able to reproduce the global temporal dynamics of evapotranspiration, at least for four of the datasets, with a correlation coefficient at 0.8 or above. For Hesse, however, the correlation coefficient is lower. A possible explanation is that the actual evolution of the canopy does not match with the monthly vegetation index used. The behaviour of ET variations is consequently affected on this short period. This conclusion is reinforced in view of the good results obtained in Table A2 for Hesse. At Tojal, representative of a drier environment, the correlation coefficient, equal to 0.74, is lower than in the other

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stations. A close analysis allows us to incriminate for a part of the year the soil moisture we input in the model for this location (see Sect. 6).

Fairly good results have been obtained from this validation, showing that the model is able to reproduce the global patterns observed at local scale. However, this exercise also shows the limitation of such validation methodology. Even if the correlation coefficient is fairly high, it will intrinsically not reach scores as in point-wise simulation using observed data as input, as in Appendix A, because the spatial scale differs between local scale measurements and meso-scale simulation of the model using SEVIRI derived data. Because of this limitation, and considering experimental uncertainty on observations, we introduce a quality criterion called “Product Requirement on Data quality” (PRD) applied on the model output. The PRD index is defined to score the rate of good estimations of the model given accuracy of reference observed measurements and with respect to future applications of MET results. To be considered as good the error should be less than 25% for the highest day time ET values. We selected a threshold of 0.4 mm h<sup>-1</sup> for this purpose. For other cases (night time, winter, morning and evening values), we adopt an absolute criteria: if ET is less than 0.4 mm h<sup>-1</sup>, then the error on ET should be less than 0.1 mm h<sup>-1</sup>. This quality criterion can be visualised on the scatterplots of Fig. 3, as dashed lines forming an envelope for good quality estimates. Overall results are also listed in Table 5. Using this score index, we obtain very good rates for all stations (from 80 to 90%), excepted for Tojal, where it reaches only 60%.

## 5 Intercomparison with ECMWF and GLDAS ET

Complementarily to the validation with local ground measurements, we propose here an assessment of the ET regional distribution. To achieve it, we compare MET output to other exiting products available operationally. While this intercomparison exercise is not a formal assessment of the MET capabilities compared to standard measurement techniques, it shows, however, if MET produces estimates within an acceptable range. For that purpose, ECMWF forecasts and GLDAS data (Rodell et al., 2004) are used to

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compare results at the regional scale. Main characteristics of used data are listed in Table 4.

The intercomparison spans over April to November 2007 (from March for the European area). In order to insure a consistent analysis of the results, LSA-SAF ET has been projected in latitude-longitude on the common coarser spatial resolution of  $1^\circ \times 1^\circ$  and cumulated tri-hourly. Figure 4 illustrates on a test case (Europe, 6 July 2007, 09:00 to 12:00 UTC) how the three model estimates compare. The corresponding surface short-wave downward radiation used as forcing is displayed as well. Note here that the tri-hourly GLDAS  $S \downarrow$  was not available and that the instantaneous flux at 12:00 UTC is displayed instead for a visual interpretation. On this test case, evident similarities of values range and patterns are recognisable. However, it clearly appears on a closer look that the three models do not give the same results and that large regional differences occur. On Fig. 4, it is obvious that, even if differences in  $S \downarrow$  could explain some differences in ET, it should not be the sole explanation. Interpretation of the differences will be discussed hereafter.

For a global comparison of the results, we first compute two-dimensional correlation between LSA SAF MET images and respectively ECMWF and GLDAS ET images. Figure 5 displays the evolution of 3-h mean image correlation over MSG European window, for the total period of comparison, between LSA-SAF ET and ET forecasts from ECMWF on one hand, and with GLDAS ET images on the other hand. The computed image correlation is nearly constant for 12:00 UTC and 15:00 UTC tri-hourly averages, with a correlation generally above 90%. For 18:00 UTC, a seasonal effect with a good correlation for March to September and a decreasing correlation during autumn is due to the progressive change from day to night, implying less contrast in ET images when ET drops to zero. Especially for the summer months, image correlation is slightly better with ECMWF than with GLDAS for 12:00 and 15:00 UTC. This observation confirms that the general patterns characterising European ET maps, like meteorological and land cover effects, are found in both products. However, better correlation with GLDAS is observed for 18:00 UTC towards the end of the time series. Similarly to Europe,

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spatial correlation between MET and ECMWF ET and GLDAS ET is computed for the 3 other geographical windows for the mid-day periods, 09:00 to 12:00 UTC and 12:00 to 15:00 UTC for Africa, 12:00 to 15:00 UTC and 15:00 to 18:00 UTC for South America. Spatial correlation is found higher than 80% in Africa and 90% in South America.

Correlation values obtained with ECMWF and GLDAS are similar, indicating that the three outputs agree on the general patterns of ET variations.

Getting further in our analysis, we compare the distributions of ET estimates occurrence of the three models. The mean distributions of tri-hourly averaged ET (09:00 to 12:00 UTC) for July 2007, as well as the mean value of the distributions, denoted by a vertical bar, are represented for the 4 geographical areas covered by MSG (Fig. 6). The distribution functions of the three model output have comparable shape and magnitude, except for South America. The comparison of means shows slight differences for Europe and South Africa. However, we find larger differences for South America and Northern Africa. For both, LSA SAF MET estimates are globally lesser than ECMWF and GLDAS estimates. For South America, the right tail of the LSA SAF MET distribution indicates a small occurrence of high ET values contrarily to ECMWF and GLDAS. Note that those observations are valid for the other months of the year (not shown).

At last, after comparing the spatial monthly differences between models, we examine, pixel-wise, the mean difference of the time series. Maps of the differences over the whole comparison period allow detecting where the models diverge. Figure 7 illustrates the  $1^\circ \times 1^\circ$  maps of bias between ECMWF and LSA SAF MET and between GLDAS and LSA SAF MET over the whole period of inter-comparison, for Europe and North Africa. To show more clearly the differences, a relative bias to the mean pixel-wise LSA SAF MET has been chosen as metrics. Positive bias means ECMWF or GLDAS exhibits larger estimates than LSA SAF MET. Local differences exist between the three model outputs. The highest differences occur in some parts of Southern Europe and around the Sahara desert. For Southern Africa (not shown), conclusions are similar to Northern Africa with less differences and a better correspondence between LSA SAF MET and GLDAS, than with ECMWF. As for Northern Africa, the larger differences are

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found near the desert, corresponding to dry regions with low evaporation rate.

To attempt explaining the observed differences between the three models, we calculate time series of spatial correlation from mean relative differences between MET and the two other considered models on one hand and three envisaged candidates to explain discrepancies between models on the other hand. The three suspected sources are (1)  $S \downarrow$  input in the models, since it is presumably the main driver of ET (Teuling et al., 2009), (2) the land cover and, more specially the high vegetation percentage, and (3) its associated parameterization, in particular the ration  $LAI/r_{s, \min}$  used in Eq. (6). In the following paragraph,  $\Delta\% \text{ Var}$  denotes the mean relative bias in the variable Var, that can be ET,  $S \downarrow$  or  $LAI/r_{s, \min}$ .  $\Delta \text{ CVH}$  is the absolute difference in high vegetation percentage. For Europe, North and South Africa, the spatial correlation time series of  $\Delta\% \text{ ET}$  with  $\Delta\% \text{ DSSF}$ ,  $\Delta\% \text{ LAI}/r_{s, \min}$  and  $\Delta \text{ CVH}$  are computed using the tri-hourly estimates (09:00 to 12:00 UTC). As shown in Fig. 8, for Europe, solar radiation is the main source of ET difference, as expected, especially during summer. Differences in surface global radiation are the main source contributing to differences in ET at each time step.  $\Delta\% \text{ LAI}/r_{s, \min}$  is the second main source of ET differences. The time series of this index shows an important seasonal behaviour. The correlation with ECMWF is positive (0.2 to 0.6) in Spring and Autumn, and with GLDAS during Summer. Contrarily to the solar radiation, that affects ET at all temporal scales, in particular at the shorter considered time steps,  $\Delta\% \text{ LAI}/r_{s, \min}$  biases ET estimates at a monthly time scale (as seen in Fig. 6). Land cover difference with ECMWF shows no correlation with ET differences, while with GLDAS, it exhibits a weak constant correlation (0.2 to 0.3).

The above investigations were extended to North and South Africa. The correlations computed over the whole period are given in Table 5. Figures with correlation time series over Africa are not shown: the information is globally redundant or otherwise stated. The two major sources of differences between LSA SAF MET and ECMWF ET at daily and annual time scales are  $\Delta\% \text{ DSSF}$  and  $\Delta\% \text{ LAI}/r_{s, \min}$ .  $\Delta\% \text{ ET}$  with GLDAS indicates  $\Delta\% \text{ DSSF}$  as the main driver of the differences, followed by  $\Delta\% \text{ LAI}/r_{s, \min}$ , at short time scale, and by  $\Delta \text{ CVH}$  over the entire period. A weak seasonal cycle,

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between  $-0.2$  and  $0.2$ , is observed (not shown) in the correlation with  $\Delta\% \text{LAI}/r_{s, \min}$ . This cycle in 2-D correlation can explain why  $\Delta\% \text{LAI}/r_{s, \min}$  does not give a reason for  $\Delta\% \text{ET}$  at the annual time scale, in the comparison with GLDAS.

To summarize, we have shown here that, despite high spatial correlations between the three investigated modelled ET, main reasons of differences are due to (1) differences in radiation fluxes used as forcing, (2) differences in land covers and (3) differences in parameterizations, in particular values adopted for the ratio  $r_{s, \min, i}/\text{LAI}_i$  in Eq. (6).

## 6 Discussion

As stated in Sect. 4, the lower scores obtained at Tojal incriminate the soil moisture input for this location. The initial coarser resolution of the ECMWF forecasts is a possible explanation: the soil moisture used in our model differs from the actual one. By replacing the ECMWF soil moisture forecasts by the actual observations of soil moisture in a point-wise simulation of our model, we show that the results of the comparison are far better than previously, with a correlation coefficient of  $0.84$ , a bias almost equal to zero and a RMS of  $0.06$ . The 5-days averaged ET dynamics is clearly improved (Fig. 9, left part and comparison between Figs. 3 and 9, right parts). The Tojal case indicates that using ECMWF soil moisture forecasts as input of our model may lead to erroneous ET estimates.

Such result encourages continuing research to particularly investigate model quality in driest regions of the world and to further improve the results globally. Soil moisture input accuracy is one main axe of activity. Different ways are explored simultaneously. First tests show that using an explicit modelling of soil thermal and moisture fluxes are beneficial provided that good quality rainfall rates are available. Improvement in rainfall assessment by remote sensing in the future could be profitable to this approach. Another option is to assimilate into the current model remote sensing products sensitive to soil moisture conditions, like LSA-SAF Land Surface Temperature (Trigo et al., 2008)

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and ERS/ASCAT SSM (Wagner et al., 1999; Drusch et al., 2009). Vegetation products (Verger et al., 2009) are also considered for this purpose and for refining values of parameters currently derived from the ECOCLIMAP database. In such configurations, benefits of the current method will be conserved but results should be improved thanks to the complementary information provided by additional consolidated remote sensed products.

## 7 Conclusions

The baseline version of the model (MET) is currently running in near-real time in the LSA-SAF operating system, producing half-hourly ET results at continental scale (over Europe, Africa and the Eastern part of South America), at the MSG spatial resolution (3 km at sub-satellite point). The results are produced for all weather conditions. This is particularly useful for applications that need continuous time series of ET and that cannot be limited to cloud free cases. Validation against ground measurements shows that LSA-SAF MET algorithm has high overall performances, at least in temperate regions, and is able to reproduce the temporal evolution of ET, at both diurnal to annual scales. The validation methodology used in this study allows a meaningful comparison by evaluating the model at the tile level. From the inter-comparison with ECMWF and GLDAS ET, we conclude that MET estimates are in a range compatible with those estimates and a spatial correlation between 80% and 95% for midday images through the studied period for the whole MSG field of view. For high co-zenithal angles better correlation is found with ECMWF while for low angles (spring/late autumn and morning/evening) with GLDAS. Observed discrepancies between models estimates are in most cases not systematic and can be explained in terms of differences in input variables and model parameterization.

Therefore, good confidence on MET results has been gained through the validation presented. However, assessing the quality of such model is still challenging, and more research is needed to confirm conclusions for all areas. It is why we will extend the

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validation to full disk, and, in particular, we must collect sufficient datasets in Africa (Merbold et al., 2009) and in dry climatic zones. In addition, validation supports our operational developments by detecting possible causes of uncertainty in some areas and leading the way towards further improvements. For example, it appears that a potential weakness of the model is the use of ECMWF soil moisture forecasts as input.

Refined versions of MET will be implemented in the LSA-SAF operational system as soon as on-going research and developments activities will demonstrate any significant improvement in capturing the ET process, applicable over the full MSG disk. Privileged means encompass using additional RS input, related to soil moisture and vegetation, and enhanced modelling capability. Users can access data and documentation from the LSA-SAF web site (<http://landsaf.meteo.pt/>). Interaction with the authors is welcome to better fit ET product with their requests and, in a general way, to improve the LSA-SAF products in the future.

## Appendix A

### Validation of MET algorithm

Validation of MET model itself is necessary to evaluate the pertinence of the formulation. Therefore, point-wise MET simulations forced by local measurements are compared to surface flux data provided by local ground stations, listed in Table A1. A broad range of climate zones and targeted vegetation types are represented through the validation. MET is forced by local observations, excepted for the soil moisture provided by ECMWF forecasts, and the vegetation indices provided by ECOCLIMAP when local measurements are not available.  $L \downarrow$  is not always available, and, if missing, is computed as prescribed in Stöckli et al. (2008). Results from the comparison of the half-hourly  $LE$ , converted to  $E$  by means of Eqs. (12) and (13), are presented in Table A2. Four complementary statistical indices are tabulated for each dataset: the global bias, the root mean square error (RMS), the global correlation coefficient and the

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Nash index (Nash and Sutcliffe, 1970). The lowest scores are obtained at Bondville, Puéchabon and Loobos. For the Puéchabon simulation, ECOCLIMAP database vegetation parameters have been used: the results could be the consequence of a bad capture of the canopy evolution essential dynamics. For Bondville and Loobos, however, the source of discrepancies has to be searched elsewhere, and could be due to unsuitable either soil moisture dynamics from ECMWF or parameters values. Overall, the results show that the model itself is able to reproduce the observed variations of ET, with high correlation coefficients and Nash indexes for most stations of the dataset.

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**Table 1.** Vegetation types and associated minimum stomatal resistance ( $r_{s, \min}$ ).

$i$	Vegetation type	$r_{s, \min, i}$ [ $\text{s m}^{-1}$ ]
1	Bare soil	50
2	Snow	NA
3	Deciduous Broadleaved Trees	300
4	Evergreen Needleleaved Trees	250
5	Evergreen Broadleaved Trees	250
6	Crops	180
7	Irrigated crops	180
8	Grass	110
9	Bogs and Marshes	250

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**Table 2.** Used flux stations for validation. Network (Net): Royal Meteorological Institute of Belgium (RMI), Koninklijk Nederland Meteorologische Instituut (KNMI), CarboEurope (CarboEur). North Latitude (Lat), East Longitude (Long). Biome types: mixed forest (MF), evergreen needle leaf forest (ENF), deciduous broadleaf forest (DBF), grassland (G). Elevation (Alt) of the site above sea level. Climate: temperate (Temp), Mediterranean (Med). Reference (Ref).

Station (country)	Net	Lat (deg)	Long (deg)	Biome	Climate	Alt (m)	Ref
Buzenol (B)	RMI	46.62	5.59	G	Temp.	320	Gellens-Meulenberghs (2005)
Cabauw (NL)	KNMI	51.97	4.93	G	Temp.	0	Beljaars and Bosveld (1997)
Tojal (PT)	CarboEur	38.48	-8.02	G	Med.	190	Peireira et al. (2007)
Hesse (FR)	CarboEur	48.67	7.07	DBF	Temp.	300	Granier et al. (2000)
Wetzstein (DE)	CarboEur	50.45	11.46	ENF	Temp.	785	Rebmann et al. (2010)
Vielsalm (B)	CarboEur	50.30	6.00	MF	Temp.	450	Aubinet et al. (2001)

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**Table 3.** Comparison between LSA-SAF ET and observed ET at validation stations: statistical results (Bias [ $\text{mm h}^{-1}$ ], RMS [ $\text{mm h}^{-1}$ ], correlation coefficient (Corr), Nash index, PRD criterion (see text) [%]); vegetation type: Grassland (G), Deciduous Broadleaved Forest (DBF), Evergreen Needleleaved Forest (ENF), Mixed Forest (MF).

Station	Vegetation Type	Bias	RMS	Corr	Nash	PRD
Buzenol	G	0.02	0.10	0.81	0.51	80.1
Cabauw	G	0.02	0.07	0.90	0.66	90.1
Tojal	G	0.05	0.10	0.74	0.18	59.9
Hesse	DBF	0.00	0.09	0.56	0.31	89.9
Wetzstein	ENF	-0.02	0.08	0.79	0.59	87.9
Vielsalm	MF	0.02	0.06	0.80	0.54	88.2

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**Table 4.** Summary of models characteristics and output used for inter-comparison.

	ECMWF	GLDAS
Versioning	Cycle 31r1	GLDAS/Noah 2.7.1.
Land Surface Scheme	TESSEL	Noah
Coupled to atmosphere	Yes	No
Domain	Global	Global
Horizontal spatial resolution	0.25	1°
Available temporal resolution	3 h	3 h
Land Cover Used	IGBP	University of Maryland

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**Table 5.** Spatial correlation between the mean  $\Delta\%$  ET and the mean of (1)  $\Delta\%$  LAI/ $r_{s, \min}$ , (2)  $\Delta$  CVH and (3)  $\Delta\%$  S  $\downarrow$  for North and South Africa (see text).

		$\Delta\%$ LAI/ $r_{s, \min}$	$\Delta$ CVH	$\Delta\%$ S $\downarrow$
NAfr	MET-ECMWF	0.31	0.12	0.42
	MET-GLDAS	-0.02	0.19	0.48
SAfr	MET-ECMWF	0.54	0.01	0.65
	MET-GLDAS	-0.09	0.10	0.38

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**Table A1.** Flux stations. Network (Net): AmeriFlux (AmFlux), Koninklijk Nederland Meteorologische Instituut (KNMI), Coordinated Energy and water cycle Observations Project (CEOP), CarboEurope (CarboEur), Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA). Latitude (Lat), Longitude (Long). Biome types: crops (C), grassland (G), deciduous broadleaf forest (DBF), evergreen needle leaf forest (ENF), evergreen broadleaf forest (EBF). Climate: temperate (Temp), Mediterranean (Med), tropical (Trop). Period (years). Reference (Ref).

Station	Net	Lat [° N]	Long [° E]	Biome	Climate	period	Ref
Bondville	AmFlux	40.00	-88.29	C	Temp.	2002–2003	Meyers et al. (2004)
Cabauw	KNMI/CEOP	51.97	4.93	G	Temp.	1995–1996	Beljaars and Bosveld (1997)
Hainich	CarboEur	51.07	10.45	DBF	Temp.	2003	Knohl et al. (2003)
Hesse	CarboEur	48.67	7.07	DBF	Temp.	1997–1998	Granier et al. (2000)
Le Bray	CarboEur	44.72	-0.77	ENF	Temp.	1997–1998	Porté et al. (2000)
Loobos	CarboEur	52.17	5.74	ENF	Temp.	2003	Dolman et al. (1998)
Puéchabon	CarboEur	43.74	3.59	EBF	Med.	2002–2003	Joffre et al. (1996)
Santarem	LBA/ CEOP	-3.02	-54.97	EBF	Trop.	2002–2003	Goulden et al. (2004)

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**Table A2.** Comparison between half-hourly ET measurements and ET estimates obtained by MET forced with local observations. Bias [ $\text{mm h}^{-1}$ ], RMS [ $\text{mm h}^{-1}$ ], correlation coefficient (Corr), Nash index. Out of range (OR) refers to negative Nash index.

	Bias	RMS	Corr	Nash
Bondville	0.015	0.10	0.71	0.38
Cabauw	0.014	0.06	0.91	0.78
Hainich	0.019	0.05	0.81	0.60
Hesse	0.018	0.08	0.80	0.60
Le Bray	-0.024	0.08	0.81	0.63
Loobos	0.024	0.10	0.50	OR
Puéchabon	0.012	0.07	0.68	0.09
Santarem	0.013	0.14	0.76	0.56

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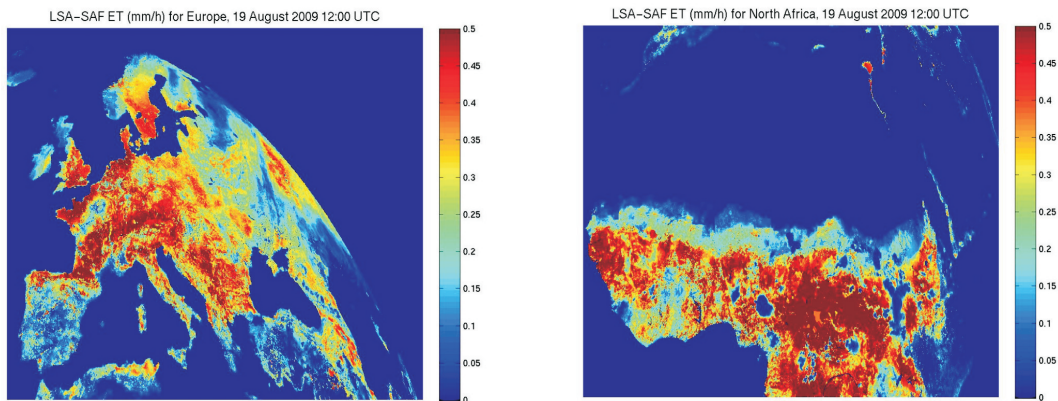
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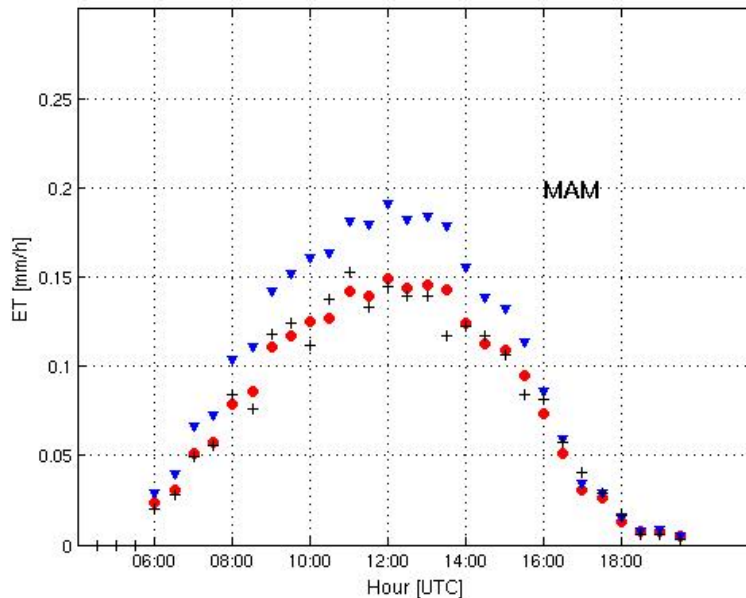


**Fig. 1.** LSA-SAF ET (mm/h) over Europe (left) and North Africa (right) on 19 August 2009 at 12:00 UTC.

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**Fig. 2.** Mean seasonal diurnal cycle of ET for the CarboEurope-IP Vielsalm station for March to May 2007. Observation (+), pixel (v) and “tile” (o) estimate from LSA-SAF MET.

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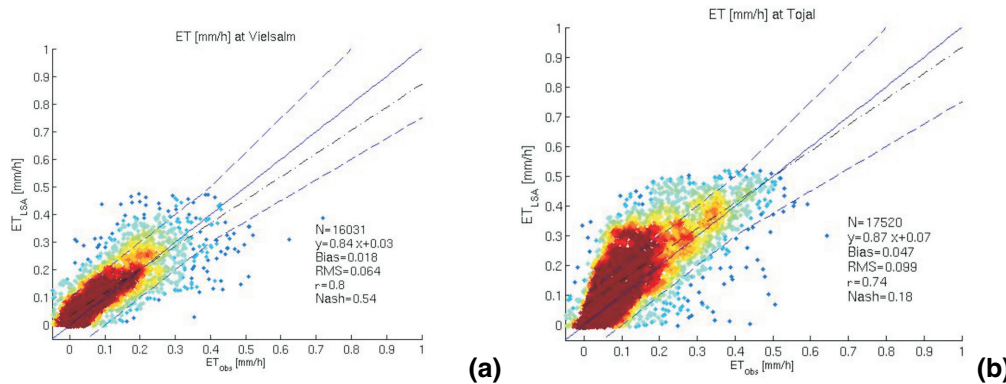
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**Fig. 3.** Comparison between 30 min LSA-SAF ET ( $\text{mm h}^{-1}$ ) and observations at **(a)** Vielsalm FLUXNET station (Belgium) and **(b)** Tojal (Portugal). Period: March to November 2007. Dashed line: envelop associated to PRD criteria (see text); straight line: 1:1 line; Dashdotted line: linear regression line.

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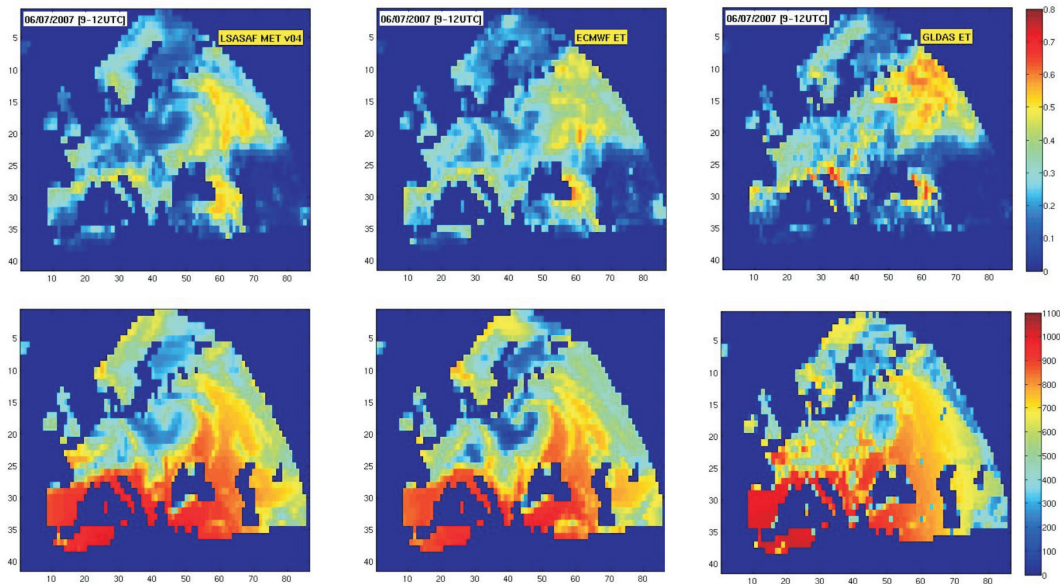
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**Fig. 4.** Comparison of LSA-SAF (left), ECMWF (middle) and GLDAS (right) ET (top) and global radiation (bottom), 3-h averages (09:00 to 12:00 UTC, excepted GLDAS global radiation: instantaneous 12:00 UTC) for the 6 July 2007.

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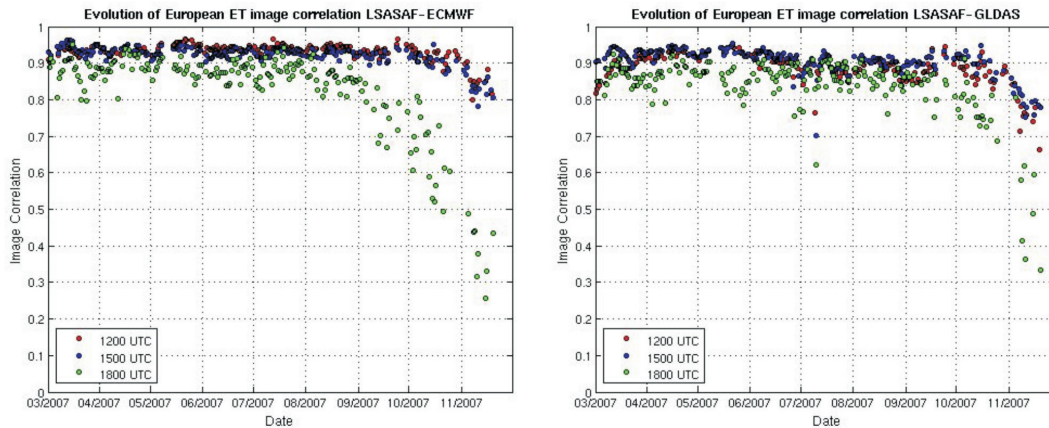
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**Fig. 5.** Evolution of 3-h mean image correlation over MSG European window between LSASAF ET and ET ECMWF forecasts (left), and with GLDAS ET images (right), from March to November 2007.

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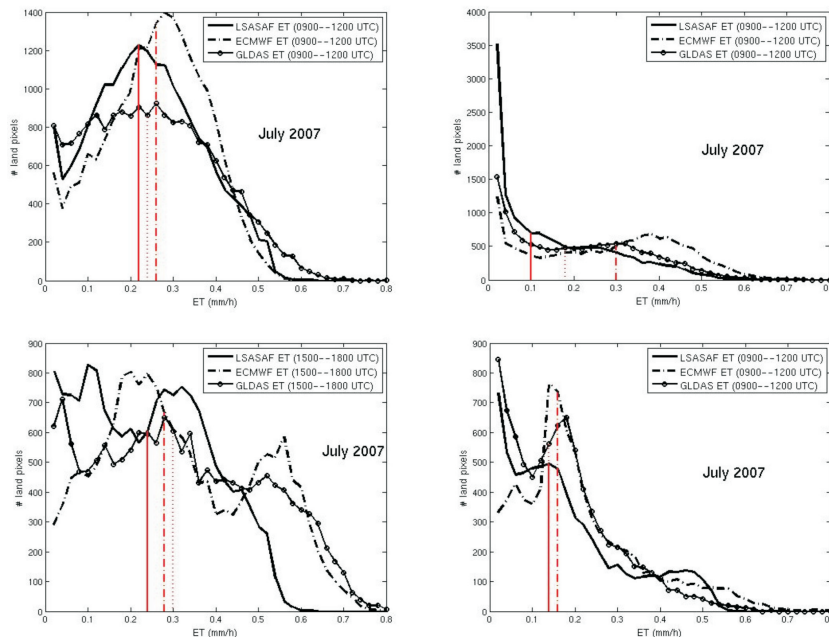
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**Fig. 6.** Distributions of ET estimates from LSA-SAF (solid line), ECMWF (dash-dotted line) and GLDAS (solid line and circles). Each figure encompasses the mean distribution of the 3-h averaged ET (09:00 to 12:00 UTC) for July 2007, as well as the mean values of the distributions (vertical lines). Europe (upper left), North of Africa (upper right), South of America (lower left), South of Africa (lower right).

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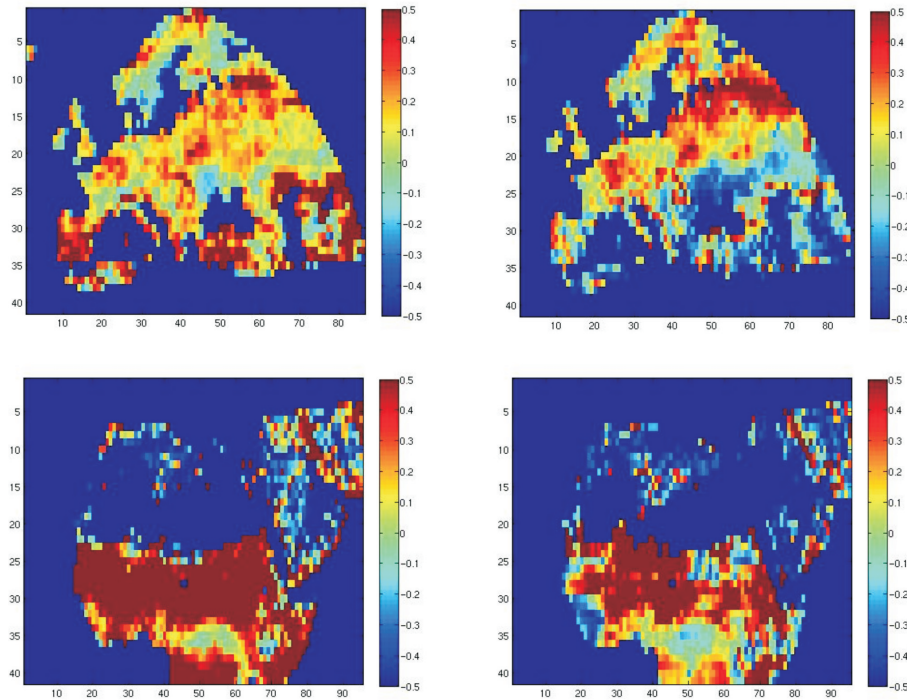
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**Fig. 7.**  $1^\circ \times 1^\circ$  maps of bias between ECMWF ET and LSA SAF MET (left) and between GLDAS and LSA SAF MET (right) over the whole period of inter-comparison. Europe (upper part), North of Africa (lower part).

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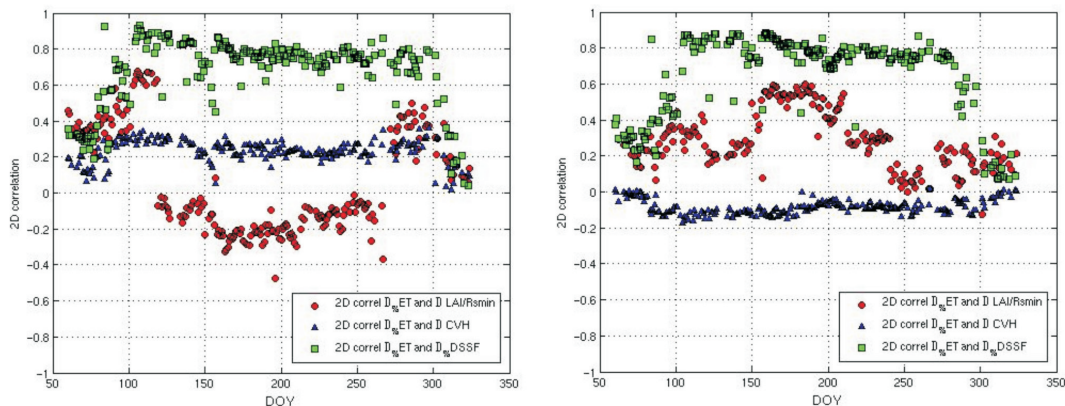
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**Fig. 8.** Spatial (2-D) correlation over Europe between the ET mean relative bias (based on the images between 09:00 to 12:00 UTC) and model differences: (1)  $LAI/r_{s,min}$  (red diamonds), (2) High vegetation percentage (CVH, blue triangles), and (3)  $S \downarrow$  mean relative bias (DSSF, green squares). At left: comparison between LSA SAF MET and ECMWF. At right: comparison between LSA SAF MET and GLDAS.

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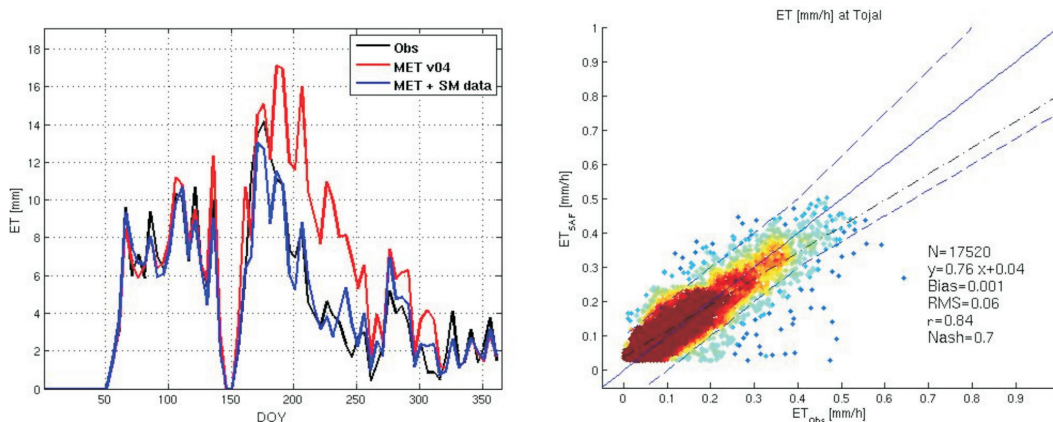
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**Fig. 9.** Left: time series of the 5-days cumulated ET measured (black) and modelled (red) for the CarboEurope-IP Tojal station (Portugal) for the period from March to November 2007 as provided by LSA SAF MET. Modelled ET using soil moisture measured at the station (blue) has been superimposed. Right (as in Fig. 3) but modelled ET computed with soil moisture measured at the station compared to 30 min mean observed ET.

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