

Continental Scale Monitoring of Subdaily and Daily Evapotranspiration Enhanced by the Assimilation of Surface Soil Moisture Derived from Thermal Infrared Geostationary Data

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1 INTRODUCTION

Monitoring evapotranspiration (ET) over large areas is required in some environmental applications that need regularly updated information about water loss from the soil. Such information, if delivered daily, could benefit different sectors relying on warning systems of drought or flood occurrence (Sepulcre-Canto et al., 2014; Petropoulos et al., in press). But not only that, as some energy, transport (Wade et al., 2006; Dierickx, 2014), and recreational infrastructures (Throssell et al., 2009) also rely on this information to take appropriate measures. Daily ET estimations over continents can already be obtained by the time integration over the day of short-term forecasts by numerical weather prediction (NWP) models. However, the limited timely access to observation data for the surface characterization and the coarse resolution of the final products constrains their use in the aforementioned applications.

A monitoring system based on more Earth observation satellite data seems a valuable option. In the EUMETSAT (European Organization for the exploitation of Meteorological Satellites), Satellite Application Facility (LSA-SAF) (Trigo et al., 2011), an algorithm delivering operationally half-hourly and daily ET maps in near-real time using a combination of numerical weather forecasts and surface variables (mainly surface radiation) derived from the SEVIRI

sensors onboard the European Meteosat Second Generation (MSG) geostationary satellites (Ghilain et al., 2011).

Its capabilities have been demonstrated in several studies (Ghilain et al., 2011; Petropoulos et al., 2015; Hu et al., 2015; Jovanovic et al., 2014). However, difficulties of this monitoring system arise in some places from the strong dependence of the ET model parameterization to some forcing variables from the numerical weather forecasts, and especially on the modeled soil water status (Ghilain et al., 2011). Therefore, we have explored ways to further constrain the model by assimilating more available satellite data. We included, among others, a daily variation of the vegetation status, and an estimation of daily averaged soil moisture using the satellite-derived land surface temperature, wherever it was possible to adequately relate both variables in a near-real time operation mode. The special focus on soil moisture is justified by its strong connection with ET in semiarid regions: a strong reduction in soil moisture generally implies a restriction on plant transpiration (Williams and Albertson, 2004). Therefore, soil moisture is found to be one of the major components limiting ET in semiarid regions (Teuling et al., 2009).

In this chapter, we review the proposed strategy to monitor ET over Europe and Africa in the LSA-SAF context (half-hourly/daily at 3–5 km spatial resolution). The impact on surface heat fluxes of assimilating vegetation state and surface soil moisture from Earth observation (EO) thermal infrared (TIR) data is assessed by comparing the new proposed prototype with ground observations of surface heat fluxes, and we discuss possibilities for further research lines.

2 OPERATIONAL PRODUCTION OF EVAPOTRANSPIRATION MAPS USING GEOSTATIONARY SATELLITE OBSERVATIONS IN NEAR-REAL TIME

To face the demand from the different regional, national, and international organizations for natural hazard management, and especially in agriculture and hydrometeorology, the EUMETSAT LSA-SAF has set up a service to deliver products related to continental land surface, exploiting the capabilities of the European meteorological satellites. Evapotranspiration is one of the variables that is so far drawing the most interest among public and private sectors (<http://landsaf.meteo.pt/viewDocument.jsp?id=599>), as it provides an indicator of early drought warning due to its high sensitivity to soil moisture deficit. In providing a near-real time service with freely available products, LSA-SAF has therefore launched an almost unique service (Romaguera et al., 2010, 2012, 2014a,b) (http://aramis.obs-pm.fr/~jimenez/Docs/WACMOSET/WACMOSET_WP3300_approved.pdf). With the daily ET product, continuous in time, available in near-real time with continental coverage, and a spatial resolution of 3–5 km, LSA-SAF is therefore complementing nicely and partially filling the gap in current scientific services.

The uniqueness of the product finds its roots in the exploitation of continuous satellite data, in comparison to products delivered by integrated forecast systems, like the European Center for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS). The products are designed for land surface processes with a spatial sampling that is better than the worldwide forecasts. On the other end, LSA-SAF ET product is complementary to the different ET data sets that have been worked out for climate analyses, usually at a coarser spatial resolution (e.g., [Miralles et al., 2010](#); [Balsamo et al., 2015](#)). LSA-SAF ET also responds to several of the requirements from the agriculture sector (http://aramis.obspm.fr/~jimenez/Docs/WACMOSET/WACMOSET_WP1100_approved.pdf).

2.1 Physical Principles

The ET algorithm developed in the framework of the LSA-SAF ([Trigo et al., 2011](#)) targets the estimation of the flux of water vapor and heat release from the ground surface into the atmosphere using physical drivers retrieved from MSG satellites. Satellite remote sensing (SRS) stays as the only method capable of providing wide area coverage of environmental variables at economically affordable costs. However, a major difficulty to the use of SRS for monitoring ET at regional and global scale is that the phase change of water molecules produces neither emission nor absorption of an electromagnetic signal. Therefore, the ET process cannot directly be quantitatively observed from satellites: it has to be modeled, taking advantage of information retrieved from the satellite observations about surface variables having a direct influence on ET ([Choudhury, 1991](#)). Most of the proposed methods use SRS-derived data combined into models with different degrees of complexity, ranging from empirical direct methods to complex deterministic models based on land surface schemes that compute the different components of the surface energy budget ([Courault et al., 2005](#); [Verstraeten et al., 2008](#)). The simplest methods are only applicable locally and should be calibrated again when applied elsewhere. Most methods can only be applied for clear sky conditions, as necessary observations from EO satellites cannot be retrieved in cloudy situations.

The methodological approach selected in the framework of the LSA-SAF intends to be applicable at regional to global scales, to be able to provide a monitoring at short time step, as it allows to follow the diurnal cycle evolution, and to obtain results continuously for all cloudiness conditions. In addition, it has been conceived to ingest an increasing number of remote sensing-derived products as they are released to the community through time. The adopted method can be described as a soil vegetation and atmosphere transfer scheme modified to work in the LSA-SAF operational chain and accept input data from external sources ([Ghilain et al., 2011](#)). It is based on the physical model of the Tiled ECMWF surface scheme for exchange processes over land (TESSEL) ([Viterbo and Beljaars, 1995](#); [van den Hurk et al., 2000](#)). Main modifications

operated to the initial model allow the model to run uncoupled from the atmospheric model and to use data from external sources like SRS-derived data, NWP output and recent information about land-cover characteristics. The adopted methodology combines the forces of remote sensing approaches and NWP models.

In this approach, the area for which ET has to be assessed is divided into independent pixels, in a one-to-one correspondence with the pixels of a satellite image. Each pixel is in turn considered as being a mix of homogeneous *tiles*, each tile representing a particular soil surface: bare soil, C3 crops, grass, deciduous broadleaf forest, and so on. The global pixel value is obtained through the weighted contribution of each tile. Theoretically, ET can be derived in near-real time at the time resolution of MSG satellite images. In practice, the generation of ET will be limited by the availability of input data.

The ET model is conceived to solve an energy balance at the surface for each tile composing each pixel, taking into account the specificity of each tile by a dedicated set of parameters (Ghilain et al., 2011). Once a solution has been found by iteration for each tile, a value of the surface heat fluxes is computed as a weighted average of each tile. Evapotranspiration is directly computed from latent heat flux. At the end of the day, the individual values are summed to compose a daily estimate, without requiring further assumptions.

The needed drivers of the ET model are short and longwave radiation reaching the surface, the near-surface air temperature and humidity, the wind speed at a few meters above the surface, soil moisture and temperature at various depths, the surface albedo, the type of surface and associated characteristics: fraction of vegetation, leaf area index (LAI), roughness lengths, and emissivity.

2.2 Earth Observation Satellite Data

The suite of Meteosat meteorological satellites is interesting for a close monitoring of fast evolving processes in the atmosphere, but also at the surface of the Earth, because of their strategic position in geosynchronous orbit. The SEVIRI instrument carried on board, delivers information in 12 spectral channels in the optical, and near to thermal infrared range, for an observation of the different essential atmospheric and land surface processes (<http://www.eumetsat.int>). Of interest for land surface, channels operating in the optical, near infrared, and thermal infrared spectral ranges present an excellent opportunity to monitor land surface at every full scanning time (i.e., every 15 min). Meteosat satellites are good candidates for monitoring as they are operational satellites committed in continuous service that has not been interrupted since the early stage by the launch of the Meteosat satellites of the first generation in the 1980s. After the suite of the four second-generation satellites, EUMETSAT is preparing actively the launch of the next series of the third generation, providing with the flexible combined imager instrument, continuity to MVIRI and SEVIRI sensors aboard previous satellite generations, but complemented with

new technology allowing new observation capabilities in terms of spatial and temporal sampling.

For ET monitoring, the Meteosat satellites provide possibilities to have access to a continental coverage every 15 min. Within the LSA-SAF, a whole operational production chain has been set up to derive variables of interest for land surface monitoring. Products related to surface energy budget, vegetation, water stress, and fires are being generated mostly from Meteosat data, but also from the polar orbiters MetOp-A and -B (see Fig. 1).

In a first algorithm, delivering ET maps operationally since 2009, only radiation products from LSA-SAF have been exploited: the half-hourly surface short and longwave downwelling radiation components (Geiger et al., 2008a; Trigo et al., 2010) and the daily surface albedo (Geiger et al., 2008b). For the surface state characterization, and vegetation parameterization, the ECOCLIMAP database (Masson et al., 2003) projected and aggregated to the variable resolution of the Meteosat view is used: it gives the needed information on land cover type, its decomposition into a few plant functional types, a classification useful for SVAT models, a monthly varying vegetation parameterization, including LAI, fraction of vegetation cover, the surface roughness, and the surface albedo in case LSA-SAF product is missing. The database is simple to use

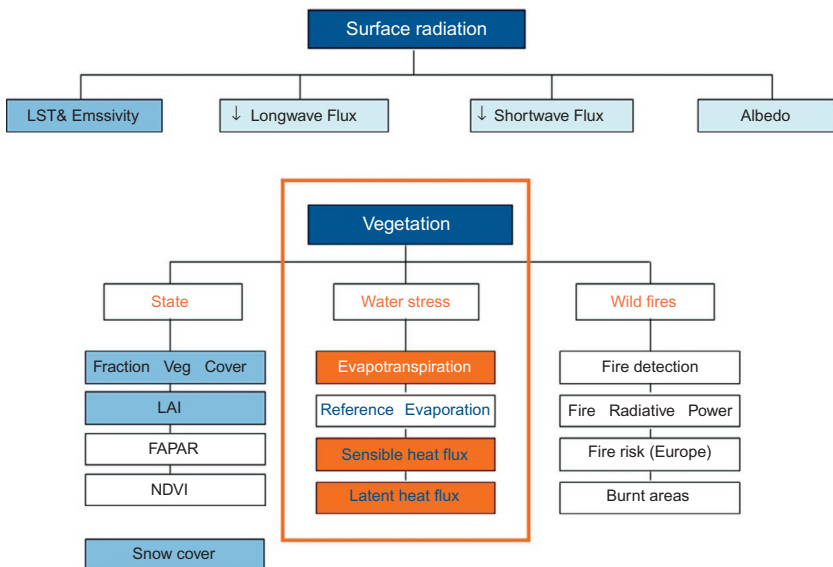


FIG. 1 List of the existing and foreseen products in LSA-SAF in the structure defined during the continuous development and operation phase 2 (2012–2017). Evapotranspiration products are part of a broad class gathering information on vegetation and characterizing water stress. Sensible and latent heat flux are foreseen to be delivered at the same time as evapotranspiration. In the operational evapotranspiration algorithm, three LSA-SAF products are used (*light blue*). In a later version, LSA-SAF ET v2, the use of four additional products is foreseen (*darker blue*).

as it refers to a monthly varying look-up table. Only the three dominant plant functional types are retained per observing surface unit for computation efficiency.

The other input information is obtained from ECMWF IFS. Forecasts between 12 and 24 h departing from the initial analysis of wind speed at 10 m, air temperature and humidity at 2 m, soil moisture and temperature at four depths, initially at 0.25 degree spatial resolution and temporal sampling of 3 h, are disaggregated to 1 h and to the spatial resolution of MSG using a bilinear interpolation, and a topographical correction on air temperature (De Bruin et al., 2010).

2.3 Operational Production and Dissemination

The ET algorithm is run by the operational chain of LSA-SAF every 30 min for each of four districts of interest composing the MSG field of view: Europe (Euro), Africa-North (NAfr), Africa-South (SAfr), and South America (SAm). The ET rates are stored in mm h^{-1} in a hierarchically formatted file together with a quality flag, informing the user on the expected accuracy of the estimates and the possible causes of degradation (see Fig. 2).

Daily ET are obtained by temporal integration of instantaneous values generated by the ET algorithm according to

$$\text{DMET} = \int_{h_1}^{h_2} \text{MET}_i(t) dt \quad (1)$$

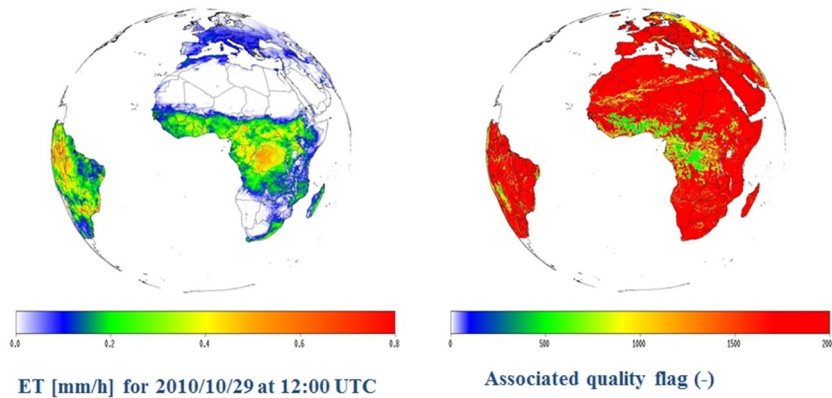


FIG. 2 Visualization of an example of half-hourly ET product. The MSG field of view has been recomposed from the four districts of interest. The instantaneous evapotranspiration rate of 12 coordinated universal time (UTC) for Oct. 29, 2010, is accompanied by its quality flag, showing pixels of reduced quality (in yellow and in green).

where MET_i are the instantaneous ET estimates provided by the ET algorithm every 30 min for a given day. The integration limits (h_1, h_2) correspond to the first (theoretically at 00:30 UTC) and last (theoretically at 24:00 UTC) existing slots for a given day. In the best situation, a total of 48 images are generated by day what means that for each MSG pixel, 48 ET values have to be integrated. It happens that some images are missing for a given day. To provide a daily consistent value for each pixel, a linear interpolation between the closest slots is applied according to

$$MET_j = MET_{j-1} + 0.5(MET_j + MET_{j-1})N \quad (2)$$

where MET_{j-1} and MET_j are previous and next existing ET values for the same pixel in considered day and N is the number of time steps between previous and next existing ET values.

The daily product consists of three layers in file: the daily ET per pixel, the percentage of values used for time integration, and the number of missing slots (Arboleda et al., 2011).

Once generated, the products are stored, disseminated via satellite telecommunication to the users via EUMETCAST service, the LSA-SAF website (<http://landsaf.meteo.pt>), from where it feeds other dissemination tools owned by third-parties for targeted users after some transformations (e.g., Water Observation and Information System, Guzinski et al., 2014).

2.4 Accuracy and Caveats of the Operational Retrieval

The accuracy of the LSA-SAF ET product has been reported in several studies (see Fig. 3). Comparisons have been made with observations from the ground measurements networks (e.g., FLUXNET, RMI-AWS (Gellens-Meulenberghs, 2005)), either on a reprocessed archive (Ghilain et al., 2011) or directly on the disseminated product (Hu et al., 2015; Jovanovic et al., 2014). Also comparisons at continental scale or basin scales with other models have been reported (Hofste, 2014; Ghilain et al., 2011; Helman et al., 2015), and usage of it for other applications (Sepulcre-Canto et al., 2014; Romaguera et al., 2012, 2014a,b; Cammalleri et al., 2014). The studies have reported good accuracies over Europe, with an ability to represent well the seasonal cycle of vegetation, the daily variations, and effects of specific events, like vegetation fires (Hu et al., 2015). In Africa, contrasted accuracies have been reported, but mostly with a better accuracy over temperate regions of Africa (Jovanovic et al., 2014) and low accuracies over semidesert areas (Hofste, 2014; Ghilain et al., 2011; Petropoulos et al., in press). After careful examination, it was concluded that soil moisture input used by the model could be inadequate in those areas (Ghilain et al., 2011). Also, the vegetation representation in the model could play a role in adjusting the transpiration to the actual annual vegetation cycle (Ghilain et al., 2012).

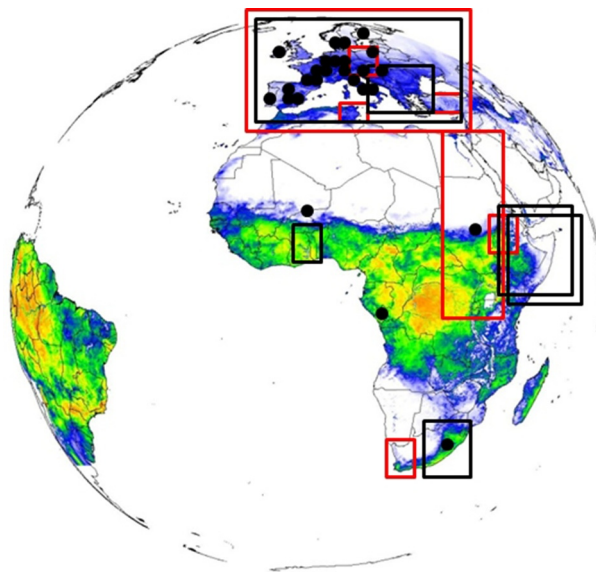


FIG. 3 Areas where validation (*black dots and red frames*) or usage (*black frames*) of LSA-SAF ET products have been reported in the scientific literature are mostly localized in Europe, but also cover parts of the African continent.

Stability over time of the incoming information is a crucial element in setting up and maintaining a proper continuous near-real time operational production. The ET algorithm of LSA-SAF relies on various sources of information with a strong dependency. A change of satellite, for example, replacing the exploitation of MSG-3 by MSG-4, might have an impact on all the primary and secondary satellite products, due to calibration problems, faulty onboard devices, or in the numerous processing software packages. For meteorological fields, ECMWF IFS has been selected for its stability and high performance, providing very high quality meteorological variables at an ever-increased spatial resolution. However, to maintain this, changes of ECMWF forecast system cycles can bring a discontinuity in the supplied fields, triggering large efforts to adapt the processing of application products downstream. Over the years, several updates have been applied to the land surface scheme TESSEL used in operational weather forecasts at ECMWF (see [Table 1](#)), a few of them having heavy consequences on the nominal generation of the ET products of the LSA-SAF, and especially related to soil moisture.

Both arguments, degraded quality over semiarid Africa and strong dependence in ECMWF soil moisture, pushed further development in relying less on ECMWF IFS soil moisture and more on remote sensing data, if at all possible. This initiative was eased by the increasing accessibility and maturity of soil moisture products derived from satellites. In addition to soil moisture, the new developments have considered vegetation-related products obtained through remote sensing.

TABLE 1 List and Dates of Implementation of Changes in the IFS at ECMWF, Relevant to Land Surface

Cycle	Date	Changes
32r3	2007-11-06	New soil hydrology scheme
35r2	2009-03-10	Revised snow scheme
35r3	2009-09-08	Routine monitoring of soil moisture observations from Metop-A ASCAT
36r1	2010-01-26	Deterministic forecast and analysis horizontal resolution is increased (16 km)
36r4	2010-11-09	Monthly varying climatology of LAI based on MODIS data
		Change of parameterization of the bare soil evaporation
		Recalibration of vegetation parameters

Source: <http://www.ecmwf.int>.

3 A NEW PROTOTYPE OF THE EVAPOTRANSPIRATION ALGORITHM CONSTRAINED BY MORE EO SATELLITE DATA

3.1 Surface Soil Moisture Index Derived From Land Surface Temperature

Soil moisture is one of the important environmental factors constraining ET rates in semiarid environments. Finding a source for soil moisture is constrained by the operational timeliness of the monitoring system, but also by the continuity of the generation of such data and products. A potential source of information for soil moisture from EO are products derived from the microwave scanning aboard polar orbiters (Bartalis et al., 2007; Kerr et al., 2010; Petropoulos et al., in press). In the framework of EUMETSAT, an easy and fast transmission of data is possible between EUMETSAT centralized (headquarters) and decentralized (SAF) production facilities. Therefore, the products based on MetOp-ASCAT sounders are on the first line, as they are processed at EUMETSAT headquarters. However, as the surface soil moisture product is provided at a spatial resolution coarser (~25 km) than the ET product from MSG, an alternative proposed in the early stage of development was to first exploit the TIR signal, and especially the diurnal variation of the land surface temperature, from Meteosat-SEVIRI. It had the advantage of avoiding any delay in the production by relying on LSA-SAF-derived products only, with the desired spatial resolution of a few kilometers.

The exploitation of the land surface temperature for soil moisture monitoring has been studied for decades by scientists showing an increasing interest over the years and yielding promising results mostly at regional scale (Verstraeten et al., 2006; Stisen et al., 2008; Garcia et al., 2014). Within the framework of LSA-SAF production, a stable methodology had to be developed for continental scale application in near-real time. As proposed in earlier studies (Stisen et al., 2008; Garcia et al., 2014), the daily morning heating rate computed from LST at a specific location is used to estimate a daily surface soil moisture estimate using a low-order model.

However, this combination of TIR observations from a geostationary satellite and of a simple low-order model is expected to render meaningful surface soil moisture estimates only in a set of geographical zones depending on the surface characteristics (vegetation and soils) and climates. A simple model has therefore been developed, applied with the land surface temperature product from LSA-SAF (Trigo et al., 2008; Freitas et al., 2010; Ermida et al., 2014) and an extensive validation has been carried out sampling climates of Europe and Africa (Ghilain et al., 2015) revealing the accuracy and limitations in applying this methodology. The results showed acceptable accuracy in soil moisture retrieval using this technique over semiarid and arid areas, including Mediterranean regions and Sahelian regions. Mitigated to insignificant performances were found for temperate climates of Europe and humid climates of Africa. A further analysis showed that the new indicator could be better than, or as accurate as, ECMWF IFS soil moisture short-term forecasts for semiarid regions of Africa and Southern Europe (see examples in Fig. 4) for days with available satellite observations.

In semiarid regions, the TIR signal exploitation brings additional information: wetland extents and irrigation can be easily detected, as shown in Fig. 5, because of their clear contrasts with their neighboring environment.

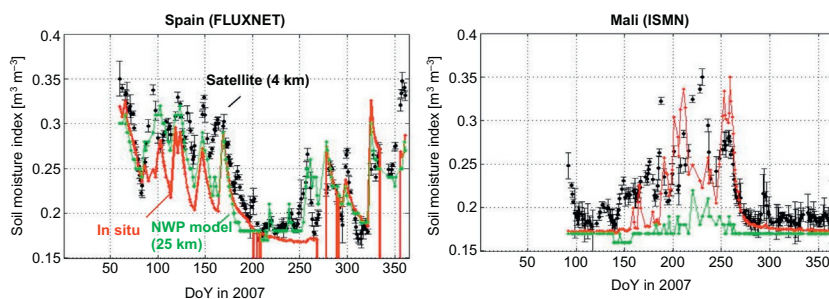


FIG. 4 Examples of validation of the surface soil moisture retrieved from land surface temperature (black) with in situ observations (red) and comparison with the ECMWF IFS soil moisture input of the current operational ET product (green). The satellite-derived soil moisture relates better than the numerical weather prediction (NWP) soil moisture for the African site.

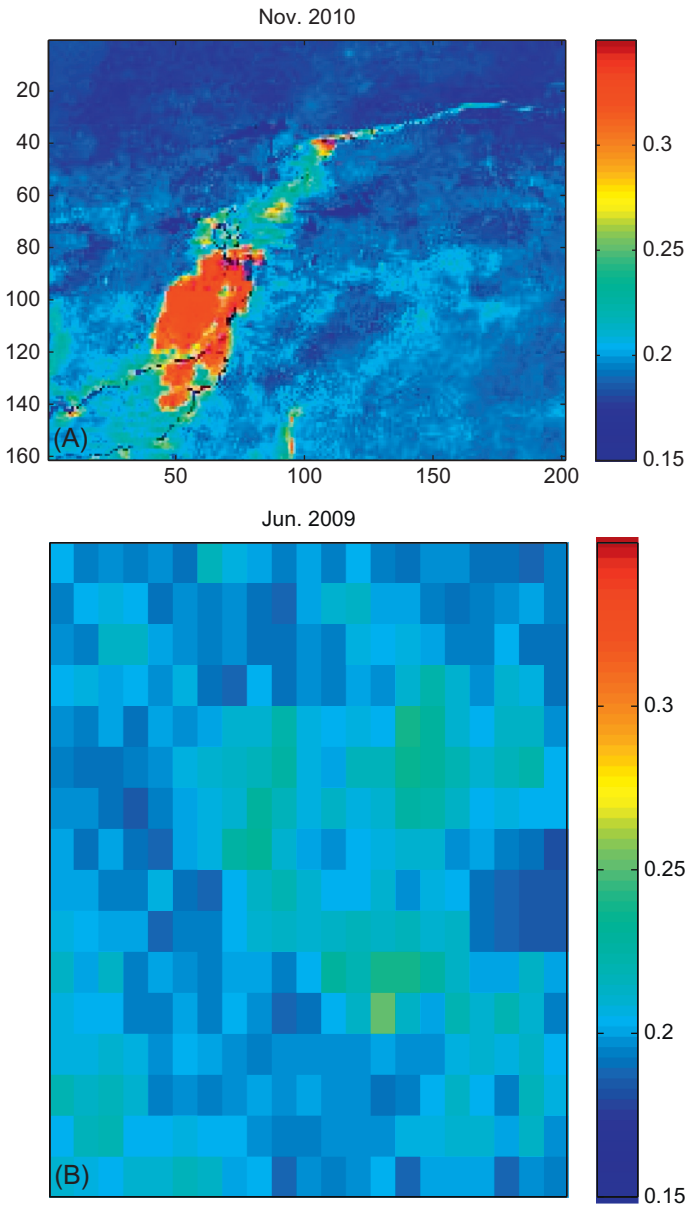


FIG. 5 Wetlands are identified as areas of high soil moisture, as here for the inner Niger delta in Nov. 2010. Irrigation patterns are also recognizable as zones of higher soil moisture even at the coarse resolution of the satellite, as in the area of Barrax-Albacete, Spain, in Jun. 2009. Soil moisture represented is rescaled between 0.171 and $0.35 \text{ m}^3 \text{ m}^{-3}$.

3.2 Assimilation of Vegetation Products From EO Satellites

LAI is a variable characterizing the vegetation vertical abundance of leaves, quantifying the vertically integrated area of green material per surface unit on the ground. The LAI used in this context is produced daily by LSA-SAF at a spatial resolution of a few kilometers in the SEVIRI projection (Garcia-Haro et al., 2005). Using that product presents several advantages resulting from an up-to-date follow-up of the vegetation state pixelwise: it allows the detection of short-term local fluctuations to interannual variability of vegetation health and productivity. Those are expected to bring a clear improvement to the ET model, as its vegetation information is varies monthly in the operational context, based on past data and does not vary from year to year.

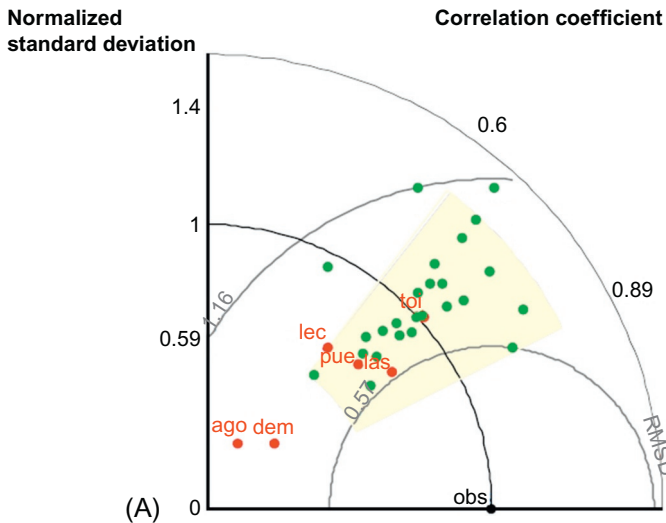
After having implemented the change from the ECOCLIMAP customized database to the LSA-SAF LAI for use in the ET algorithm (Ghilain et al., 2012), we have reprocessed archives for the year 2007 over Europe and Africa. The result of the comparison between the new version and ground observations shows a clear improvement over semiarid areas especially in Europe: correlation scores have been improved, and variability is comparable to the observations (see Fig. 6). However, the scores at Sahelian sites have been found to be still very low, showing that the model is quite more sensitive to soil water availability than vegetation input and that the current soil moisture information was not adequate for those regions.

3.3 Prototype Usage of Soil Moisture Products

Land surface temperature is not a universal indicator of soil moisture. Past studies (Prigent et al., 2005) discovered that the amplitude of the land surface temperature diurnal cycle was related to soil moisture in regions controlled by thermal inertia, not in transpiration-driven regions (Teuling et al., 2009). The validation study presented in Ghilain et al. (2015) exhibits the same conclusions: results from the comparison show an overall good performance over semiarid regions and degradation toward more wet and vegetated areas. As an operational application should not be of degraded quality by a change in the model or in its settings, a comparison of the performances of the two sources was undergone over Africa and Europe to select the best source of soil moisture data in function of climate zones. One of the indicators used in this comparison with observational ground-truthing data sets was the correlation coefficient, which is one of the measures of soil moisture products quality requested by the EUMETSAT users (http://hsaf.meteoam.it/documents/docs/20130100/SAF_HSAF_CDOP2_PRD_1_0.pdf). By grouping the results of the statistical comparison for the different sites within a climate zone, it was possible to state the actual performance of the two sources, and to define where the soil moisture derived from Meteosat satellite data could better characterize soil moisture than

Comparison MET (4.0.3) and observations

Mar. 1, 2007–Dec. 31, 2007

**Comparison MET (4.1.0) and observations**

Mar. 1, 2007–Dec. 31, 2007

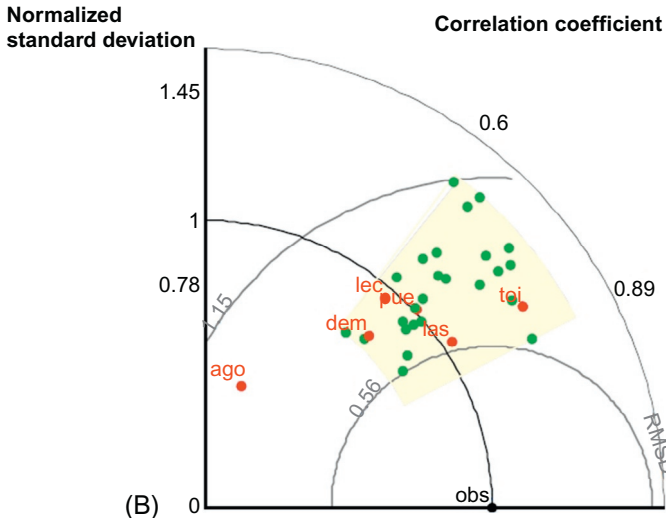


FIG. 6 Statistical scores of the comparison of LSA-SAF ET in its nominal configuration (MET 4.0.3), or with the use of LSA-SAF vegetation products (MET 4.1.0) with observations from the FLUXNET sites over Europe and Africa. Each point (*green* in unstressed and *red* (with label) in stress soil moisture conditions) in the Taylor diagram (Taylor, 2001) represents the comparison of 1 year time series. Sites in Africa are Agoufou (ago) and Demokeya (dem).

ECMWF IFS forecasts for days with not completely overcast conditions (see Fig. 7). The interpretation of the diurnal variation of LST in terms of soil moisture is further hampered by the specific viewing geometry of the SEVIRI sensor and its relation to terrain orography. Areas with complex terrain are assigned to ECMWF IFS soil moisture, as more research would be needed to disentangle the signal from the soil moisture from its perturbation due to shadows and facing south observation. In the Mediterranean region, scores of the ECMWF IFS are slightly higher than the thermal signal from the satellite. But, as irrigation is a common agricultural practice in that zone, and ECMWF IFS does not perform up to now to a spatial resolution where irrigation may have an impact on weather, we select the thermal signal for soil moisture primary source in the regions where irrigation is significant (at least 10% based on the cadastral map of agricultural infrastructure (Siebert et al., 2010, 2013) and the available data from the Food and Agriculture Organization).

Finally, for regions where the primary source is the satellite-derived soil moisture, unavoidable gaps due to persistent cloudy conditions or to missing satellite data are filled by ECMWF IFS soil moisture, locally adapted to match the temporal dynamics imposed by the soil moisture derived from the satellite (Liu et al., 2011) (see Fig. 8).

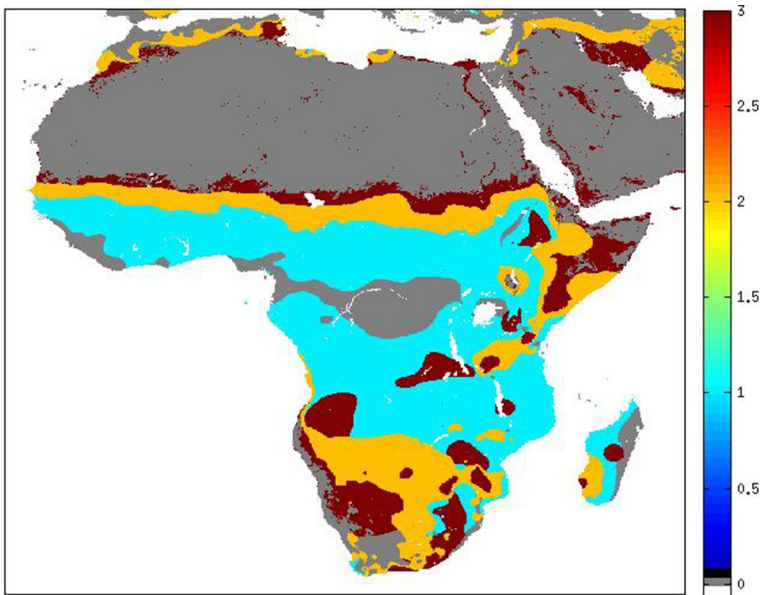


FIG. 7 Map of choice of input data for soil moisture based on the clustering by climate of comparison of both sources to in situ observations: EO derived is best based on correlation (*brown areas*), ECMWF IFS is best (*light blue*), equal/slightly better ECMWF IFS (within 3% difference in correlation) (*orange*), and unknown accuracy (*grey*). The best source possible is used by the LSA-SAF ET new prototype.

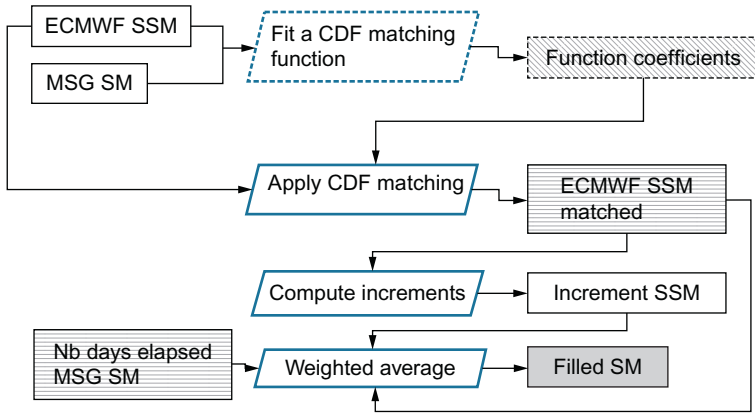


FIG. 8 Flowchart of the process of filling gaps due to persistent cloud coverage in time series of soil moisture derived from LST. ECMWF IFS soil moisture is matched to past series and coefficients are applied to transform it when needed.

Once a surface soil moisture map has been obtained, the root-zone soil moisture is computed for zones with prevalence of the satellite input using an exponential filter (Albergel et al., 2008), differentiated for high and low vegetation types. For zones where ECMWF IFS is selected as the primary source for soil moisture, nothing is altered in the algorithm exposed in the first section.

3.4 A Revised Scheme for Evapotranspiration Modeling

The physical equations and parameterizations behind the algorithm have not been substantially revised. New processes were added to the model: interception of rain and dew by the vegetation canopy and its evaporation, snow sublimation in the case of permanent or temporary snow, and evaporation over small water bodies. Revision of the soil moisture limitation over bare soils and parameters related to vegetation resistance to transpiration was undergone. The representation of the vegetation development in the model has been revised, especially for crops and forests.

The formulation canopy resistance, r_c , of the vegetation to transpiration is based on van den Hurk et al. (2000), while the parameterization for crops and nonperennial grasslands has been slightly changed, such as to introduce more sensitivity of the model for low green biomass conditions.

For crops and grass in semiarid ecosystems:

$$r_c = \left(\frac{r_{s,\min}}{0.25 \cdot (\exp(\text{LAI}) - 0.8)} + 50 \right) f_1(S_{\downarrow}) f_2(\bar{\theta}) f_3(D_a) \quad (3)$$

For the other cases:

$$r_c = \frac{r_{s,\min}}{\text{LAI}} f_1(S_{\downarrow}) f_2(\bar{\theta}) f_3(D_a) \quad (4)$$

where $S_{\downarrow}$ is the surface shortwave radiation, $\bar{\theta}$ is the average unfrozen soil water content, D_a is the atmospheric water pressure deficit, LAI is the leaf area index, $r_{s,\min}$ is the minimum stomatal resistance, and $f_1(S_{\downarrow})$, $f_2(\bar{\theta})$, $f_3(D_a)$ are functions parameterizing the effect of environmental factors on the plant transpiration rate.

The minimum stomatal resistance, $r_{s,\min}$, scaled by LAI or the effective LAI (crops and nonperennial grasslands) fixes the maximum rate of ET observed for each vegetation type in the absence of any constraints. Values of $r_{s,\min}$ were recalibrated.

A separate formulation is used for bare soil. A minimum stomatal resistance is associated with bare soil to represent the minimum soil resistance and the only stress assumed for soil evaporation is due to soil water deficit, via a modified Jarvis function $f_{2,\text{BS}}$, which allows a broader range of soil moisture sensitivity. f_{liq} is the fraction of the soil water content that is in liquid phase, θ_{pwp} is the soil water content at wilting point, chosen to be the minimum soil water content possible, and θ_{fc} is the soil water content at field capacity, value above which ET is not restrained anymore by soil water content. Both θ_{pwp} and θ_{fc} act as values to rescale the soil water content of the surface soil layer (0–7 cm) θ_1 . In the model, they are set to values prescribed in the TESSEL model for average soils, 0.171 and 0.323 $\text{m}^3 \text{m}^{-3}$, respectively.

$$r_c = r_{s,\min} \cdot f_2(f_{\text{liq}} \cdot \theta_1) \quad (5)$$

$$f_{2,\text{BS}}(\bar{\theta})^{-1} = 1 + \exp\left(-50 \cdot \frac{\theta - \theta_{\text{pwp}}}{1000 \cdot (\theta_{\text{fc}} - \theta_{\text{pwp}}) + 1}\right) \quad (6)$$

4 GAIN AND LOSS OF ACCURACY IN CHOOSING A NEW SOURCE FOR SOIL MOISTURE INPUT: VALIDATION OF THE PROTOTYPE BY COMPARISON WITH IN SITU OBSERVATIONS

The revised algorithm was tested over FLUXNET stations in Europe and Africa with soil moisture received from ECMWF IFS and, in addition for Mediterranean and African regions, also with the new soil moisture input derived from land surface temperature retrievals. The result of both implementations was compared to ground measurements. For each site, and each year, statistical measures of agreement have been computed: bias, root mean square difference and correlation index. The difference of each score between both configurations is represented in Fig. 9, highlighting the gain (in green) and loss (in red) of

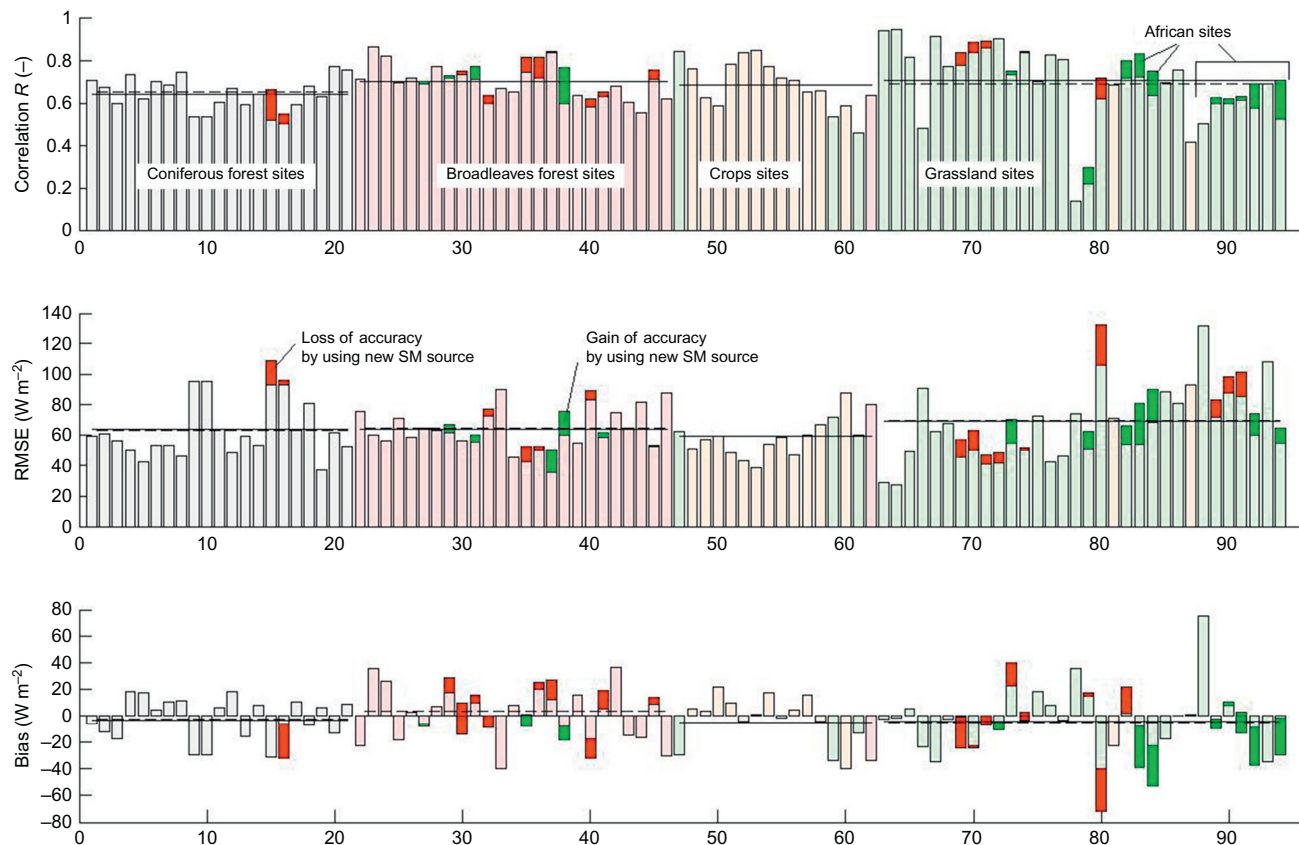


FIG. 9 Statistical scores of comparison of the new evapotranspiration prototype algorithm using and not using EO soil moisture with yearly ground observation data sets of latent heat flux. Gain and loss of accuracy in using EO soil moisture are represented in *green* and *red*, respectively.

accuracy in using satellite-derived soil moisture to derive half-hourly ET, here presented as an energy component, the latent heat flux.

From Fig. 9, it is clear that the assimilation of remote sensing derived soil moisture improves the daily variations of ET over African savannahs with dominance of herbaceous species: the correlation is improved, the bias is reduced, and the dispersion is reduced most of the time. However, the result of assimilation in the Mediterranean European grassland sites shows no improvement or even a slight degradation in the statistical scores. This is mostly attributed to the high-quality forecast of soil moisture by ECMWF IFS over Europe, supposedly because of the assimilation of near-surface meteorological observations from the dense European network. For the Mediterranean forests, no systematic effect can be detected, with some sites presenting gain and loss of accuracy alternatively over the years.

5 COMPARISON WITH THE OPERATIONAL PRODUCT

A comparison with the operational product has been initiated at the location of measurement sites (see Fig. 10). As expected, the ET patterns have been largely improved in the Sahel region, where the operational algorithm has difficulties in accounting for the large seasonality of water fluxes. The combination of assimilating vegetation and soil moisture products from EO seem to work out the actual daily variations, with some exceptions. In Spain, however, the comparison does not show a large improvement, as the operational version gives results already close to the in situ observations.

6 CONCLUSIONS

The LSA-SAF delivers near-real time products derived from Meteosat satellites, as a decentralized production center of EUMETSAT. It is targeting the near-real time provision of land surface variables, such as radiation components at the surface, but also the surface characterization (vegetation monitoring, snow, and fire detection), and finally the heat and water fluxes from the land surface. The operational algorithm for deriving half-hourly ET is based on a model driven by three radiation components produced by LSA-SAF and by short-term forecasts from the ECMWF. When assessing its accuracy, both the development team and the users have reported its accuracy and limitations. One of the limitations in accuracy has been found to be pronounced in semiarid regions, and especially in Africa. After careful examination, the ET algorithm was found to exploit an inappropriate soil moisture source, which is derived from the ECMWF forecasts, caused either by the forecast quality of the soil moisture in those regions or by the regular updates of the forecast system that can cause degradation in downstream applications if they are not well studied beforehand.

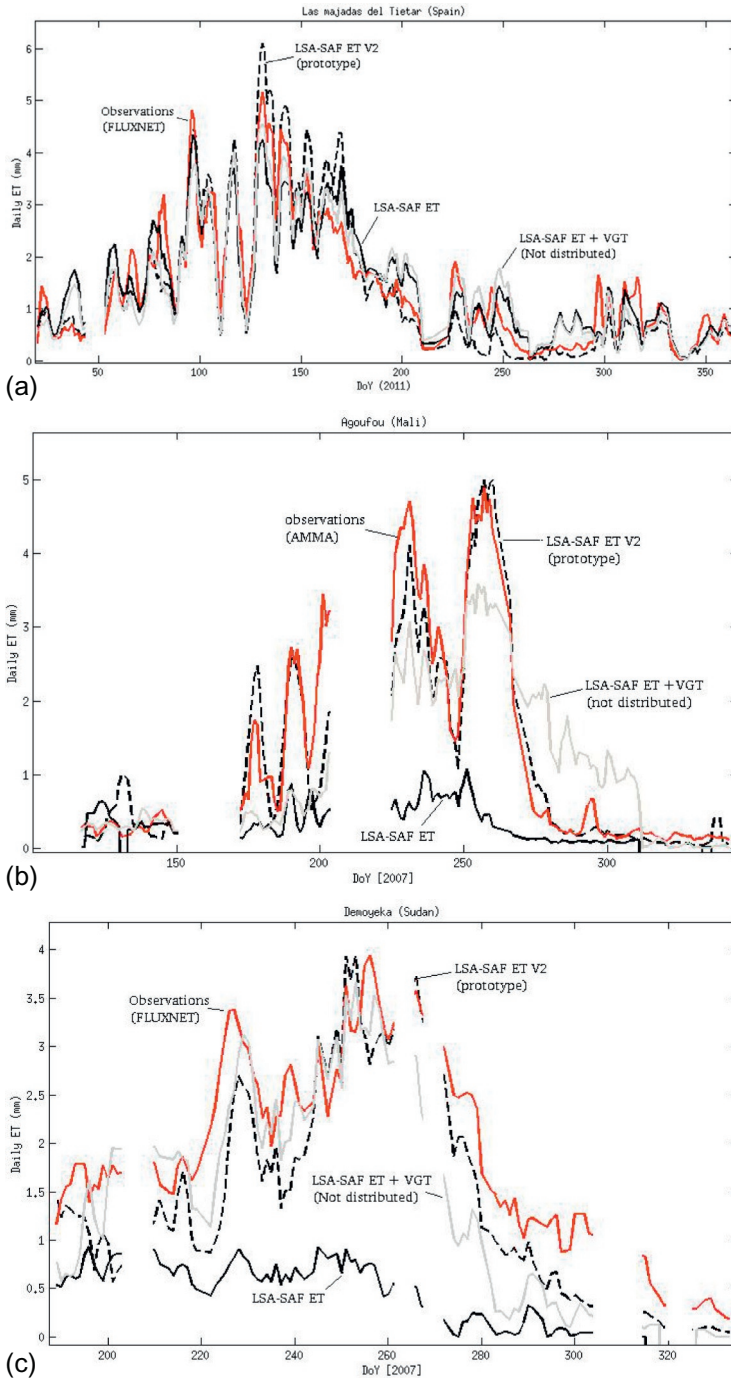


FIG. 10 Comparison of daily evapotranspiration rates at three sites of the operational algorithm (LSA-SAF ET), a modified version using EO-derived vegetation parameters from LSA-SAF (LSA-SAF ET+VGT) and the new proposed algorithm LSA-SAF ET V2. While it is clear that the assimilation of soil moisture derived from land surface temperature and vegetation dynamics does not specifically improve the evapotranspiration rates for the Dehesa site in Spain, the quantification is much more accurate for the tested African semiarid savannahs [Agoufou-Mali (Kergoat et al., 2011; Timouk et al., 2009); Demoyeka—Sudan (Merbold et al., 2009; Sjöström et al., 2009)].

To reduce the dependence in ECMWF forecasted soil moisture and improve the quality of the soil moisture input to the ET model, a new strategy has been developed to assimilate the land surface temperature derived from MSG/SEVIRI as a proxy for soil moisture. Jointly, daily vegetation parameters have been assimilated in the model. Assimilation of the soil moisture derived from land surface temperature is only considered in parts of African and Mediterranean regions, where soil water stress is frequent. The evaluation of those changes shows that ET monitoring will definitely gain in accuracy at least in African grassland savannahs if using the land surface temperatures from the satellite, while results do not show a significant improvement, or even sometimes a degradation, in using it in the Mediterranean regions, except for the practical consequences of relying less on the ECMWF system changes. However, the soil moisture from remote sensing allows the detection of irrigation areas and wetlands that cannot be resolved by ECMWF forecasts, and will impact ET monitoring. The new implemented strategy is leading to a new version of ET products in LSA-SAF, which will cope with deficiencies reported in the semi-arid regions.

7 FUTURE LINE OF OPERATIONAL RESEARCH

In this study, TIR signal from Meteosat, specifically the land surface temperature product from LSA-SAF, has been exploited to constrain the soil moisture availability for ET processes. From an operation point of view, research should now focus on localizing where the microwave soil moisture products, which are becoming more and more mature, could still further improve the soil moisture constraint, also in cloudy sky conditions, and how it could be achieved in near-real time. One privileged line would be the exploitation of the EUMETSAT H-SAF soil moisture products, from microwave observations delivered by the ASCAT sensors aboard MetOp-A/B polar satellites (Bartalis et al., 2007; Wagner et al., 2007). In addition, the use of the soil moisture delivered by the SM-DAS-2 analysis (Albergel et al., 2012), assimilating jointly synoptic meteorological observations and soil moisture derived from microwave sensors aboard space technology, could be an interesting alternative to the ECMWF IFS, if delivered on time, as it integrates the latest information on the land surface readily accessible using an efficient integrated infrastructure and communication lines in Europe and globally. On the other hand, efforts should carry on to improve the estimation of soil moisture using TIR signal from satellites and on the possibilities of combining the different sources of information (e.g., Zhao and Li, 2013), as precursor studies have undergone for climate studies (Liu et al., 2011).

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