

Monitoring evapotranspiration at continental scale: enhanced contribution from geostationary satellites

PhD thesis

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Monitoring Evapotranspiration at Continental Scale: Enhanced Contribution from Geostationary Satellites

by

Nicolas Ghilain



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To Laurence, Louise & Jeanne

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Abstract

Water resource is a major concern for sustainable development in many semi-arid areas. Early detection of drought and monitoring water consumption by agriculture are highly important for adaptation in policy of regional water use. As a crucial component of the water cycle, still poorly known accurately, land evapotranspiration is a primary source of information for such water resources assessments. Remote sensing from geostationary satellites offers the possibility to monitor evapotranspiration over large areas at relatively high temporal and spatial resolutions. The Satellite Application Facility on Land Surface Analysis (LSA-SAF) of the European meteorological satellites organization (EUMETSAT) provides a suitable framework for an operational production of evapotranspiration maps: it proposes a suite of datasets related to land surface partition of energy and vegetation status derived from the SEVIRI instrument aboard the Meteosat Second Generation (MSG) and provides an infrastructure for the near-real time production of relevant variables. The objective of this thesis are firstly to expose new findings in the use of geostationary satellites data for evapotranspiration monitoring at continental scale, and secondly on the way it could be complemented and improved by information from sun-synchronous satellites, especially from SPOT-Végétation and in prevision of the recent Proba-V mission. The developments presented concern the use and impact of variables such as radiation components at the surface, biophysical variables, land use and land surface temperature as derived from the sensors aboard satellites. All developments are conducted with the clear goal of near-real time evapotranspiration monitoring in the LSA-SAF context, but also in view to their possible application in land surface models used by the meteorological community. The quality of the results is assessed by a comparison with in-situ measurements across Europe and Africa, and by inter-comparison with other operational evapotranspiration products.

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1

Introduction

1.1. Why monitoring evapotranspiration over land ?

Droughts cause major disasters in regions relying on natural occurrence of rain for food production. It causes a serious decrease in crop productivity, leading to lack of food, livestock and direct accessibility to water for local communities. National and international actions can only be taken if warned in due time, especially if early warnings are issued. In setting up such service (eg. European Commission on agriculture forecasts or drought/desertification management, United States Famine Early Warning Systems Network, <http://www.fews.net/>), experts must know very accurately the different water gains and losses. An important loss of water from land is the water vapour released into the atmosphere, by plant transpiration and evaporation from the soil, altogether called evapotranspiration.

1.2. The water cycle and the evapotranspiration: facts and numbers

The evapotranspiration is one component of the so-called water cycle, which describes the continuous movement of water above, on and under the Earth's surface. While the global mass of water remains approximately constant over time considering the Earth as a whole, water is constantly regionally and locally transferred between the main conceptual reservoirs on Earth: ice, fresh and saline rivers, lakes, estuaries, soil and groundwater, vegetation and the atmosphere. Throughout those transfers, water experiences phase changes from solid to liquid (ice melting), from solid to vapour (snow and ice sublimation), from vapour to liquid or solid by condensation and from liquid to vapour by vaporization. Understanding the partition of water in the different conceptual reservoirs requires the estimation of the transfers from each to others accounting for phase transformations. For land management, precipitation is a very important component, as it is the source for most water reservoirs located on the land surface, ice caps, rivers, ponds, soil and aquifers. Contrarily, evapotranspiration over land can be viewed as a loss of water, gained by precipitation input. All in all, evapotranspiration returns on average 58% of the precipitation on land at the global scale (Dirmeyer, 2011). Of the total land evapotranspiration, 48% returns by transpiration of plants, 36% by bare soil evaporation, and 16% from direct evaporation of water intercepted by vegetation and temporarily stored on leaves, branches and trunks.

Transpiration of plants results from a complex interaction between plants, soil and atmosphere. During the photosynthesis process, the plants uptake water from the soil into the roots and xylem cells. Water is then conveyed up to the leaves where water vapour is stored. Again, with the impulse from photosynthesis, stomata, generally located on one side of the leaves, open to uptake carbon dioxide, while releasing, among other constituents, oxygen and part of the water vapour stored, which indicates how the transpiration and biochemical processes are intertwined. The release of water vapour by transpiration of the plants does not take place at a constant rate. It depends on many ambient factors and plant species and state (Allen et al., 1998). Solar radiation, direct or diffuse, is the main driver of the transpiration process: the more energy the plant receives, the more it transpires. This process can however be seriously limited when

stomata close due to reduced water uptake in case of low soil moisture content. This mechanism is an essential part of the defensive behaviour of plants. In addition, the air humidity partly controls the openness of stomata, as the inside water vapour will tend to escape more easily in drier air than in a saturated atmosphere. The wind plays a similar role, by removing the air humidity around the leaves. A senescent plant will less transpire than one in fully developed stage. Evapotranspiration involves a large range of mechanisms.

Beyond the important contribution of evapotranspiration to the water cycle, its contribution to the energy cycle is remarkable. The release of evapotranspiration into the atmosphere causes a cooling of the surface, as the process of vaporization requires a lot of energy. The study of the evapotranspiration process is by nature multi-disciplinary and is therefore useful to be examined at various scales: in biophysics, scientists focus on the processes occurring at the plant level, ecologists on the plot scale, agronomists on the field scale, hydrologists and meteorologists, for which evapotranspiration acts as respectively an outgoing and incoming quantity of water and energy, focus at scales from several meters to few kilometers scales.

1.3. How can we measure evapotranspiration ?

There is no direct or straightforward observing system for the evapotranspiration monitoring. However, scientists have developed techniques to estimate it indirectly at different spatial and temporal scales (Figure 1.1). The most direct observations can be achieved with a lysimeter. A lysimeter consists of a bucket filled with earth and planted with grass or other vegetation, whose weight variations can be measured regularly. Between two consecutive periods of watering, eg rainfall, the evapotranspiration is simply obtained by converting the weight loss of the system into equivalent water volume. The method is relatively simple, but is quite limited in terms of representativity of the measurement, as the footprint depends on the size of the lysimeter, of the order of a meter square or less, and in terms of landscape representativity, as lysimeters mostly have short vegetation types. Lysimeters are particularly interesting for local agricultural applications at the field scale.

At the 100 to 1000 m scale, indirect methods can be implemented using information

given by the rapid fluctuations of the atmospheric conditions near the surface. Those methods, eddy covariance and profile method, have a variable footprint, as they strongly depend on the stability of the atmosphere (Schmid, 1994; Hsieh et al., 2000). Both methods require numerous assumptions to be fully valid, and practical implementation is very often a compromise between the fulfillment of those theoretical assumptions and material constraints (Aubinet et al., 2000). Due to their footprint, both systems are useful for regional applications and have the advantage of being able to provide continuous time series of observations over long periods of time. While the profile method is often limited to short vegetation types environments due to material limitation, the eddy covariance technique has been implemented for diverse landscapes, including forests.

At the kilometer to tenths of kilometers scale, the scintillometry technique is emerging to give continuous series of measurements over a same location over long periods of time (Ward et al., 2013). Based on the delay of signal between an emitter and a receiver installed at a certain height over the surface and separated by a few kilometers, it is possible to reconstruct the variations in the energy released by the surface called turbulent heat fluxes, and therefore the evapotranspiration. Though this method does not suffer from the difficult assumptions needed for the eddy covariance technique, the footprint of such measurements is still a matter of debate (Timmermans et al., 2009). The same representativity issue applies to airborne eddy covariance devices taken on-board airplanes, although this technique allows a quasi-instantaneous shot of evapotranspiration over a certain area (Miglietta et al., 2009). Therefore, this observation is representative of larger areas than ground-based eddy covariance and is suitable for spatial quantification of evapotranspiration at a given time, but is not suitable for monitoring over time.

At the hundred kilometers scale, spaceborne geodetic observations have proven to be useful for estimation of evapotranspiration for large hydrological basins. Such instruments measure changes in the Earth's gravitational field, and therefore monitor mass changes as a result of fluxes between compartments of the hydrological cycle (Rodell et al., 2004a; Ramillien et al., 2008).

The typical footprint of applications requiring evapotranspiration monitoring, especially in agricultural areas, range between 30 m to a few kilometers. At that scale, interesting measurement techniques exist to retrieve evapotranspiration from local rapid fluctuations of meteorological conditions. Among those measurement techniques, the

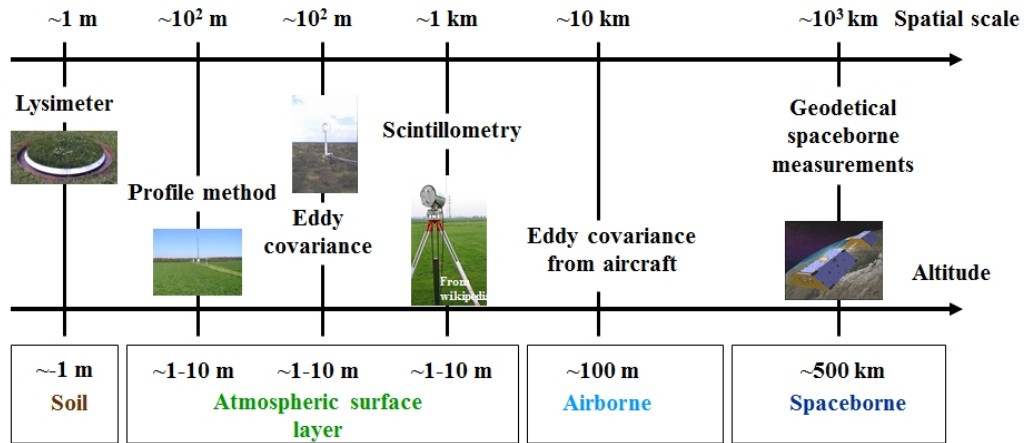


Figure 1.1.: **There is no straightforward observing system for the evapotranspiration monitoring. However, many techniques have been developed to estimate it at various spatial scales, from 1 m to hundreds of km.**

eddy covariance, the profile method and the scintillometry are probably the most used today.

The eddy covariance method is probably the most used method for deriving heat fluxes in the air surface layer. It relies on the measurement by a sonic anemometer of wind speed at a high rate, of the order of 20 Hz, installed above the vegetation canopy (Aubinet et al., 2000). These measurements provide quantitative information on turbulent fluctuations, i.e. vertical wind speed fluctuation, potential air temperature fluctuation, and specific humidity fluctuation. Cross-correlation between these fluctuations averaged over ten to thirty minutes allows deriving the surface turbulent sensible, H , and latent, LE , fluxes, the latter one being the energy equivalent of evapotranspiration.

The profile method relies on standard meteorological variables acquired from sensors mounted at several heights (mandatory for air temperature and humidity) on meteorological towers. Because of the insufficient accuracy of standard humidity sensors, the profile of humidity cannot be used to determine the evapotranspiration with high confidence. Therefore, a combination of a profile method based on air temperature measurements at several heights (at least 2 m and 10 m) and a residual energy balance calculation is usually set up (Gellens-Meulenberghs, 2005). The necessary observations for this method include all components of the radiative balance averaged over 10 to 30 minutes to compute the net radiation at the surface and the air temperature from at least

two heights on the tower.

1.4. Monitoring evapotranspiration over large continental areas: a critical issue

With the experimental set-ups described above, however, it is not possible to get an areal observation of evapotranspiration covering larger scales, although there is a strong interest in achieving it for many land and water management applications. Monitoring evapotranspiration over large continental areas is therefore both a critical issue and a highly expected service. Two major ways have been envisaged by the scientific community to overcome the lack of spatial distributed observations of evapotranspiration: modelling and remote sensing approaches.

The modelling approach, widely used in meteorology through numerical weather prediction models, consists of building a mathematical model able to predict the response of physical mechanisms giving way to the release of evapotranspiration at the land-air interface. Those physical models are based on in-situ observations and their synthesis in terms of conceptual mechanisms. A complete model of the total earth system is usually needed to reduce the number of in-situ observations used to constrain the model. This approach is also based on the finding of a general mechanism based on local observations and the belief it can be applied to a larger panel of cases, relying on the possible generalization of it. The physical models used in numerical weather prediction are called land surface models or SVAT models as they simulate the Soil-Vegetation-Atmosphere Transfers. Their reliability is improving over time as an evergrowing number of processes are understood. For example, the land surface model, TESSEL, used for global numerical weather predictions from the European Centre for Medium-Range Forecasts, ECMWF, has undergone many changes in the physical description over the past 20 years (Viterbo and Beljaars, 1995; van den Hurk et al., 2000; Balsamo et al., 2009, 2013). However, despite the merit of this approach, the imperfection of models may lead to erroneous results if they are not constrained by an influx of observations. Today, the models are more frequently reinitialized using up-to-date information provided by standard meteorological measurements at the surface, with a very dense network over

Europe, but very scarce over entire regions of Africa, for example.

Hydrological models, like WetSpa (Wang et al., 1996) or Bultot-RMI (Bultot and Dupriez, 1976a,b), also allow the diagnostic and forecast of evapotranspiration, from the underground perspective. Evapotranspiration is usually estimated over an entire catchment in view to an accurate forecast of runoff and drainages components, useful to evaluate the risk of drought or flood, but also the recharge of the aquifers. Like the land surface models, hydrological models can suffer from modelling simplifications leading to errors. Therefore, at the catchment scale, it is very frequent to calibrate the model parameters with historical series of observed river discharges. In addition, those models could benefit from an assimilation of observed hydrological variables, like evapotranspiration.

1.5. The role of remote sensing from space in the quest for evapotranspiration

Remote sensing offers an interesting alternative to modelling, as it provides imaging techniques from which it is possible to retrieve an areal distribution of several surface characteristics, based on the natural emission of energy from the surface in response to illumination natural/artificial stimuli at several energy frequencies. Sensors aboard satellites are particularly attractive in regional to global monitoring of the earth surface. Although there is no electromagnetic signal detectable from the release of water vapour from the surface into the atmosphere, scientists have developed models based on the interpretation of the satellite imagery. Sensors aboard earth observing satellites and designed for land surface monitoring can operate in various geometrical conditions and provide imagery in several frequency bands. For land surface applications, the most relevant information is provided by optical and thermal imagery, spectrally speaking in the visible to infra-red wavelengths. Microwave frequencies are now more used, especially to retrieve information from cloudy sky conditions for which visible and thermal imagery does not allow to monitor the surface. The sensors built for land surface monitoring are embarked selectively on platforms with various orbital characteristics. The most common satellites are sun-synchronous, called polar satellites. This orbital

geometry presents the advantage, in addition to the possibility to globally observe the Earth, of a relatively fine spatial resolution imaging of the Earth's surface due to their lower altitude and an observation over a same location at approximately the same time of the day. Depending on the purpose of the mission, there is a trade-off between spatial resolution and revisiting time: finer the spatial sampling is, the lower the revisiting time and hence the availability of imagery is. With this geometry, only *tracks* can be recorded and continental views at a certain time is not possible, unless there is a composite of several polar satellites orbiting at a certain delay between one another. Continental views can however be obtained as multi-days composites. On the other hand, geosynchronous or geostationary satellites are on an orbit along the equator at the same angular speed as the Earth, favouring a fine temporal sampling, wide instantaneous coverage to the size of continents and a continuous monitoring of areas in the field of view, although the spatial resolution is coarser due to their relatively distance from the Earth surface (36,000 km), the limitation of the field of view due to Earth's shape, and the impossibility to finely sample the near polar regions.

An evergrowing number of models relying on visible and thermal bands of sensors aboard polar satellites has been developed (Su, 2002; Mu et al., 2007; Wang et al., 2007), with the aim of retrieving evapotranspiration on a daily to weekly basis, for regional to continental applications. Most of those models are based on the surface energy balance concept. They assume that the net radiation balance at the surface, resulting from the subtraction of outgoing radiation to the incoming direct, diffuse and longwave radiation, is redistributed in energy release into the atmosphere, by sensible or latent heat fluxes, and propagation of energy into the soil. With polar satellites, however, only discontinuous monitoring of evapotranspiration can be achieved with such techniques because of the gap between two consecutive satellite information and the unavoidable effect of clouds that screen the signal emitted from the surface. Alternatively, geostationary satellites provide the fine temporal sampling necessary to monitor the sub-daily variations of surface properties and therefore of evapotranspiration (Gellens-Meulenberghs, 2000). Movement of clouds are better monitored and the high repetition rate of sensing allow to detect the variations of the surface properties.

1.6. A close eye on Europe and Africa: the METEOSAT programme

In Europe, the European Space Agency, ESA, and the European Organisation for the Exploitation of Meteorological Satellites, EUMETSAT, are in charge of the space programs and the various missions among which are the earth observation missions. EUMETSAT has been in charge of the METEOSAT geostationary satellites for nearly 30 years, taking over responsibilities of this program that was managed by ESA before. The METEOSAT suite of satellites was initiated in 1977 by the launch of the first geostationary satellite covering Africa and Europe for the purpose of weather surveillance and forecasting. With an almost uninterrupted service, the METEOSAT program has delivered up to now imagery from successively improved sensors, MVIRI for the first generation of seven satellites, and SEVIRI for the second generation of satellites, MSG, counting now three satellites. The SEVIRI sensors have improved capabilities compared to the MVIRI as they allow a sampling of 3.1 km at the equator, a global scan in less than 10 minutes, and measurements in 12 distinct spectral channels (0.635, 0.75, 0.81, 1.64, 3.92, 8.70, 9.66, 10.8, 12.0, 13.4, 6.25 and 7.35 μm).

1.7. Operations: a constraint in the algorithm design, a powerful application potential

Although the primary objective of the METEOSAT program was to improve the capabilities of weather monitoring and forecasting, in 1999, EUMETSAT launched a series of initiatives, called satellite applications facilities (SAF), to fully exploit its second generation of geostationary satellites and propose new operational products of interest. SAF topics range from atmospheric composition to land and ocean observations, and time scales between the near-real time and the long-term climate trends. One of the topics covered by SAF's is dedicated to the derivation of variables related to the land surface. The Satellite Application Facility on Land Surface Analysis (LSA-SAF) (Trigo et al., 2011) has constituted from the beginning an ideal nest for evapotranspiration monitoring activities, as most of the variables needed by the evapotranspiration models were foreseen

to be produced at time steps of 15 minutes, 30 minutes or daily (Figure 1.3). The continental areas covered by LSA-SAF are Europe, Africa, Middle East and South America (Figure 1.2).

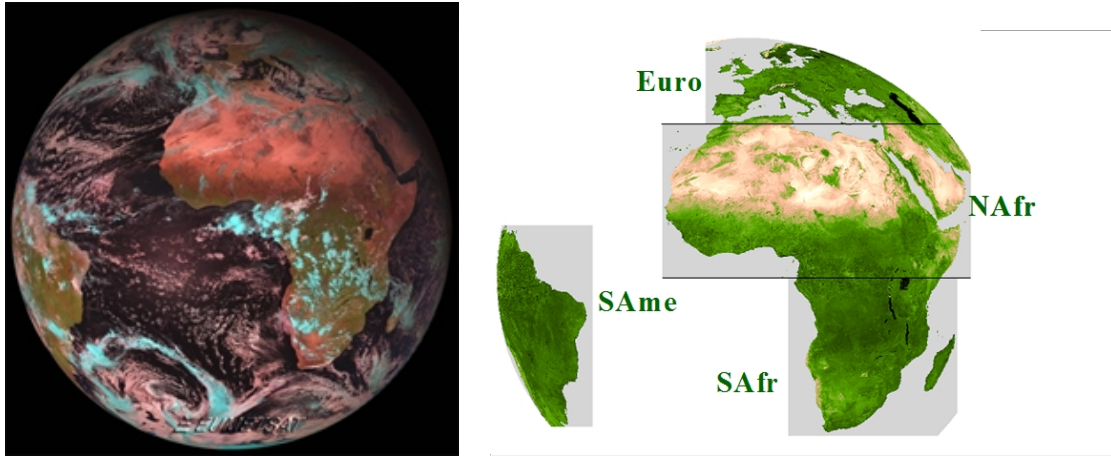


Figure 1.2.: The SEVIRI sensor aboard the Meteosat Second Generation satellites allow an instantaneous monitoring of large continental using 12 spectral channels. The LSA-SAF focuses on land areas: Europe, Africa and South America.

A combination of land surface modelling and remote sensing from the SEVIRI sensor aboard MSG geostationary satellites has formed the baseline of the early developments of the evapotranspiration algorithm to be implemented for operational production of evapotranspiration maps. This choice has been motivated by the need of potential users of the product, which required the product to be produced in near-real time, and, if possible, continuously, meaning that there must be a retrieval even for cloudy periods. In the LSA-SAF, the evapotranspiration product can be considered as an end product, because of its dependencies on most of the other products (Figure 1.3). A wide range of variables is produced by the LSA-SAF operational system: radiation variables and others related to vegetation, water and fire. Most of those variables are pertinent for land surface models and surface energy balance models.

The operational production strongly constrains the design of the retrieval algorithm, as it imposes the architecture of the processing, the time by which the algorithm should deliver the maps. In addition, in designing the end product, there are big challenges to face, as unexpected issues from primary products, concerning specifications, quality or even cancellations of products. While an expected goal of the LSA-SAF

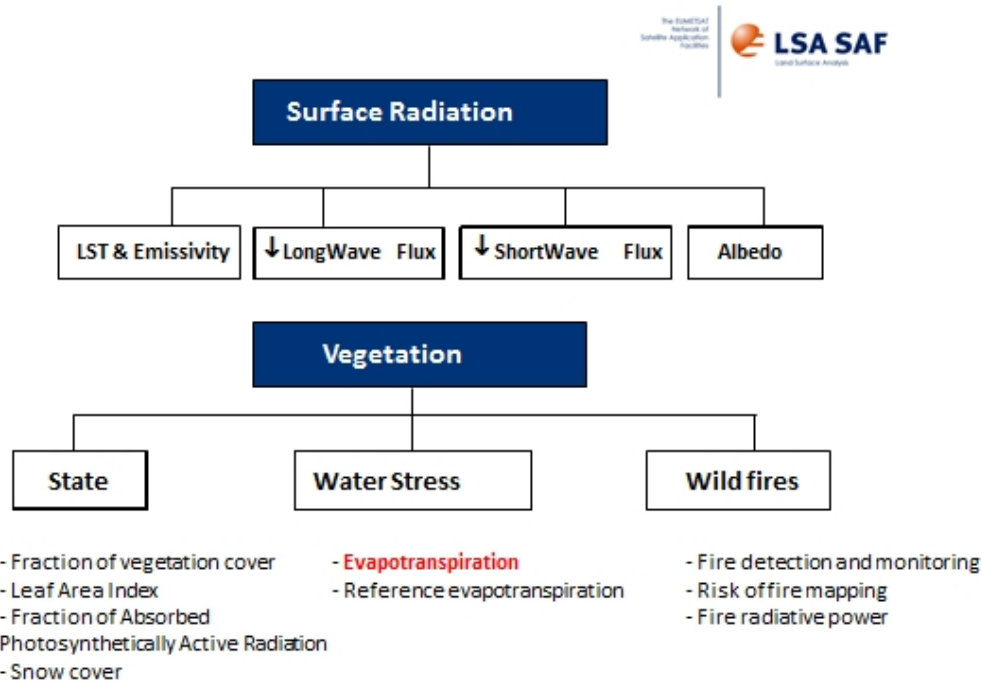


Figure 1.3.: **The EUMETSAT LSA-SAF delivers variables grouped in two separate classes: the radiation and the vegetation-related variables. Evapotranspiration is one of the end variables, as it depends on many other variables from both classes.**

evapotranspiration algorithm is to produce a complete land surface model, constrained by satellite derived data, the current architecture of the operational production system does not allow this. Especially, the informatic infrastructure has a limited output storage capacity, and a short allowed computing time. Nevertheless, while research continues towards this long-term goal, operational activities can still be based upon a reduced model on the short to medium range, without affecting too much the accuracy.

On the user's perspective, the operational evapotranspiration product generated by LSA-SAF finds its utility for a wide range of applications: drought monitoring (Sepulcre-Canto, 2013), agricultural yield monitoring (Durgun et al., 2014), and even irrigation detection (Romaguera-Albentosa et al., 2012). The hydrological community could find in this product an interesting source of information for calibration (Immerzeel and Droogers, 2008), comparison of distributed evapotranspiration estimates, or even an assimilation in monitoring hydrological systems (Roulin, 2002).

My personal contribution in the operational activities is to develop new methods and

integrate them in a computer-based algorithm transferred to the operational system in Lisbon, Portugal. In addition, I report changes, analyze re-processed results, and follow-up the product quality to both EUMETSAT and the user community in conjunction with my colleague Alirio Arboleda and in concertation with Françoise Meulenberghs, both from the Royal Meteorological Institute of Belgium. At last, I help interested scientists in using the products, either by direct communication or by means of small workshops.

1.8. Validation: informing the users community on accuracy

Beside the model development and the better use of information derived from remote sensing data, validation is a critical step for the adoption of a new approach. It helps in determining the reliability of new products being delivered to the community. The purpose of validation activities is to inform on the accuracy achieved by the model, and on the consequent product by comparing with other observations techniques or other models. The comparison with ground-based observations techniques is called here in-situ validation, and is considered to be one of the ultimate ways for benchmarking the model improvements and assess the global quality of the generated evapotranspiration estimates. Comparing with other models or operational systems allow to better identify strengths and weaknesses of the evapotranspiration model if other models have an already assessed accuracy in some regions, or to identify situations for which there is no consensus between models and not yet any benchmark available to go further. Both activities are relevant to inform the potential users on the accuracy of the evapotranspiration estimates, and quantify the temporal and spatial error of the model.

However, it is important to notice that there exist neither a direct measurement method nor universal reference for evapotranspiration and associated surface turbulent fluxes. The methods involved for the ground estimation of surface turbulent exchanges rely on theoretical assumptions that are not always verified (for example, homogeneity assumption for Monin-Obukhov theory) and on models with intrinsic errors or uncertainties, or even instrumental misuses. Today, some problems remain unsolved, among them the exact representativity of the measurements and the closure of the energy

balance. Today, measuring accurately surface turbulent fluxes and evapotranspiration is still challenging.

Nevertheless, an increasing number of long-term observation sites has developed, under the impulsion of international programs or national initiatives. Different networks and measurements techniques are involved in the validation of most evapotranspiration models. I provide here an overview of the most important networks used for the validation in this thesis.

CarboEurope-IP coordinates flux measurement stations for continuous monitoring in Europe, with more than 50 sites, covering a large panel of the ecosystems existing in Europe (<http://gaia.agraria.unitus.it>). This project, embedded into the global scale FLUXNET network of stations, is mainly directed towards the observation of carbon fluxes and experimental studies to better understand the mechanisms that play a role in plant respiration process. For this reason flux stations are fully equipped for the measurements of all meteorological variables and are measuring the turbulent exchanges between soil-vegetation-atmosphere. The Royal Meteorological Institute of Belgium has developed a network of automatic weather stations spread over Belgium and measuring, over short grass environment, standard meteorological variables at two or three levels. The measurements include all components of the radiative balance, wind speed, air temperature and relative humidity. The sites have been chosen to have a homogeneous fetch as large as possible to avoid the contamination of obstacles on measurements. The methodology used for deriving surface turbulent fluxes (Gellens-Meulenberghs, 2005) follows a combination of a profile method and a residual method. Sensible heat flux is deduced from the profile of wind speed and air temperature (two levels at 2 m and 10 m respectively) with careful choice of stability functions. Latent heat flux is deduced as the residual of the energy balance, for which each component is measured, except the soil heat flux considered as a fixed proportion of the net surface radiation. CarboAfrica project coordinates the largest network for continuous monitoring in Africa, with about 25 sites, covering different climate regions in Africa (http://www.carboafrika.net/index_en.asp). This project is intended to fill the gap of measurements in Africa. Most of the stations have been set up in 2006 and 2007. Stations operating in the western part of Africa are also used in the framework of the AMMA project (<http://www.amma-international.org/>). Cabauw is a site of meteorological

measurements in the Netherlands, operated by the Dutch Royal Meteorological Institute (KNMI), (see Beljaars and Bosveld (1997) for a description of the site). Surface turbulent fluxes have been monitored for more than 20 years, through different field campaigns, and now on a routine basis. The system used before 2000 was based on the profile approach and widely used for comparison with land surface models (Beljaars and Bosveld, 1997). Different other methods have been tested at Cabauw: Bowen ratio method, eddy covariance method and more recently scintillometry. However, continuous monitoring was only made by means of the eddy covariance method during the last few years. The station is involved in CEOP (Kato et al., 2007; Su et al., 2007). As for CarboEurope-IP network, Cabauw station is equipped with a sonic anemometer/thermometer (Kroon, 2004) to derive surface heat fluxes by eddy correlation method.

While in-situ observations are essential for a proper validation of models or satellite remote sensing retrievals, the ground-based techniques have their own limitations and uncertainties. The eddy covariance technique, used for deriving heat fluxes in the air surface layer, has been successful to derive evapotranspiration over a wide range of conditions. While errors in eddy covariance systems are hard to obtain due to the lack of an absolute reference available for comparison, different criteria can indicate the quality of the measurements: 1) the closure of the surface energy balance, which is still a matter of debate (Foken et al., 2011; Leuning et al., 2012; Stoy et al., 2013); 2) the stationarity of the fluctuations measurements (Rebmann et al., 2005); and 3) the land use representative of the measurements must be known (Göckede et al., 2008). The observed surface energy imbalance has been quantified for 50 contrasting *site-years* of the FLUXNET network (Wilson et al., 2002). The surface energy imbalance ranges between 1% and 47% with a mean of 17%, due possibly to erroneous measurement of energy storage in the vegetation, advection and biases in instrumentation. At Cabauw, during the 2 years TEBEX campaign of 1995 and 1996, Kroon (2004) found that the energy balance was not closed either. While no generalized conclusion has been drawn on the impact on latent heat flux errors, it is generally admitted that error on estimates, excluding cases of very low turbulence, ranges between 5% and 20% (Aubinet et al., 2000; Wesely and Hart, 1985; Goulden et al., 2004). The stationarity of the measurement is a measure of the quality of the flux estimation (Foken and Wichura, 1996). Rebmann et al. (2005) showed the statistics of the application of a quality test

on several sites, showing sometimes mitigated sites. Hence, representativity of the measurements has a key role in model validation. Without further studies, as it is the case for stations for which the targeted vegetation is low, homogeneous fetch gives an indication of the representativity of the site. For CarboEuro-IP forested stations, a past study (Göckede et al., 2008) analyzed quantitatively the measurements representativity of 25 sites by means of a lagrangian footprint model (Göckede et al., 2004; Rebmann et al., 2005; Reithmaier et al., 2006; Göckede et al., 2006), showing contrasted results in classifying homogeneous/heterogeneous sites. The Cabauw site is homogeneous, flat, surrounded by grassland: the homogeneous fetch is considered to be between 400 m to 2 km depending on the wind direction. This characteristic makes it an exemplary site for validation of evapotranspiration models. More recently, studies have focus on the error arising from the misuse of operating devices and erroneous corrections applied to retrieve the physical variables (Kochendorfer et al., 2012; Frank et al., 2013).

1.9. Objectives of the thesis

The overall objective of the research is to develop an operative evapotranspiration model for an entire continent at a few kilometers resolution. Moreover, a validation and benchmarking framework is built as part of an improvement cycle for an accurate evapotranspiration monitoring system. Two central research questions underline this study:

- How can geostationary satellites derived data contribute to an efficient operational monitoring of evapotranspiration ?
- How can evapotranspiration monitoring based on geostationary satellite data be complemented and improved by information derived from sun-synchronous satellites built for vegetation monitoring ?

To reach those objectives, the developments focus on the use and impact of variables derived from data acquired by the sensors aboard satellites. In particular, I investigate the use of the radiation components at the surface, biophysical variables, land use and land surface temperature. All developments are conducted with the clear goal of near-real time continuous evapotranspiration monitoring in the LSA-SAF context, using data from the

SEVIRI sensor aboard Meteosat Second Generation suite of satellites, but also in view to their possible application in land surface models used by the meteorological community. For that reason, the utility and impact of the remote sensing derived variables is assessed in some cases with a land surface model, before bringing any changes to the LSA-SAF evapotranspiration model. The complementarity of polar satellites for vegetation monitoring is focussed towards the exploitation of the recent enhanced PROBA-V satellite data, successor of the successful SPOT-Végétation programme. The quality of the results are assessed by a comparison with in-situ measurements across Europe and Africa using such measurements sites described above, and by inter-comparison with other operational evapotranspiration products.

The work is conceived to proceed step-by-step towards gradual quality improvement of the evapotranspiration maps (Gellens-Meulenberghs et al., 2007). In this thesis, the satellite derived products are studied the same way, taking into account their own characteristics for the formulation of a solution for evapotranspiration monitoring. Their specific interest for the improvement of the results from land surface models and LSA-SAF evapotranspiration model is studied here, gradually, as more reliable products became available for operational purposes.

1.10. Structure of the thesis

In this thesis, I present first the LSA-SAF evapotranspiration operational model to which I have contributed and elaborated. This model is a simplified land surface model forced by meteorological short-term forecasts and radiation components, short and long wave downward fluxes and surface albedo, derived from MSG/SEVIRI data. Its validation thanks to in-situ measurements over Europe and inter-comparison with other operational models available at the time of the study is then exposed (Chapter 2). From this initial set-up, I have looked for ways to improve the overall quality of the results obtained and rely more on MSG/SEVIRI, mainly in ingesting other remote sensing derived variables to further constrain the evapotranspiration model. I have especially concentrated the research towards a better representation of the land use and vegetation in a land surface model using the high temporal resolution of MSG/SEVIRI derived products (Chapter

3), improving therefore the variability of the main source of evapotranspiration over land. This set-up has been integrated for the LSA-SAF evapotranspiration model (Annex C), for a routine production. In parallel, I have dedicated some efforts to explore the complementarity of information acquired by sensors aboard polar satellites in view of a better monitoring (Chapter 4 and 5). Uncertainties from the land use map derived from such sensors, partly unveiled in Chapter 3, were further investigated. In Chapter 4, I present the effect on evapotranspiration simulations at various spatial scales caused by geolocation error in contemporary land use maps. In Chapter 5, I review the variables of interest available from such sensors to complement geostationary data for evapotranspiration monitoring in the LSA-SAF context. The evaluation of their effect on the resulting evapotranspiration is presented. A crucial input variable for evapotranspiration models based on land surface schemes is the soil water availability for evaporation and transpiration, especially in semi-arid to arid areas. In Chapter 6, I present a novel approach to derive soil moisture from the SEVIRI sensor for a daily monitoring. Its validation against in-situ observations across Europe and Africa is exposed, showing the interest of such technique for semi-arid areas. Chapter 7 brings together the developments from the previous chapters, showing the successive improvements of the evapotranspiration monitoring using SEVIRI derived variables, especially radiation, biophysical variables and the first tentative to further constrain the model using remote sensing observation of soil water availability. At last, I conclude by summarising my work, giving some possible applications of the present work and outline future research directions towards the improvement of the operational monitoring already set-up.

2

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

This chapter is based on N. Ghilain, A. Arboleda, F. Gellens-Meulenberghs (2011), Evapotranspiration modelling at large scale using near-real time MSG SEVIRI derived data, Hydrol. Earth Sys. Sci., 15, 771-786.

Abstract

We present an evapotranspiration (ET) model developed in the framework of the EUMETSAT 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 (DSLW). They are available with the spatial resolution of the MSG SEVIRI instrument. ET maps covering the whole MSG field of view are produced from 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 mm.h^{-1} and the root-mean square error is between 0.06 and 0.10 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. Nevertheless, some discrepancies are also observed and are due to the different input variables and parameterisations used.

2.1. 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 (Dolman and de Jeu, 2010). A correct 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 et al., 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 (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. (2004b); Albergel et al. (2010) have been investigated and applied to a variety of spatial scales, from local and regional (Bastiaanssen et al., 1998; Su, 2002; Stisen et al., 2008; Miglietta et al., 2009) to global scales (Jimenez et al., 2009a). 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 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 (Su et al., 2010) (<http://wacmos.itc.nl/>), a recent initiative of ESA in collaboration with GEWEX, is currently developing a new global ET product (Timmermans et al., 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 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; Gentile 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., 2011) (<http://landsaf.meteo.pt/>), of which the objective is to develop algorithms for the estimation of operational land products using meteorological satellites. Main input data is derived from 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 the study is that it proposes 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 parameterizations used in Soil-Vegetation-Atmosphere Transfer (SVAT) schemes. 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 output. We therefore compare the 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 the results over the whole MSG field of view with two operational models that provide ET at global scale, ECMWF and the Global Land Data Assimilation System, GLDAS (Rodell et al., 2004b). While ECMWF ET is forecasted using a global atmospheric model, GLDAS ET is the result of land surface models (Noah, CLM or Mosaic) not coupled to an atmospheric model, but ingesting satellite (snow cover (Rodell and Houser, 2004), radiation products (Idso, 1981)) and ground-based observational (precipitation, CMAP (Xie and Arkin, 1997)) data products to provide regularly updated ET maps accessible on request. This paper is organised as follows. The model formulation and its use in the context of LSA-SAF are presented (Section 2) and are followed by a short description of the LSA-SAF ET product (Section 3). Comparison with in-situ observations at local scale in Europe is the subject of Section 4. We present in Section 5 the results of the comparison with ECMWF and GLDAS. A cross-check with independent produced in LSA-SAF is presented as a potential tool to assess deficiencies in the model (Section 6). We finally discuss the results and draw conclusions and guidelines for future research directions (Sections 7 and 8).

2.2. 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.

2.2.1. 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).

The basic spatial unit for the model is called *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. A decomposition of the pixel surface is done by considering the fraction fully covered by vegetation and the remaining fraction of bare soil for each land cover. The considered smaller homogeneous entities (vegetation or bare soil) are called *tiles*. Then, the set of equations of the model is solved for each tile before spatially averaging at the pixel level. The sensible H_i and latent LE_i heat fluxes are computed for each tile i using the following classical bulk relationships.

$$H_i = \frac{\rho}{r_{a,i}} [c_p (T_{sk,i} - T_a) - g \cdot z_a] \quad (2.1)$$

$$LE_i = \frac{L_v \rho}{r_{a,i} + r_{s,i}} [q_{sat}(T_{sk,i} - T_a) - q_a(T_a)] \quad (2.2)$$

ρ is the air density, $r_{a,i}$ is the aerodynamic resistance, c_p is the heat capacity at constant pressure, $T_{sk,i}$ is the surface *skin* temperature at level z_a above the surface, g is the acceleration due to gravity, L_v is the latent heat of vaporization, $r_{s,i}$ is the stomatal resistance, q_a is the air specific humidity at height z_a and q_{sat} is the value of the surface specific humidity at saturation. The aerodynamic resistance $r_{a,i}$ is computed as a function of the atmospheric stability following Monin-Obukhov similarity theory (W. H. Brutsaert, 1982)

$$\frac{1}{r_{a,i}} = \frac{ku_{*,i}}{\ln\left(\frac{z_a - d_i}{z_{0h,i}}\right) - \psi_h\left(\frac{z_a - d_i}{L_i}\right) + \psi_h\left(\frac{z_{0h,i}}{L_i}\right)} \quad (2.3)$$

with friction velocity given by

$$u_{*,i} = \frac{ku}{\ln\left(\frac{z - d_i}{z_{0m,i}}\right) - \psi_m\left(\frac{z - d_i}{L_i}\right) + \psi_m\left(\frac{z_{0m,i}}{L_i}\right)} \quad (2.4)$$

and Monin-Obukhov stability parameter computed as

$$L_i = \frac{\rho u_{*,i}^3}{kg\left(\frac{H_i}{c_p T_a} + 0.608 \frac{LE_i}{L_v}\right)} \quad (2.5)$$

In Eq. 2.3 to 2.5, k is the von Karman constant ($k = 0.40$). u_a is the wind speed at height z above the surface, ψ_h and ψ_m are respectively the sensible heat and momentum stability functions (Beljaars and Viterbo, 1994) defined in Eqs 2.6, 2.7, 2.8 and 2.9, d_i is the displacement height, $z_{0h,i}$ and $z_{0m,i}$ are respectively the roughness lengths related to sensible and momentum fluxes.

The stability functions are computed differently in unstable and stable atmospheric conditions. If $\frac{z}{L} \leq 0$, Eqs 2.6 and 2.7 are applied, while Eqs 2.8 and 2.9 are used otherwise.

$$\psi_m = \frac{\pi}{2} - 2 \operatorname{atan}(x) + \log \left(\frac{(1+x)^2 \cdot (1+x^2)}{8} \right) \quad (2.6)$$

$$\psi_h = 2 \cdot \log \left(\frac{1+x^2}{2} \right) \quad (2.7)$$

$$\psi_m = -b \cdot \left(\zeta - \frac{c}{v} \right) \cdot \exp(-v \cdot \zeta) - a \cdot \zeta - \frac{b \cdot c}{v} \quad (2.8)$$

$$\psi_h = -b \cdot \left(\zeta - \frac{c}{v} \right) \cdot \exp(-v \cdot \zeta) - \left(1 + \frac{2}{3} \cdot a \cdot \zeta \right) - \frac{b \cdot c}{v} + 1 \quad (2.9)$$

$\zeta = z/L$ and $x = (1 - 16 \cdot \zeta)^{0.25}$, $a = 1$, $b = 2/3$, $c = 5$ and $v = 0.35$.

The stomatal resistance is obtained following the Jarvis (1976) approach adopted in ECMWF TESSEL SVAT scheme (van den Hurk et al., 2000). For vegetation, the general formulation is given by

$$r_{s,i} = \frac{r_{s,min,i}}{LAI_i} f_1(S_{\downarrow}) f_2(\bar{w}) f_3(\delta q_a) \quad (2.10)$$

where $r_{s,min,i}$ is the minimum stomatal resistance, LAI_i is the leaf area index, $\bar{w}$ is the average unfrozen soil water content, δq_a is atmospheric moisture deficit and f_1 to f_3 are the Jarvis functions, defined in Eqs 2.11, 2.12 and 2.13, with $w_{pwp} = 0.171 m^3 \cdot m^{-3}$ and $w_{fc} = 0.323 m^3 \cdot m^{-3}$ the soil moisture at the permanent wilting point and the field capacity respectively.

$$f_1^{-1}(S_{\downarrow}) = \min \left(1, \frac{b \cdot S_{\downarrow}}{a \cdot (b \cdot S_{\downarrow} + 1)} \right) \quad (2.11)$$

$$f_2^{-1}(\bar{w}) = \max \left(0, \min \left(\frac{\bar{w} - w_{pwp}}{w_{fc} - w_{pwp}}, 1 \right) \right) \quad (2.12)$$

$$f_3^{-1}(D_a) = \exp(-g_D \cdot \delta q_a) \quad (2.13)$$

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

$$r_{s,i} = r_{s,min,i} f_2(w_1) \quad (2.14)$$

with w_1 being the unfrozen soil water content in first soil layer. In Eq 2.10 and 2.14 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 according to Masson et al. (2003). Adopted values for $r_{s,min,i}$ are listed in Table 2.1.

Table 2.1.: **Vegetation types and associated minimum stomatal resistance**
($r_{s,min,i}$)

i	Vegetation type	$r_{s,min,i}$ [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	Deciduous Broadleaved Trees	250

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

$$Rn_i - H_i - LE_i - G_i = 0 \quad (2.15)$$

where Rn_i is the net radiation at the surface and G_i is the ground heat flux. In Eq 2.15 all fluxes, excepted Rn_i , are computed positively upward.

Net radiation is given by

$$Rn_i = (1 - \alpha)S_{\downarrow} + \varepsilon(L_{\downarrow} - \sigma T_{sk,i}^4) \quad (2.16)$$

where α is the albedo, $S_{\downarrow}$ is the downwelling surface short wave flux (DSSF), ε is the emissivity, $L_{\downarrow}$ is the downwelling surface longwave flux (DSLFL), σ is the Stefan-Boltzmann constant and $T_{sk,i}$ is the skin temperature. This latter is the model variable representing the surface temperature at tile level. It acts as an aerodynamic temperature in Eq 2.1 and is used to estimate surface thermal emission in Eq 2.16. 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

$$G_i = \beta_i Rn_i \quad (2.17)$$

the method of Chehbouni et al. (1996) being adopted to derive β_i from LAi_i .

The system to be solved is composed of four non-linear Eqs 2.1, 2.2, 2.4 and 2.15 with four unknowns (H_i , LE_i , $T_{sk,i}$ and $u_{*,i}$). Given the non-linear interdependency between the unknowns, an iterative procedure is used to solve the system taking relationships 2.3, 2.5, 2.10, 2.14, 2.16 and 2.17 into account. Neutral stability is assumed as initial condition. Iteration is stopped when pixel estimates of latent and sensible heat fluxes are numerically stabilized. In particular a modelled surface or 'skin' temperature is computed from Eqs 2.1, 2.2 and 2.16.

The averaged LE flux at pixel level is given by

$$LE = \sum \zeta_i LE_i \quad (2.18)$$

where ζ_i and LE_i are respectively the coverage fraction and the latent heat flux of the tile i in the considered pixel. For vegetation, ζ_i is the fraction occupied by a land cover type in the pixel, which only the fraction covered by vegetation has been kept. The land cover types associated to tiles (grassland, crops, forests, bare soil, etc.), the respective coverage fraction ζ_i and associated parameters are deduced from the ECOCLIMAP land

cover database (Masson et al., 2003).

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

$$E = LE/L_v \quad (2.19)$$

with L_v the latent heat of vaporization [$J.kg^{-1}$] computed as

$$L_v = [2.501 - 0.00234(T_a - 273.15)].10^6 \quad (2.20)$$

T_a being the air temperature [K] at the height z_a above the surface. In the above expressions, all fluxes are expressed in Wm^{-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. More details on the practical implementation of the model are given in the next section.

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.

2.2.2. Forcing data and practical algorithm implementation

In the context of EUMETSAT LSA-SAF, the evapotranspiration model is forced with data derived from MSG SEVIRI instrument. The daily Albedo, α , (Geiger et al., 2008b; Carrer et al., 2010) and half-hourly short-wave $S_{\downarrow}$ (Geiger et al., 2008a) and long-wave $L_{\downarrow}$ (Ineichen et al., 2009) surface fluxes are the main forcing for MET model. 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

Table 2.2.: **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	Net	Lat	Long	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	(Pereira 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)

resolution and vegetation parameters required in SVAT models, i.e. LAI_i , ζ_i , $z_{0m,i}$, $z_{0h,i}$. In addition, the emissivity ε used in the presented model is the monthly emissivity provided by the ECOCLIMAP database (ranging from 0.96 for bare soil to 0.99 for fully vegetated surfaces). 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 2.1. We adapted ECOCLIMAP, such as it could be used by our model. First, ECOCLIMAP is projected onto the grid defined by SEVIRI. ECOCLIMAP must then be obtained at a coarser spatial resolution. The number of vegetation tiles in each pixel is limited to three and monthly vegetation parameters are used. ECOCLIMAP provides the monthly coverage fraction of vegetation ($fveg_i$) for each tile and the fractions ξ_i covered by vegetation compared to bare soil. The model considers separately the contribution from vegetated parts and parts of soil exposed to direct radiation. The energy balance is performed on each of the 3 dominant vegetated fractions (i.e. $\zeta_i = fveg_i \xi_i$) plus on the bare soil fraction of the pixel (i.e. $\zeta_i = 1 - \sum(fveg_i \xi_i)$).

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, reinitialized twice a day by the ECMWF 4DVAR analysis process, 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. 2.2. 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. 2.10 and 2.14, 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.

2.3. 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, using the latest available information 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 2.1 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). 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-users can access earlier results (from new model versions) through LSA-SAF ftp site. By interacting with the development team, users can contribute to improve the results or better adapt the proposed products to their specific needs.

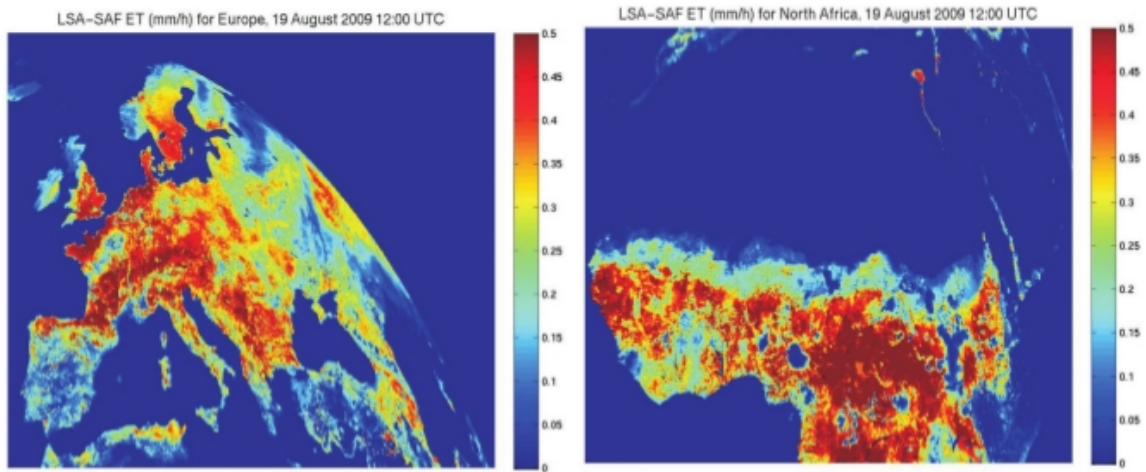


Figure 2.1.: **LSA-SAF ET (mm/h) over Europe (left) and North Africa (right) on 19 August 2009 at 12:00 UTC.**

2.4. In-situ validation

The MET model has been 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 2.2). 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 with the eddy correlation technique, as used in FLUXNET, has been shown to lead to uncertainty on fluxes measurement around 20% (Wilson et al., 2002). Therefore, possible accuracy limitation will be considered by comparison to a quality criterion defined at the end of this section. However, it should be underline that the good standardisation of the measurement technique over the entire FLUXNET network enables to do comparisons with measurements in a uniform way.

We consider the period spanning from 1 March to 31 December 2007. This period is particularly relevant for Europe, because it includes a whole vegetation cycle and, in the same time, the periods for which the evaporation demands are the largest, due to the solar forcing. At Hesse station, there was no data available for 2007, instead, comparisons were performed with data from 1 May to 30 June 2006, which includes the entire period

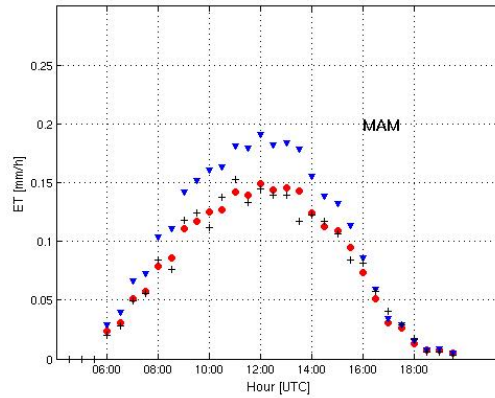


Figure 2.2.: **Mean seasonal diurnal cycle of ET for the CarboEurope-IP Vielsalm station for March to May (MAM) 2007. Observations (+), pixel (v) and "tile" (o) estimate from LSA-SAF MET.**

of canopy development. In the comparison of the ET variable 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 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 different vegetation types. An example for March to May 2007 over a forest site in Belgium (Figure 2.2) shows that the pixel mean seasonal diurnal cycle of ET is larger than observed. However, the tile 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, the operational procedure systematically forces the model to output the ET estimate at the tile level for a set of validation stations location. We select then ET for the tile that corresponds to the vegetation type representative of the local measurements.

In Table 2.3, we present the statistical results obtained from the comparison with the half-hourly measurements for the selected stations. All ET estimates are expressed in $mm.h^{-1}$. Four statistical indices are tabulated for each dataset: the global bias, the root mean square error (RMS), the correlation coefficient and the Nash index (Nash and Sutcliffe, 1970), which definition is given in Eq 2.21 and a short interpretation can be found in Albergel et al. (2010):

Table 2.3.: Comparison between LSA-SAF ET and observed ET at validation stations: statistical results (Bias [$mm.hr^{-1}$], RMS, correlation coefficient (Corr), Nash index, PRD criterion (see text) [%]; vegetation type:mixed forest (MF), evergreen needle leaf forest (ENF), deciduous broadleaf forest (DBF), grassland (G).

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

$$Nash = 1 - \frac{\sum (y_{i,est} - y_{i,obs})^2}{\sum (y_{i,obs} - \bar{y}_{i,obs})^2} \quad (2.21)$$

where $y_{i,est}$ and $y_{i,obs}$ are respectively estimated and observed values, $\bar{y}_{i,obs}$ is the mean of observations and n is the sample size.

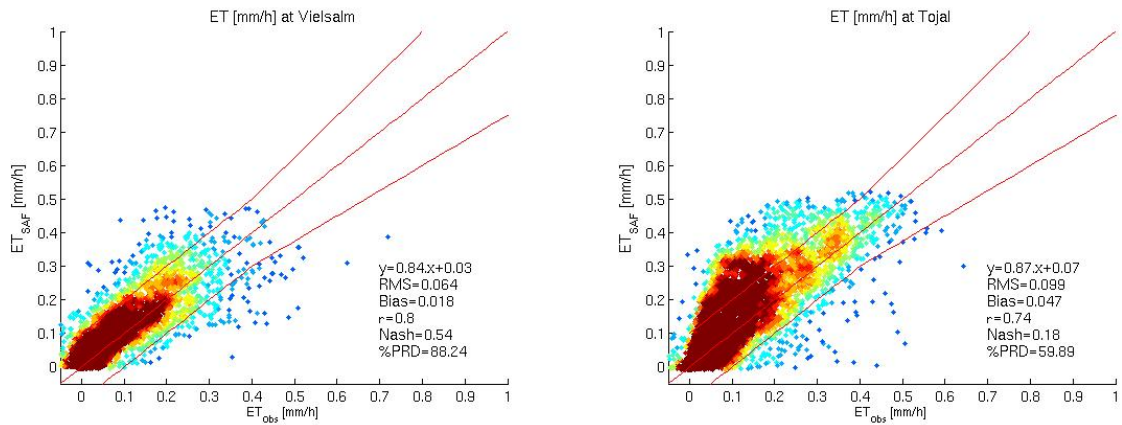


Figure 2.3.: Comparison between 30 min LSA-SAF ET [$mm.h^{-1}$] and observations at (left) Vielsalm FLUXNET station (Belgium) and (right) Tojal (Portugal). Period: March to November 2007. Dashed line: envelop associated to PRD criteria (see text); straight line: 1:1 line.

As well, a density scatter plot is shown in Figure 2.3 for Vielsalm and Tojal, allowing an easy visualization of the statistical results. Bias is low, not exceeding $0.02 mm.h^{-1}$ 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 indices 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 stations. A close analysis allows us to incriminate for a part of the year the soil moisture used as input for this location (see Sect 6). The Nash-Sutcliffe indices summarise the scores obtained through different statistical indices, and are given in Table 2.3. Scores above 0.50, already good given the noisiness of observations, are found for four of the six stations. Low scores are obtained for Hesse (0.31) and for Tojal (0.18), in agreement with the above mentioned observations.

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, it 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). This can be applied uniformly on all model output whatever the particular case of each station can be regarding data accuracy and possible energy imbalance. The PRD index is defined to score the rate of good estimations of the ET model given accuracy of reference observed measurements and with respect to expected accuracy for possible applications with 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^{-1} 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^{-1} , then the error on ET should be less than 0.1 mm.h^{-1} . This quality criterion can be visualised on the scatterplots of Fig. 3, as dashed lines forming

Table 2.4.: Summary of models characteristics and output used for inter-comparison.

	ECMWF	GLDAS
Versioning	Cycle 31r1	GLDAS/Noah2.7.1
Land surface scheme	TESSEL	Noah
Coupled to atmosphere	Yes	No
Domain	Global	Global
Horizontal spatial resolution	0.25	1
Available temporal resolution	3h	3h
Land cover used	IGBP	University of Maryland

an envelope for good quality estimates. Overall results are also listed in Table 3. Using this score index, we obtain very good rates for all stations (from 80 to 90%), excepted for Tojal, where it reaches only 60%.

2.5. Intercomparison with ECMWF and GLDAS ET

To complement the validation against local ground measurements, we additionally compare MET output to other existing products available operationally at regional scale. While the intercomparison is not a formal assessment of the MET capabilities compared to standard measurement techniques, it shows, however, if MET produces estimates within a similar range. For that purpose, ECMWF forecasts and GLDAS data (Rodell et al., 2004b) are used to compare results at the regional scale. The main characteristics of these data products are listed in Table 2.4.

The intercomparison is achieved for the period from April to November 2007 (from March for the European area). In order to achieve a consistent analysis of the results, LSA- SAF ET has been projected in latitude-longitude on a common grid with a coarser spatial resolution ($1^\circ \times 1^\circ$). Three maps per day are then produced by averaging ET rates over three successive periods of three hours each: P1 covers the time interval from 09:00 to 12:00 UTC, P2 from 12:00 to 15:00 UTC and P3 from 15:00 to 18:00 UTC.

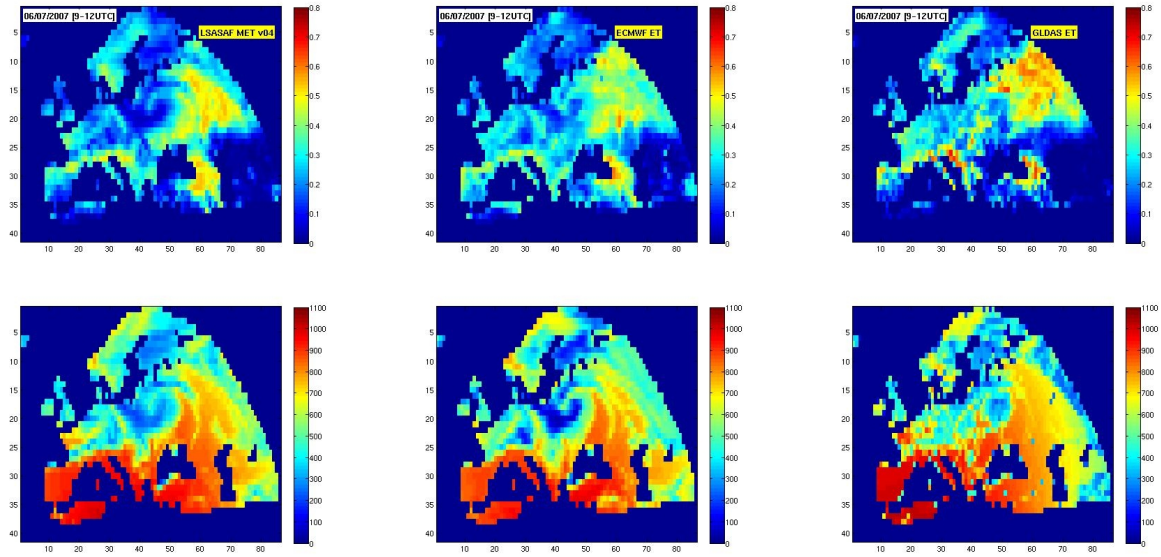


Figure 2.4.: Comparison of LSA-SAF (left), ECMWF (middle) and GLDAS (right) ET (top) and global radiation (bottom), 3-hourly averages (9:00 to 12:00 UTC, excepted GLDAS global radiation: instantaneous 12:00 UTC) for the 6 July 2007.

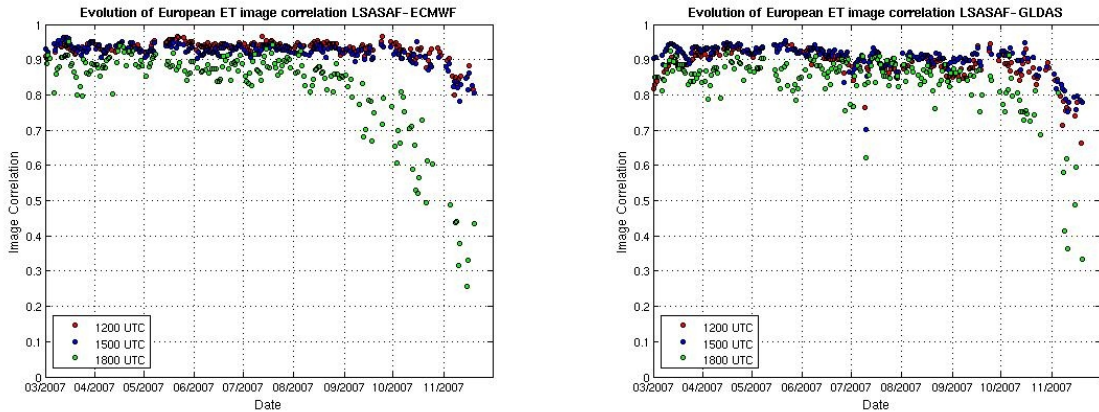


Figure 2.5.: Evolution of 3-hourly mean image correlation over MSG European window between LSASAF ET and ET ECMWF forecasts (left), and with GLDAS ET images (right), from March to November 2007.

2.5.1. Intercomparison results

Figure 2.4 illustrates on a test case (Europe, 6 July 2007, P1) 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, similar values range and spatial patterns are easily 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. Differences in $S_{\downarrow}$ input could explain some differences in ET. However, it is also noticeable that it should not be the sole explanation. Interpretation of the differences will be discussed later.

After this example, we compare the results globally by means of three different statistical approaches: cross-correlation, monthly mean occurrence distribution, and spatial distribution of the mean difference over the total period.

First, we compute spatial correlation between pairs of images by considering LSA SAF MET images and successively ECMWF and GLDAS ET images. Figure 2.5 displays the correlation evolution, for time periods P1 to P3 over Europe, between LSA-SAF ET and ET forecasts from ECMWF on one hand, and with GLDAS ET images on the other hand.

The computed spatial correlation between images is nearly constant for P1 and P2, with a correlation generally above 90%. For P3, 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. For the summer months, image correlation is slightly better with ECMWF than with GLDAS for P1 and P2. 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 P3 towards the end of the considered period. Similarly to Europe, spatial correlation between MET and ECMWF ET and GLDAS ET is computed for the 3 other geographical windows for the mid-day periods, P1 and P2 for Africa, P2 and P3 for South America. Spatial correlation is 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

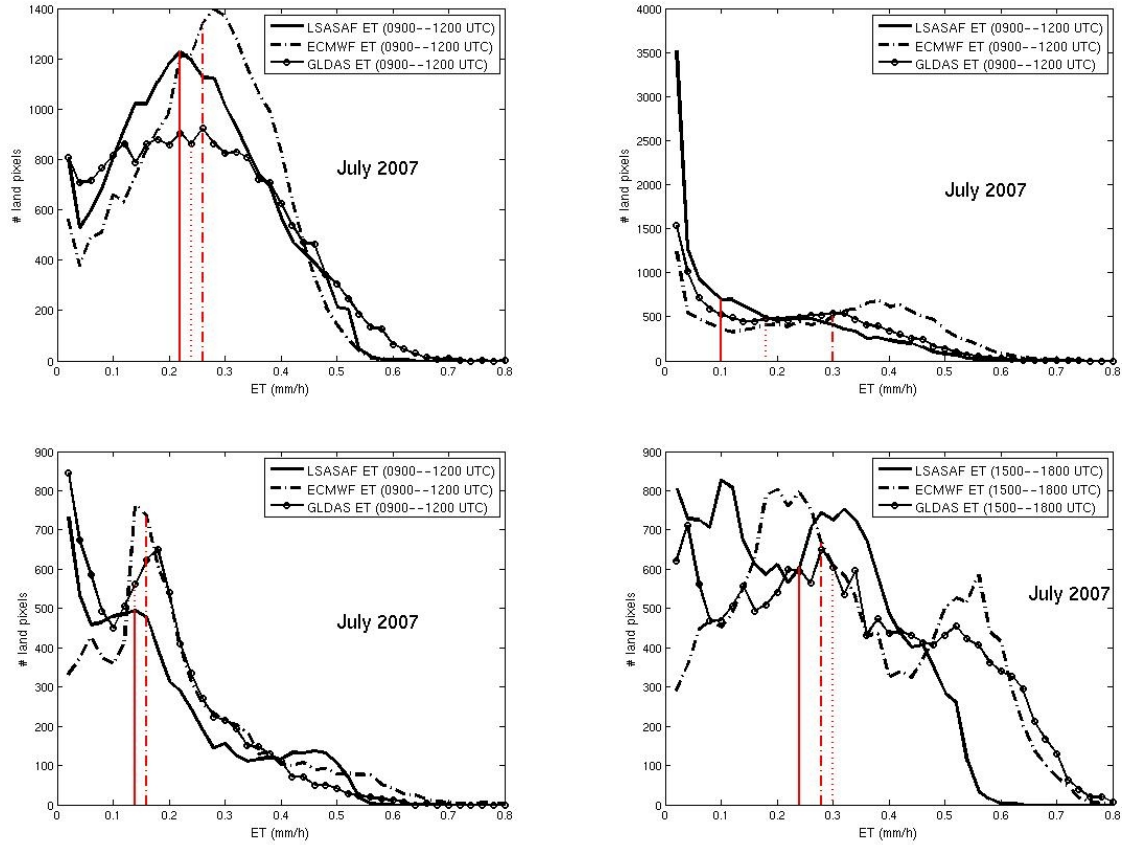


Figure 2.6.: Distributions of ET estimates from LSA-SAF (solid line), ECMWF (dash-dotted line) and GLDAS (solid line and circles). Each figure encompasses the mean distribution of the 3-hourly averaged ET (09:00 to 12:00 UTC) for July 2007, as well as the mean values of the distributions (vertical lines). Europe (upper left), North of Africa (upper right), South of America (lower right) and South of Africa (Lower left).

on the general patterns of ET variations.

As second step, we compare the monthly mean distributions of ET estimates produced by the three models. The mean distributions of P1 ET for July 2007, as well as their mean values (vertical bar) are represented for the 4 geographical areas covered by MSG (Figure 2.6). The mean distributions of the three model output have comparable shape and magnitude, except for South America. The comparison of the 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, 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 2.7 illustrates the bias between ECMWF and LSA SAF MET and between GLDAS and LSA SAF MET over the whole period of inter-comparison. Maps are presented for Europe and North Africa. To show clearly the differences, a relative bias to the mean MET values has been chosen as metrics. Positive bias means ECMWF or GLDAS exhibits larger estimates than LSA SAF MET. Local differences between the three model outputs are clearly visible. 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 MET and GLDAS, than between MET and ECMWF. As for Northern Africa, the larger differences are found in dry regions with low evaporation rate close to deserts.

2.5.2. Intercomparison interpretation

Table 2.5.: **Spatial correlation between the mean and the mean of (1) $\Delta\%LAI/r_{s,min}$, (2) ΔCVH and (3) $\Delta\%S_{\downarrow}$ for North and South Africa (see text).**

		$\Delta\%LAI/r_{s,min}$	ΔCVH	$\Delta\%S_{\downarrow}$
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

Despite the good correlation between the three models ET estimates shown in Sect. 5.1, discrepancies are observed. There are three possible sources of differences that could be considered here to explain them: input variables of the respective models, model formulation and model parameters. The three models are based on the similar formulation, with some differences in model parameterizations, but involving compara-

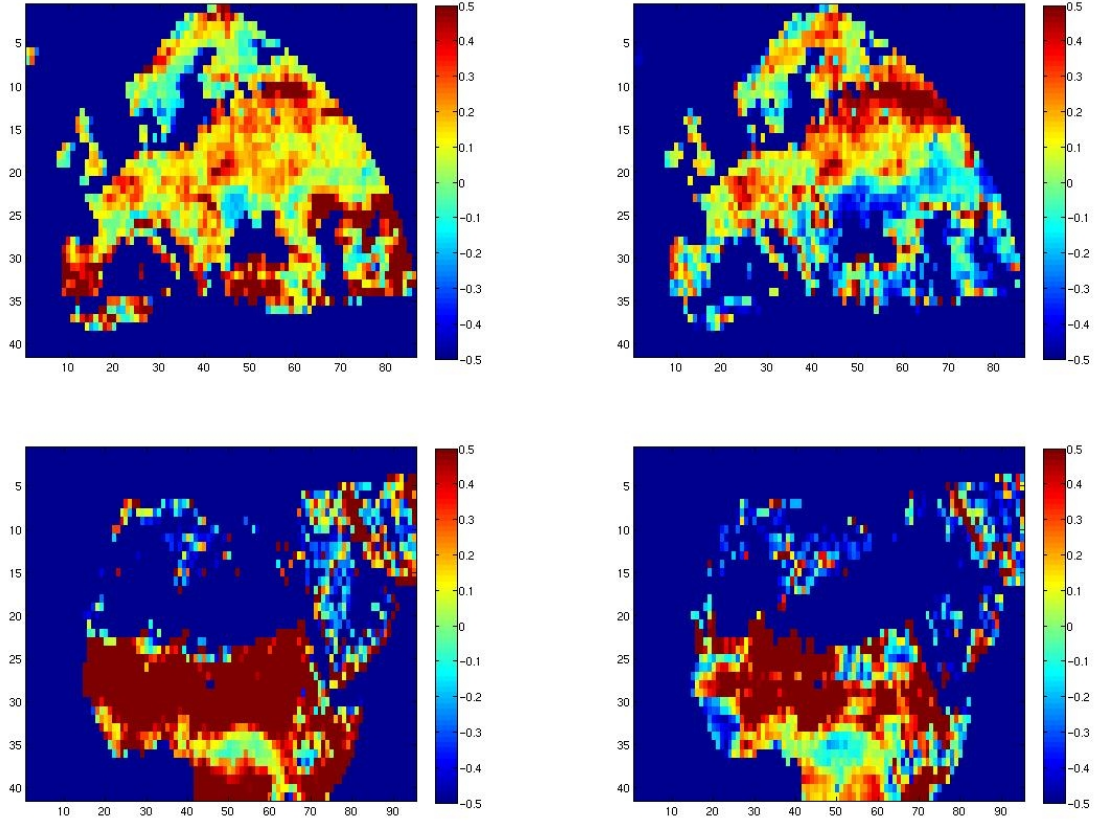


Figure 2.7.: $1^\circ \times 1^\circ$ maps of bias between ECMWF ET and LSA-SAF MET (left) and between GLDAS and LSA-SAF MET (right) over the whole period of inter-comparison. Europe (upper part), North of Africa (lower part).

ble model parameters types. One of the most sensitive parameters of these models is the parameter that determines the maximum transpiration rate a vegetation type can bear, i.e. $r_{s,min}$. In the same way, information from vegetation database influences the surface fluxes calculation. The Leaf Area Index (LAI) is crucial because it scales the $r_{s,min}$ at model spatial resolution. Therefore, as the ratio $r_{s,min}/LAI$ is explicitly used in the three models (used in Eq 2.10 in the present study), we choose it as one of the major potential sources of discrepancies. Furthermore, since the evaporative fraction is quite different for forests than grass or crops, land cover, and more particularly the fraction of high and low vegetation, is one very important field that needs to be considered in such study. Land cover is by consequence chosen as another possible source of ET differences between the models. At last, focusing on meteorological fields used as input, $S_\downarrow$ is one

of the most sensitive input of the models. Three motivations are considered here: (1) $S_{\downarrow}$ is presumably the main driver of the global behavior of ET in the temperate regions (Teuling et al., 2009), (2) $S_{\downarrow}$, related to cloudiness, is difficult to predict accurately in numerical weather forecast models, and (3) it can be different for each model considered here, as it consists in weather forecasts (for ECMWF and GLDAS) and in LSA-SAF DSSF (for the MET model). $S_{\downarrow}$ is therefore considered as a third major possible source of ET differences. Other model differences could have been investigated, such as air temperature or soil moisture. However, as MET is forced by both the air temperature and the soil moisture forecasted by the ECMWF atmospheric model, we have only chosen in our present analysis variables that are different for the three models. The three envisaged candidates to explain ET discrepancies are (1) differences of $S_{\downarrow}$ input in the models, (2) the land cover and, more specially the difference in high vegetation percentage (CVH), and (3) difference in the ratio $LAI/r_{s,min}$. In the following paragraph, $\Delta\%Var$ denotes the mean relative bias in the variable Var, that can be ET, $S_{\downarrow}$ or $LAI/r_{s,min}$. The absolute difference in high vegetation percentage is noted ΔCVH . In order to evaluate the impact of the three possible causes on ET, we calculate time series of spatial correlation between $\Delta\%ET$ and (1) $\Delta\%S_{\downarrow}$, (2) $\Delta\%LAI/r_{s,min}$ and (3) ΔCVH . The period P1 is used in the following for Europe, North and South Africa. As shown in Figure 2.8, for Europe, correlation suggests that solar radiation be the main source of ET difference, as expected, especially outside winter. $\Delta\%LAI/r_{s,min}$ is indicated as the second main source of ET differences, notably by comparison with GLDAS with a positive correlation all along the year. The time series show an important seasonal behaviour in the case of the comparison with ECMWF: the correlation is positive (0.2 to 0.6) in spring and autumn and negative the rest of the year. Solar radiation affects ET at all temporal scales, at the shorter considered time steps and globally. $\Delta\%LAI/r_{s,min}$ biases ET estimates most at short and medium range with ECMWF, and on all time scales with GLDAS. As regards land cover, difference with GLDAS shows no correlation with ET differences, while with ECMWF, 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 2.5. Figures with correlation time series over Africa are not shown: the information is globally redundant with results of Table 2.5 or otherwise stated. The two major sources of differences between LSA SAF

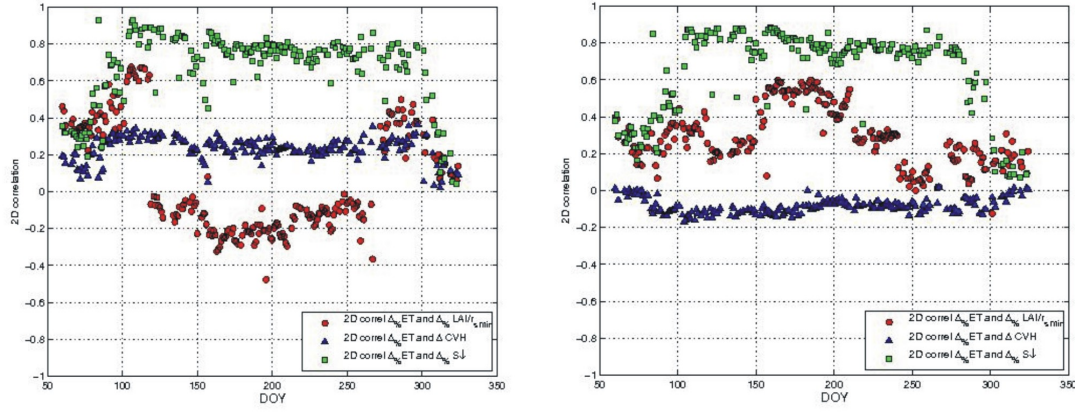


Figure 2.8.: **Spatial (2-D) correlation over Europe between the ET mean relative bias (based on the images between 09:00 to 12:00 UTC) and model differences: (1) $LAI/r_{s,min}$ (red diamonds), (2) High vegetation percentage (CVH, blue triangles), and (3) $S_{\downarrow}$ mean relative bias (DSSF, green squares). At left: comparison between LSA-SAF MET and ECMWF. At right: comparison between LSA-SAF MET and GLDAS.**

MET and ECMWF ET at daily and annual time scales are $\Delta\%S_{\downarrow}$ and $\Delta\%LAI/r_{s,min}$. Correlation suggests $\Delta\%S_{\downarrow}$ as the main driver of the differences with GLDAS ET, followed by $\Delta\%LAI/r_{s,min}$, at short time scale, and by ΔCVH over the entire period. A weak seasonal cycle, between -0.2 and 0.2, is observed (not shown) in the correlation with $\Delta\%LAI/r_{s,min}$. This cycle in 2-D correlation could explain why $\Delta\%ET$ is not sensitive to $\Delta\%LAI/r_{s,min}$ at the annual time scale, in the comparison with GLDAS.

To summarize, we have shown that, there is a high spatial correlations between the three investigated models. The ET differences could be 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 $r_{s,min,i} LAI_i$ in Eq 2.10. The correlations computed suggest that $S_{\downarrow}$ differences be the most influential on ET differences. $LAI/r_{s,min}$ is the second envisaged source of difference between models in magnitude. Differences with GLDAS ET could have also been explained with soil moisture discrepancies between models, especially in the (semi-) arid areas. However, when the water availability for ET is low, $\Delta\%LAI/r_{s,min}$ tend to amplify the observed $\Delta\%ET$, because it is a very sensitive model parameter in such conditions, making difficult the separation of both effects.

2.6. Consistency of LSA-SAF ET and LST

A last part in the validation is to check if there is a good consistency between the LSA-SAF products. This exercise is important in view to ensure a consistent portfolio of variables for further applications. Three variables from LSA-SAF are used by the evapotranspiration model, namely the surface albedo, the short- and long-wave incoming radiation at the surface. As they are involved in the calculation of the energy balance at the surface in the model, their variations are automatically propagated in the evapotranspiration estimates. More interesting from the validation point of view is the consistency of the evapotranspiration estimates with variables not involved in the model formulation. Land surface temperature (LST) is one of those variables.

LST does not compare easily to evapotranspiration, but it can be compared to the surface temperature calculated by the evapotranspiration model (T_{skin}). These variables are generated independently, since LST is not used in the LSA-SAF evapotranspiration algorithm. However, the computed 'skin temperature' is neither a radiative temperature nor an aerodynamic temperature, but a mix of both definitions as it is used in both the energy budget at the surface and in the estimation of the sensible heat flux. As well, the physical interpretation of LST retrieved from the satellite data by split-window technique is not straightforward. LST and T_{skin} clearly have different definitions and therefore should not be equal. However, we expect a coherent evolution of both temperatures. As an example, we provide in Figure 2.10 a comparisons of T_{skin} and LST for three sites collectively chosen by the LSA-SAF consortium to assess the consistency of the LSA-SAF products. Melle (50.98°N, 3.82°E) is situated in Belgium, Carpentras (44.08°N, 5.04°E) in France and Evora (38.47°N, 8°W) in Portugal, close to the Tojal station cited in section 4. The three sites sample different climates and vegetation covers of western Europe. For Melle, LST and T_{skin} evolves in the same way, and are therefore consistent, with a RMS of the order of 3.5 K, which is acceptable considering the uncertainty of 3 K of the LST product (Kabsch et al., 2008). No systematic difference can be observed for Carpentras. although the root-mean squared difference is larger than at Melle. In Evora, we observe in the scatter plot that for small values of LST, corresponding to morning/evening, spring and autumn, LST is very close to T_{skin} . However, for summer estimates, there is a evident bias, with increasing differences for the highest absolute

values. This deviation was observed for the same period on ET at Tojal station (close to Evora). Therefore, the cross-check of internal variables from ET model with other satellite products, like LST, seems to provide a great opportunity to detect problems in ET maps, and should be more exploited in the future.

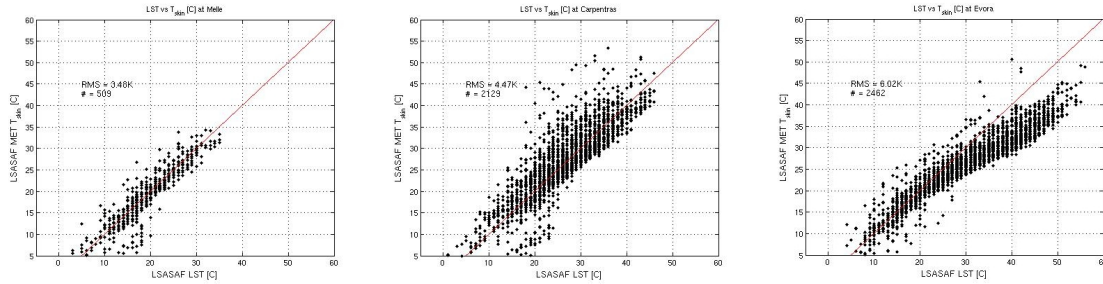


Figure 2.9.: Half-hourly T_{skin} computed by the ET model are compared to corresponding LSA-SAF LST retrievals for three european sites (Melle, Carpentras and Evora) over March to November 2007. While no systematic or seasonal bias can be detected for the temperate sites, a seasonal bias is observed as a deviation from the unity line for the Evora site, indicating an inconsistency between the ET model and the LST retrievals. The root-mean squared difference (RMS) varies between 3.5 K and 6 K depending on the site. The number of time steps used for statistics (#) shows clearly the effect of cloudiness on the availability of LST retrievals.

2.7. 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 MET 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 MET model, we show that the results of the comparison are clearly improved, 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 (Figure 2.10, left part and comparison between Figures 2.3 and 2.10, right parts). The Tojal case indicates that using ECMWF soil moisture forecasts as input of MET model may lead to erroneous ET estimates.

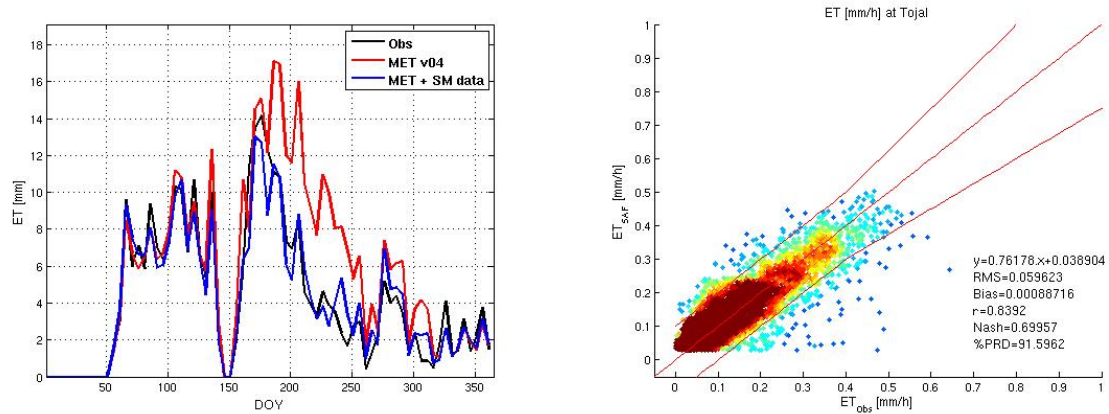


Figure 2.10.: **Left: time series of the 5-days cumulated ET measured (black) and modelled (red) for the CarboEurope-IP Tojal station (Portugal) for the period from March to November 2007 as provided by the LSA-SAF MET. Modelled ET using soil moisture measured at the station (blue) has been superimposed. Right (as in Figure 2.3) but modelled ET computed with soil moisture measured at the station compared to 30 min mean observed ET.**

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) and ERS/ASCAT SSM (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.

2.8. 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 validation to full MSG field of view, and, in particular, we must collect sufficient datasets in Africa 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 can 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.

3

Improving land surface modelling of evapotranspiration using LSA-SAF biophysical variables

This chapter is based on N. Ghilain, A. Arboleda, G. Sepulcre-Canto, O. Batelaan, J. Ardö & F. Gellens-Meulenberghs (2012), Improving evapotranspiration in land surface models by using biophysical parameters derived from MSG/SEVIRI satellite, Hydrol. Earth Sys. Sci., 16, 2567-2583.

Abstract

Monitoring evapotranspiration over land is highly dependent on the surface state and vegetation dynamics. Data from spaceborn platforms are desirable to complement estimations from land surface models. The success of daily evapotranspiration monitoring at continental scale relies on the availability, quality and continuity of such data. The biophysical variables derived from SEVIRI on board the geostationnary satellite Meteosat Second Generation (MSG) and distributed by the Satellite Application Facility on Land surface Analysis (LSA-SAF) are particularly interesting for such applications, as they aimed at providing continuous and consistent daily time series in near-real time over Africa, Europe and South America. In this paper, we compare them to monthly vegetation parameters from a database commonly used in numerical weather predictions (ECOCLIMAP-I), showing the benefits of the new daily products in detecting the spatial and temporal (seasonal and inter-annual) variability of the vegetation, especially relevant over Africa. We propose a method to handle Leaf Area Index (LAI) and Fractional Vegetation Cover (FVC) products for evapotranspiration monitoring with a land surface model at 3-5 km spatial resolution. The method is conceived to be applicable for near-real time processes at continental scale and relies on the use of a land cover map. We assess the impact of using LSA-SAF biophysical variables compared to ECOCLIMAP-I on evapotranspiration estimated by the land surface model H-TESSEL. Comparison with in-situ observations in Europe and Africa shows an improved estimation of the evapotranspiration, especially in semi-arid climates. Finally, the impact on the land surface modelled evapotranspiration is compared over a North-South Transect with a large gradient of vegetation and climate in Western Africa using LSA-SAF radiation forcing derived from remote sensing. Differences are highlighted. An evaluation against remote sensing derived land surface temperature shows an improvement of the evapotranspiration simulations.

3.1. introduction

In the past decades, an increasing number of models were developed to monitor evapotranspiration (ET) at different scales using remote sensing measurements. Simple empirical or statistical methods to fully detailed physical models have been developed, using a wealth of information provided by various satellites (e.g., Courault et al., 2005; Kalma et al., 2008; Li et al., 2009). In all methods, vegetation has been recognized to be a cornerstone of the evapotranspiration process, since plants are the main medium for exchange of water between the soil and the atmosphere. In particular, land surface models are widely used for meteorological and climate studies. They are based on a conceptual and semi-empirical description of, respectively, the physical and physiological processes of heat and water exchanges between soil, plants and atmosphere media. Information usually needed for land surface models is 1) the exact coverage of Plant Functional Types (PFT) (Bonan et al., 2002), information given by a land cover map, 2) the state of the vegetation development, mostly given by the variable Leaf Area Index (LAI). While most of those models require explicit external information on the vegetation status (e.g., Balsamo et al., 2009; Noilhan and Planton, 1989), a new generation of models considers it as a new model variable (e.g., Jarlan et al., 2008; Gibelin et al., 2006; Blyth et al., 2006). But, for both model classes, information on vegetation status is highly relevant. For the first class, it is a necessary information to provide. For the second one, it is recommended for updating the model forecasts (e.g., Jarlan et al., 2008; Albergel et al., 2010), or at least evaluate their output (e.g., Brut et al., 2009). Past studies have used variety of land surface models or crop growth models and different vegetation products issued from remote sensing (e.g., Dorigo et al., 2006). By this way, the use of remote sensing vegetation indices has revealed an improved forecast of surface variables.

Different exploitations have become possible along with the ever growing length of time series available from remote sensing. Early usage of the vegetation indices in Soil-Vegetation-Atmosphere Transfer (SVAT) models focused on a mean vegetation status by plant type throughout a year. New available long time series and reprocessing capabilities have given rise to vegetation databases, that include a mean monthly or weekly evolution of vegetation parameters, PFT and geographically dependent (e.g. ECOCLIMAP). Those two approaches have been widely used for operational purposes (e.g., van den Hurk et al.,

2000, 2003) for practical reasons: easy to handle, not dependent on necessary incoming information from an external source, and hence on timeliness. However, the direct use of remote sensing time series is an important step towards a closer monitoring of the land surface, because it captures better both spatial and temporal variations, including intra-species and inter-annual variability. For long-term monitoring of ET, it is necessary to capture the inter-annual variability of the vegetation state signal, which can be caused, for example, by a different date of bud-break for deciduous forests, harvest timing shifts (Cooley et al., 2005), rain occurrence in semi-arid areas, where the vegetation growth is driven by the hydrological regime, or else by land re-allocation or fires. For the short term monitoring, at a daily time scale, poor time sampling of the vegetation phenology can have negative impact on ET, especially during the rapid development stage of the canopy (e.g., Sepulcre-Cantó et al., 2013). Moreover, even if the classification in ecosystems of ECOCLIMAP-I is quite fine, the assumption of equal properties across different spatial scales for one ecosystem is an oversimplification of the problem.

Previous efforts have been carried out mainly using time series from polar orbiters (e.g., Albergel et al., 2010; Rodell et al., 2004b). However, most of those studies focus on assimilation in a reanalysis mode, and cannot be used for a near-real time monitoring of the evapotranspiration. Recently, the EUMETSAT Land Surface Analysis Satellite Application Facility (LSA-SAF) developed a coordinated service in the area of remote sensing of the land surface and proposes products based on the geosynchronous MSG satellites (<http://landsaf.meteo.pt>) (Trigo et al., 2011). Among these products, remotely sensed biophysical parameter products, i.e. leaf area index, LSA-SAF LAI, and fractional vegetation cover (Fveg), LSA-SAF FVC, are delivered daily at the spatial resolution of the SEVIRI instrument on board MSG (Garcia-Haro et al., 2008), 3.1 km sub-satellite, and are available since 2007. This study is done in the framework of land surface modelling for the purpose of ET monitoring at MSG/SEVIRI spatial resolution. It focuses on the applicability and gain of using biophysical variables issued from geostationary satellites, compared to monthly variables provided by databases.

In this paper, we demonstrate the advantages of using LSA-SAF biophysical variables. We compare them to those from ECOCLIMAP-I, and describe a method to use them in a land surface model at the same spatial resolution. A set of validation results over Europe and Africa, and an example of application over West Africa, further evaluated by

comparison with complementary remote sensing data are presented.

In section 2, we give a short description of the material for this study, which consists of a land surface model, the vegetation database used (ECOCLIMAP-I), and the LSA-SAF biophysical variables. In section 3, we present a method to use the LSA-SAF biophysical variables in the land surface model in view of operational implementation. In section 4, we compare the new vegetation dataset to ECOCLIMAP-I, highlighting its advantage. We analyze its characteristics and deduce a practical estimation mean to obtain robust estimates of biophysical variables. Then we evaluate the impact of using the new vegetation dataset on the modelled evapotranspiration against in-situ observations in Europe and Africa. At last, different aspects of the methodology and its application are discussed and conclusions from this work are outlined.

3.2. Material

3.2.1. The land surface model

The land surface model is based on H-TESSEL, the ECMWF land surface model (Beljaars and Viterbo, 1994; Viterbo and Beljaars, 1995; van den Hurk et al., 2000; Balsamo et al., 2009). It follows a bulk resistance formulation for the estimation of the surface turbulent fluxes, with two resistances modulating the variation of the sensible and latent heat fluxes. The aerodynamical resistance accounts for the turbulence generated by air temperature or wind gradient, while the stomatal resistance includes the influence of vapor pressure deficit, fraction of absorbed energy and soil water availability on the opening of the leaves stomata via a simple parameterization (van den Hurk et al., 2000). In addition, vertical distribution of moisture and temperature in the soil is modeled as a solution to diffusion equations. Direct evaporation from interception is modelled.

The needed forcing of this model consists of short and long-wave radiation reaching the land surface, surface albedo, wind speed, air temperature, air humidity and precipitation. In this model, the spatial unit for the energy balance assessment is divided into different tiles, associated to PFTs. The estimation of the surface fluxes is performed for each PFT before averaging over the spatial unit. The formulation uses parameters

describing the vegetation state for each PFT separately: LAI, Fveg, roughness lengths, a minimum stomatal resistance, and the vertical distribution of the roots in the soil. The PFT classes have been changed from the original formulation of H-TESSEL to match the classification of ECOCLIMAP-I (Ghilain et al., 2011) and the model parameters have been calibrated.

The land surface model can be used at different spatial scales, from a single point simulation using as input local measurements up to coarse grids used by global circulation models. In this paper, the model is applied at meso-scale and investigate the utility of the LSA-SAF biophysical variables. We therefore work in the MSG/SEVIRI grid, with a pixel as the basic model spatial unit.

The radiative terms used here are provided by the LSA-SAF: the downward surface short-wave (LSA-SAF DSSF) the long-wave fluxes (LSA-SAF DSLF) (Geiger et al., 2008b; Ineichen et al., 2009), and the surface albedo (LSA-SAF AL) (Geiger et al., 2008a; Carrer et al., 2010). LSA-SAF DSSF and DSLF are available half-hourly, while surface albedo is produced daily.

Meteorological forcing is provided by the Global Circulation Model re-analyses ERA-Interim (Simmons et al., 2006). The spatial resolution available is 0.5° and temporal sampling is 3 hours. Meteorological forcing is linearly interpolated in time to half-hourly values. Tri-hourly precipitation rates are distributed equally for each 30 minutes steps. If radiative forcing is missing, ERA-Interim is used to fill the gaps.

Complementary information on vegetation is needed: a land cover map and biophysical variables. Since each pixel can be composed of different PFTs, biophysical parameters must be known for each PFT inside the pixel, as well as the exact percentage that the PFTs occupy. The land surface model outputs an ET estimate each 30 minutes.

3.2.2. The ECOCLIMAP-I vegetation database

ECOCLIMAP-I (Masson et al., 2003; Champeaux et al., 2005) is a land cover map at 1 km resolution. In addition, it provides a vegetation parameterization for use in SVAT models in the form of a synthetic global vegetation database. It is widely used by numerical weather prediction models in European countries (e.g., ALADIN

International Team, 1997), also used for inter-comparison of land surface models in Western Africa (Boone et al., 2009; Grippa et al., 2011), and in specific applications of H-TESSEL (Wipfler et al., 2011). Mixed ecosystems are decomposed into PFTs (defined in Table 3.1), and each PFT is associated to a 10 days or monthly varying set of biophysical variables (LAI, Fveg, roughness lengths), averaged spatially over all the grid cells occupied by the concerned ecosystem. ECOCLIMAP-I is used as in Ghilain et al. (2011).

The ecosystems are decomposed into PFTs compatible with the vegetation parameterization of the model, and the land cover map obtained at 1 km is projected onto the coarser model grid. The land cover map obtained gives the 5 dominant PFTs and their contribution to a satellite pixel. But, since one PFT can result from the combination of several ecosystems, LAI for each PFT is computed as the weighted mean contribution of the involved ecosystems LAI. Monthly LAI maps at the satellite resolution are then created.

Table 3.1.: List of PFTs defined in ECOCLIMAP-I and used in the land surface model.

code	PFT
1	Bare Soil
2	Rocks
3	Snow (Permanent)
4	Deciduous Broad leaf Forest (DBF)
5	Evergreen Needle leaf Forest (ENF)
6	Evergreen Broad leaf Forest (EBF)
7	C3 crops
8	C4 crops
9	Irrigated crops
10	Grassland (G)
11	Swamp areas and bogs

3.2.3. The LSA-SAF vegetation products

LSA-SAF LAI and FVC products (García-Haro et al., 2005a) are derived from MSG/SEVIRI using a two components Spectral Mixture Analysis method (García-Haro et al., 2005b; Verger et al., 2009). LSA-SAF operational center generates both variables

daily, based on the past 5-days estimations, at the sensor spatial resolution. Retrieval uncertainty, as well as a quality flag indicating the quality and reason for possible no production (e.g. snow, traces of snow, traces of inland water) is also provided (Garcia-Haro et al., 2008).

LSA-SAF products represent an interesting alternative to SPOT-VGT or MODIS for meso-scale applications, because of its relatively high generation frequency, its near-real time availability and its improved time stability (Garcia-Haro et al., 2008). LSA-SAF LAI and FVC have been produced routinely since August 2005, with successive algorithm (VEGA) improvements, related to methodology (VEGA v2.0, September 2006), input data quality (December 2006), and post-processing (VEGA v2.1, May 2008).

3.3. Methods

3.3.1. Exploitation of the LSA-SAF biophysical variables

LSA-SAF LAI and FVC are provided daily at the MSG/SEVIRI spatial scale over the whole field of view. At that scale, landscapes can be very heterogeneous, especially over Europe, and one pixel can represent a mixed signal of different ecosystems or PFTs. This information cannot be used as such in SVAT-type models, because more details on each PFT is necessary to compute surface fluxes. In addition, there can be some gaps in the products, or pixels in the images could be unprocessed, while the models require continuous, stable and consistent LAI time series. It is therefore needed to implement a procedure able to retrieve LAI at sub-pixel (or PFT level), and to cope with continuity and stability issues. A two-steps procedure is implemented to, first, provide LSA-SAF LAI maps consistent in time, and then, to compute vegetation parameters for each PFT of the considered pixel. A schematic view of the process is shown in Figure 3.1.

For every pixel, it is necessary to build continuous and consistent LAI time series as close as possible to the actual LSA-SAF LAI product, LAI_{SAF} . First, an annual LAI climatology is built pixelwise using daily LSA-SAF LAI images from 2007 to 2010. The climatological year is divided in periods of 10 days. For each 10 days period, a mean

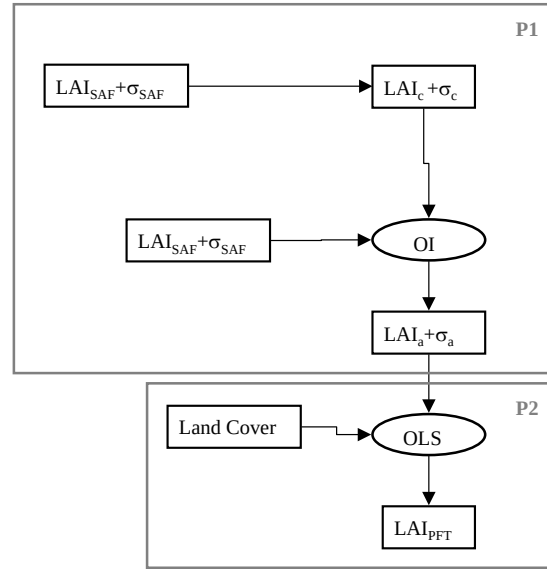


Figure 3.1.: **Flowchart of the two-steps procedure to obtain LAI for each PFT in a given MSG/SEVIRI pixel. First, continuous and consistent LAI series are created at pixel level, LAI_a , using a 4-years climatology from LSA-SAF LAI, LAI_{SAF} , actual LAI_{SAF} , and an optimal interpolation (OI) method. Then, the pixel LAI is decomposed into LAI_{PFT} for each PFT contributing to the pixel area, using a land cover map, LAI_a and an ordinary least square method (OLS).**

LAI, LAI_c , is calculated pixelwise, along with an error bar, σ_c , corresponding to the standard deviation of the LSA-SAF LAI sample used.

Even if snow cover is detected, some spurious data, occurring especially during the 2007-2008 winter in northern latitudes and over coniferous forests, still persist. Similar problems have been encountered by Jiang et al. (2010) with NOAA satellite. In May 2008, LSA-SAF changed the algorithm to VEGA v2.1 to screen those data by applying a post-processing on the problematic areas. However, in order to take advantage of the longest time series available, the spurious data are filtered out using a threshold. Winter LAI higher than 85% of the mean summer value are filtered out. The extent of the filtering period is based on the collection of the spurious data: it is longer for Northern european countries (e.g. Sweden, Finland) and shorter for the european mid-latitude countries (e.g. Germany, France).

In order to get continuous time series needed by operational models (Jiang et al., 2010), a linear interpolation is applied to both LAI values and standard deviations to fill the gaps in the climatological series.

Finally, for each actual LSA-SAF LAI, an optimal interpolation scheme (Gu et al., 2006) is applied. In our case, LSA-SAF LAI time series are more stable in time than the MODIS LAI (Garcia-Haro et al., 2008), and the LAI climatology is created from 4 years of data. Appropriate weighting factors have been tuned and the error on the climatology, σ_c , is multiplied by 2.5 and noted $\tilde{\sigma}_c$. In consequence, the weight of the climatology is decreased to better follow the daily remote sensing product. The result is a LAI for each pixel (LAI_a), corrected using a background climatological information (Eq 3.1). Therefore, most dubious data are removed, the time series are smooth and gaps are filled.

$$LAI_a = \frac{\tilde{\sigma}_c^2}{\sigma_{SAF}^2 + \tilde{\sigma}_c^2} \cdot LAI_{SAF} + \frac{\sigma_{SAF}^2}{\sigma_{SAF}^2 + \tilde{\sigma}_c^2} \cdot LAI_c \quad (3.1)$$

As in (Gu et al., 2006), when $|LAI_{SAF} - LAI_c| > 2\sqrt{\sigma_{SAF}^2 + \tilde{\sigma}_c^2}$, LAI_{SAF} is unusable, and $LAI_a = LAI_c$.

An ordinary least-square algorithm (OLS) is then applied to derive LAI for each PFT, using LSA-SAF LAI and PFT percentages over a neighbourhood of 9 (3×3) or 25 (5×5) pixels (see Annex A). Two assumptions are needed: 1) the percentage of each PFT in one pixel represents exactly the real cover of the land surface, 2) the vegetation parameters, e.g. LAI, in close neighbourhood are assumed to be homogeneous. This hypothesis is reasonable if we consider that, in a close neighbourhood, meteorological and climatic conditions are similar, and one can assume the growth of the natural vegetation will be the same for one specific plant type. For human-forced vegetation, like for crops, the assumption can still hold if we assume that agricultural practices are homogeneous in the region of interest, which is often the case for large areas.

Repeating the operation by moving the size-defined neighbourhood by one pixel at a time, we obtain a smoothed spatial average estimate of LAI for each PFT.

Special attention has been paid on the correct handling of remote sensing derived vegetation products in the land surface model, avoiding a simultaneous variation of LAI

and Fveg (Oleson and Bonan, 2000; van den Hurk et al., 2003; Jiang et al., 2010; Miller et al., 2006) and defining the LAI for the vegetation needed by the model from the remote sensing derived product (Ge, 2009). Fveg is therefore constant and is built pixelwise using the complement to the absolute minimum LSA-SAF FVC over 2007 and 2008. Assuming that the bare soil fraction has a nul LAI, consistent handling of LAI for the land surface model is ensured through OLS.

Because of the uncertainty of land cover maps due to misclassification (e.g., Jung et al., 2006), some erroneous LAI could be estimated from the least-square algorithm. We propose to assess the impact of the uncertainty on the retrieved LAI_{PFT} at 120 pixels selected randomly over the *Euro* window. The uncertainty is evaluated by applying the LAI decomposition using 3 different land cover maps for 2007. For each PFT in each selected pixel, the PFT percentage differences (rescaled to Fveg) are computed and the time correlation and root-mean square difference (RMS) between the LAI_{PFT} series obtained from the 3 land covers are estimated, by PFT and by pixel. Results are presented in section 4.2.

Since a PFT is a *class* of vegetation (Alton, 2011; Williams et al., 2009), pixel-to-pixel variation of LAI_{PFT} may occur, and could affect the retrieval. In section 4.2, we analyze those variations. For a given PFT, only the LAI value of homogeneous pixels (PFT covers more than 99% of the pixel surface), LAI_{Hg} , are taken into account. A reference sample of LAI_{Hg} is selected randomly from the total population. The difference between the reference sample and the remaining LAI_{Hg} gives a probability density function of LAI_{PFT} variability as a function of the distance to the reference, up to 3 pixels, being the maximum size of the neighbourhood window used in OLS (3×3 , 5×5 and 7×7). As the probability density functions are nearly symmetric and unimodal, very close to a gaussian, we study the normalized standard deviation, as a proxy for the uncertainty. Results are given in section 4.2.

3.3.2. Evapotranspiration modelling and validation strategy

The impact of using LSA-SAF LAI instead of ECOCLIMAP-I database in the land surface model is evaluated at two different scales: at local scale and over a larger region covering a sample of different vegetation dynamics and climate.

Locally, the impact is quantified against measurements at different local observation sites equipped with eddy covariance devices. Results of point scale simulations are compared to in-situ observations of latent heat flux, LE (list of stations in Table 6.1), equivalent to ET. Four sites are situated in Africa and five in Europe, with a good sample of different climates. The four sites in Africa are installed in a savannah landscape, but with different precipitation regimes, ranging from mostly dry (Agoufou) to mostly wet (Tchizalamou). The European sites are situated in mediterranean (Puéchabon and Tojal), temperate (Vielsalm and Wetzstein) and boreal (Sodankylä) regions. Four European stations monitor the exchanges between a forest stand and the atmosphere: coniferous forest (Wetzstein and Sodankylä), evergreen forest (Puéchabon) and mixed forest (Vielsalm). The station of Tojal monitors exchanges over a C3/C4 grassland site. Most of the sites selected have a large homogeneous fetch, that allows a good representativity of the measurements.

Table 3.2.: **In-situ eddy covariance observations used in this study.**

Site	Country	Years	Reference
Skukuza	S. Africa	2008-2009	Kutsch et al. (2008)
Vielsalm	Belgium	2007-2008	Aubinet et al. (2001)
Tojal	Portugal	2007	Pereira et al. (2007)
Puéchabon	France	2007	Joffre et al. (1996)
Agoufou	Mali	2007	Merbold et al. (2009)
Tchizalamou	R. Congo	2007	Merbold et al. (2009)
Wetzstein	Germany	2007	Rebmann et al. (2010)
Sodankylä	Finland	2007	Suni et al. (2003)
Demokeya	Sudan	2007-2009	Sjöström et al. (2009)

At the selected sites, the model is forced as described in section 2.1. However, in order to better assess the impact of LAI on the simulations, in-situ measurements are used for radiation and precipitation input when available. ERA-Interim precipitation rates are used for Agoufou and Vielsalm sites. Precipitation is especially important in semi-arid environment (Merbold et al., 2009), and the more accurate the input is the better is the model output. Soil moisture and soil temperature for the four soil layers are initialized with ERA-Interim analysis, and the model is run over one year before the analyzed run. Model parameters are not tuned for the selected sites, and the general parameterization for a global simulation is set.

At large scale, we evaluate the impact on ET by comparing the daily ET rates over a latitudinal transect crossing a vegetation density gradient. As ECOCLIMAP-I gives an oversimplification of LAI spatial variability over Africa (Kaptué Tchuenté et al., 2010), we compare the simulations along a North-South transect in West Africa, 15° N to 6° N, 0° E, for the year 2007, that samples a full range of vegetation dynamics from an evergreen humid forest to desert. This exercise is especially relevant in the context of the growing interest in the land surface monitoring in Western Africa, where quantitative remote sensing is expected to play an important role (Stisen et al., 2008; Boone et al., 2009). The land surface model is forced as described in section 2.1 and half-hourly simulated LE are converted to ET rates and daily cumulated.

As there is no ET observation dataset to validate/verify the improvements at large scale over West Africa, other remote sensing products are of interest for output verification. We can assess the impact of using LSA-SAF LAI in the land surface model by comparing other modeled variables to complementary remote sensing derived data. The modeled *skin* temperature from H-TESSEL can be compared to the land surface temperature derived from infra-red sensors. Even if the model *skin* temperature has not the exact same physical meaning as the radiative land surface temperature measured by the satellite (LST), it is often considered to be comparable (e.g., Ghent et al., 2011) and LST is used for indirect models verification (e.g., Edwards, 2009; Jimenez et al., 2008). A particular interest of LST for ET verification is its link with soil moisture. For example, during observation campaigns in Western Africa, LST was linked to the soil moisture retrieved with passive microwave sensors (Kergoat et al., 2011). In addition, LST from MSG has been used to derive evaporative fraction (Stisen et al., 2008), which should likely be mainly driven by soil moisture in that region. LSA-SAF provides land surface temperature images, LSA-SAF LST, every 15 minutes, based on MSG/SEVIRI, at the sensor resolution (Trigo et al., 2008). LST product is suitable for comparison as it is provided with the same spatial resolution.

To avoid the effect of short-term fluctuation of the temperature or cloud contamination, daily surface heating rates, expressed in $K \cdot h^{-1}$, are calculated from LSA-SAF 15 minutes LST data, and from the simulated 30 minutes skin temperature separately. The heating rates are the slope of the linear fit through the land surface temperature data between sunrise and local noon.

3.4. Results

3.4.1. Comparison of ECOCLIMAP-I and LSA-SAF LAI

To show the advantages of the new LSA-SAF products, we illustrate comparison of LAI with ECOCLIMAP-I database. The mean monthly LAI from ECOCLIMAP-I and LSA-SAF are compared by PFT (Figure 3.2) in Europe for March to November 2007. Each monthly LAI is based on homogeneous pixels, i.e. pixels occupied by exclusively one PFT, and six LSA-SAF LAI images per month. In addition, the monthly spatial and temporal LAI variability is estimated from LSA-SAF LAI. In Figure 3.2, it is shown that ECOCLIMAP-I LAI has a bias of about $1 \text{ m}^2 \cdot \text{m}^{-2}$ compared to LSA-SAF LAI. It is especially visible for evergreen coniferous forests during the summer months and crops for beginning of autumn. This bias had also been reported in comparison with other products and in-situ data (Garrigues et al., 2008). A larger variability is found in LSA-SAF LAI for Swamp areas, forests and partly for grasslands. For crops, the variability is comparable.

For Europe, small differences are observed in average, probably because the number of defined ecosystems in the land cover map is sufficiently high. However, over Africa, LSA-SAF LAI provides more spatial variability compared to the database. As an example, we compare the LAI variability of PFTs from 3 different homogeneous ECOCLIMAP-I ecosystems (Tropical African grassland, Semi arid African grassland, and Nile Valley and desertic crops). Three LSA-SAF LAI images are selected for the comparison at 3 different dates (15 April, 15 August and 15 December), and the LAI distribution is compared to the single value given by ECOCLIMAP-I monthly estimates (Figure 3.3). For Tropical African grassland, LAI given by ECOCLIMAP-I ranges between 2.0 and 3.0, while LSA-SAF LAI gives in one image a distribution ranging between 0 and 4. For the ecosystem Nile Valley and desertic crops, LSA-SAF LAI analysis shows a double peaked distribution, poorly represented by the LAI database climatology. The difference is especially striking for April. The database gives a LAI of 0.5, while the peak reaches its maximum around 2.8. Those differences will inevitably impact on land surface model applications at MSG/SEVIRI scale.

LSA-SAF LAI product allows a better temporal representation of the inter-annual

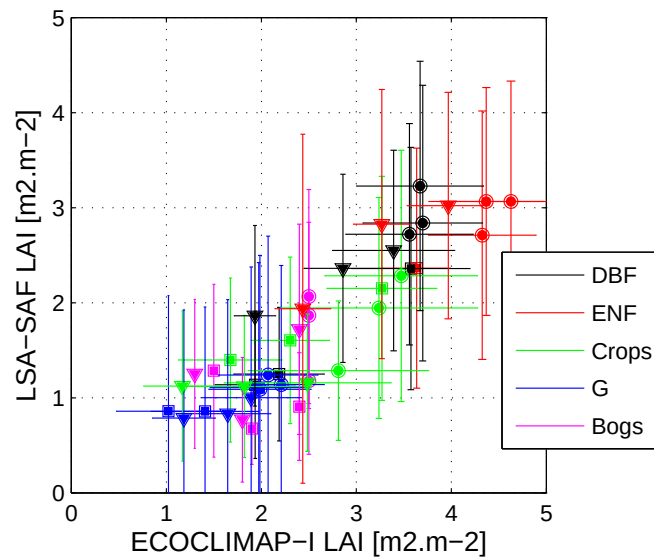


Figure 3.2.: **Comparison of monthly mean and variability of LAI between ECOCLIMAP-I and LSA-SAF, for March to November 2007 over Europe. March to May ($\square$), June to August ($\circ$), September to November (∇)**

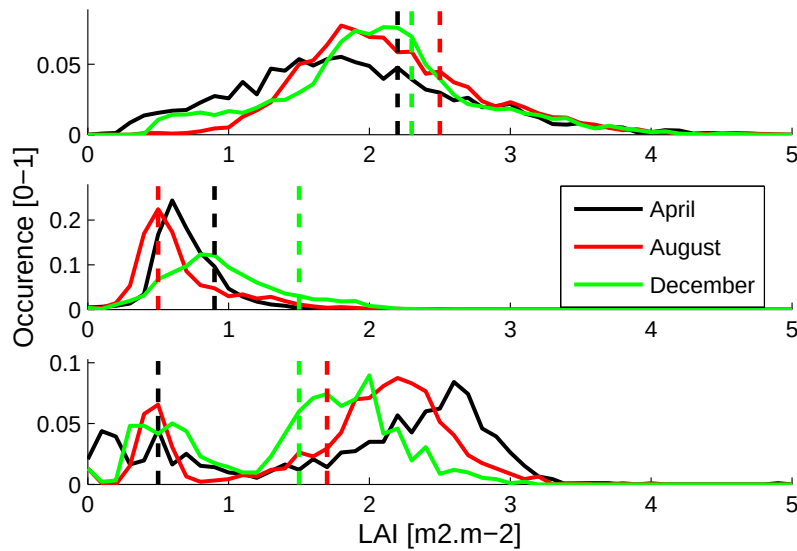


Figure 3.3.: **Distribution of LSA-SAF LAI (continuous lines) against ECOCLIMAP-I monthly values (dashed vertical lines) for 3 dates (15 April, 15 August and 15 December 2007) for 3 homogeneous ecosystems: Tropical African Grassland (top), Semi-Arid African grassland (middle) and Nile Valley and desertic crops (bottom).**

LAI evolution. As an example, we compare the LAI time series from ECOCLIMAP-I and LSA-SAF over a pixel in Western Africa corresponding to the ground measurement station Agoufou (15.29° N, 1.49° W) for 2007, 2008 and 2009. The variability is mostly driven by the occurrence of rain during the wet season. In the comparison LSA-SAF LAI has been rescaled by the complement to unity of the minimum fraction of vegetation, while ECOCLIMAP-I LAI has been rescaled to the range of LSA-SAF LAI, and linearly interpolated. In Figure 3.4, we observe the time shifts in the wet season onset, as well as the differences in duration of that season and LAI peak. Differences up to 10 days in the shift are observed for the wet season onset (Day 200-210). During the onset of the dry season (DoY 260-270), there is a large difference between ECOCLIMAP-I LAI and LSA-SAF LAI, with a sharp decrease of LSA-SAF LAI. Impact on the ET simulation with the land surface model is assessed in section 4.3.

3.4.2. Retrieval of sub-pixel leaf area index

As presented in section 3, LSA-SAF LAI needs to be processed to obtain continuous and coherent time series. We illustrate that process on one specific LAI time series over Wetzstein, a forested site in Europe (Figure 3.5). The MSG/SEVIRI pixel is mainly composed of coniferous forest. LSA-SAF LAI (red points) presents unrealistic high values in the 2007-2008 winter. During the next winters, most of those unrealistic estimates have been screened out in the product. The LAI climatology (black points) follows the trend given by LSA-SAF LAI, with very high values in winter. Using the filter, we remove all the spurious data, and a linear interpolation is applied. After correction, the optimal interpolation procedure is applied to produce the LAI analysed, LAI_a .

With the new pixel estimates LAI_a , the method to decompose at sub-pixel scale is applied. However, as mentionned, the method is subject to two sources of error. The impact of the uncertainty of the land cover map and of the pixel-to-pixel LAI variability of PFTs is assessed here.

The impact of the land cover map uncertainty on the LAI retrieval is represented in Figure 3.6, where the relation between the mean PFT percentage obtained from the 3 land cover maps and the RMS of the LAI time series for the 120 pixels defined in section

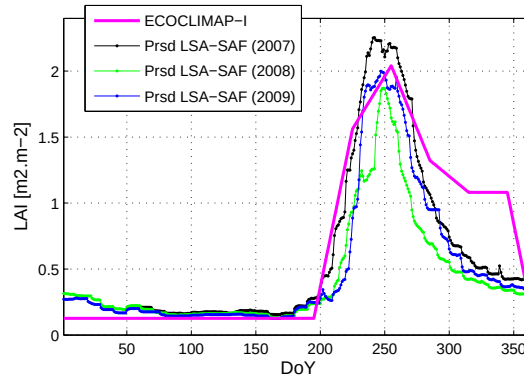


Figure 3.4.: Time series comparison of processed LSA-SAF LAI (Prsd LSA-SAF) for 2007, 2008 and 2009, and re-scaled and linearly interpolated ECOCLIMAP-I LAI for a pixel in Western Africa (15.29° N, 1.49° W).

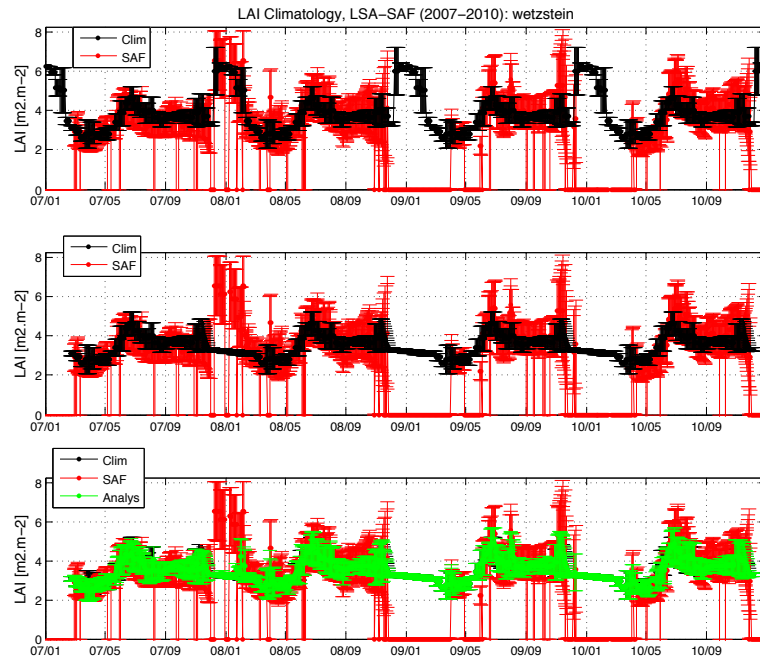


Figure 3.5.: Illustration of the pre-processing of LSA-SAF LAI images on a test case over a forest (Wetzstein) in Germany. a) A 10-days composite (black) is derived from LSA-SAF LAI daily data (red). b) Spurious data are filtered out, and linear interpolation is applied to create the climatology, LAI_c (black). c) At last, an optimal interpolation scheme (OI) is applied using the climatology and the actual LSA-SAF LAI, LAI_{SAF} , to provide the analysed LAI, LAI_a .

3.1 is shown. The mean correlation decreases with smaller PFT percentage, and RMS increases. It implies that land cover differences have little impact on the retrieved LAI for the dominant PFTs, but that it has a big impact on the less dominant PFTs. In addition, we observe less uncertainty for crops class than for evergreen forests compared to the mean.

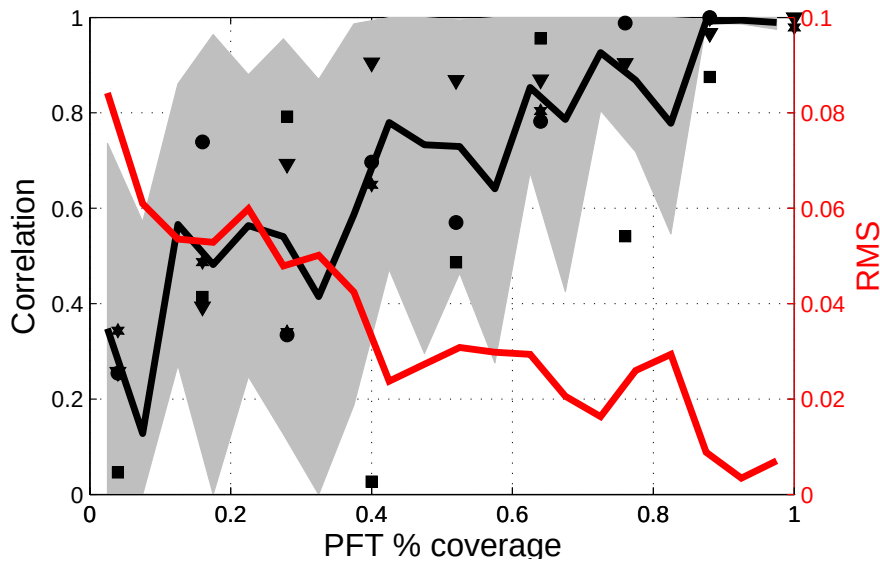


Figure 3.6.: **Mean correlation (black line) between LAI time series obtained using ECOCLIMAP-I, GLOBCOVER and MODIS land covers, and its dependence in the PFT percentage in a given MSG/SEVIRI pixel for a 3×3 neighbourhood. The grey shaded area represents the dispersion of the correlation. PFT dependent correlation is superimposed (DBF: $\circ$, ENF: $\square$, Crops: ∇ , Grass: $*$). In addition, RMS resulting from the comparison of the time series is shown in red.**

As shown in Figure 3.7, effect of enlarging the neighbourhood to 5×5 and 7×7 pixels for OLS lessens the impact of land cover uncertainty: the correlation decreases only to 0.5 for very small PFT percentages. The effect of enlarging to 7×7 has no big impact compared to 5×5 .

The impact of the pixel-to-pixel LAI variability by PFT is represented in Figure 3.8. For each homogeneous PFT represented in Europe and Africa, the normalized standard deviation increases with the OLS neighbourhood size (Fig 3.8). For Europe, the variability inside a 3×3 neighbourhood ranges between 13% and 19%. Increasing the pixel number to 5×5 degrades the quality of the assumption for all PFTs. The variability

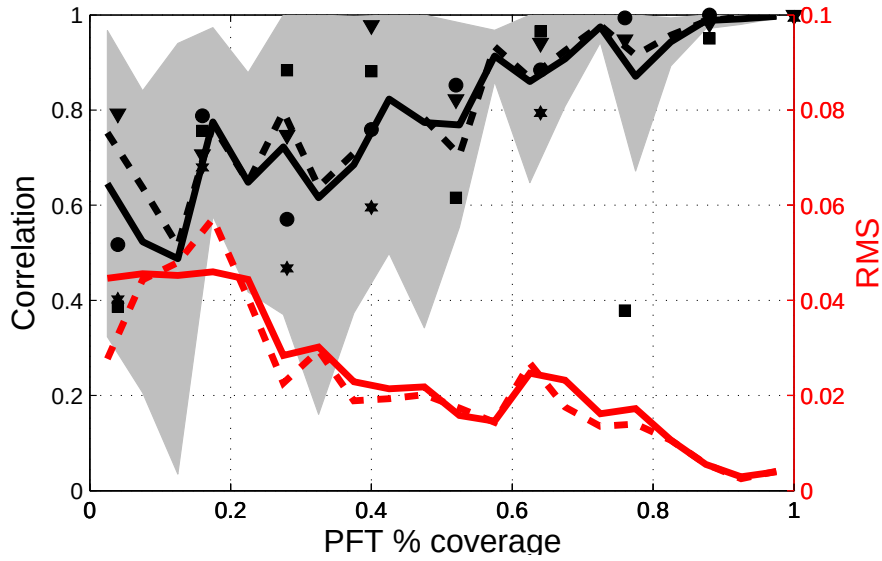


Figure 3.7.: Same as Figure 3.6, but for a 5×5 (solid) and 7×7 (dashed) neighbourhood.

increases gradually from 3×3 to 7×7 for C3 crops and grasslands. For Africa, the uncertainty is much less than for Europe, ranging between 5% and 9% for all classes in the case of the 3×3 neighbourhood. In addition, enlarging the neighbourhood to 5×5 or 7×7 has no big impact for most PFTs in Africa, except for grassland in Northern Africa. Variability could not be assessed for deciduous broadleaved forests over Africa, because no african ecosystem defined in ECOCLIMAP-I is homogeneously covered by that PFT.

The method proposed in section 3 leads to a more robust estimate of LAI_{PFT} when applied over a larger neighbourhood (Figure 3.7), since impact of land cover map uncertainty is reduced. However, at least for Europe, LAI variability of a given PFT increases with the size of the neighbourhood (Figure 3.8). Therefore, depending on the application, a compromise has to be found between accuracy and robustness. In applications involving spatial resolution equal to MSG/SEVIRI, the smallest size is obviously preferred since it implies less uncertainty. However, it has been shown that the quality of the OLS algorithm is decreasing along with PFT occupation fraction, due to the land cover uncertainty. Therefore, in waiting for a better agreement between land cover maps, a correction has to be applied, to estimate a reliable LAI_{PFT} even for the least contributing PFT to the total pixel ET. A corrected estimate, $LAI_{PFT,PostP}$, is derived from a weighted average of LAI_{PFT} and a reference estimate, LAI_R (Eq 3.2).

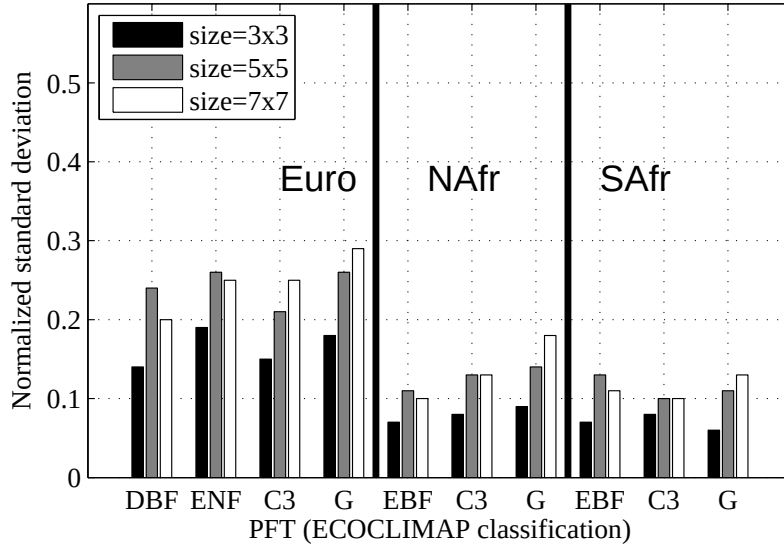


Figure 3.8.: **Normalized PFT intra-variability (standard deviation) of LAI in function of the neighbourhood size for Europe (Euro) and Africa (NAfr and SAfr).**

The weight α (Eq 3.3) is proportional to the PFT percentage, and we choose it to be the linear regression of Figure 3.6.

$$LAI_{PFT,PostP} = \alpha \cdot LAI_{PFT} + (1 - \alpha) \cdot LAI_R \quad (3.2)$$

$$\alpha = \min(0.75 \cdot PFT_{\%} + 0.32, 1) \quad (3.3)$$

LAI_R could be the LAI pixel value, LAI_a , or the LAI value corresponding to the nearest pixel homogeneous of that PFT, LAI_{Hg} . Since african ecosystems are mostly mix of PFTs, LAI_a is adopted. For Europe, clear homogeneous PFTs can most of the time be identified and isolated, and LAI_{Hg} is preferred. This choice is further discussed in section 5.

3.4.3. Impact on modelled evapotranspiration

Statistical results for the 30 minutes model estimates of LE are presented in Table 3.3. Statistical scores show an improvement in the modelling of the surface latent heat flux, or equivalently ET, especially for semi-arid regions where the signal shows an interannual

variability in amplitude and phase. The largest improvements are observed for Skukuza and Agoufou sites, with a significant decrease of the global bias compared to data (-37 to $-6 \text{ W} \cdot \text{m}^{-2}$ for Skukuza, and -32 to $-18 \text{ W} \cdot \text{m}^{-2}$ for Agoufou), as well as an improved Nash-Sutcliffe (NS) index (0.46 to 0.60 , and 0.26 to 0.45 , respectively) (Nash and Sutcliffe, 1970). Even if the scores are largely improved in the Agoufou comparison, most of the remaining bias is due to non ideal precipitation forcing, i.e. ERA-Interim in that simulations. The other simulations over african sites, i.e. Demokeya and Tchizalamou, also show an improvement of the statistical scores when compared to data (NS: 0.53 to 0.62 , and 0.51 to 0.53 , respectively). Those results confirm the findings of Kahan et al. (2006), over the Sahel region in Western Africa.

Table 3.3.: Comparison of simulations with ECOCLIMAP-I (ECO) or LSA-SAF LAI (LSA) against 30 min observed LE (W/m^2): statistical scores: correlation coefficient (ρ), root mean square error (RMSE), bias and NS (Nash and Sutcliffe, 1970). Improved NS with LSA compared to ECO are highlighted.

Station	Mode	ρ	RMSE	Bias	NS
Skukuza	ECO	0.754	85.07	-37.86	0.46
	LSA	0.787	73.25	-6.25	0.60
Demokeya	ECO	0.768	53.41	-18.55	0.53
	LSA	0.795	48.39	-5.26	0.62
Tchizalamou	ECO	0.760	60.14	3.16	0.51
	LSA	0.775	58.68	9.11	0.53
Agoufou	ECO	0.612	83.56	-32.40	0.26
	LSA	0.695	72.42	-18.37	0.45
Puéchabon	ECO	0.817	44.42	-9.29	0.61
	LSA	0.85	40.83	2.71	0.67
Tojal	ECO	0.849	41.98	-5.94	0.66
	LSA	0.828	45.37	-6.95	0.61
Vielsalm	ECO	0.747	46.89	10.88	0.47
	LSA	0.712	47.75	8.73	0.46
Wetzstein	ECO	0.832	53.14	-26.78	0.57
	LSA	0.850	48.83	-22.94	0.64
Sodankyla	ECO	0.711	29.59	-8.68	0.39
	LSA	0.735	28.16	-11.08	0.44

As an example, we present in Figure 3.9 the time series of the simulated and observed LE in Demokeya for the year 2007 to 2009. The simulation is clearly improved with the use of LSA-SAF LAI, with a better match during the wet season. Also the simulations

of LE during the dry season is closer to the observations.

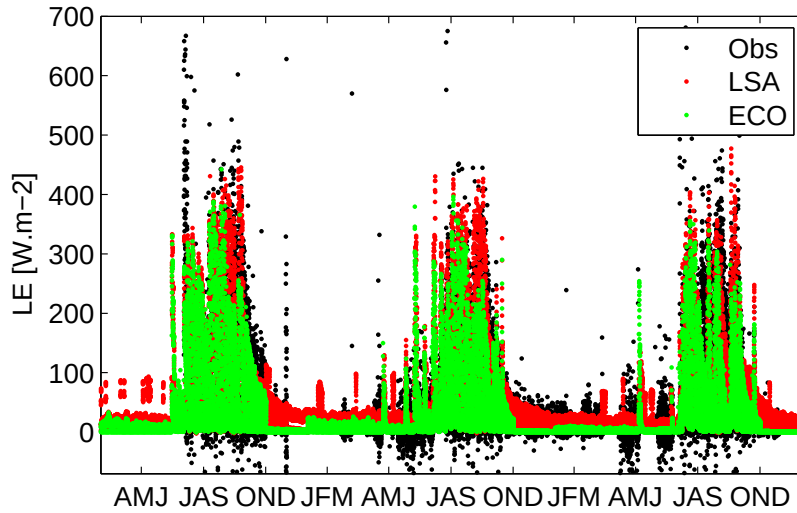


Figure 3.9.: **Comparison of LE for Demokeya for 2007, 2008 and 2009; observed in (Obs: black), simulation using ECOCLIMAP-I (ECO: green), simulation using LSA-SAF LAI (LSA: red).**

Results over Europe show an improvement for 3 sites over the 5. In Puéchabon, the scores are well improved, with a global bias reduction, from -9 to $3 \text{ W} \cdot \text{m}^{-2}$, and a better NS, from 0.61 to 0.67. As well, the results are improved for 2 forested sites in different climates, i.e. Wetzstein and Sodankylä. For Tojal and Vielsalm, the model performs well with ECOCLIMAP-I and the statistics are either slightly degraded or equal.

The evolution of the LAI on the latitude gradient is shown in Figure 3.10 for monthly ECOCLIMAP-I and daily LSA-SAF. The northern bound of the transect is completely arid with no vegetation. Southwards, vegetation is seasonal, with longer periods of vegetation cover, and higher amplitudes. The global pattern for ECOCLIMAP-I and LSA-SAF is similar, however, the most striking difference is seen on the length of the vegetation period, that is noticeably shorter for LSA-SAF at highest latitudes. Between 6° N and 8° N , the transect meets lakes, resulting in zero LAI as observed from the dark blue stripes in the figures.

The evolution for 2007 along the transect is shown in Figure 3.11, when using ECOCLIMAP-I and LSA-SAF LAI respectively. The global pattern is mostly the same, as ET is driven by precipitation. However, large differences are found between September

and December (also in April), with higher ET produced using ECOCLIMAP-I database.

An indirect evaluation of the changes is based on the comparison of the daily surface heating rates modelled and derived from the satellite. The heating rates are shown in Figure 3.12. Vegetated areas are characterized by lower mean surface heating rates than bare soil. As well, surface heating rates are said to be increased with decreasing soil moisture (Stisen et al., 2008). The global pattern with the contrast low/high heating rate is seen in the 3 images. Good correspondance is found in the patterns of both simulations. That is probably due to the same precipitation forcing for the model. The absolute differences between simulated heating rates and those derived from LSA-SAF LST are represented in Figure 3.13. A closer agreement, especially with a global lower bias, is found with the skin temperature simulated using LSA-SAF LAI than with ECOCLIMAP-I when compared to LSA-SAF derived heating rates, suggesting than simulation is improved using LSA-SAF LAI.

3.5. Discussion

Different aspects of the method to use LSA-SAF biophysical variables in H-TESSEL and its application for ET monitoring are discussed, especially in the perspective of continuous operational monitoring.

3.5.1. Retrieval stability of the biophysical variables

With one observation every 15 minutes over the same location, a higher level of stability of biophysical variables is reached when derived from MSG/SEVIRI comparatively to polar orbiters. Indeed, it has been shown that LSA-SAF LAI was more reliable than SPOT-VGT over central Africa where cloud cover is most frequent (Pekel et al., 2010). However, stability problems, that have been addressed by the methodology proposed in section 3, are found in the original LSA-SAF time series for Northern european regions covered by coniferous forests for 2007 and 2008, while further production by LSA-SAF made used of a filter to screen out those spurious data. Similar problems are encountered for the generation of other biophysical products. GLOBCARBON LAI product show

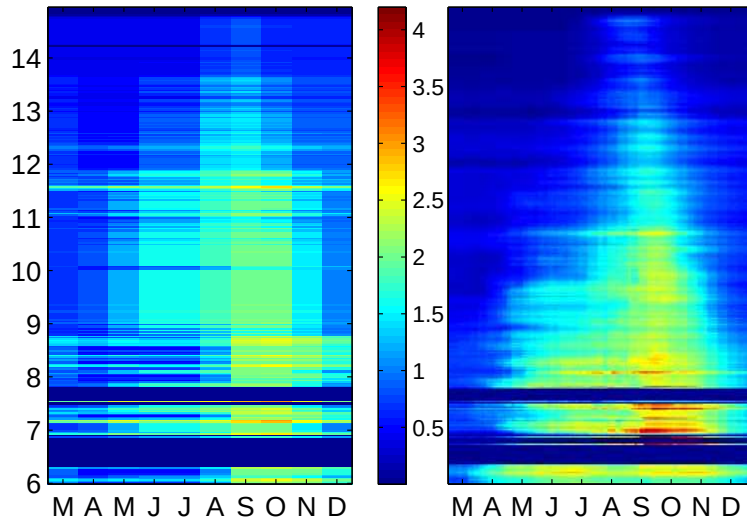


Figure 3.10.: LAI evolution (March to December 2007) along the North-South transect in West Africa from 15° N to 6° N: ECOCLIMAP-I (left) and LSA-SAF LAI (right)

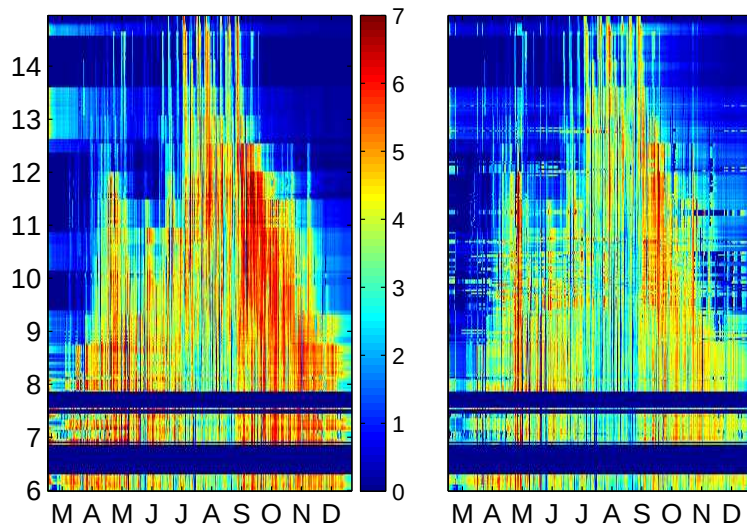


Figure 3.11.: Simulations along the North-South transect in West Africa from 15° N to 6° N: daily ET [mm] simulated using ECOCLIMAP-I (left) and LSA-SAF LAI (right).

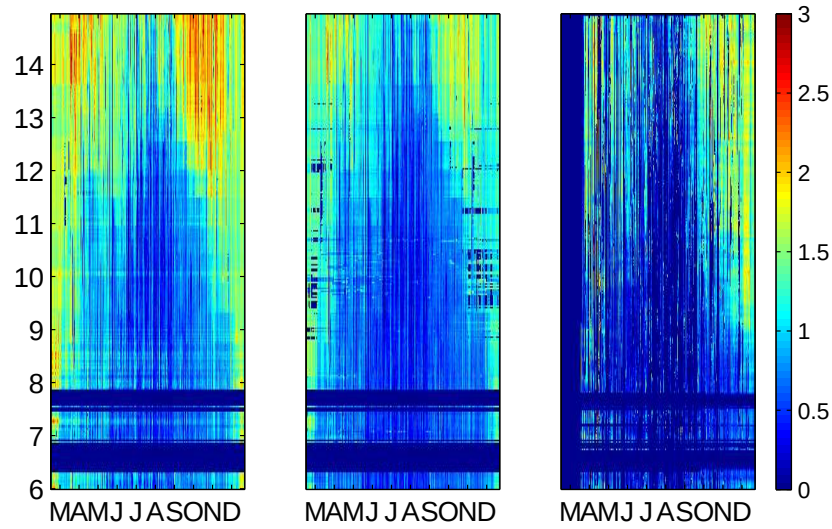


Figure 3.12.: Daily morning surface heating rates [$K.h^{-1}$] for a transect in West Africa from $15^{\circ}N$ to $6^{\circ}N$: simulation using ECOCLIMAP-I (left) or LSA-SAF LAI (middle), obtained from LSA-SAF LST (right).

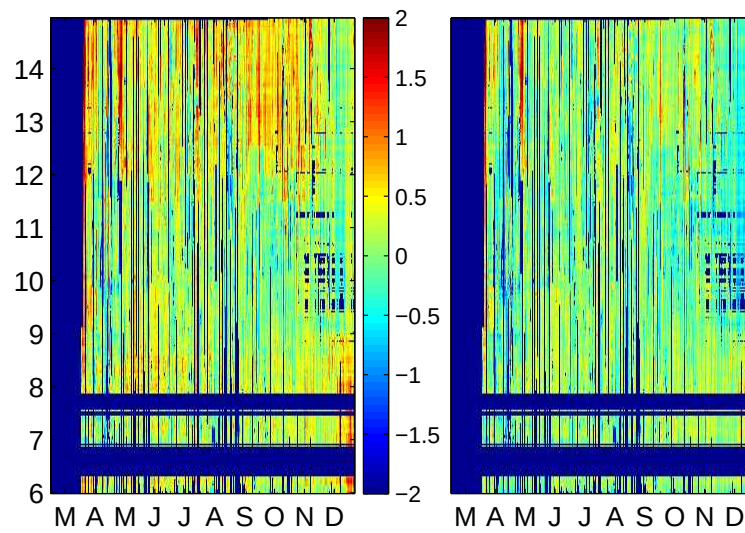


Figure 3.13.: Differences in the daily morning surface heating rates [$K.h^{-1}$] (same transect Figure 3.12): simulated heating rates using ECOCLIMAP-I vs LSA-SAF LST(left), simulated heating rates using LSA-SAF LAI vs LSA-SAF LST (right).

unexpected variations for boreal forests, with possible overestimated LAI (Garrigues et al., 2008). The MODIS Collection 4 and 5 LAI product present a spurious seasonal variability over boreal forests due to the low data availability with weak illumination, extreme solar zenith angles conditions, snow and cloud contamination (Yang et al., 2006a; Tian et al., 2006; Yang et al., 2006b; Garrigues et al., 2008) and low spatial continuity due to regular failures from the main retrieval algorithm (Garrigues et al., 2008). Retrieval problems are also encountered during peak seasons over deciduous broadleaf forests (Garrigues et al., 2008). Corrections and smoothings are therefore needed for an optimal use in land surface models (Gu et al., 2006).

3.5.2. Towards an operational use of LSA-SAF biophysical products

In section 4.2, it has been shown that the land cover map uncertainty has an effect on the LAI retrieval at sub-pixel scale, and that a correction need to be applied to obtain reliable estimates using a reference. It has been proposed, for Europe, to use as reference the LAI of the nearest homogeneous pixel, LAI_{Hg} . However, the success of it depends on the relative invariability of LAI for one PFT in a neighbourhood, and therefore on finding a LAI_{Hg} within a close area. The analysis of 1) its variability within an increasing area (Figure 3.14) and 2) the distribution of distance to the nearest LAI_{Hg} (Figure 3.15) leads to PFT specific conclusions in using it as a correction for the retrieved LAI_{PFT} . As expected, the relative variability increases with the distance for every PFT, with the sharpest difference within the 5 first pixels. In addition, the total increase is most important for grasslands (up to 55% variability 30 pixels away) and crops (45%), while it is less for forests (32% and 37%).

Fig 3.15 represents the distribution, based on ECOCLIMAP-I land cover map, of the distance from each pixel to the closest homogeneous pixel for the same PFTs in Europe. For every PFT, the number of occurrence decreases with the distance. The decrease is sharp for crops, with more than 70% of homogeneous pixels no further than six distance units. For the other types, there are less homogeneous pixels and the decrease is quasi linear. In 90% of the cases, the nearest homogeneous pixel is found at a distance of 16 pixels (Crops), 30 (ENF), 31 (G), and 33 (DBF).

From Fig 3.14 and Fig 3.15, we conclude that 1) the farther the homogeneous pixel used for correcting the OLS solution comes from, the larger is the introduced error, especially for crops and grasslands, 2) the most uncertain correction in the post-processing will be for grasslands in Europe. LAI_a is used as reference in that case, as well as for PFTs not represented by an homogeneous pixel in the neighbourhood.

We therefore propose a post-processing scheme, summarized by a flowchart in Fig 3.16, integrating the results discussed here. If the area to process is Europe, C3 crops, and forests (DBF and ENF) LAIs are corrected with LAI_{Hg} (option 2). For grassland, if the distance is higher than 10 pixels, the pixel LAI is used as surrogate (option 1). For other PFT classes, i.e. C4 crops, Irrigated crops and Swamp areas, and for other areas, correction follows option 1.

3.5.3. A decreased uncertainty associated to LAI

While a thorough analysis of the uncertainty is out of the scope of the present paper, we compare estimates of LAI uncertainty for ECOCLIMAP-I ($\sigma_{LAI_{ECO}}$), and retrieved from LSA-SAF ($\sigma_{LAI_{SAF}}$). $\sigma_{LAI_{ECO}}$ can be evaluated with the spatial and temporal variability of LSA-SAF LAI. $\sigma_{LAI_{SAF}}$ is the combination of the error on OLS, σ_{OLS} , and the error on assumptions, σ_{dist} (Fig 3.8).

For Europe, LAI variability for a given PFT increases with the distance from a reference pixel (previous section). But, while for forests the variability remains almost steady with the distance, crops and grasslands are the most affected PFTs, giving a clear methodological advantage in using LSA-SAF LAI and a lower uncertainty. However, since ECOCLIMAP-I proposes a very fine classification into 92 ecosystems, e.g. 27 different types of crops and 21 types of grasslands, the difference between $\sigma_{LAI_{SAF}}$ and $\sigma_{LAI_{ECO}}$ is not expected to be large.

For Africa, Fig 3.3 shows examples representative of wide areas in *NAfr* region for a given year (2007). Consequently, the deduced $\sigma_{LAI_{ECO}}$ can be very large. Contrarily, $\sigma_{LAI_{SAF}}$ is expected to be much less, because σ_{dist} is less than 10%, and σ_{OLS} is very small due to the relative homogeneity of the landscape over the OLS neighbourhood. Especially, $\sigma_{LAI_{SAF}}$ is expected to be much smaller than $\sigma_{LAI_{ECO}}$ in semi-arid to arid

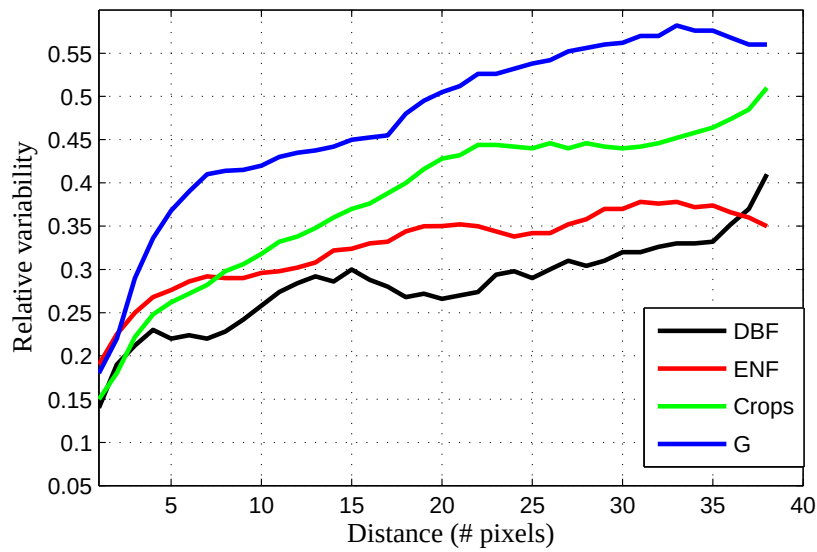


Figure 3.14.: **Relative variability of LAI with distance (# pixels) to nearest homogeneous pixel, by PFT, i.e. C3 crops (black), DBF (red), ENF (blue), G (green), in Europe. A sliding average window of 5 distance units has been applied to the curve.**

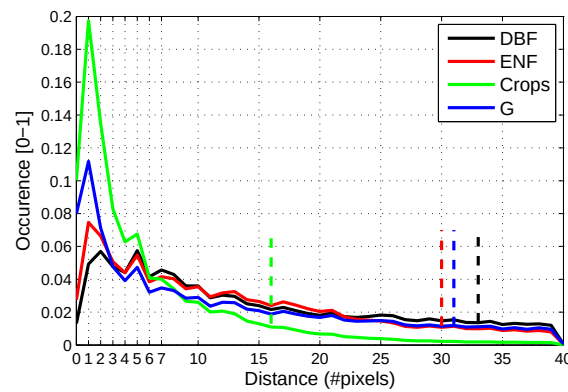


Figure 3.15.: **Distance (# pixels) to nearest homogeneous pixel by PFT, i.e. C3 crops (black), DBF (red), ENF (blue), G (green), in Europe. Vertical dashed lines denote the 90% of the cumulative distribution for each PFT (based on ECOCLIMAP-I).**

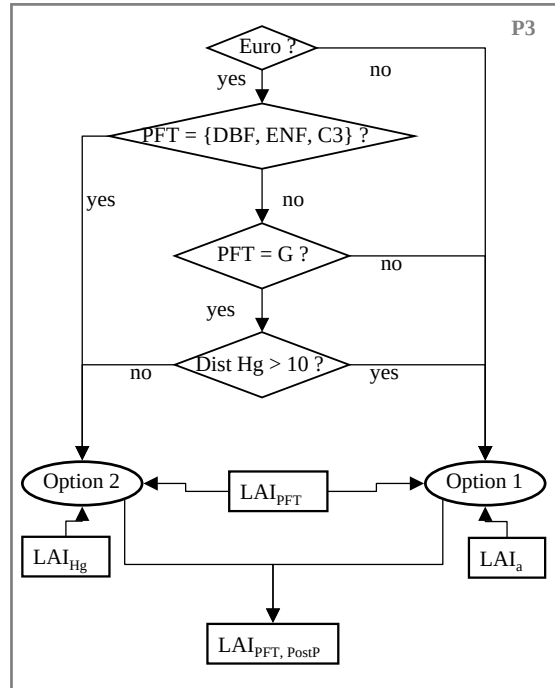


Figure 3.16.: **Flowchart with post-processing steps of PFT derived LSA-SAF LAI, LAI_{PFT} , to obtain a consistent LAI, $LAI_{PFT,PostP}$. Option 1 refer to the correction of the retrieved LAI with the pixel estimate, while option 2 points to the nearest homogeneous pixel as the reference LAI.**

environments in Africa, giving a more reliable LAI estimate for Sahel. That difference should obviously be exacerbated if we take into account the inter-annual variability not represented in ECOCLIMAP-I, as in Fig 3.4.

3.5.4. Towards a continuous ET monitoring

The scheme presented in this paper and assessed with the land surface model has been developed to comply with requirements for near-real time applications. Applied to LSA-SAF LAI and FVC, it is convenient for ET monitoring through land surface modelling at spatial scales equal or coarser than MSG/SEVIRI. However, for a correct evaluation of LAI at PFT level, it is necessary to use a land cover map that proposes a sufficient accuracy in locating, classifying and decomposing into PFTs accepted by the land surface models. The gain in spatial resolution (ECOCLIMAP-I: 1km; GlobCover: 300m) and satellite overpass frequency are clear advantages to obtain more accurate LAI at PFT

level, reducing σ_{OLS} , and therefore to provide an optimal input for land surface models.

In line with the monitoring concept, it would be necessary to have a clear assessment of the land cover changes, as it can affect our method. Regular updates of land cover would therefore be appreciated, to address land conversion issues like deforestation or fires.

3.6. Conclusions

In the present contribution, we show the benefits of using the daily biophysical variables derived from SEVIRI sensor aboard the geostationary satellite MSG for the evapotranspiration modelling and monitoring using the model H-TESSEL over Europe and Africa, compared to the use of the semi-static database ECOCLIMAP-I.

LAI maps from LSA-SAF and ECOCLIMAP-I are compared at different time and spatial scales, showing that ECOCLIMAP-I LAI presents less variability than LSA-SAF LAI, with respect to spatial coverage and temporal frequency. A rough analysis of the uncertainty on ECOCLIMAP-I LAI and LSA-SAF LAI over Africa suggests that LSA-SAF LAI is beneficial for land surface models intended for short time scales, e.g. half-hourly and daily, at MSG/SEVIRI resolution.

We propose a practical methodology to use the biophysical products LSA-SAF LAI and FVC in land surface models, correcting spurious data, filling gaps, and deriving sub-pixel LAI estimates needed by the models using a land cover map. Effects of the spatial scale and land cover map uncertainty on the method have been investigated, and results show that land cover uncertainty has an increasing impact on the less represented PFTs. The proposed method is shown to be more robust as the spatial scale considered is coarser. While waiting for land cover maps with reduced uncertainty, corrections of the errors on LAI by PFT are proposed for monitoring at the finest possible scale.

Given the respective features of both LAI sources investigated here, we have assessed the impact of using LSA-SAF LAI instead of ECOCLIMAP-I in H-TESSEL evapotranspiration simulations at MSG/SEVIRI resolution, both at local scale and at large scale.

Statistical scores of the comparison of simulated latent heat flux against local observations from ground measurement sites are improved in most cases, and especially in semi-arid climates. Amplitudes of annual cycles, as well as phase shifts are more correctly taken into account in the model compared to the use of the ECOCLIMAP-I database.

A 9-months simulation over a North-South transect in Western Africa using LSA-SAF radiation products and ERA-Interim meteorological variables, illustrates the impact of using LSA-SAF vegetation parameters compared to ECOCLIMAP-I database. An evaluation of the improvement is based on the similarity of the simulated skin temperature daily heating rates and the observed land surface temperature heating rates from MSG/SEVIRI, showing a better global agreement by using LSA-SAF biophysical variables.

Use of LSA-SAF LAI and FVC is therefore recommended for near-real time applications of land surface models working at the MSG/SEVIRI scale or coarser and intending at closely monitoring evapotranspiration. Especially, it will improve the land surface model applications over Africa, capturing the full spatial, seasonal and inter-annual variability.

4

Improvement opportunities from moderate spatial resolution satellites for vegetation: land cover map

This chapter is based on N. Ghilain & F. Gellens-Meulenberghs (2014), Impact of land cover map resolution and geolocation accuracy on evapotranspiration simulations by a land surface model, Remote Sensing Letters, in review

Abstract

The chosen approach for operational evapotranspiration monitoring has been justified in the previous chapters by a possibility of fully exploiting the temporal sampling of MSG/SEVIRI, the strength of the land surface model to evaluate evapotranspiration even in cloudy sky conditions and the possibility to further develop depending on new advances in modeling and earth observation. In this approach, it is not expected that MSG/SEVIRI will provide alone all the necessary information to derive the most accurately evapotranspiration at that scale. Especially, processes occurring at the earth surface and involving much higher spatial resolutions will probably be missed by such coarse resolution satellite imagery. Therefore, there is a need to make a tour of the complementary variables derived from sensors aboard other satellites that have the potential to improve the evapotranspiration results and which present a great potential towards operational monitoring. In this chapter, the land cover map used by the models is studied. Other variables of interest are considered in the next chapter.

The land surface models used in numerical weather forecasts and hydrological applications rely on the accuracy of land cover maps available from satellite remote sensing to simulate the energy and water balance at the surface of the Earth. While the impact of classification accuracy on land surface simulations has already been reported, little attention has been paid on the consequences of land cover maps uncertainty driven by geolocation accuracy. This impact on the evapotranspiration estimates from the land surface model H-TESSEL at spatial resolutions ranging from 1 to 30 km is evaluated here, making use of land cover maps at two different initial spatial resolutions, 300 and 1200 m, derived from the GlobCover global product. Geolocation uncertainty affects the land cover maps aggregated at different resolution (from 1.2 to 30 km). However, the effect decreases toward the coarsest resolutions. In addition, aggregated land cover maps are less affected by geolocation errors when the finest original resolution (300 m) is used. The maximum possible effect on evapotranspiration is quantified over a heterogeneous/transition area in Europe. The result shows an impact up to 10% at 1.2 km to less than 1% for 10 km resolution, at daily time scale, stressing the importance of such issues for kilometer scale applications of land surface models. The use of the highest initial land cover resolution (300 m) reduces by a factor 3 the impact of geolocation on

evapotranspiration at 1.2 to 3 km scale. This study therefore stresses on the importance of a careful choice of the land cover map before carrying on land surface model simulations at the kilometer scale.

4.1. Introduction

Land cover maps derived from satellite remote sensing is a primary input to land surface models used in meteorological and climate models, selecting the most appropriate parameters available for the estimation of soil-plant-atmosphere transfers of energy and water, namely the turbulent fluxes and the evapotranspiration (ET). Though land surface models require a large amount of input data, e.g. precipitation, radiation terms, meteorological variables, biophysical parameters and land use fractions, the evapotranspiration, or equivalently the latent heat flux, is especially sensitive to precipitation and land cover (Kato et al. (2007)) Therefore, it stresses the importance of the quality of remote sensing input for a large range of applications, including numerical weather forecasts.

The typical spatial resolution available from contemporary global land cover maps used by most continental to global numerical weather prediction models and land data assimilation systems ranges between 300 m and 1 km (Bicheron et al., 2008; Masson et al., 2003; Loveland et al., 2000; Bartholomé and Belward, 2005). They are used in land surface models for large scale applications at grid resolutions between approximately 1 and 50 km. The choice of land cover map is crucial for land surface model simulations, as many surface parameters depend on it.

In previous studies (Quaife et al., 2008; Harris et al., 2010), focus has been drawn on the land cover uncertainties and their impact in biospheric carbon fluxes estimations over Great Britain. Their result showed contemporary global land cover maps resulted in large errors in carbon estimations over heterogeneous zones, with uncertainties up to 15.8% for gross primary production and to 67% for the Net Ecosystem Production.

Harris et al. (2010) has mentioned three different sources of uncertainty in contemporary land cover maps: 1) the selected map, 2) the class assignment, and 3) the class decomposition into plant functional types (PFT). The uncertainty in class assignment is due either to the imperfect methodologies applied or to the length of reliable remote sensing data (Bontemps et al., 2012). The uncertainty in geolocating the signal from the satellites sensors could also be crucial. Several studies report that the effect of this error can be reduced through post-processing of remote sensing data (Wolfe et al., 2002; Bicheron et al., 2011).

The goal of the present study is to evaluate the effect of land cover uncertainty induced by geolocation error on land surface model simulations of ET. To achieve this, two land cover map resolutions, 300 and 1200 m, are used, as they correspond to contemporary land cover maps available at global scales at no cost for users and ingested by most continental to global numerical weather prediction models and land data assimilation systems. The effect is quantified for simulations at spatial resolutions ranging from 1.2 km to 30 km, aiming at providing information on geolocation effect for a large range of land surface model applications from regional to global scale.

As a follow-up of SPOT-VGT (Satellite Pour l'Observation de la Terre - Végétation) which has been used to map the earth surface at 1 km resolution for more than ten years, the PROject for On-Board Autonomy-Vegetation (PROBA-V) satellite (Mellab, 2009) has been launched in 2013 to provide a global view of the earth surface at an enhanced spatial resolution of 330 m. This study is therefore particularly relevant to evaluate the interest of forthcoming PROBA-V derived land cover maps compared to SPOT-VGT for land surface model simulations. SPOT-VGT pixels have a size of 1.15 km and 1.7 km at nadir and on the edges of the tracks, respectively, which are resampled at a fixed spatial resolution of 1 km. Compared to SPOT-VGT, PROBA-V will deliver data at an enhanced spatial resolution, allowing a resampling at 330 m. This spatial resolution is similar to the GlobCover 300 m land cover map derived from the MEdium Resolution Imaging Spectrometer (MERIS) sensor aboard the ENVIronment SATellite (ENVISAT) (Bicheron et al., 2008). Updated land cover maps are therefore expected from PROBA-V data with the similar spatial resolution.

4.2. Data, Model, Study areas and Methodology

4.2.1. EO-derived land cover map

In our study, we have chosen the GlobCover land cover product v2.2 (Bicheron et al., 2008). The land cover map has a global coverage, with a spatial resolution of ~ 300 m, and a classification into twenty-two classifiers defined with the UN Land Cover Classification System (LCCS). In turn, those first layer classifiers are detailed further

in a total of sixty-three regionally tuned classifiers. The legend provided by LCCS is flexible enough to reach a maximum number of potential applications. Because those classifiers are not concisely defined categories, they can be composed of different plant functional types (PFT) only with fuzzy percentages. However, the represented plant functional types are used by most land surface models (Bontemps et al., 2012). For each classifier, GlobCover legend allows the decomposition into PFTs with percentage intervals. For more detailed information, the reader may refer to Bicheron et al. (2008). The mean values of these intervals have been used in this study. A correspondance with the eleven classes (Ghilain et al., 2012) of the land surface model is applied. Note that the PFT decomposition proposed by GlobCover matches straightforwardly the classes of the model.

4.2.2. H-TESSEL, the land surface model, and the input datasets

The land surface model H-TESSEL (Balsamo et al., 2009) is operationally used at the European Center for Medium-range Weather Forecasts for the numerical weather predictions at global scale. It follows a resistance approach in order to simulate the surface turbulent fluxes (van den Hurk et al., 2000). Diffusion equations are solved at half-hourly time step to obtain the vertical distribution of moisture and temperature in the soil, rain interception is modeled, and runoff is parameterized accounting for the soil type and topography. The model is forced by short and long-wave surface radiation, surface albedo, precipitation, wind speed, air temperature and air humidity. The spatial unit for the energy balance assessment is divided into different tiles, corresponding to PFTs. The estimation of the surface fluxes is performed for each tile before averaging over the model spatial unit. The model relies on parameters associated with each tile, i.e. leaf area index, fraction covered by the vegetation, roughness lengths, the minimum stomatal resistance, and the vertical distribution of the roots in the soil.

In the present study, H-TESSEL is forced by LSA-SAF (Land Surface Analysis - Satellite Application Facility) radiation products derived from Meteosat Second Generation satellite (Trigo et al., 2011) and by meteorological output from the ERA-Interim re-analyses (Simmons et al., 2006) over the year 2007. Monthly varying leaf area index and roughness lengths are provided by the ECOCLIMAP-I database (Masson

et al., 2003), the fraction covered by the vegetation is prescribed by PFT following van den Hurk et al. (2003), and the roots distribution is given in van den Hurk et al. (2000). The model applied in the present configuration has been validated with local observations across Europe and Africa (Ghilain et al., 2012).

4.2.3. Methodology

The land cover uncertainty due to geolocation is assessed using the original GlobCover 300 m resolution map, and an aggregated map at 1200 m, to mimic the approximate spatial resolution of PROBA-V and SPOT-VGT. Both land cover maps constitute the baseline material for this study. They are qualified here as initial maps and they are then separately aggregated at successive coarser resolutions, i.e. 1.2, 3, 6, 9 and 30 km. The maps obtained at coarser resolution by aggregating the initial land cover maps are used to create the reference simulations with the land surface model.

As far as geolocation is concerned, the technical characteristics of SPOT-VGT are such that the accuracy is better than 1 km in absolute, and better than 500 m and 300 m for temporal and multispectral co-registration. The absolute geolocation error of PROBA-V is between 300 and 450 m, while multispectral and temporal co-registration stands between 100 and 225 m. Those misregistration of geolocation lead to errors in land cover maps, both in classifying and clearly identifying the exact parcel located in a given pixel. Part of the geolocation errors can be corrected by an appropriate processing before classification, although there always remains residual errors (Bicheron et al., 2011). Depending on the quality of the sensor registration and positioning system and the processing of the data, the uncertainty of geolocation of the land cover map can be large.

In our study, the absolute accuracy of one pixel of the initial land cover map is set as the lowerbound scenario, as for Corine 2000 land cover map (Steenmans, 2002) and for the IGBP DISCover land cover map (Bontemps et al., 2012). Such accuracy acts also as a minimal quality assumption on remote sensing derived data for per pixel analyzes. On the other hand, the upperbound is set to one-third of the absolute accuracy. Such threshold is seen as the goal accuracy corresponding to several mission expectations for multispectral and temporal co-registration. This corresponds approximately to the

geolocation accuracy of the 1 km GLC2000 land cover map (Bartholomé and Belward, 2005), which is shown to be around 300 m (Bontemps et al., 2012; Defourny et al., 2012). It is noted here that the goal accuracy chosen for this study does not necessarily correspond to the best achievable accuracy, however it is representative of the uncertainty of contemporary land cover maps. An example of higher accuracy is seen through the processing used for Globcover land cover map building. The accuracy reaches 70 m of uncertainty on a map at 300 m resolution, approximately 25%, prefiguring improvements in correcting geolocation errors in future land cover maps.

In order to mimic the geolocation error, both initial land cover maps (300 and 1200 m) are shifted one pixel east before being aggregated at the mentioned coarser resolutions. Note here that the shift direction has no influence, and that any other direction is equivalent. Shift of one pixel has to be seen as the lowerbound scenario for geolocation accuracy. Conversely, one-third pixel accuracy is taken as the goal accuracy in geolocation. As a result, the maps at initial 300 and 1200 m are shifted and aggregated to the coarser adopted resolutions. It means that the lowerbound geolocation accuracy is 300 m for every aggregated map built up on the initial 300 m land cover map, while it is 1200 m for the coarse maps obtained by aggregation of the 1200 m land cover map. Mean fraction differences by PFT are then estimated by comparing the references and the shifted maps for the lowerbound scenario. In order to evaluate the effect in the goal scenario, the fraction differences are divided by three to evaluate the impact of a one-third pixel shift. As the largest effect is expected in heterogeneous/transition zones, we have focused on Western Europe (from 83°N to 34°N, and from 11°W to 41°E), as landscapes tend to be very fragmented (Jaeger et al., 2011).

The effect on ET simulations is evaluated against reference land surface model simulations over a defined area of 30x30 km². The reference simulations use the average PFT fractions over the area. As we aim at providing an order of magnitude of the maximum impact geolocation error can have on simulated ET, we focus on the largest changes between the reference and the shifted land cover map. Therefore, for each investigated spatial resolution for simulation, we select the model grid unit within the test area which reaches the highest difference in PFT percentage due to the shift. The corresponding maximum change of percentage is applied to the PFT fractions used for the reference simulation. The adapted land cover fractions form the baseline for the

perturbed simulations accounting for the error on geolocation. At the 1.2 km resolution, a maximum variation of 100% in the PFT percentage can be obtained. In order to account for this maximum change, the reference land surface simulation must be representative of a fully covered model unit by one PFT, while the shift of land cover map will induce a 100% change to another PFT. Five time series of ET for each spatial resolution are therefore analysed: a reference, two lowerbound scenario and two goal scenarios for both the initial 300 and 1200 m resolution land cover maps. Those simulations are listed in Table 4.1.

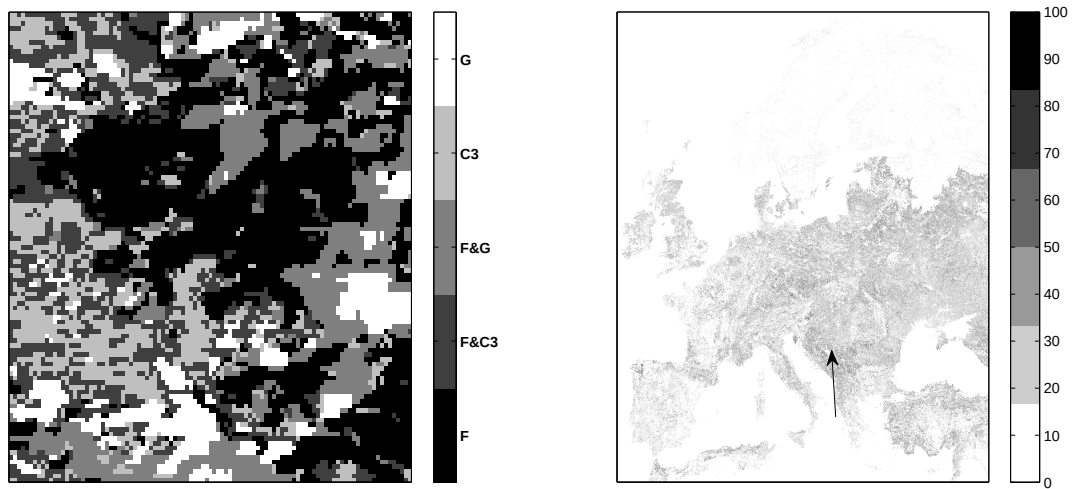


Figure 4.1.: (a) Vegetation types distribution over the focus area in Bosnia, composed of forests (F), cropland (C3), grassland (G), mix of forest and grassland (F&G) or cropland (F&C). (b) The study area (indicated with the arrow) is situated in a region of dense changes due to geolocation uncertainty, with noticeable high percentages of difference at 1200 m resolution between high and low vegetation types.

We evaluate the impact on ET simulated by H-TESSSEL in a realistic case. We have chosen an area representative of the global land cover accuracies obtained in heterogeneous and transition areas. The area is localized in Bosnia (43.5°N, 18.5°E), is 30x30 km² wide and is composed of forests (69%), crops (18%) and grasslands (13%) (Figure 4.1). The land surface model simulation covers the year 2007. The area is a transition between an alpine and a sub-Mediterranean climates, characterized by a high annual amount of precipitation (Krajnovic, 2012). The landscape is composed of

Table 4.1.: **Settings for the reference and perturbed land surface model simulations: simulation resolution, initial resolution of the land cover map, maximum change in forest coverage within the area compared to the reference, PFT fractions used for simulation.**

Simulation	Simulation resolution	Initial resolution land cover map	$\Delta\%$ Forest	Forest	Crops	Grass
<i>Reference</i> ₁	1.2 - 30 km	300 m	-	69%	18 %	13 %
<i>Perturbed</i> _{1,1}	1.2 km	300 m	25%	44%	30.5%	25.5%
<i>Perturbed</i> _{1,2}	3.0 km	300 m	7%	62%	21.5%	16.5%
<i>Perturbed</i> _{1,3}	6.0 km	300 m	2%	67%	19%	14%
<i>Perturbed</i> _{1,4}	9.0 km	300 m	2%	67%	19%	14%
<i>Perturbed</i> _{1,5}	30.0 km	300 m	1%	68%	18.5%	13.5%
<i>Reference</i> ₂	1.2 km	1200 m	-	100%	0%	0%
<i>Perturbed</i> _{2,1}	1.2 km	1200 m	100%	0%	100%	0%
<i>Reference</i> ₁	3.0 - 30 km	1200 m	-	69%	18%	13%
<i>Perturbed</i> _{2,2}	3.0 km	1200 m	22%	47%	29%	24%
<i>Perturbed</i> _{2,3}	6.0 km	1200 m	11%	52%	26.5%	21.5%
<i>Perturbed</i> _{2,4}	9.0 km	1200 m	1%	62%	21.5%	16.5%
<i>Perturbed</i> _{2,5}	30.0 km	1200 m	1%	67%	19%	14%

PFTs for which the evapotranspiration is well modelled by H-TESSSEL. In addition, an especially high density of large changes in PFT percentages is observed over this region by applying the pixel shift to the land cover map (Figure 4.1), making it an interesting test area for this study. The different settings for the simulations are listed in Table 4.1. The reference land cover is set to 69% of forest, 18% of crops and 13% of grass. The 1.2 km reference simulation based on the initial 1200 m resolution land cover map is an exception, as the maximum change corresponds to 100%. To account for the full change in cover, we have chosen a forest cover of 100% as the reference. For all the perturbed simulations, the change of percentage of forest is reported equally on both the crop and the grass percentages.

The effect on the simulations is analyzed at daily time scale. We compute for each time series, month by month, the difference of the monthly mean between the reference and the perturbed land surface model simulations aggregated to daily time scale. For each set of two series, the monthly differences are averaged and a relative difference is obtained. This relative difference is an estimation of the error on ET due to geolocation uncertainty of the land cover map.

4.3. Results

In Figure 4.2, the mean error on PFT percentages is represented as a function of the spatial resolution, using the initial land cover maps at 300 and 1200 m resolutions, respectively in the lowerbound and the goal scenarios. The successive aggregations with the shifted 300 m land cover map result in smaller differences of PFT percentages than with the 1200 m land cover map. The effect is especially noticeable for resolutions between 1.2 and 3 km. At 1.2 km, shift induced differences of PFT percentages reach in average 30% with the 1200 m land cover map over western Europe, while it is reduced to 5% with the 300 m map. At 3 km, the mean difference in PFT percentage is 7% and 2.5% for 1.2 km and 300 m land cover maps, respectively. The coarser the resolution is, the lesser the impact of geolocation is seen. This is a direct consequence of the spatial aggregation of the land cover map which tends to homogenize the land cover characteristics towards coarsest resolutions. The dependency of the change in PFT percentage to the spatial resolution is far from being linear, especially in the first few kilometers for which the average error drastically decreases.

The ranges of maximum relative difference in PFT percentage and in ET due to geolocation (lowerbound-/goal-scenario) for the study area in Bosnia are represented as a function of the spatial resolution in Figure 4.2, left and right respectively. At first, we note that the spatial resolution of the initial land cover map has an impact on the ET simulation accuracy: a decrease of the relative ET uncertainty with the increased spatial resolution of the initial land cover map is observed. At 1.2 km resolution, the ET uncertainty ranges between 3 and 10 % at maximum when using the land cover map at the same resolution, while the error is between 1 and 2.3% if using the land cover map at 300 m. At second, we observe that the relative ET uncertainty decreases towards the coarsest resolutions, consistently with the uncertainty of land cover fraction, with negligible impact of the land cover spatial resolution over 5 km. Over 10 km resolution, the ET uncertainty is less than 1%. At last, we also notice the large impact of the selected geolocation accuracy scenario on the ET uncertainty. Using the goal scenario, corresponding to an error of one-third the initial land cover map resolution, the error of ET is reduced by a factor ranging between 2 and 3 compared to the lowerbound scenario. That latter observation highlights the importance of the work towards georeferencing uncertainty reduction in

land cover mapping. While no seasonality of the relative error has been observed in the present study, the largest variations are observed during rain events. An explanation is that the land surface model allows water storage in the canopy for direct evaporation, and the amount of water available for evaporation is dependent on the vegetation type.

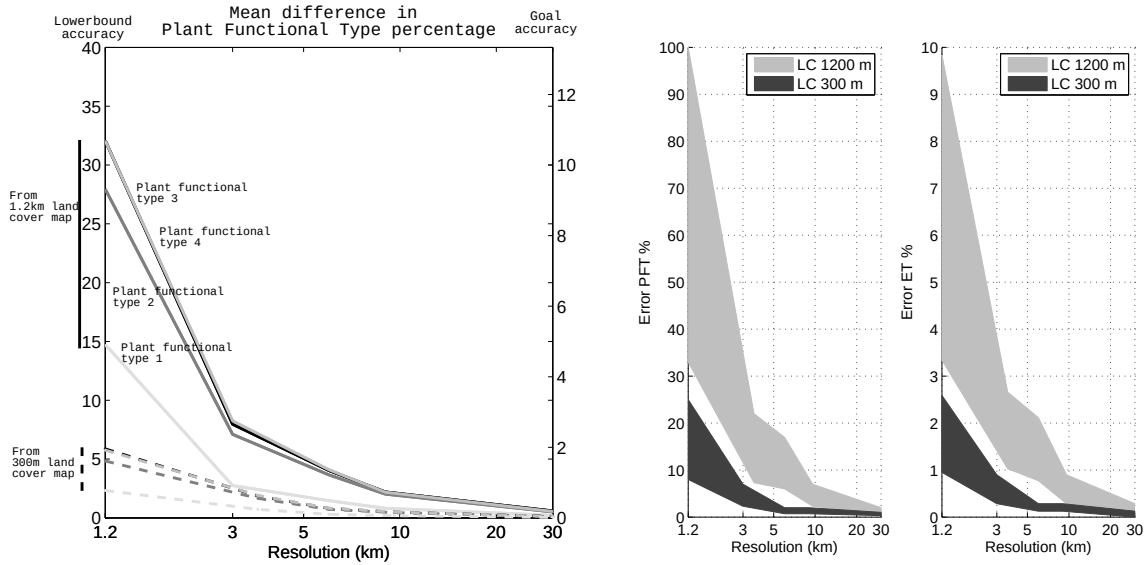


Figure 4.2.: **In average over Europe, lowerbound geolocation inaccuracies generate an error of about 30% on the land use fraction at 1.2 km if using the land cover map at the same resolution, while it reduces to 5% if a map at 300 m is considered. Over an transition zone, geolocation inaccuracies under the lowerbound to goal scenario can generate an error between 30% and 100%, using the 1.2 km land cover map for simulations at the same resolution, while it is not more than 25% using the 300 m land cover map. This has a direct effect on the evapotranspiration rates simulates by the land surface model: the error attain 10% with the 1.2 km land cover map, while it stays below 2.5% with the 300 m land cover map.**

In most regions of Europe geolocation errors induce locally large uncertainty on the land cover map, with up to 100% differences between the reference and the shifted map at 1.2 km. However, only heterogeneous regions, like in Great-Britain or most of central Europe, exhibit a high density of large land cover map differences (Fig. 4.1), highlighting the need of using either a land cover map at 300 m or a coarser map (e.g. 1 km) based on carefully georeferenced data for ET simulations with land surface models. This conclusion draws attention on the need to use a land cover map at an adequate

resolution with respect to the simulation resolution, and with a sufficient quality in terms of geolocation corrections. This remark is especially relevant for off-line applications of land surface model and numerical weather predictions models that tends to increase their horizontal resolution to a few kilometer resolutions (Hamdi et al., 2012; Bernier and Belair, 2012; Tang et al., 2013).

It should be mentioned here that the magnitude of the maximal errors obtained for ET estimations are of a few percents, while the error generated by a misclassification in the land cover map can be up to 15% relative error (Pauwels and Wood, 2000). Therefore, it is also concluded that geolocation accuracy of land cover map has potentially a much lower impact on ET simulations for coarse spatial resolution compared to land cover misclassification.

4.4. Conclusion

We have evaluated the impact of geolocation accuracy on the land use percentages given by two land cover maps (300 and 1200 m initial spatial resolution), at spatial resolution ranging from 1.2 to 30 km. The effect on the accuracy of the daily evapotranspiration simulated by a land surface model (H-TESSSEL) has been evaluated on an area of 30 km x 30 km in Europe, for different spatial resolutions used for numerical weather predictions, 1.2 to 30 km. We have found that the geolocation uncertainty has a decreased effect on simulated evapotranspiration with coarser resolutions. In addition, the initial land cover map resolution plays an important role in decreasing the effect of geolocation error on the simulations. Land cover maps derived from satellite imagery at 300 m resolution will tend to reduce the impact of geolocation accuracy on ET estimates by land surface models, compared to the 1 km resolution. Land surface model applications from 1 to 5 km resolution therefore benefit from using land cover maps with enhanced resolution. Such maps have been derived from MERIS onboard ENVISAT, and updates are expected to be derived from data of the new PROBA-V mission.

5

Improvement opportunities from moderate spatial resolution satellites for vegetation

This chapter is based on N. Ghilain, F. De Roo & F. Gellens-Meulenberghs (2014), Evapotranspiration monitoring with Meteosat Second Generation satellites: improvement opportunities from moderate spatial resolution satellites for vegetation, *International J. Remote Sens.*, 35, 7, 2654-2670.

Abstract

The Satellite Application Facility on Land Surface Analysis proposes a land evapotranspiration product, generated in near real time. It is produced by an energy balance model forced by radiation components derived from data of the Spinning Enhanced Visible and Infrared Imager aboard Meteosat Second Generation geostationary satellites, at a spatial resolution of approximately 3 km at the equator and covering Europe, Africa and South America. We assess in the present paper the improvement opportunities from moderate spatial resolution satellites for evapotranspiration monitoring at Meteosat Second Generation satellite scale. Four variables, namely the land cover, the leaf area index, the surface albedo and the open water fraction, derived from moderate resolution satellite for vegetation monitoring are considered at two spatial resolution, 1 km and 330 m, corresponding to the imagery provided by SPOT-Vegetation and future Project for Onboard Autonomy Vegetation (ProbaV) spaceborne sensors. The variables are incorporated into the evapotranspiration model, replacing or complementing input derived from the sensor aboard the geostationary satellite, and their relative effect on the model output is analyzed. The investigated processes at small scales unresolved by the geostationary satellite are better taken into account in the final evapotranspiration estimates, especially over heterogeneous and transition zones. Variables derived from sensors at 250-300 m are shown to have a noticeable effect on the evapotranspiration estimates compared to the 1 km resolution, demonstrating the interest of ProbaV 330 m derived variables for the monitoring of evapotranspiration at Meteosat Second Generation resolution.

5.1. Introduction

Evapotranspiration (ET) is a key component of the water cycle. Water is re-emitted into the atmosphere through direct evaporation of surface water, bare soils and transpiration of the plants. Alongside, the ET process causes a cooling of the land surface, as it consumes part of the energy stored by the surface. Therefore, ET plays an important role in meteorological as well as in hydrological processes. With the increasing demand for ET monitoring in a broad range of applications, including water management and agriculture, more and more techniques have been developed, and some automated. However, its monitoring is still a challenge as no direct observation is possible at large scale (Dolman and de Jeu, 2010), and only a combination of modeling and observations can help achieving that goal. Spaceborne remote sensing has therefore been seen as a great opportunity to bypass the need of local observation, especially in poorly sampled regions.

Recently, EUMETSAT's Satellite Application Facility on Land Surface Analysis, LSA-SAF, (Trigo et al., 2011) has started the distribution of two near-real time products aiming at the ET monitoring: instantaneous every half-hour (MET) and daily cumulated, over the full field of view of the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on board of the geostationary satellite Meteosat Second Generation (MSG). It covers Europe, Africa and Eastern South America (Ghilain et al., 2011). ET is monitored at an unprecedented rate of one image every half-hour and is delivered through an operational continuous service provided by LSA-SAF host center in Lisbon (<http://landsaf.meteo.pt>).

As it is based on geostationary satellite data, the spatial resolution becomes coarser towards the high viewing angles, with a resolution of 4 to 5 km over most Western Europe. Given that spatial resolution, small scale processes are unresolved, though their contribution might be not negligible to the total areal evapotranspiration. Besides, information with an increased sub-grid resolution can help to increase the accuracy of ET.

New products derived from remote sensing at moderate spatial resolution are now available and make a synergy possible with the coarse resolution information from MSG. However, in the context of continuous monitoring, it is recommended to have

access to long data time series provided by continuous services. In that perspective, Geoland2 has begun providing, with its BioPar division (Lacaze et al., 2010), a service of continuous production of land related variables (<http://www.geoland2.eu>). Système Pour l'Observation de la Terre - Végétation (SPOT-VGT) plays a major role for the production of such variables, as 2 successive SPOT satellites allow a continuous global monitoring of the vegetation for about 15 years, at a spatial resolution of approximately 1 km. However, in 2013 the expected life time of the satellite will be exceeded. Its foreseen successor in the framework of the Global Monitoring for Environment and Security programme, Sentinel-3, designed to monitor globally the vegetation at a spatial resolution of 300 m during 7 years, is not expected to be exploited before 2014, leaving a gap in the continuous monitoring. The Project for Onboard Autonomy (ProbaV) mission has then been set up to act as a gap-filler mission (Van Achteren et al., 2014), with sensors about the same characteristics as SPOT-VGT, an expected life time of 2.5 years and an enhanced spatial ground resolution of 330 m. Therefore, continuous service is secured, and spatial resolution is improved. As well, the relatively high revisiting frequency of ProbaV (global coverage once a day) makes its future data potentially interesting in terms of stability and reliability, valuable for operational production. The interest in the variables derived from moderate resolution spaceborne sensors and the benefits that could be obtained from the enhanced spatial resolution are particularly relevant for ET monitoring. The objective of this study is therefore to investigate the interest in complementing the ET model based on MSG with variables derived from 250 to 1000 m spatial resolution sensors imagery. Especially, we focus on the impact of four different variables derived from such imagery: land cover, leaf area index, water bodies fraction and land surface albedo. Land cover is examined on the geolocation accuracy aspect: we assess further previous findings showing the reduced effects of an increase in the spatial resolution of satellite imagery on ET simulations at a few kilometers scale (Ghilain and Gellens-Meulenberghs, 2014).

In the present paper, we briefly describe the ET model, review the various products derived from moderate resolution satellites that are of interest for the LSA-SAF ET products (Sect. 2), present the study sites and methods (Sect. 3), and assess their respective impact on test cases (Sect. 4). At last, we give a general conclusion and draw some perspectives towards the forthcoming launch of ProbaV from the enhanced

spatial resolution point of view.(Sect. 5).

5.2. Model and data

5.2.1. LSA-SAF evapotranspiration: model and output

The LSA-SAF proposes two ET variables-products: the instantaneous actual ET rate, MET, and the daily cumulated actual ET. Maps are operationnally and continuously produced from September 2009 and cover Africa, Europe and part of South America, at the MSG/SEVIRI spatial resolution. The ET model implemented to derive the variables-products is an energy balance model (Ghilain et al., 2011) fed by remote sensing derived products for radiation (Geiger et al., 2008b,a; Trigo et al., 2010), the daily land surface albedo derived from MSG and short-term numerical weather forecasts from the European Center for Medium-range Weather Forecasts. Land cover information, and decomposition of vegetation classes into the model plant functional types, is needed to assign specific model parameters related to the maximum evapotranspiration rate, and is currently provided by ECOCLIMAP-I, derived from 1-yr NDVI Advanced Very High Resolution Radiometer (AVHRR) data, at 1 km resolution (Masson et al., 2003). In addition, the vegetation state, characterized by the leaf area index, LAI, and the fractional vegetation cover, FVC, is assigned using the ECOCLIMAP-I database. A new version of MET algorithm, noted here V1, is a variant of the same model, including the use of other daily LSA-SAF products, i.e. LAI, FVC and snow cover, following the methodology described in Ghilain et al. (2012). The variables derived from remote sensing used in the model are listed in Table 5.1. A schematic of the model is shown in Figure 5.1: the connections of the variables derived from the 300 to 1000 m imagery examined in this study with the different steps of the model and definition of input are highlighted. Those variables influence the evapotranspiration model at different steps: the evaluation of plant functional type dependent canopy resistance to transpiration, the estimation of the aerodynamic resistance of the lower atmosphere to the vertical transfer of moisture, the calculation of the net radiation at the surface and the surface heat fluxes computed iteratively until convergence. In addition, the weights of the different plant functional types and land uses needed to give an areal composite of evapotranspiration are also

Table 5.1.: Variables and satellite derived products used by LSA-SAF evapotranspiration model.

Name	Variable	Sat.-Sensor	Resol.	Frequency
ECOCLIMAP-I	Land cover map	NOAA/AVHRR	1 km	fixed
LSA-SAF LAI	Leaf Area index	MSG/SEVIRI	3.1 km	daily
LSA-SAF FVC	Fractional vegetation cover	MSG/SEVIRI	3.1 km	daily
LSA-SAF SC2	Snow cover characterization	MSG/SEVIRI	3.1 km	daily
LSA-SAF AL	Surface albedo	MSG/SEVIRI	3.1 km	daily
LSA-SAF DSSF	Shortwave radiation reaching the surface	MSG/SEVIRI	3.1 km	30 min
LSA-SAF DSLF	Longwave radiation reaching the surface	MSG/SEVIRI	3.1 km	30 min

affected.

The model has been validated over Europe and Africa, by comparison with in-situ measurements and intercomparison with other models (Ghilain et al., 2011).

5.2.2. SPOT-VGT and ProbaV instruments

The Vegetation programme is composed of a suite of two nearly identical sensors onboard of two satellites SPOT-4 and 5 and has been monitoring vegetation on Earth surface every 10 days from 1998. The satellites are on a sun-synchronous orbit, with a time pass at 10:30, at 830 km from the ground. The sensor acquires one image per day for locations beyond 35° and five every six days for equatorial regions. The sensor acquires data in four spectral bands: blue (0.43-0.47 μ), red (0.61-0.68 μ), near infrared (0.78-0.89 μ), and short-wave infrared (1.58-1.75 μ). The ground spatial resolution is 1.15 km at nadir and 1.7 km on the sides, with a swath width of 2200 km.

The ProbaV satellite is expected to be launched in 2013. Most of the characteristics from Vegetation sensor acquisition are maintained as it is considered as a continuation mission. The satellite will fly at 820 km from the ground, the time pass will be maintained between 10:30 to 11:30, and there will be one acquisition every day, except for equatorial areas, with a 90% coverage every day. Spectral bands and swath width are similar to Vegetation. A major change in the characteristics is the ground spatial resolution, as it will be 330 m in average, with 100 m resolution at the center of the swath and 350 m on the sides for the 3 first bands, and twice for the short-wave infrared. Both systems are expected to be characterized by the same relative geolocation accuracy.

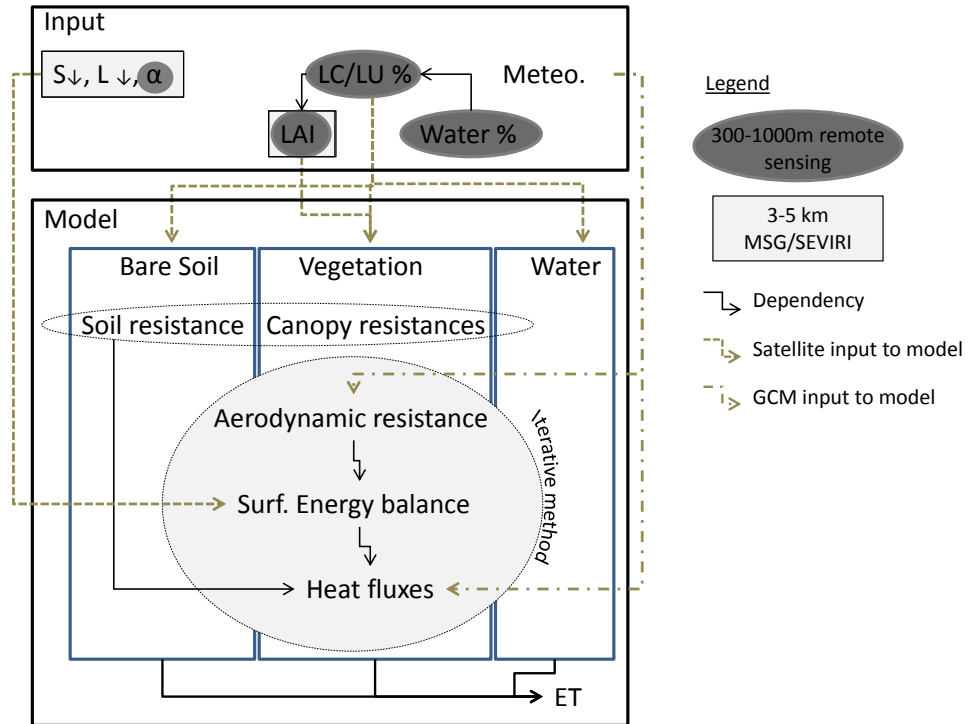


Figure 5.1.: **Schematic of the model steps and input.** The process is shown for one model unit, with a differentiation between input provided by the global circulation model (GCM) ECMWF, the variables derived from the SEVIRI sensor aboard the geostationary MSG satellite, and finally the complementary variables derived from 300 m to 1000 m spatial resolution imagery from sensors aboard polar satellites examined in this study. $S_{\downarrow}$ and $L_{\downarrow}$ are respectively the shortwave and longwave radiation reaching the surface, α is the surface albedo, $LU/LC\%$ is the fraction of each plant functional type within a model unit given by the land cover map, and $Water\%$ is the fraction of open water surface given by satellite derived products.

5.2.3. Variables of interest derived from moderate spatial resolution spaceborne sensors

Two pools of variables derived from moderate resolution satellites are of interest for the improvement of the evapotranspiration monitoring in the LSA-SAF context. First, variables with the potential to improve the reliability of the results by a gain in spatial resolution. More specifically, those are variables already retrieved from MSG/SEVIRI, but their increased spatial resolution can lead to a more accurate estimation by spatial aggregation. Then, variables allowing the detection of unresolved features by MSG/SEVIRI. In the first pool, the land cover map, the biophysical parameters describing the vegetation and the land surface albedo are envisaged candidates. The second pool is composed of the small water bodies and regularly flooded areas detection.

For each variable of interest, the two ground spatial resolutions of SPOT-VGT and ProbaV are needed to evaluate the gain from using data from higher spatial resolution sensors to complement the evapotranspiration model at coarse scale. The lower product resolution corresponding to SPOT-VGT is 1 km. For this preparatory study in view of the ProbaV launch, other similar remote sensing derived products are used to surrogate the future data, and the higher product resolution corresponding to ProbaV varies between 250 and 500 m depending on the finest global product available.

Land cover map

Because land cover map is the second most influential input on the modelled evapotranspiration (Kato et al., 2007), an optimal choice has to be taken in order to comply with the necessary conditions for continuous monitoring. New global or continental scale land cover maps have emerged using more recent remote sensing data and longer time series. As an example, ECOCLIMAP-II has been developed on the basis of SPOT-VGT data (Kaptué Tchuenté et al., 2011), at 1 km resolution over Africa, with a better accuracy than ECOCLIMAP-I due to a multi-year analysis of the SPOT-VGT NDVI data. Globcover v2.2 has been derived from MERIS data at an enhanced resolution of 300 m (Bicheron et al., 2006). MODIS land cover map (MCD12Q1) is derived yearly from MODIS data and is available at 500 m spatial resolution. Each land cover map is

provided with a legend: it allows the decomposition of the classes into plant functional types used by land surface models, and therefore ensures the compatibility with the LSA-SAF evapotranspiration model. In this study, the land cover maps considered are ECOCLIMAP-I and Globcover at 1000 and 300 m resolution respectively. Different aspects of the land cover maps are relevant for LSA-SAF model: the quality of the land use classification, the geolocation accuracy and the continuity of a series of updated land cover maps. In a recent study (Ghilain and Gellens-Meulenberghs, 2014), we have shown that the use of a land cover map at 330 m allowed reduction of geolocation uncertainty on ET at meso-scale compared to land cover maps produced from 1 km data. The effect is particularly visible for spatial resolutions from 1 to 5 km. LSA-SAF model is concerned with resolutions such as 3.1 km over Western Africa, 4 to 5 km over most of Europe, and up to 10 km over northern Scandinavia, Russia and part of South America. Therefore, we study the effect of this geolocation uncertainty on ET produced with MSG/SEVIRI data over Europe.

Leaf area index

The biophysical parameter LAI is essential to the evapotranspiration model, as it scales the transpiration process from a single leaf unit to the landscape level. In addition, in several models or databases (Masson et al., 2003), LAI is associated to FVC by means of an exponential relation. The latter variable is used to determine the portion of land occupied by bare soil, and allows to compute separately bare soil evaporation and plant transpiration. Available LAI products at moderate resolution are derived from MODIS at 1 km, e.g. MCD15 (Tian et al., 2000), and from SPOT-VGT at the same resolution, e.g. CYCLOPES LAI product (Baret et al., 2007). Recent advances have been made to derive LAI at higher resolution using MERIS 300 m (Bacour et al., 2006) or MODIS 250 m (Kouadio et al., 2012). Using such high resolution LAI in the LSA-SAF evapotranspiration model has proven to be beneficial in estimating more accurate evapotranspiration rates over a winter wheat field in Belgium (Sepulcre-Cantó et al., 2013). A further assessment is proposed here using LAI from SPOT-VGT and MODIS at 1000 and 250 m respectively.

Water bodies

The evapotranspiration is known to be much higher over open water bodies than over vegetated areas. While permanent water bodies are usually mapped and used in land surface model applications, seasonal/eventual water bodies, like ponds and flooded plains, are scarcely represented, casting inevitable errors on the model estimates. While sensors at MSG/SEVIRI spatial resolution have shown the possibility to detect flooded areas in Africa (Proud et al., 2011), they could hardly detect small size water bodies and high-resolution sensors between 250 and 1000 m offer a more adequate imagery to monitor those seasonal surface water bodies (Gond et al., 2004). Such small water bodies and regularly flooded areas regularly updated maps are therefore useful input for the LSA-SAF evapotranspiration model. Gond et al. (2004) have developed a method to detect small water bodies and flooded areas from SPOT-VGT using NDVI and NDWI indices. More recently, Pedinotti et al. (2012) have used MODIS/Terra NDVI and band 5 atmospherically corrected reflectance at 500 m resolution to monitor the surface water in the Sahel. In this study, NDVI and NDWI retrieved from SPOT-VGT and MODIS are used to derive the fraction covered by water bodies at 1000 and 250 m respectively.

Land surface albedo

Since the evapotranspiration model is an energy balance model, radiation components are required, and, in particular, the land surface albedo. The surface albedo is an important term to compute the energy available at the surface for evaporation. Surface albedo generally differs among different land uses. In the model, ET is computed for each land use class defined in the model, but the surface albedo is the same for all classes belonging to the very same MSG/SEVIRI pixel. One albedo for each sub-pixel land cover type would change the local energy budget, and potentially affect the ET calculation. Although assuming a single albedo for every vegetation types belonging to a MSG pixel may be fully valid for mixed landscapes, homogeneous at MSG resolution, it could possibly be uncertain for heterogeneous areas, fragmented landscapes and transition zones, and it could induce there a noticeable effect on evapotranspiration. Using higher spatial resolution albedo allow the estimation of an albedo aggregated by vegetation type, necessary to compute the surface energy balance for each sub-pixel type. Ten-

Table 5.2.: **Variables and satellite derived products used in our study.**

Variable	Product Resol. 1			Product Resol. 2		
	Name	Sat.-Sensor	Resol.	Name	Sat.-Sensor	Resol.
Land cover	ECOCLIMAP	AVHRR	1 km	Globcover v2.2	MERIS	300 m
Leaf Area index	CYCLOPES	SPOT-VGT	1 km	MOD13Q1	MODIS-Terra	250 m
Albedo	Geoland2	SPOT-VGT	1 km	MCD43A3	MODIS-Terra/ Aqua	500 m
Water bodies	Geoland 2 NDVI	SPOT-VGT	1 km	NDVI	MODIS-Terra	500 m
	Geoland2 NDWI	SPOT-VGT	1 km	Reflectance	MODIS-Terra	500 m

days composites of the land surface albedo from SPOT-VGT at 1 km are now available, as well as at 500 m and 1 km from MODIS. The products at 1000 and 500 m derived from SPOT-VGT and MODIS are used in this study.

We have tabulated in Table 5.2, the products whose utility are explored in the context of the LSA-SAF MET algorithm, bearing in mind the continuity secured by the suite composed by SPOT-VGT and ProbaV satellites.

5.3. Study sites and methods

The optimal demonstration of the effect of each considered variable is expected in different conditions depending on the variable. Therefore, the present study does not focus on a standardized methodology for assessing the impact on the LSA-SAF evapotranspiration. The study sites specific to each variable are described here, as well as the method employed to show the impact on the resulting evapotranspiration estimates.

To assess the impact of geolocation uncertainty of land cover map on the evapotranspiration estimation, we have focused on Europe, which is expected to be more affected by it. Land cover maps at two spatial resolutions, 1000 and 300 m, are needed to assess the difference between maps derived from SPOT-VGT and ProbaV. In order to separate the effect of geolocation accuracy with the mis-classification due to different methodologies or sensors characteristics, we choose to use GlobCover land cover map at 300 m and an aggregated version at 1 km, called the reference maps. Given that the absolute geolocation accuracy is one pixel for both SPOT-VGT and ProbaV, both maps are shifted by one pixel, and called shifted maps. The difference between the reference

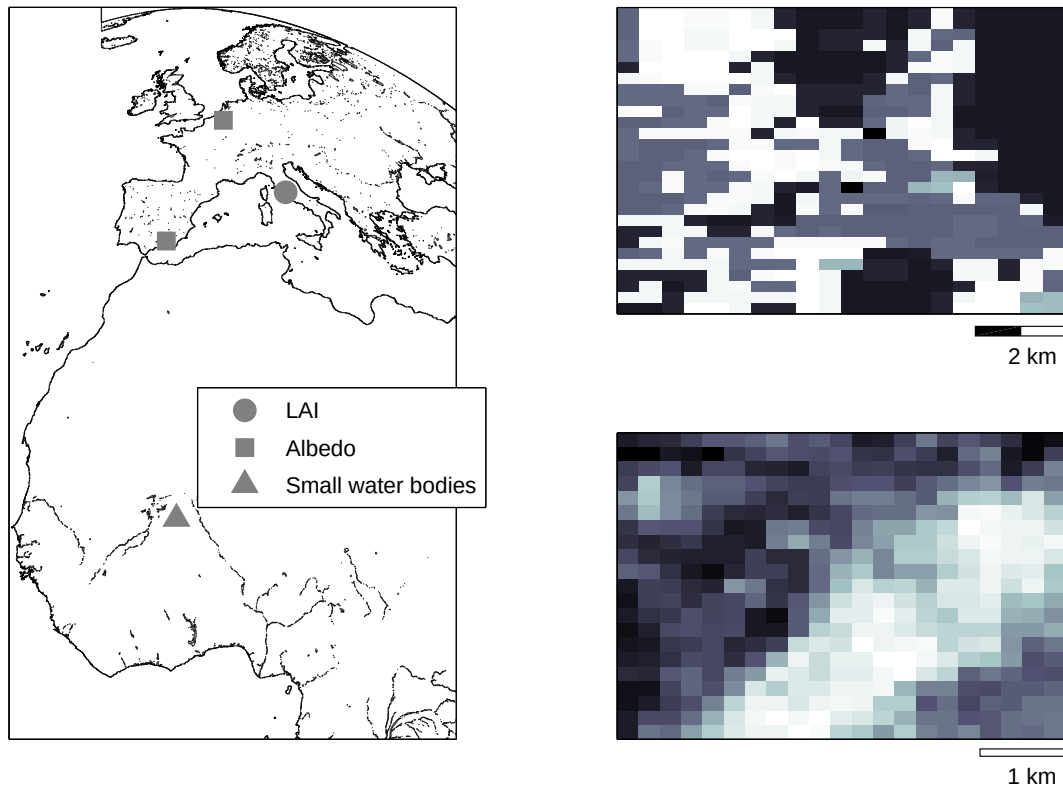


Figure 5.2.: The sites in Europe and Africa used in this study in the projection of MSG/SEVIRI (left). Focus on two sites used: (top) the land cover types (Sparse vegetation, irrigated and rainfed crops) from GlobCover at the Spanish site, (bottom) MODIS NDVI during Summer 2007 at the Italian site revealing an oblique narrow band of forest within the agricultural landscape.

and the shifted map is a measure of the effect of geolocation error on the land cover map input in the model. In order to assess the impact on evapotranspiration, the maps are aggregated at the coarser variable MSG/SEVIRI resolution in view of their use in the LSA-SAF model. Each class of GlobCover is decomposed into three broad vegetation types, high vegetation, low vegetation and other types. In order to evaluate the impact on the evapotranspiration model, we have derived a function to approximate the relation between the error on the change of percentage of forested areas to low vegetation, based on the findings of Ghilain and Gellens-Meulenberghs (2014). Using this relation, the change of land cover change $\Delta LC\%$ is converted into relative error on evapotranspiration

$\Delta_{\%}ET$.

$$\Delta_{\%}ET = 0.1560 + 0.1167\Delta LC_{\%} - 0.002\Delta LC_{\%}^2 \quad (5.1)$$

As mentioned in Sect. 2, LSA-SAF MET takes input from ECOCLIMAP-I database for vegetation phenology. The new variant V1 takes advantage of the recent LSA-SAF LAI product, available at MSG/SEVIRI spatial resolution. However, in patchy landscapes, a statistical post-processing procedure needs to be applied, using vegetation signals from distant neighbour pixels. A high-resolution land cover map (Globcover) is used along with CYCLOPES LAI (1 km) derived from SPOT-VGT and MOD13Q1 (250 m) derived from MODIS/Terra for the year 2007. The MOD13Q1 product offers NDVI at 250 m, but there is no available LAI product at such resolution. Therefore it is necessary to convert into LAI time series, accepted by the energy balance model. Different methods have been under focus. The method of Lu and Shuttleworth (2002) that proceeds by cumulative distribution matching reduces the difference in LAI that can occur due to a difference in the LAI retrieval algorithms. Such a *processed* difference should be distinguished from a *physical* difference in LAI, which is instead the result of a better characterization of the surface, e.g. due to an increased spatial resolution or a more precise time sampling of the annual evolution of the vegetation. Because of that limitation, another method was adopted. From the match of SPOT-VGT NDVI to CYCLOPES LAI, we derive an exponential function that is used to convert MODIS NDVI into LAI at 250 m resolution. We aggregate the LAI by vegetation types within a MSG/SEVIRI pixel making use of the land cover map (Figure 5.3) and then limit the number of spatial units to run the model. The surface roughness parameters required by the model are derived from the LAI obtained using the formulation of ECOCLIMAP-I. This method has been applied over a particular site in Roccarespampani, Italy ($42.41^{\circ}N$, $11.93^{\circ}E$), composed of a deciduous forest (*Quercus cerris*) and crops. The site is equipped with an eddy correlation device that measures the fluxes of heat and moisture from the underlying surface, mostly represented by the forest (Tedeschi et al., 2006).

As surface albedo can be estimated from moderate resolution satellites (250 - 1000 m), it is theoretically possible to create an average albedo for each vegetation class inside a MSG pixel, using the methodology depicted in Figure 5.3, but using albedo instead of

LAI. Because the effect is expected to be most sensible in heterogeneous and transition zones, we focus on two areas with contrasted land uses. Both areas have been chosen for their different climate and known contrasts: East of Brussels ($50.81^{\circ}N$, $4.59^{\circ}E$), and South of Spain ($37.35^{\circ}N$, $3.18^{\circ}W$), and have an extent of 3x3 MSG pixels. The region east of Brussels is composed of urban areas, as well as deciduous forests (beech stands), and croplands (mostly sugar beets and wheat). Those 3 tiles are well localized. The Spanish region is composed of irrigated crops, annual crops and sparse woodland, mainly. For the construction of the 'tile' albedo time series, HR (SPOT-VGT or MODIS) albedo is selected according to the land covers, i.e. Globcover v2.2, MODIS and ECOCLIMAP-I. Using separately each land cover to tag the albedo values does not give reliable results, because of the land cover map discrepancies found in the selected areas. As well, a per-pixel analysis seems not to be useful (results not shown here), so an analysis on a 3x3 MSG pixels area has been done. A way to by-pass the problem of land cover mismatch is to use simultaneously the land covers, and use only the pixels with acceptable agreement between land cover maps to derive the 'tile' values. For the Belgian region, the best match is between MODIS LC and GlobCover (bare areas are set to be agricultural land), and for the Spanish region, ECOCLIMAP-I matches with GlobCover. Mean time series of cropland and forest albedos are retrieved for the Belgian region. For the Spanish region, time series are retrieved and aggregated for both types of crops, irrigated (15%) and non irrigated (10%), and for sparse woodland (73%). The evapotranspiration model has then been modified to accept not only one pixel albedo from LSA-SAF, but an albedo estimate for each tile.

To show the effect of water bodies detection by moderate resolution sensors for vegetation, we focus on a specific sahelian region in Mali, known to be covered with seasonal ponds during and after the west African monsoon (Timouk et al., 2009). The region is of special interest, because, in the framework of an international project aiming at understanding the mechanism of the west african monsoon (Redelsperger et al., 2006), devices have been installed to measure on flux tower the exchanges of energy between the surface and the atmosphere (Mougin et al., 2009). Of particular interest in the present context are the observations of ET at the Kelma site ($15.22^{\circ}N$, $1.57^{\circ}W$), monitoring a forested area (acacia trees) situated in a clay depression, where ponds are observed from July to January approximately. Seasonality is strong in that area, and

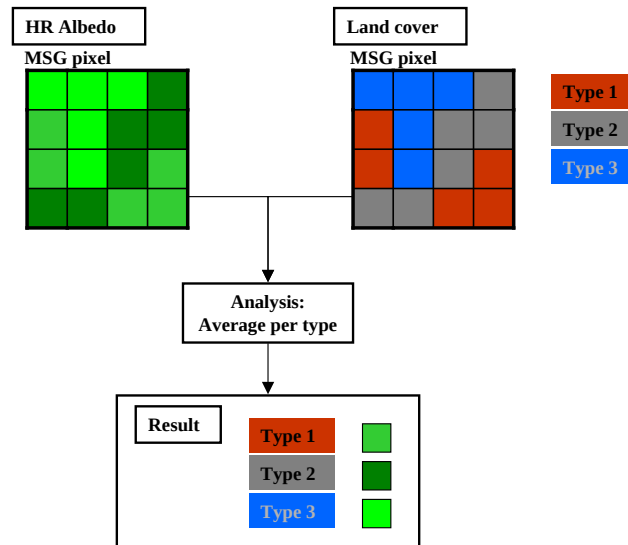


Figure 5.3.: **Aggregation methodology to obtain one albedo per vegetation type at the selected MSG/SEVIRI pixel from moderate resolution variable-product: a land cover map is used to discriminate the albedo values per vegetation class before averaging. The same methodology is applied to obtain aggregated time series of LAI.**

small clay depressions collect the run-off during the rainy period. The ponds created, slowly evaporate during the dry season. The highest measured evapotranspiration is connected with the vegetation growth, but as the vegetation senescence begins, high evapotranspiration rates are still measured. Such high ET rates without a full vegetation cover can only be attained by the direct evaporation from water bodies. LSA-SAF ET results are known to be deficient over that specific location, probably because of the seasonal ponds not taken into account in the ET modelling. We consequently investigate here the possibility to improve the ET estimates on that specific location using remote sensing products able to detect open water surfaces. It is possible to monitor the small water bodies using NDVI and NDWI derived from SPOT-VGT at 1 km (Gond et al., 2004). The *threshold* method has been applied on a set of NDVI and NDWI images

derived from SPOT-VGT and MODIS for the period from 11/2009 to 10/2010 over a region of 25 km^2 around Kelma in Mali. Higher resolution should provide more accurate estimation of the fraction of open water bodies, as it is able to detect smaller water surface than at 1 km, and, at least, it provides a more robust statistical NDWI mean over the area for use in the 'threshold' method of Gond et al. (2004). LSA-SAF ET model has been slightly modified to accept as input a map of fraction of surface water, and re-processing of year 2007 has been applied to obtain a new time series of ET over Kelma station, using the series of fraction of surface water derived from MODIS.

5.4. Impact on LSA-SAF evapotranspiration

The effect on the LSA-SAF evapotranspiration of each considered variable is detailed in separate subsections.

5.4.1. Land cover maps

At MSG/SEVIRI resolution, the error on the forest fraction due to geolocation uncertainty is variable as expected with the viewing angles of the geostationary satellite: the largest errors are found where the viewing angle is the smallest. A mean and a maximum error in forest fraction within a region of 25 neighbouring pixels is represented in Figure 5.4 for both maps at 300 and 1200 m. Some regions are not much affected by the shift in the land cover maps, while others can reach mean values of 2% and 10% for 300 and 1200 m maps respectively. When examining the maximum change within each 25 pixels region, an error of 6% and 30% is observed over Spain for respectively both resolutions.

The impact on evapotranspiration is also dependent on the viewing angle and the spatial resolution of the used land cover map as seen in Figure 5.5. The relative error on evapotranspiration is about 1% when using a land cover map at 300 m (Figure 5.5), while the use of the 1200 m map generates a relative error ranging up to 5% at some locations (Figure 5.5). It is therefore expected to reach a better confidence level in the

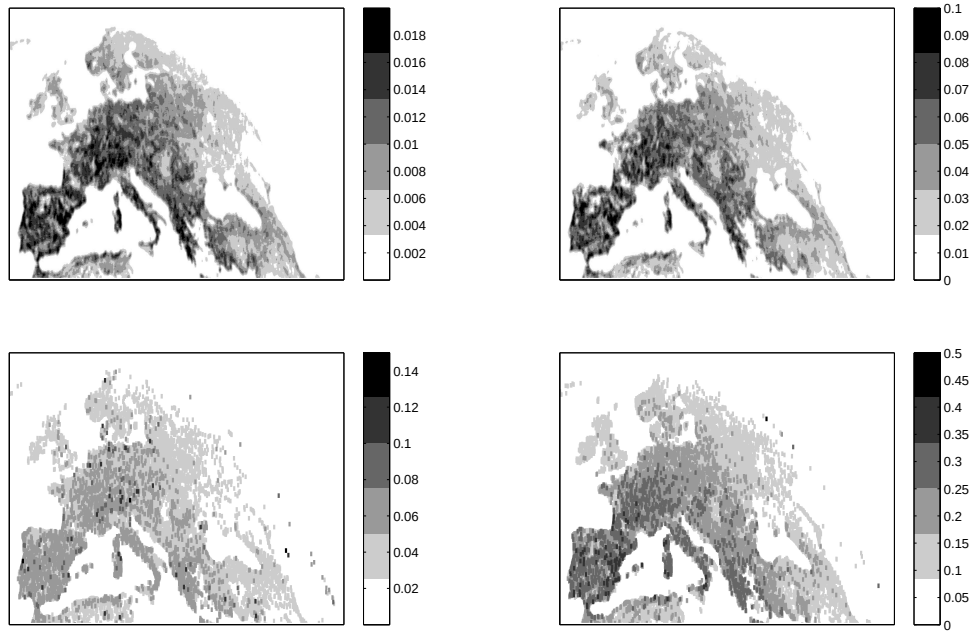


Figure 5.4.: **Mean uncertainty on 25 neighbouring pixels at MSG/SEVIRI resolution in the forest fraction over Europe due to geolocation error on land cover maps at 300 m and 1200 m spatial resolution (a) and (b). The distribution of the maxima over each 25 neighbouring pixels is shown in (c) and (d).**

evapotranspiration results over Spain, Italy and Southern France if using a land cover map generated from ProbaV.

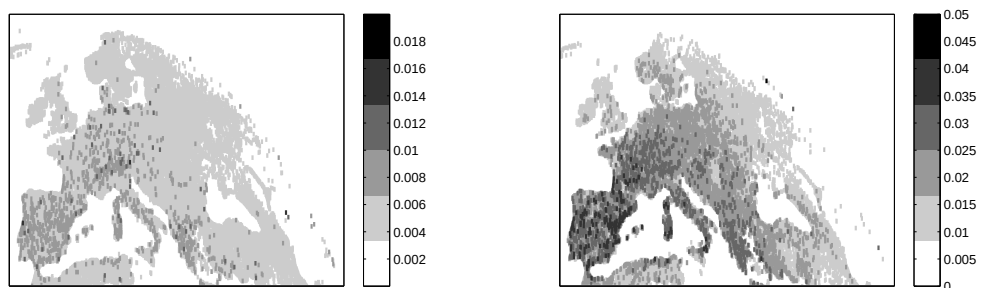


Figure 5.5.: **Relative difference in evapotranspiration due to geolocation uncertainty of 300 m (a) and 1200 m (b) land cover maps.**

5.4.2. Leaf Area Index

The retrieved LAI time series from SPOT-VGT (CYCLOPES) and MODIS for the two dominant vegetation types at Roccarespampani site show differences in the amplitude and timing of the full canopy cover characterizing the deciduous forest (Figure 5.6), while there is an agreement for the crop class phenology. This observed difference in the retrieved LAI impacts the evapotranspiration estimated by the LSA-SAF model, with higher daily rates for the forest using the 250 m product aggregated to MSG/SEVIRI resolution (Figure 5.6). However, at the coarse pixel scale, because the forest occupy a mere 10-12% of the pixel area, the difference is still noticed but greatly reduced (Figure 5.7). In comparison to the evapotranspiration model V1 output, most changes occur during the summer months for which the estimates using the 250 m LAI are slightly closer to the in-situ daily cumulated observations (July). This could be the sign that LAI series at 250 - 300 m resolution could have a beneficial impact, minor though, on ET simulations at MSG scale compared to the series obtained at 1 km, especially in such transition (crop/forest) areas. It should be noted here that part of the observed difference between observations and model estimates is due to different representativity: observations are representative of the forest, while the model estimates are representative of a surface dominated by crops. However, from Figure 5.6, it is seen that the LSA-SAF model may have some difficulties in simulating the observed evapotranspiration rates in April. However, the use of 250 m or 1000 m LAI does not allow to correct the model deficiency.

5.4.3. Land Surface Albedo

For the Spanish region, the most contrast is expected from the separation between annual crops and irrigated crops. The albedo time series retrieved from MODIS for both crop types are shown in Figure 5.8, along with the LSA-SAF Albedo product. The albedo retrieved from MODIS for the sparse forest (not displayed) is very similar to the irrigated tile albedo. No series is shown for Geoland2 series as no clear separate signals could be found for each land use classes, showing the potential limitation of 1 km data for such types of landscapes. Mean values are represented as continuous lines, while the shaded areas are bounded by the maxima and minima of each sample. LSA-SAF Albedo

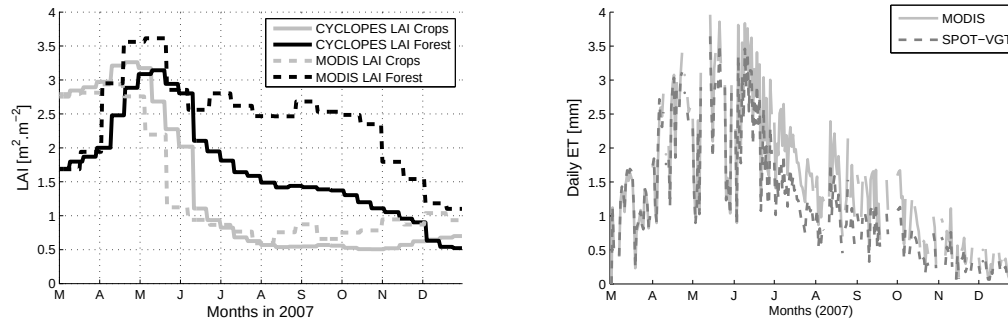


Figure 5.6.: Leaf Area Index time series aggregated from the 1 km and the 250 m imagery over Roccarespampani, and their effect on the evapotranspiration estimation over the forest. Leaf area index time series aggregated for the two main vegetation types (forest and crops) over the Roccarespampani site, as derived from SPOT-VGT and MODIS data (left). Evapotranspiration estimated using the LSA-SAF model and leaf area index time series for the forest from MODIS NDVI and SPOT-VGT CYCLOPES LAI. (right)

agrees with MODIS albedo in the studied areas: the global annual cycle is similar and the estimates are in the same range of magnitude. The 'tile' albedo time series can be, however, different. For the Spanish area, the difference can be as large as 0.07 between the 2 types of crops in July and August, with an albedo 30% lower for irrigated than annual crops. For the Belgian area, snow is detected in December 2009 and January 2010 and the biggest difference observed, except for the snow event, is about 0.02, i.e. 10% (not shown), leading to almost no change in evapotranspiration estimation. It must be mentioned here that the weighted contribution of the 'tile' albedos derived from MODIS follows fairly well the averaged LSA-SAF albedo for the study sites.

The result of the evapotranspiration model V1 is considered as the control simulation for the area in Spain, where albedo from high resolution is expected to affect ET estimates at MSG scale. The effect of using an albedo assigned with MODIS for each vegetation type of the coarse model unit is seen by comparison with the simulation results from the modified evapotranspiration model for which a relative difference between daily evapotranspiration is calculated (Figure 5.8). As expected, ET is affected by the tile albedo values. Apart from the winter peak which leads to very little change in evapotranspiration rates, the difference has a seasonal cycle with the largest difference during the summer season. Daily ET cumulates are lower by 15 to 20% by using MODIS

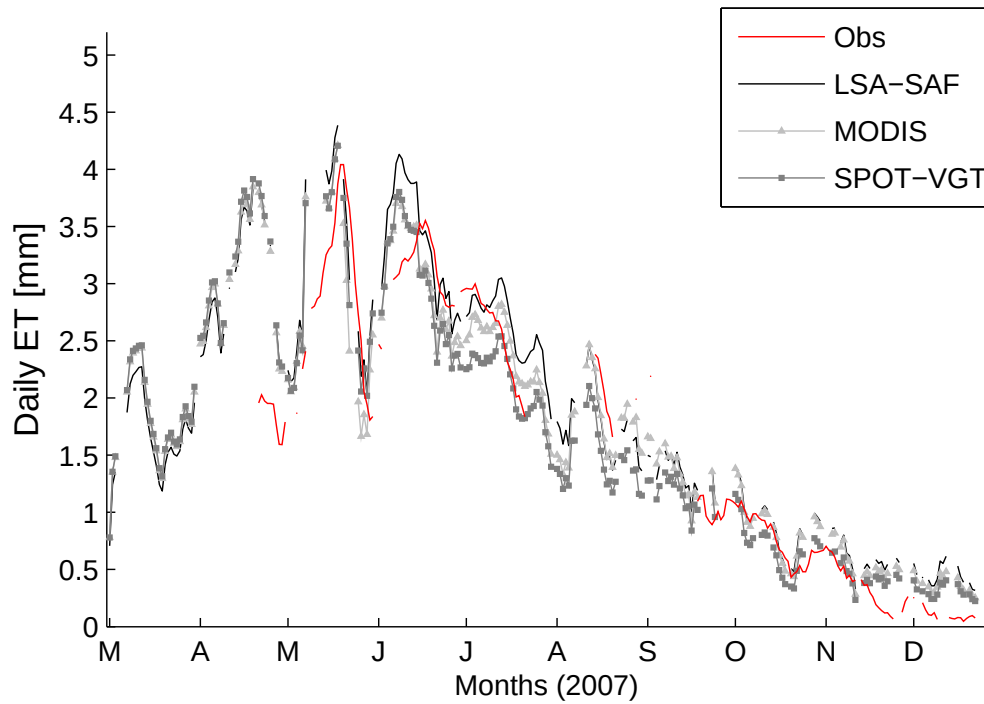


Figure 5.7.: **Comparison of the model daily evapotranspiration to in-situ observation at Roccarespampani site. The control output has been produced using LSA-SAF model V1, and the two other simulations with SPOT-VGT and MODIS LAI respectively. The evapotranspiration estimates are representative of the MSG/SEVIRI pixel encompassing the site.**

albedo. This is an effect of the use of tile albedos in the model, especially caused by the higher albedo found for annual crops, which allows less energy at surface to be used for turbulent transfers with the atmosphere.

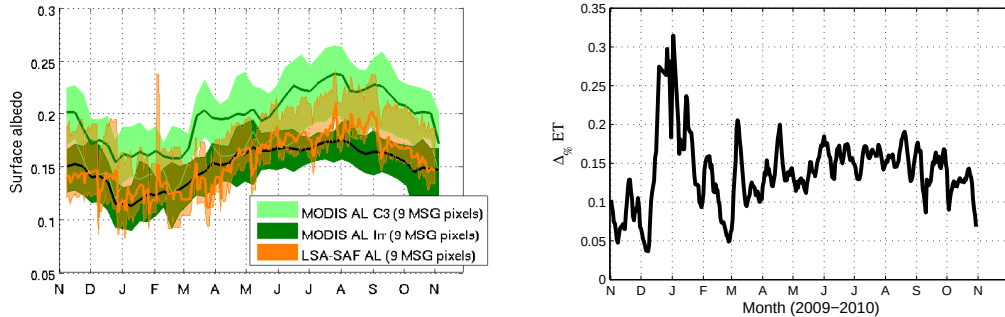


Figure 5.8.: **Surface albedo time series aggregated from MODIS imagery over the test area, and the effect of a vegetation type dependant albedo on the total daily evapotranspiration estimation over the study site. (Left) Surface albedo time series for the test area in Spain for a group of 3×3 MSG/SEVIRI pixels: LSA-SAF albedo (orange), vegetation type MODIS derived albedo (dark green for irrigated (Irr) tile and light green for annual (C3) crops). Albedo for sparse forests (not displayed) is similar to the albedo of irrigated crops. Maximum, minimum and mean area sample are represented. Relative difference between daily evapotranspiration cumulates (5 days sliding average) $\Delta\%ET$ estimated by the LSA-SAF model in its nominal configuration (with the LSA-SAF albedo) and in the variant accepting vegetation aggregated albedo from MODIS. (right)**

5.4.4. Small water bodies and flooded areas detection

The time series of open water bodies fraction obtained from SPOT-VGT and MODIS exhibit similar seasonality for the period from November 2009 to October 2010 (Figure 5.9), with an abrupt apparition of large portions ($\geq 20\%$) of the land surface occupied by water bodies during July, and a progressive evaporation of this water from September to February. The information derived from the 250 m remote sensing data is however more stable, probably due to the the increased size of the sample used for averaging. For both remote sensing resolution, differences in the water bodies percentage are observed for various sizes of the averaging window, showing a higher concentration

of flooded areas centered around the Kelma site. Because of more stable time series derived from the imagery at 250 m, it is recommended to use such data to be input in the evapotranspiration model. The time series of water bodies fraction derived from MODIS data for the same site over the period from June to December 2007 exhibits approximately the same seasonality but characterized by an abrupt increase showing up earlier at the beginning of July and a higher proportion of land flooded during the wet season (Figure 5.10).

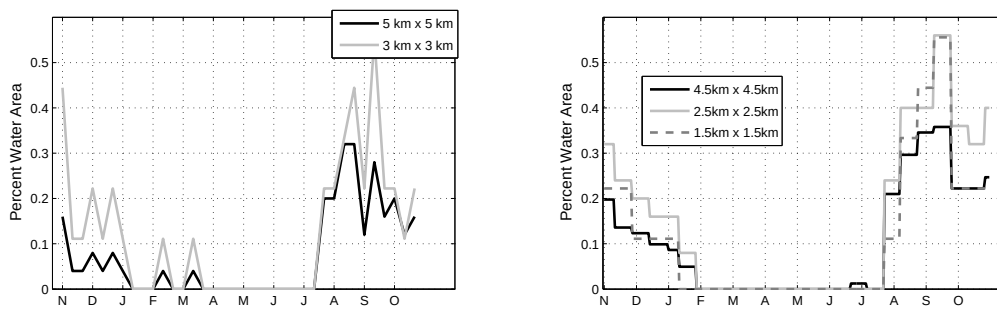


Figure 5.9.: Comparison of the time series of small water bodies fraction cover over the Kelma site as derived from SPOT-VGT and MODIS over November 2009 to October 2010. Time series retrieved from SPOT-VGT NDVI and NDWI using different averaging windows. Time series retrieved from MODIS NDVI and NDWI using different averaging windows.

A comparison between in-situ observation and both simulations using the LSA-SAF model V1 with and without the open water fraction for the period from June to December 2007 has revealed that the evapotranspiration rate is more realistically estimated using the open water fraction derived from high-resolution satellites (Figure 5.10). The fit is especially good for the beginning of the rainy season. A progressive decrease of the modelled evapotranspiration from October to December is in agreement with the decrease in the percentage of water bodies obtained from remote sensing. However, simulation at MSG scale does not necessary fit the exact situation around the in-situ measurement site, that can be affected by a higher percentage of flooded land than prescribed.

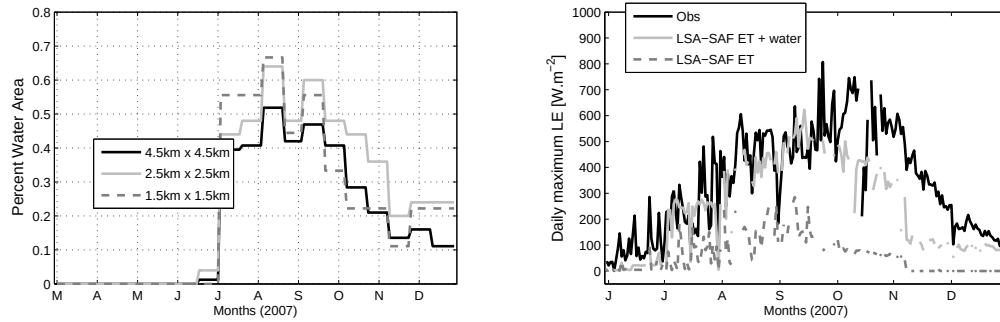


Figure 5.10.: Kelma (Mali): taking into account the time series fraction of open water derived from moderate resolution sensor improves the monitoring of evaporation with the LSA-SAF model. Same as in Figure 5.9, but for 2007. The series at 2.5 km is used for the evapotranspiration estimation. In-situ observations against simulations of latent heat flux from LSA-SAF ET model V1 in its nominal configuration, and using additionally the open water fraction derived from remote sensing.

5.5. Conclusion and perspectives

On the basis of the test cases presented here, we have shown the utility of moderate resolution satellites towards the improvement of the LSA-SAF evapotranspiration products derived from MSG/SEVIRI. In particular, four different variables derived from moderate resolution satellite for vegetation monitoring have been assessed regarding the LSA-SAF ET products. Processes at small scales unresolved by the geostationary satellite are better taken into account in the final ET estimates. The effect is particularly strong for the detection of small seasonal water bodies that allows the model to better capture the observed dynamics. It is still seen but in a lesser extend for land surface albedo, with differences in daily evapotranspiration rates up to 20% in a contrasted site in Southern Spain. However, leaf area index at higher resolution has a minor impact at the investigated site, possibly highlighting a weak dependance of the model in this variable. Effects of the increased spatial resolution of the moderate satellite imagery have been shown to be beneficial for ET estimations, especially for heterogeneous and transition areas. The variables derived from SPOT-VGT are therefore highly expected to be generated from its successor ProbaV in view of the continuous time series it could offer to evapotranspiration models at MSG/SEVIRI resolution.

With respect to spatial resolution from the complementary satellite, it has been highlighted that variables derived at 250 to 500 m improve better the LSA-SAF evapotranspiration than the 1 km derived products do. Evapotranspiration uncertainty due to geolocation errors in the land cover map is reduced when a land cover map at 300 m resolution is used, compared to the map at 1 km. More stable time series of water bodies fraction can be retrieved from 250 m imagery compared to 1 km, and a better recognition of landscape patterns is done at 250 m. This resolution allows an accurate aggregation of the biophysical and surface variables for each vegetation type at MSG/SEVIRI resolution. Consequently, sensors such as ProbaV are expected to be an improvement compared to SPOT-VGT towards the use of their derived data in the LSA-SAF model and land surface models at meso-scale resolutions. As well, an increased spatial resolution of the moderate satellite imagery is expected to be complementary to the future geostationary satellites Meteosat Third Generation which is expected to monitor Europe and Africa at 1 km spatial resolution in replacement of the MSG suite of satellites.

Further work will focus on the applicability of integrating such variables derived from moderate resolution sensors in the LSA-SAF evapotranspiration model with respect to timeliness and long-term continuity for a proper monitoring of ET in near-real time.

6

Monitoring soil moisture with MSG/SEVIRI: model and validation

This chapter is based on: N. Ghilain, A. Arboleda, O. Batelaan, I. F. Trigo & F. Gellens-Meulenberghs (2014), Tracking down soil moisture with MSG/SEVIRI: fulfilling the promises of geostationary satellites, in preparation.

Abstract

Monitoring soil moisture at the Earth's surface is of great importance for drought early warnings. Spaceborne remote sensing is a keystone in monitoring at continental scale, as satellites observe in places scarcely observed by ground-based techniques. Since the last few years, several soil moisture products for continental scale monitoring are available from the main space agencies around the world. Making use of sensors aboard polar satellites sampling in the microwave spectrum, soil moisture can be measured and mapped globally at every few days at a spatial resolution as fine as 25 km. However, complementarity of satellite observations is a crucial issue to improve the quality of the estimations provided. In this context, geostationary satellites and their optical and infrared sensors are useful, as they provide information on the surface from a totally different perspective. In this study, we design a new model for daily soil moisture monitoring based only on the land surface temperature observations derived from the METEOSAT second generation geostationary satellites. Soil moisture has been retrieved from the model for a six years period over Europe and Africa at the SEVIRI sensor variable spatial resolution (3 km in Africa). The results, only available for clear sky conditions, are for the first time extensively evaluated against in-situ observations provided by the International Soil Moisture Network and FLUXNET at sites across Europe and Africa. The soil moisture retrievals have approximately the same accuracy as the soil moisture products derived from microwave sensors, with the most accurate estimations for semi-arid regions of Europe and Africa, and a progressive degradation of the accuracy towards northern latitudes of Europe. Although some possible improvements can be expected by a better use of other products derived from SEVIRI, the new approach developed and assessed here is a valuable alternative to microwave sensors to monitor daily soil moisture at a few kilometers resolutions over entire continents.

6.1. Introduction

Soil moisture at the surface of the Earth affects the everyday lifestyle of many people across the globe. The quantity of water absorbed by the soil surface may drive various meteorological events (Taylor et al., 2012) or natural hazards as floodings (Massari et al., 2013), land slides and droughts, depriving entire populations of their only nutritional resources needing water to yield. Water required to irrigate fields in semi-arid areas impacts the long-term natural resources at regional level and may impact on the local (Gil et al., 2013) to international economics and policy (Turner et al., 2004; Hunsberger et al., 2012).

Previous efforts, materialized by numerical meteorological forecasts, yielded in early estimation of soil moisture at continental scale (Delworth and Manabe, 1988). Yet, observation-based systems can afford a more realistic sketch of the situation without *a priori* knowledge. This aspect is especially important in regions where few ground-based observations are available to confront theory with nature reality. The launch of first Earth-observing satellites into space have brought hopes and promises in characterizing and following the Earth natural resources (Macauley, 2009), especially water (Koster et al., 1999). Sensors aboard polar orbiting satellites have first been intensively challenged for soil moisture retrieval (Njoku and Entekhabi, 1996), with the most successful stories leading to near-real time follow-ups at global scale down to 25 km independently from the weather type with micro-wave sensors (Njoku et al., 2003; Bartalis et al., 2007; Owe et al., 2008), with a revisiting time of one or two passages a day. Alternatively, geostationary satellites, initially designed for weather forecasting, have long been discarded from this research effort. However, the imagery in the visible and infra-red spectra covers whole continents at a few kilometers resolutions in less than an hour and is potentially powerful in detecting rapid changes of the land surface (Chesters, 1998), reducing the noise by bringing a wealth of observations every day. The SEVIRI instruments onboard the european Meteosat Second Generation satellites provide 96 images per day in the infra-red spectral bands, providing a detailed information on the sub-daily variations of the atmosphere and the surface.

Information from the infrared spectral channels of sensors can be converted to a physical land surface temperature (Wan and Dozier, 1996). From the early 1980s, the

thermal inertia concept, consisting of a linking the amplitude of the surface heating over a day with the quantity of water present in the soil, has been applied to space-based observations (Price, 1980; Gillies and Carlson, 1995). Minor and uncertain to more confirmed successes have been first reported on local to regional studies (Wagner et al., 2007; Garcia et al., 2014; Zhao and Li, 2013; Song et al., 2013; Leng et al., 2014), and though most studies based on thermal inertia show its interest and potential for soil moisture monitoring, the success of this measurement methodology has not be quantified over large datasets so far. With the increasing interest on dynamical water resources assessment, new international initiatives (Dorigo et al., 2011) have brought a wealth of soil moisture ground-based observations to the public through a unique internet-based platform, otherwise locally managed, pushing forward model developments and remote sensing validation exercises. With these new opportunities, and bringing the pieces together, we applied a new method based on the thermal inertia concept and the SEVIRI sensor data on European and African continents over a six years period (2007-2012). Its success could be quantified in an extensive sample of climate zones, therefore filling the gap left by other studies on thermal inertia by providing quantitative information regarding its accuracy and performance against in-situ ground measurements in a large panel of conditions.

Thanks to its unprecedented temporal and spatial observation rate, the SEVIRI instrument allows an accurate estimation of the daily surface heating rates, giving way to a well-sampled tracking of soil moisture, by clear sky weather over semi-arid areas. In this paper, we present first the new approach of the thermal inertia model. Then, to characterize the accuracy of the resulting soil moisture time series, we present the comparison to in situ local ground measurements and discuss the limitations of both the method and the data.

6.2. Model and data

6.2.1. Model

There is a strong evidence of the impact of soil moisture on the land surface temperature (LST) and several attempts have been carried out to derive soil moisture from thermal imagery on various landscapes, at different scales and spatial resolutions. In most studies, at least two polar satellites passes are used to derive a soil moisture index based on land surface temperature. While polar orbiters offer the possibility of global data coverage, it is usually used for local applications, and is still imprecise because of the relatively low frequency of acquired data and the possibility of inefficient cloud screening or atmospheric correction. Geostationary satellites offer an interesting alternative to polar satellite because of their high temporal sampling rate. A first attempt has been made to derive a soil moisture index from thermal inertia concept and MSG/SEVIRI satellite over various forested sites across Europe (Verstraeten et al., 2006) (referred as V2006). The methodology proposed in V2006 is fairly simple and easily applicable, but does not exploit the full capabilities of the satellite, as it only uses two observations per day, as would be the case for a system of one sun-synchronous polar orbiter like MODIS/Terra or Aqua. The methodology has been further examined in Van Doninck et al. (2011), where reconstructed LST signal from MODIS suite of satellites was used over Southern Africa and also more recently by Garcia et al. (2014) with MSG/SEVIRI data over two sites in Mali and Southern Spain. It has been shown that a more robust estimate could be obtained by using a full morning dataset of LST, as Stisen et al. (2008) showed for evaporative fraction from the same satellite. The present derivation has been built upon those previous studies to set up a new simple model to retrieve a soil moisture index from a single input variable, the MSG/SEVIRI LST produced by the Land Surface Analysis Satellite Application Facility (LSA-SAF) (Trigo et al., 2011).

In the present study, we compute morning surface heating rates through linear regression on LST data between local dawn and noon, excluding one hour on each side of the time series. Verstraeten et al. (2006); Van Doninck et al. (2011); Garcia et al. (2014) showed that a surface submitted to the same water stress exhibits higher amplitude of LST diurnal cycle under high insulation than under low one. Therefore, the daily amplitude

of the LST signal is normalized by an astronomical factor accounting for seasonality in sun zenithal angle. This is also supported by Prigent et al. (2005): they normalize LST amplitudes with incoming solar radiation. Here, because we derive heating rates, no normalization is needed. An error bar is calculated indicating the goodness of the linear fit. A poor linear fit can find its roots in a change of atmospheric conditions within the sampling period, a systematically poor cloud masking, or a rain event occurring during the period.

Because higher heating rates tend to appear in water stress affected regions, the signal is generally anti-correlated to the soil moisture. A linear relation between soil moisture and thermal inertia is usually assumed. However, no evidence of that linearity has been provided over a large set of conditions. A series of adaptations have therefore been brought to the original model to account for the behaviour of the signal locally observed. From pairing in-situ daily soil moisture measurements with daily heating rates, the relation is assumed being nonlinear, but increasingly sensitive to variations towards low soil moisture contents. In such conditions, a clear influence of the wind speed and aerosol load on the signal is perceived for sparsely vegetated areas. For such regions, an asymmetry of heating rates is observed before and after the rainy season, due to differences in surface characteristics (Samain et al., 2008), or aerosol load.

We applied the following function to derive a soil moisture (SM) index from MSG/SEVIRI daily surface heating rates (HR), where Max and Min are respectively the maximum and minimum of HR time series for a given location, and the two coefficient have been chosen to fit the exponential expression into 0 to 1 bounds. The factor 1.5 provides a curvature to the relation to allow a smaller variability of soil moisture index in function of variations of HR . In a first step, the soil moisture is modelled as in Eq. 6.1, where $C1=1.5$, $C2=-0.22$ and $C3=1.282$. Max and Min are determined pixelwise as the value corresponding to respectively 97% and 3% of the cumulative distribution function of the pixel heating rates over one year. Because full variability of soil moisture between the wilting point (pwp) and the field capacity (fc) is assumed if the series is sufficiently long, the extrema could be set to fc and pwp , as proposed by V2006.

$$SM_{step1} = C3.(\exp\left(C1.\frac{HR - HR_{min}}{HR_{max} - HR_{min}}\right) + C2) \quad (6.1)$$

This formulation allows more variability for moderate to full soil moisture contents and tends to constrain the lower values. At last, because of day-to-day variability of the thermal inertia making the time series instable at some periods (Van Doninck et al., 2011), a running exponential filter over the previous 30 days, with a characteristic time $T = 3$ days (Eq. 6.2), and a sliding average of 5 days are applied to smoothen the signal, with moderate loss of day-to-day information.

$$SM_{step2}(t_n) = \frac{\sum_{i=n-30}^n SM(t_i) \cdot e^{-\left(\frac{t_n-t_i}{T}\right)}}{\sum_{i=n-30}^n e^{-\left(\frac{t_n-t_i}{T}\right)}} \quad (6.2)$$

A correction in our model has been applied for Northern Europe to take into account variations in latitude and day of the year. The inclusion of this correction for latitudes above 40°N forces the signal to exhibit a larger soil moisture in winter, which is not seen without the correction.

6.2.2. Remote sensing data

Input variables

The necessary input variables are derived from data acquired by the Spinning Enhanced Visible and Infrared Imager (SEVIRI) sensor onboard Meteosat Second Generation (MSG). The land surface temperature (LST) and the leaf area index (LAI) are produced in near-real time by the Satellite Application Facility on Land Surface Analysis, LSA-SAF (Trigo et al., 2011), over the entire SEVIRI field of view, which covers Europe, Africa, Middle East and South America. The finest resampled spatial resolution of 3.1 km is found over equatorial Africa.

The LST is produced every 15 minutes based on a split-window algorithm using two spectral channels 10.8 and 12.0 μm (Trigo et al., 2008) of the SEVIRI instrument. The reported accuracy from comparison over selected locations in Portugal, Senegal, and Namibia, is of the order of 1.7 to 2.7 K, with a bias generally less than 1 K (Freitas et al., 2010; Göttsche, 2013).

The leaf area index is estimated on a daily basis. LAI is directly deduced through an exponential relation taking into account the geometry of the surface elements and leaves orientation from the fractional vegetation cover. The latter one is retrieved from the satellite data using a two components spectral mixture analysis (García-Haro et al., 2005a).

Both variables are provided with uncertainty bars and a quality indicator reflecting the state of the input data or the nature of the surface.

6.2.3. In-situ data

Datasets have been acquired for 5 yearly periods: 2007 from March to December, 2008, 2009, 2010 and 2011 across Europe and Africa. (Half-)hourly measurements of soil moisture at a depth of 2, 5, 10 or 30 cm have been made available from CarboEurope, CarboAfrica, AMMA, SMOSMANIA, REMEDHUS, HOBE, UMSUOL, CALABRIA, PERUGIA, VAS, UMBRIA and UDC-SMOS networks, with 121 station-years in total, sampling Spain, Portugal, Italy, France, Denmark, Mali, Niger, Sudan, Germany. In-situ set-ups intent to provide local observations of soil moisture under various land uses (coniferous, broadleaf or mixed forests, grasslands, croplands, wetlands, savannahs) submitted to a large range of climatic regimes. Sites considered for the validation are given in Table 6.1, with complementary information about their geographical location and the ground measurement depth. All measurements have been collected using various in-situ observations techniques, among them mostly TDR (see Albergel et al. (2012) for an overview of the various experimental set-ups).

Each time series has been rescaled between a permanent wilting point of $0.171 \text{ m}^3.\text{m}^{-3}$ and a field capacity of $0.323 \text{ m}^3.\text{m}^{-3}$, which corresponds to an average for different soil textures (van den Hurk et al., 2000).

6.3. Validation methodology

The time series of daily soil moisture derived from remote sensing have been compared to daily averaged local surface soil moisture measurements. Normalized time series are

Table 6.1.: **In-situ soil moisture datasets used in this study.**

Soil moisture dataset	Soil layer depth (cm)	Number of stations	Years
AMMA (West Africa)	5	7	2007-2009
REMEDHUS (Spain)	5	21	2007, 2010
UMSUOL (Italy)	10	1	2010
UDC-SMOS (Germany)	5	7	2010
CALABRIA (Italy)	30	4	2010
Hydrol-Net-Perugia (Italy)	5	2	2010
UMBRIA (Italy)	5-15	3	2010
VAS (Spain)	0-5	1	2010
HOBE (Denmark)	0-5	18	2010
CarboItaly (Italy)	2	2	2007, 2010, 2011
CarboEurope (Spain & Portugal)	0-5	2	2007, 2010, 2011
CarboEurope (France)	2	2	2007, 2010, 2011
SMOSMANIA (France)	5	12	2007, 2010
SMOSMANIA-E (France)	5	9	2010
CarboAfrica	0-5	1	2007-2009

compared to time collocated daily averaged surface soil moisture data. The statistical scores, the standard deviation of both observations and remote sensing retrieval, the root mean square difference between both datasets (RMSD, Eq. 6.3), the bias (in-situ minus satellite) and the correlation coefficient (R, Eq. 6.4), have been calculated for each time series (Albergel et al., 2012).

$$RMSD = \sqrt{(\overline{SM_{MSG}} - \overline{SM_{in-situ}})^2} \quad (6.3)$$

$$R = \sqrt{1 - \frac{\sum (SM_{MSG} - \overline{SM_{in-situ}})^2}{\sum (SM_{MSG} - \overline{SM_{MSG}})^2}} \quad (6.4)$$

A synthesis of the statistical scores is presented in a Taylor diagram (Taylor, 2001), which allows both a quantitative evaluation of per-time series comparison and a visual interpretation of how the site specific scores compare to each other. It requires the standard deviations from all retrievals to be normalized by the standard deviation by each individual in-situ dataset. Visually, the distance between the observation and the retrieval point gives the relative performance compared to other points: the closer, the

better. The normalized standard deviation (SDV) indicates if the remote sensing based retrieval can reproduce the locally observed variability: underestimated if less than 1, overestimated otherwise. The correlation coefficient indicates the match in the temporal evolution of the soil moisture, at both diurnal and seasonal scales: 1 is perfect match. The RMSD indicates the correspondence in the short term fluctuations of soil moisture index, in other words the dispersion of the results, with the mean bias removed. In-situ data are represented by a point on the x axis at $R = 1$ and $SDV = 1$, every single time series comparison is displayed in polar coordinates.

6.4. Results

The comparison of surface soil moisture time series confirms that the remote sensing data and model are well adapted to reproduced the observed signal during clear sky conditions, especially in regions where vegetation is experiencing water stress. Seasonal cycles and short-term fluctuations are very well reproduced over arid to semi-arid areas of Spain and Africa, while the signal is a bit more noisy and less correlated for temperate sites of Southern France, and clearly noisy for northern latitudes (Figure 6.1). The retrieved signal is discontinuous at african sites, mostly during the wet season, and at temperate sites throughout the year because of rain events. For the temperate sites, the retrieved soil moisture captures the dry spells and wet events, however the signal is not very well matching the observed amplitude over most SMOSMANIA sites during summer, eg. St Felix, possibly due to intensive irrigation in the region. For the site in Germany, the estimations are less accurate and sparser, a summertime dry spell is correctly retrieved from the satellite information, but another one in Spring is not detected in the local measured soil moisture. For Spain, soil moisture is globally well retrieved compared to in-situ observations. For sites in Africa, the seasonal course is well reproduced, apart from isolated apparent wet events, eg. in Wankama, which corresponds to a deficient dust storm screening in the LST retrieval.

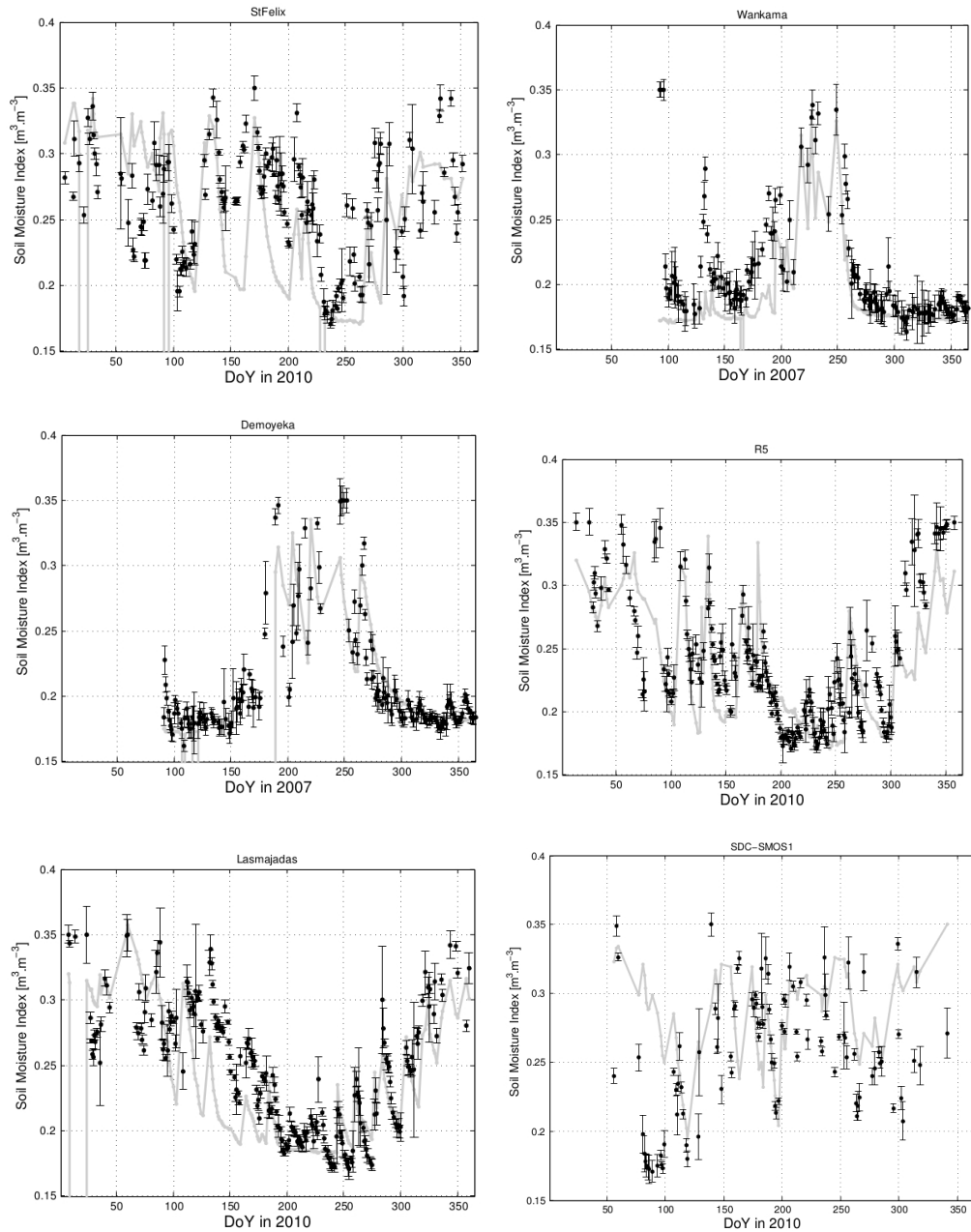


Figure 6.1.: Comparison of daily surface soil moisture retrieved from MSG/SEVIRI LST (black) and measured locally (grey), for a set of 6 sites from different networks: St Felix (France, SMOS-MANIA), Wankama (Niger, AMMA), Demoyeka (Sudan, CarboAfrica), Guarena (Spain, REMEDHUS), Las Majadas del Tietar (Spain, CarboEurope), Engersdorf (Germany, UDC-SMOS) (from top left to bottom right).

The statistical scores for each yearly dataset grouped in averages by network are provided in Table 6.4, and additional information about the number of daily observations

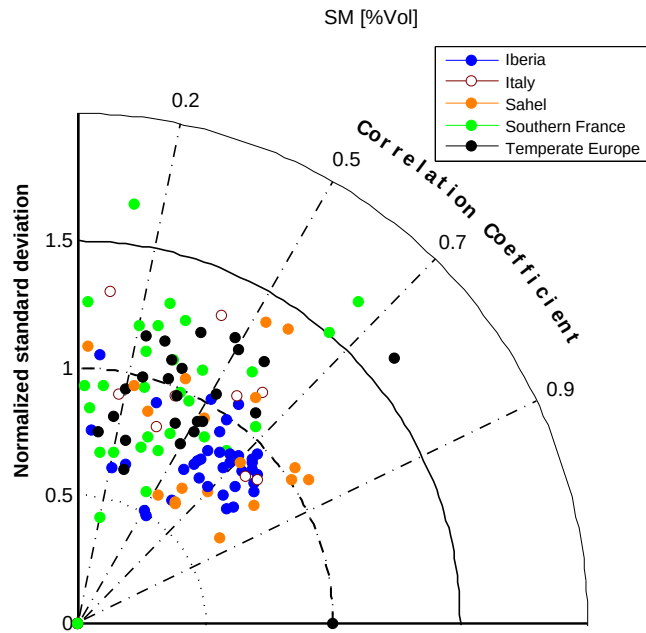


Figure 6.2.: **Statistical scores of the comparison between local observations and LSASAF derived soil moisture, presented in a Taylor diagram. Each colored point represents the comparison for a set of data at a in-situ validation site. Codes of colour indicate the network which the data belong to (left), or a country (right)**

used. This latter information reflects both the availability of the soil moisture retrieved from the satellite and availability of local observations. Correlations for Sahelian and Iberian sites are between 0.5 and 0.8. Retrieval over Southern France are less correlated to in-situ data ($0.1 < R < 0.7$) and over Denmark and Germany, the correlation is no higher than 0.6. Retrievals are mostly unbiased, and present a variability comparable to observations.

As in Albergel et al. (2012), the correlations (R) are classified by network into 4 quality classes: Inadequate ($R < 0.2$), Poor ($0.2 < R < 0.5$), Fair ($0.5 < R < 0.7$) and Good ($0.7 < R$). In addition, statistical scores are given by country, all networks together. For France, the networks are SMOSMANIA, SMOSMANIA-E, and CarboEurope. For Italy, CarboEurope, UMSUOL, Perugia, Umbria, Calabria. For Iberia, CarboEurope, VAS, REMEDHUS. Temperate Europe encompasses networks over Northern France (CarboEurope), Germany (UDC-SMOS) and Denmark (HOBE). Negative correlations

Table 6.2.: For each network, the average statistical scores of the comparison between the satellite retrievals and the in-situ observations shows the geographical variability of the performance of the developed retrieval strategy. The retrievals are the most accurate over the Mediterranean region and Sahel, and less correlated to soil moisture observations in temperate Europe.

Datasets	Correlation [-]	Bias [-]	RMSD [-]	# obs./year
SMOSMANIA	0.33	0.028	0.054	119
SMOSMANIA-E	0.30	0.019	0.058	77
AMMA	0.59	0.014	0.037	107
CarboAfrica	0.62	0.003	0.032	134
REMEDHUS	0.60	0.018	0.044	144
CarboEurope Spain & Portugal	0.77	0.028	0.035	168
CALABRIA, UMBRIA, PERUGIA, CarboItaly	0.52	0.013	0.038	58
UDC-SMOS	0.47	0.017	0.049	57
HOBE	0.40	0.022	0.049	40

have been discarded of the statistics and plots: they usually corresponds to datasets with very few observations or with unexpected jumps.

Highest scores are found in semi-arid and arid areas with a strong annual cycle in the precipitation regime. Less high correlations are found in Southern France and in Italy, where results are more scattered, and low correlations are found in temperate Europe, where annual variability of soil moisture is not dominated by an annual cycle. This result is not in agreement with the findings of Verstraeten et al. (2006), where high correlations were found for european forested sites, average correlation of 0.556, during the growing season 1997. Possible explanations for this decrease of correlation for temperate Europe can be a less accurate retrieval of land surface temperature due to a large viewing angle of the surface and associated problems (a long optical path through the atmosphere leading to a weakened signal from the surface compared to noise generated by atmospheric motion, azimuthal anisotropy effects) and to a decreased contrast in the thermal infrared signal in the presence of denser vegetation covers, that, for Europe, globally increases with latitude.

Compared to the results of Prigent et al. (2005), higher correlations have been found in the present study, that can be attributed either to the modifications of the model or to the selected regions. The application of V2006 model with MODIS data by Veroustraete

et al. (2012) revealed correlations varying between 0.173 and 0.848 with an average of 0.560 against TDR observations at six sites in China at 1 m depth. In a recent study (Zhao and Li, 2013), low correlation between a soil moisture index from SEVIRI and local observations has been found at the REMEDHUS network comparatively to what we obtain, showing the interest of the new model.

Scores are similar to results obtained with ASCAT and SMOS products for various networks (Albergel et al., 2012). We obtain higher correlations for REMEDHUS, HOBE, UDC-SMOS, but lower correlations for the SMOSMANIA sites.

Table 6.3.: Correlations between in-situ soil moisture and the LSASAF derived index. For each network and country, the correlation values are ranked as: Inadequate, Poor, Fair, Good.

Soil moisture dataset	Number Site-years	Inadequate (%) R < 0.2	Poor (%) 0.2 < R < 0.5	Fair (%) 0.5 < R < 0.7	Good (%) R > 0.7
SMOSMANIA	20	25	60	15	0
SMOSMANIA-E	8	25	50	25	0
AMMA, CarboAfrica	19	5	16	42	37
REMEDHUS	32	3	9	60	28
UMSUOL	6	33	17	17	33
CarboEurope	8	12.5	50	12.5	25
UDC-SMOS	5	0	80	20	0
HOBE	18	17	44.5	33.5	5
(All networks)					
South France	29	24	55	21	0
Sahel	19	5.25	15.75	42	37
Italy	9	22	33.5	22.5	22
Iberia	36	5.5	8.25	53	33.25
Temperate	24	12.5	54.33	29.33	4.33

Finally, the correlation coefficients are mapped for a spatial interpretation of the results (Figure 6.3). For the readability of the figure, we have made an average on 5x5 pixels and over the successive years, removing dubious observations. The retrieval correlates best with in-situ measurements over Southern Europe. Still good correlations are found in sub-saharian regions of Africa. However, the correlation decreases with increasing latitude in Europe, as a result of both a limitation of the methodology to capture the soil moisture variability in temperate regions and the reduced number of retrieval used for the statistics.

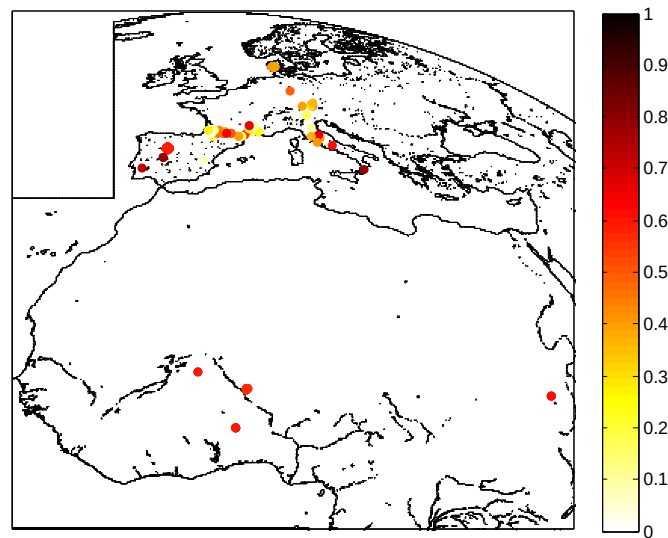


Figure 6.3.: **Spatial distribution of the correlation of the remote sensing soil moisture index with local in-situ observations.**

6.5. Discussion

The availability of retrievals, the comparison with other studies and the limitations of the data/methodology need discussion.

6.5.1. Limitation of the validation strategy: spatial scale issue

It is clear that the mismatch between local observations and retrieval from satellite data can be partly attributed to the different spatial scales of the observations and remote sensing data (Crow et al., 2012). Though this issue has not been considered in Albergel et al. (2012), higher correlation between coarser scale soil moisture retrieval and local observations can be found if the local nature of the surface corresponds to the coarse pixel. However, better correlations could probably be obtained if we had taken into account the heterogeneity of the vegetation within a MSG/SEVIRI pixel and applied a downscaling scheme. V2006 argues that NDVI can be considered as a proxy for soil moisture and that it can be used to downscale the soil moisture of the pixel to the specific patch observed in-situ following a linear relation. However, though indicative, there is no

proof of the linear relation between both indicators. NDVI can however help in the spatial interpretation of the results in critical zones, especially subject to irrigation practice.

Time series are shown at two sites (Figure 6.4): Sabrès in France and one of the REMEDHUS stations in Spain. At both locations, irrigation occurs, as can be identified by high contrasts in MODIS NDVI values for the first decade of July 2007. At Sabrès, high soil moisture is found in the soil moisture index retrieved from MSG SEVIRI data during the period 20 June to 20 August in accordance with the irrigation timing of the dominant maize cropping (INRA report). On the REMEDHUS site, the irrigated crop does not cover a large area in comparison to the MSG pixel, and irrigation is not detected with the remote sensing technique. This proves the limitation of the validation exercise based only on statistical scores against in-situ point observations, but show that the performances are expected to be much higher than found for heterogeneous landscapes.

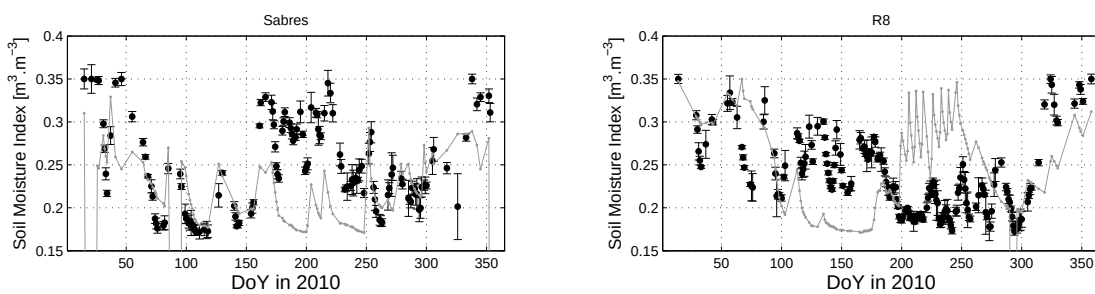


Figure 6.4.: **The quality of sites representativity within the SEVIRI pixel affects the statistical results obtained. (Left) In Sabrès, soil moisture retrievals from SEVIRI (black) compares well with ground observations (grey) except in Summer: intensive irrigation is detected, while the ground observation are taken at a non-irrigated site. (Right) Ground observations from one REMEDHUS site are taken on one irrigated parcel. However, the irrigated fields are too small to be detected by SEVIRI.**

6.5.2. Limitations for soil moisture retrieval from MSG SEVIRI

The method used to retrieve daily soil moisture index has several limitations, related to the nature of the surface, and the composition of the local atmosphere, as most remote sensing data for surface analysis from space do. A dense vegetation cover will probably screen the signal, daily retrieval is not possible for cloudy situations, while transport of

dust by wind induces wrong estimations if not properly accounted for. Those two last factors are discussed here to give an insight on limitations.

Availability of retrievals Compared to retrievals from microwave sensors aboard polar satellites, the proposed method has the advantage of being based on high repetition rate data at spatial resolution of 3 to 5 km. However, no information on the surface can be retrieved in cloudy sky situations, contrarily to microwave sensors such as ASCAT onboard MetOp satellites. This inherent limitation due to the observing system affects the use of the retrieval for continuous monitoring of the soil moisture. We have analyzed for each year (2007 to 2010) the proportion of days that were sampled with a sufficient accuracy by the retrieval algorithm, and averaged it over the four years for four three months periods, DJF (December-January-February), MAM (March-April-May), JJA (June-July-August) and SON (September-October-November) in Figure 6.5. This analysis reveals that most temperate Europe is sampled less than 10% during winter. Over most of the African continent, the availability varies between 90% during the dry season and down to 40% during the rain season. The Western coast of central Africa could be only sampled up to 50% due to almost constant cloud coverage even during the dry season (Grandcourt, pers. com.).

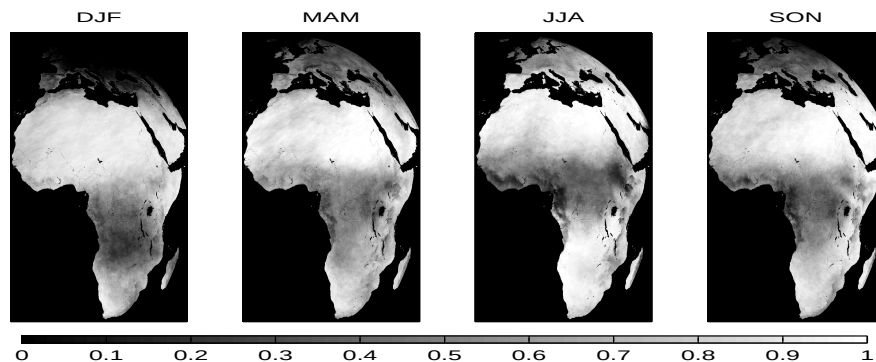


Figure 6.5.: **Tri-monthly availability of daily soil moisture retrieval averaged over 4 years. Cloud cover affects the number of available retrieval, especially over the equator and during winter over Europe. Sahelian regions are well sampled.**

Aerosol loads During the annual dry period over Sahel and Sahara desert, apparent wet events are seen in the soil moisture index retrieved from remote sensing. However,

such events are not supported by local observations of soil moisture. Those apparent wet peaks are due to sand/dust storms releasing dust particles in the cooler air above the surface misleading the land surface temperature interpretation of the surface. In Figure 6.6, an example of an apparent wet event associated to dust presence in the atmosphere is shown for the 19 February 2008. According to Ben-Ami et al. (2010), this released dust was a result of two consecutive days of active emission from the Bodélé depression in Saharian desert, with possible mixing with wild fires. Therefore, problems can occur when a change in the aerosol optical depth is not properly taken into account in the atmospheric correction of the land surface temperature. This is particularly relevant during the agricultural and wild fire season. A proper screening of those retrievals should be conducted with the help of a dedicated aerosol product derived from satellites.

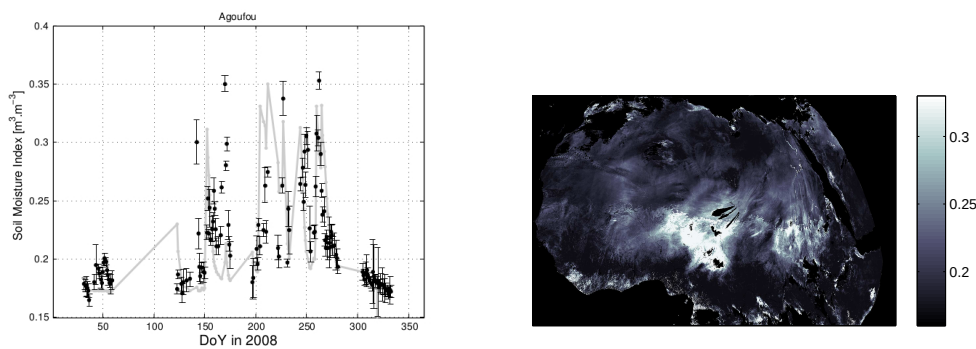


Figure 6.6.: **Soil moisture retrievals from land surface temperature evolution are affected by high atmospheric aerosol loads, especially from mineral dust particles. (Left) In Agoufou, the aerosol load tends to increase as the dry season evolves. It is erroneously perceived by the soil moisture retrieval as a wetter evolution. (Right) Soil moisture retrieved over Africa for 19 February 2008 displays an anomalously large wet area in Sahara. Again, this misinterpretation can be explained by a combination of a large dust storm originating from the Bodele depression and sweeping across the region and local fire emissions. Future available products from EUMETSAT are expected to improve the soil moisture retrievals in the future.**

6.6. Conclusion

Daily soil moisture has been derived from land surface temperature data derived from the SEVIRI sensor aboard the geostationary satellite MSG over Europe and Africa for a six years period, from 2007 to 2012. The method relies on the local morning heating rates of the land surface based on the 15 minutes data provided by the Satellite Application Facility on Land Surface Analysis, and is designed to produce it with less than 1 day delay over clear sky conditions. A thorough quantitative validation of the retrieved soil moisture against in-situ daily averaged ground measurements over 121 site-years across Europe and Africa shows correlation scores as high as 0.85 in semi-arid to arid areas (Sahel, Spain, Portugal). Seasonal behaviour, as well as day-to-day variations, are well reproduced. Despite no statistical evidence with in-situ observations due to spatial scale mismatch, irrigated areas and wetlands dynamics are observed. Relatively low correlations are obtained over temperate regions, with correlations between 0.0274 and 0.77. Limitations are found over dense vegetation cover, where the noise/signal ratio is significant, and in arid areas during dust storms or increase of the aerosol load in the atmosphere.

This methodology is recommended to derive daily surface soil moisture at the MSG SEVIRI spatial resolution of 3.1 km over Africa and Southern Europe, and can potentially be applied to other geostationary satellites to cover other continents. It is expected to be useful in applications needing global view of soil moisture state every day to be assimilated by models, especially in regions where in-situ data are scarce and if details about the surface is needed, as for example irrigation. Since this observation technique is only valid for clear sky conditions, other sources of soil moisture data can potentially complement the information provided by thermal inertia to provide an all-weather daily monitoring of soil moisture.

7

Evapotranspiration monitoring in semi-arid areas using MSG/SEVIRI derived data: improvements from the use of leaf area index and land surface temperature

This chapter is based on N. Ghilain, A. Arboleda & F. Gellens-Meulenberghs (2013), Evapotranspiration monitoring in semi-arid areas using MSG/SEVIRI derived data: improvements from the use of leaf area index and land surface temperature, Proceedings of the 2013 EUMETSAT's user conference.

Abstract

Water resource is a major concern for sustainable development in many semi-arid areas. Early detection of drought and monitoring water consumption by agriculture are highly important for adaptation in water use regional policy. As a crucial component of the water cycle, land evapotranspiration is a primary source of information for such water resources assessments, and remote sensing from geostationary satellites offers the possibility to monitor it over large areas at relatively high temporal and spatial resolutions. The Satellite Application Facility on Land Surface Analysis (LSA-SAF) of EUMETSAT proposes an operational evapotranspiration product based on radiation components (surface short and longwave incoming radiation and albedo) derived from the SEVIRI instrument of the Meteosat Second Generation (MSG). Previous validation studies had shown its success for temperate and moist regions, while semi-arid and arid areas of Africa had been shown to be more prone to model errors. In this contribution, we show that the use of the land surface temperature and leaf area index derived from MSG/SEVIRI improves the evapotranspiration monitoring over semi-arid areas of Europe and Africa. The vegetation dynamics and status of the soil water content available for the process are better represented in the model leading to more accurate results. Statistical comparisons between the current operational LSA-SAF evapotranspiration product from EUMETSAT and in-situ measurements are given to demonstrate the benefits from using new input data derived from the satellite. An updated algorithm incorporating those improvements should be integrated soon into the LSA-SAF operational production.

7.1. Introduction

Drought is a major disaster affecting regions relying on natural occurrence of rain for food production. It causes a serious decrease in crop productivity, leading to lack of food, in livestock and in direct accessibility to water for local communities. National and international actions can only be taken if warned in due time, especially if early warnings are issued. In setting up such service, experts must know very accurately the different water gains and losses. An important loss of water from land is the water vapour released into the atmosphere, by plant transpiration and evaporation from the soil.

While wide networks of towers have been installed to observe evapotranspiration from the ground, no real-time quality controlled monitoring can be achieved with a good spatial coverage. Instead, models, like global circulation models, can estimate it, but are prone to fail in regions with no or sparse observations because of parameterization deficiencies. Remote sensing from spaceborn sensors is one valuable option, especially aboard geostationary satellites, because of its wide sensing view (several continents) in a short time (5 to 15 minutes), with a spatial resolution of 3 to 5 km.

An evapotranspiration algorithm has been implemented in the operational framework of EUMETSAT Satellite Application Facility on Land Surface Analysis (LSA-SAF) (Trigo et al., 2011), which produces variables related to land surface from the SEVIRI sensor aboard the Meteosat Second Generation satellites (view figure 1 for a sketch of the different variables derived). The implemented evapotranspiration algorithm is largely based on the ECMWF land surface scheme (van den Hurk et al., 2000), without any derivation of the soil variables evolution. Specific parameterizations have been added to work at the resolution of SEVIRI sensor, and several modifications have been applied to the original scheme (Ghilain et al., 2011). The model is forced by radiation components produced by LSA-SAF, vegetation state provided by a customized database based on ECOCLIMAP (Masson et al., 2003), meteorological fields (surface air temperature, air humidity, wind speed) and soil moisture provided by the short-term forecasts of the ECMWF global atmospheric model.

The operational LSA-SAF system produces in near-real time every half-hour evapotranspiration estimates at continental scale over the field of view of SEVIRI sensor. This product and its derivative, the daily cumulated product, have been in operation for

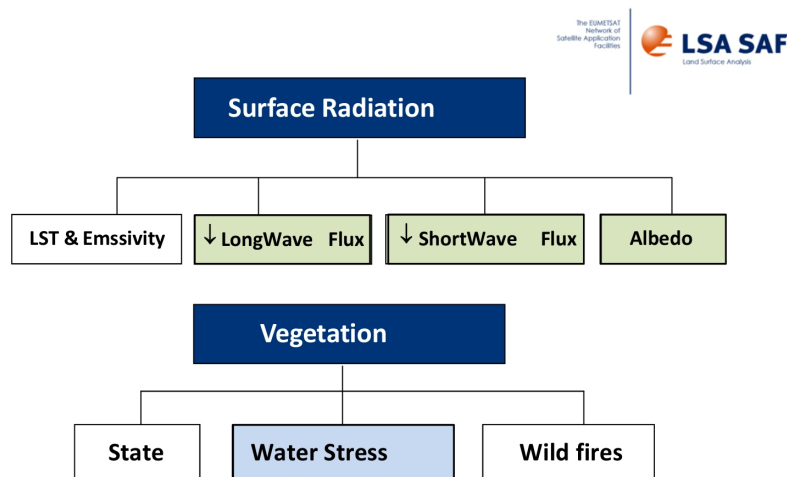


Figure 7.1.: **The evapotranspiration is one of the variables derived from SEVIRI aboard MSG satellites in the context of the EUMETSAT's LSA-SAF service. In this schematic view, evapotranspiration is part of the vegetation/water stress component. The operational algorithm makes use of three radiation components, the albedo, the short/long- wave downward radiations. In this study, we have added the vegetation state, leaf area index, and the land surface temperature.**

4 years, disseminating the information among the user community, targeted mainly as drought warning services.

However, while its accuracy has been demonstrated over temperate regions of Europe (Ghilain et al., 2011) and could be used for an early application of drought monitoring over Europe (Sepulcre-Canto, 2013), the product obviously suffers from deficiencies, particularly in semi-arid areas with lower correlation scores with ground observations and an underestimated annual variability (results presented in a Taylor diagram (Taylor, 2001) in Figure 7.2). Those deficiencies have been attributed to inadequate forcing, related to vegetation, the main medium through which the transpiration process occurs, and soil water availability. Correcting those drawbacks could help a better drought monitoring in view to issue early warnings and prevent as much as possible damages.

In this contribution, we briefly show the improvements of the results in ingesting leaf area index and land surface temperature into the evapotranspiration model of the LSA-SAF. We have proceeded step-by-step, ingesting first the vegetation component, then

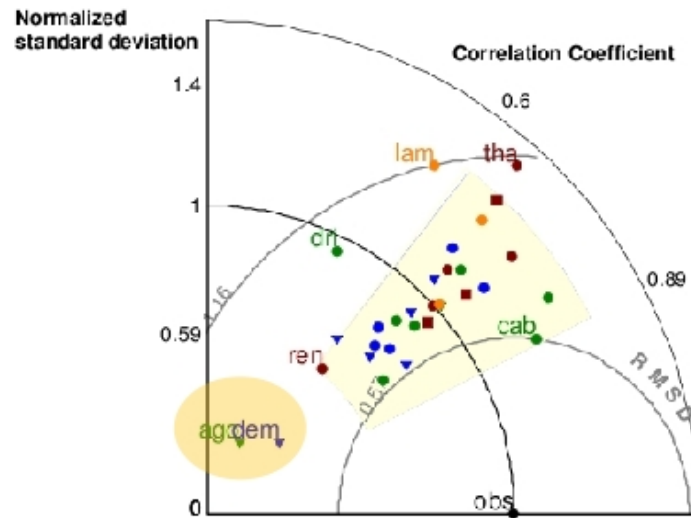


Figure 7.2.: The LSA-SAF evapotranspiration product is in good agreement with ground observations for temperate regions of Europe, especially over grasslands. However, it disagrees at semi-arid sites, especially in Africa (elliptical shaded area), uncovering some model deficiencies linked to vegetation or/and soil moisture in those regions.

adding the information derived daily from land surface temperature.

7.2. Improvements from leaf area index

Leaf Area Index 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 leaf area index used in this context is produced daily by LSA-SAF at a spatial resolution of a few kilometres in the SEVIRI projection. 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 inter-annual variability of the vegetation health and productivity. Those are expected to bring a clear improvement to the evapotranspiration model, as its vegetation information was monthly varying, based on past data and not varying from year to year.

After having implemented the change from ECOCLIMAP customized database to the LSA-SAF LAI (Ghilain et al., 2012) for use in a modified version of the evapotranspiration algorithm, we have reprocessed archives for the year 2007 over Europe and Africa (more details about the implementation of input and algorithmic changes in the annex C). The result of the comparison between the new version and ground observations shows a clear improvement over semi-arid areas especially in Europe: correlation scores have been improved, and variability is comparable to the observations (Figure 7.3). 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.

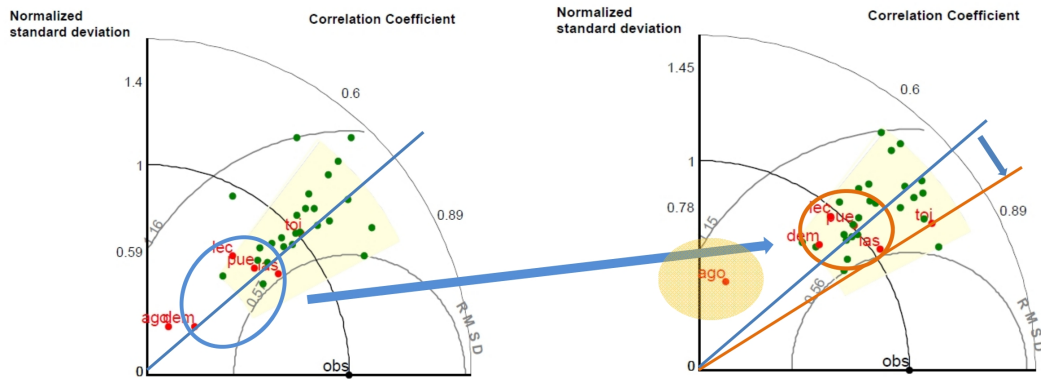


Figure 7.3.: The evapotranspiration is better estimated at sites experiencing strong water stress (red points) when using LSA-SAF vegetation variables.

7.3. Additionnal improvement from land surface temperature

LSA-SAF does not produce a soil moisture index that could be used by the evapotranspiration model. However, the international community has recognized land surface temperature as being a proxy for soil moisture, with some limitations. Land surface temperature is one of the key variables from LSA-SAF: it is produced every 15 minutes at

SEVIRI spatial resolution, and is carefully being validated in several locations of Europe and Africa (Göttsche, 2013).

In the previous chapter, we have used the morning heating rates from the land surface temperature pixelwise to infer a surface soil moisture index applicable at continental scale, using a simple empirical function, only for clear sky days. This daily soil moisture estimation over a period between 2007 and 2011 has been validated extensively with the help of ground measurements from FLUXNET and ISMN networks, showing very good performances over Sahelian landscapes and semi-arid regions of Europe, and outperforming the current model input (Figure 7.4). In addition, the newly derived soil moisture presents the advantage of detecting rapid changes in soil moisture, but also irrigation and wetland extends. Limitations have been shown in rocky mountainous areas, as well as over very dense vegetation for which the signal is very weak, and dust storms that are not systematically screened out during the land surface temperature production.

We have reprocessed the year 2007 with the evapotranspiration model over validation sites across Europe and Africa using LSA-SAF LAI as input and the estimated soil moisture. For this reprocessing, we have assumed a single soil layer to which the surface soil moisture has been attributed. The estimated evapotranspiration has been largely improved compared to the first version, especially for the site in Mali, with a better correlation to the observations and a better match with the observed variability (Figure 7.5).

7.4. Conclusion and perspectives

In this study, we have shown the interest of ingesting new surface variables derived from MSG/SEVIRI in the evapotranspiration model of EUMETSAT's LSA-SAF for a more accurate monitoring over semi-arid areas. Leaf area index, which describes quantitatively the vertically integrated vegetation green material, cannot alone correct the observed model deficiencies. Land surface temperature, converted into soil moisture, can further improve the results, especially over sahelian Africa, and provide a realistic evapotranspiration evolution compared to ground observations. The natural follow-up of this study is the adaptation of the operational evapotranspiration algorithm of LSA-SAF

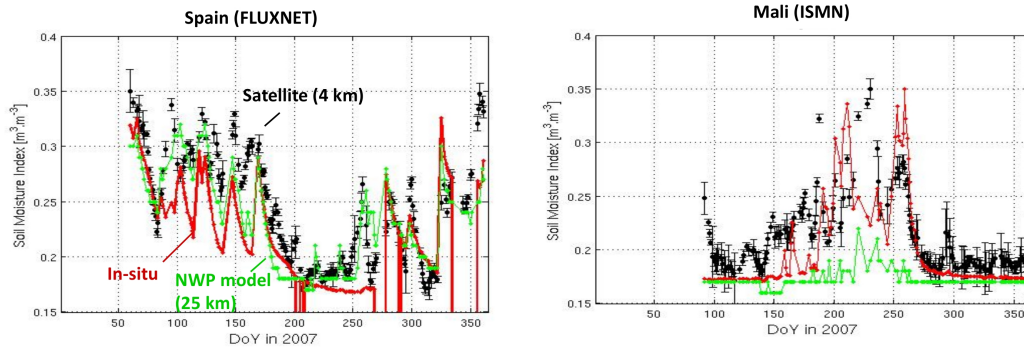


Figure 7.4.: The new soil moisture estimates derived from land surface temperature data from SEVIRI (black dots) show a good performance when compared to ground observation (red). It outperforms the NWP soil moisture forecast used in the current operational LSA-SAF evapotranspiration product at the station in Mali.

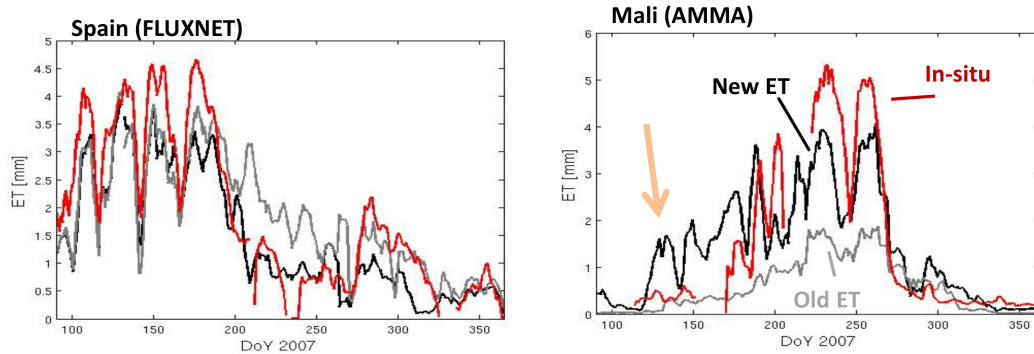


Figure 7.5.: Evapotranspiration monitoring is largely improved by the combined used of LSA-SAF vegetation variable and land surface temperature at semi-arid sites. The temporal variability of the observations is well reproduced, the order of magnitude is correct during the drying periods. Some corrections still need to be done, like dust storm screening in the land surface temperature retrievals that would imply a better tracking of evapotranspiration during the dry period over the Sahel.

to conform with the proposed changes. The resulting product will be more reliable over semi-arid areas, making use of LSA-SAF full potential. We expect this will offer new opportunities to an improved drought monitoring in those regions.

8

Conclusion

Water resource is a major concern for sustainable development in many semi-arid areas. Early detection of drought and monitoring water consumption by agriculture are highly important for adaptation of regional water use policies. As a crucial component of the water cycle, still poorly known accurately, land evapotranspiration is a primary source of information for such water resources assessments. Remote sensing from geostationary satellites offers the possibility to monitor evapotranspiration over large areas at relatively high temporal and spatial resolutions. The Satellite Application Facility on Land Surface Analysis (LSA-SAF) of the European meteorological satellites organization (EUMETSAT) provides a suitable framework for an operational production of evapotranspiration maps: it proposes a suite of datasets related to land surface partition of energy and vegetation status derived from the SEVIRI instrument aboard the Meteosat Second Generation (MSG) and provides an infrastructure for the near-real time production of relevant variables.

A framework of development and validation of an evapotranspiration model, based on a reduced set of equations from a land surface model, TESSEL, has been designed for an

operational production in near-real time using MSG/SEVIRI derived radiation variables, ECMWF numerical weather forecasts of near-surface atmospheric variables and soil moisture and a land cover database, ECOCLIMAP, over Africa, Europe and South America at a spatial resolution of a few kilometers. The analysis of the processing of nine months past data with the evapotranspiration model compared to in-situ observations from CarboEuro-IP, KNMI and RMI networks has demonstrated the ability of the model to accurately estimate the evapotranspiration over temperate regions of Europe. A part of the error has been attributed to differences in the estimation in the incoming shortwave radiation at the surface. In semi-arid regions, a sometimes inappropriate soil moisture input of the model, provided by ECMWF, was driving large errors at a measurement site in Portugal. The evapotranspiration maps derived in this context were compared to maps from the ECMWF global numerical weather forecasts and the Global Land Data Assimilation System, GLDAS. Spatial variations of evapotranspiration were well correlated at midday periods, however large discrepancies appeared between the three models, in most cases not systematically, and could be explained in terms of differences in input variables (solar radiation reaching the surface, land use and vegetation variations) and model parameterization.

However, given the potential threats of relying on a semi-static database describing the vegetation properties, ECOCLIMAP, there existed the opportunity to use the newly available LSA-SAF vegetation variables and study the benefits for land surface models and the evapotranspiration model developed, relying therefore more on MSG/SEVIRI derived data. A methodology to effectively use day-to-day the vegetation variables, leaf area index and fraction of vegetation cover, along with the available LSA-SAF snow cover maps, has been designed to match the requirements of most land surface models based on the tile approach, and requiring continuous time series of vegetation parameters. Improvements in the land surface model evapotranspiration results were clearly identified for semi-arid regions, when compared to in-situ observations. This new methodology has been implemented for routine production of evapotranspiration maps using an adapted model. The statistical comparison with in-situ observations revealed an improved estimation of evapotranspiration in semi-arid areas in the mediterranean region, and slightly better in sub-saharian regions of Africa.

Contemporary global/continental land cover maps are derived from data acquired by

sensors for vegetation monitoring aboard polar orbiting satellites. Land cover maps are the baseline of most land surface models. They drive the selection of the set of parameters necessary to estimate the evapotranspiration. Therefore, the land cover map and the strategy of its use should be carefully chosen depending on the application. In this thesis, I have shown that for monitoring evapotranspiration it is important to regularly update the land cover map used by the models. In addition, the land cover map should be chosen accordingly with the final spatial resolution expected for the evapotranspiration maps, as errors can be induced by an inaccurate geolocation of the satellite data on which the land cover map is based. Typically, for kilometer scale simulations of a land surface model, the error due to inaccurate geolocation can be up to 10% if a land cover map at the same spatial resolution is used. This error is reduced by a factor 2 to 3 if a land cover map at 330 m is used instead. For the application of the evapotranspiration in the framework of LSA-SAF, however, the error induced by geolocation inaccuracies is marginal with a deviation of only a few percents.

Besides land cover maps, a wealth of other variables at the sub-kilometer resolution can be derived from sensors for vegetation monitoring aboard polar satellites. In this thesis, I have focused on the potential improvement of LSA-SAF evapotranspiration estimates using the surface albedo, the leaf area index and the fraction of seasonal/occasional waterbodies variables derived from such sensors. While only a small effect could be identified from the use of leaf area index at higher resolution, a detectable change could be noticed from the use of the higher resolution surface albedo. The strongest effect has been noticed when using the fraction of waterbodies over a site in a sahelian landscape. Especially, time series of waterbodies fraction derived from a sensor sampling at 250 m resolution were shown to be relevant to complement variable derived from SEVIRI for evapotranspiration monitoring in regions with high evaporation demand.

The high temporal sampling rate, every 15 min, of the land surface temperature derived from SEVIRI has proven useful in measuring daily heating rate variation of the land surface and therefore in the daily monitoring of soil moisture based on thermal inertia properties of the surface. A novel approach has been described, applied over Europe and Africa and the resulting soil moisture has been validated with in-situ observations of surface soil moisture across Europe and Africa. The approach is particularly interesting for semi-arid to arid regions of Europe and Africa, providing an

accurate estimation of surface soil moisture for days with at least a few snapshots taken by clear sky condition. The method is however limited in accuracy for densely vegetated areas, regions with a frequently overcast sky screening the land surface signal for the satellite, and during periods of high aerosol loads in the atmosphere.

Finally, the combined use of vegetation variables and land surface temperature in the LSA-SAF evapotranspiration model resulted in an improved monitoring over two stations in Spain and in Mali, showing the clear interest of ingesting not only half-hourly radiation products and daily surface albedo, but also daily vegetation variables and daily soil moisture derived from 15 minutes land surface temperature observations.

8.1. A look back

The baseline version of the model (MET) presented in Chapter 2 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), giving way to an integrated daily product useful for many applications (Arboleda et al., 2011).

Under the impulse of national and international programmes, the evergrowing number of in-situ validation sites was a great opportunity to benchmark the model and propose new changes. Driven by the detection of deficiencies in the evapotranspiration monitoring during the validation, from me and my colleagues, but also from the use of the product by independent researchers (Romaguera-Albentosa et al., 2012; Sepulcre-Canto, 2013; Durgun et al., 2014; Gokmen et al., 2013), this research has led to an improved version of the model, ingesting for the first time new products measuring the vegetation characteristics daily. This version has been finalized and finally produce evapotranspiration maps on a routine basis. The role of users is here very important as they contribute to an assessment of the proposed product in view of their own application.

The complementarity of variables derived from space missions for global vegetation monitoring at the sub-kilometer scale for an improved evapotranspiration estimation is of special interest in view of the exploitation of the new continuous environmental monitoring services (Lacaze et al., 2010) set up under the impulse of the European

commission. It shows the interest of a continuous production of variables monitoring the land surface at the kilometer scale and the utility to improve the spatial resolution. The base data source of those products has been SPOT-Végétation up to now, but the follow-up mission is already in orbit, Proba-V, with an enhanced spatial sampling, which will prepare the upcoming Sentinel missions.

8.2. A way forward: prospects and challenges

I have proposed in this thesis a way to handle variables available from LSA-SAF for land surface model monitoring applications. Based on the research results presented in this thesis, I expect monitoring systems to be improved by the addition of those variables. It also includes the improvement of the LSA-SAF evapotranspiration product. Many applications, including drought monitoring or agricultural yield monitoring, should benefit from those improvements.

A natural extension of this work is the generalization of the methodology to the global scale, making use of a suite of geostationary satellites positionned for global monitoring. Such system of satellites, a combination of at least three satellites (MSG, MTSAT, GOES), is already in place and could be exploited for that purpose. The complementarity with other polar satellites should also be continued to be studied, by testing the added-value of the new services set-up by the European Copernicus land services, and also by extending the analysis to other satellites from EUMETSAT, like MetOp. As international research is always on the move, the evapotranspiration will benefit from new formulations, parameterizations or new in-situ measurements, allowing the refinement of the model.

At last, in the path of globalizing, big challenges are yet ahead of the scientific community as more and more data from an evergrowing satellites fleet sampling the Earth at a tremendous pace are acquired everyday, and more and more methods emerge. While large disparities are noticed among the evapotranspiration maps, new initiatives are trying to find the points of convergence and identify points to be addressed (Jimenez et al., 2009b).



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 A.1. 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 ET by means of Eqs. 2.19 and 2.20, are presented in Table A.1. Four complementary statistical indices are tabulated for each dataset: the global bias, the root mean square error (RMS), the global correlation coefficient and the Nash index (Nash and Sutcliffe, 1970), see Eq. 2.21. The lowest scores are obtained at Bondville (Meyers and Hollinger, 2004), Puéchabon (Joffre et al., 1996) and Loobos Dolman et al. (1998). For the Puéchabon simulation, ECOCLIMAP database vegetation parameters have been used: the results could be the consequence of an inaccurate capture of the

Table A.1.: Comparison between half-hourly ET measurements and ET estimates obtained by MET forced with local observations. Bias [$mm.h^{-1}$], RMS [$mm.h^{-1}$], 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

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, or else remaining of unexplained observations (peaks or individual outliers) not filtered out by an automated quality check of the data. 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.

B

Least Square Algorithm application

Let $\mathbf{M}$ be the linear model matrix, representing the proportion $f_{i,j}$ for each pixel i of determined PFT j .

$$\mathbf{M} = \begin{pmatrix} f_{1,1} & \cdots & f_{1,N} \\ \vdots & \ddots & \vdots \\ f_{M,1} & \cdots & f_{M,N} \end{pmatrix} \quad (\text{B.1})$$

$\tilde{\mathbf{Y}}$ is the observation vector, which contains the LSASAF LAI_i estimates for the M considered pixels.

$$\tilde{\mathbf{Y}} = \begin{pmatrix} LSA - SAFLAI_1 \\ \vdots \\ LSA - SAFLAI_M \end{pmatrix} \quad (\text{B.2})$$

Now, let $\tilde{\mathbf{X}}$ be the solution vector containing the averaged values V_i over the domain

for each involved ecosystem.

$$\tilde{\mathbf{X}} = \begin{pmatrix} V_1 \\ \vdots \\ V_N \end{pmatrix} \quad (\text{B.3})$$

Therefore, the problem has the following simple linear form (Eq B.4).

$$\mathbf{M} \cdot \tilde{\mathbf{X}} = \tilde{\mathbf{Y}} \quad (\text{B.4})$$

Taking into account the retrieval uncertainty of the LSA-SAF LAI and assuming it corresponds to the standard deviation of a normal error distribution, we scale the matrix $\mathbf{M}$ and the observation vector $\tilde{\mathbf{Y}}$ by weighting factors, $\sigma_{SAF,i}^{-1}$. A matrix $\mathbf{W}$ containing the weights is formed (Eq B.5), and new matrix M_w (Eq B.6) and vectors Y_w (Eq B.7) are defined. We get to solve Eq B.8.

$$\mathbf{W} = \begin{pmatrix} 1/\sigma_{SAF,1} & 0 & \cdots & 0 \\ 0 & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & 1/\sigma_{SAF,M} \end{pmatrix} \quad (\text{B.5})$$

$$\mathbf{M}_w = \mathbf{W} \cdot \mathbf{M} \quad (\text{B.6})$$

$$\tilde{\mathbf{Y}}_w = \mathbf{W} \cdot \tilde{\mathbf{Y}} \quad (\text{B.7})$$

$$\mathbf{M}_w \cdot \tilde{\mathbf{X}} = \tilde{\mathbf{Y}}_w \quad (\text{B.8})$$

Solving the linear set of equation using a least square method, we obtain the LAI for each PFT. The solution in the least square sense using the L2-norm, $\tilde{\mathbf{X}}$, is given by Eq B.9, whereby $\mathbf{M}_w^T$ is the transpose of $\mathbf{M}_w$.

$$\tilde{\mathbf{X}} = (\mathbf{M}_w^T \cdot \mathbf{M}_w)^{-1} \cdot \mathbf{M}_w^T \cdot \tilde{\mathbf{Y}}_w \quad (\text{B.9})$$

To fasten the numerical computation of the solution, as well as to avoid frequent difficulties in inverting large sparse matrices, we reduce the matrix $\mathbf{M}_{\mathbf{w}}$ to its irreducible dimensions, corresponding to the number of pixels times the number of PFTs occupying the size-defined neighbourhood. If the matrix is non-invertible a singular value decomposition algorithm is applied.



Implementation and validation of LSA-SAF MET v4.1.0 (V1)

Abstract

I have described in chapter 3 the methodology to use the daily biophysical variables derived from MSG/SEVIRI for land surface models that make use of the tiling approach. The proposed method is applied here to the operational evapotranspiration model and the changes are assessed. I first describe a few additions of the improved evapotranspiration model, show a set of validation results, and finally compare the new version to the previous one. The evapotranspiration model has been reprocessed over the period 2007-03-01 to 2007-12-31 over the whole SEVIRI field of view for every half-hour with a complete set of input. A validation of this new algorithm, LSASAF MET v4.1.0, is achieved by comparing pixel estimates to local in-situ measurements, comparing with other models, and verifying the consistency between the modeled skin temperature and LSASAF LST. Then, a comparison of LSASAF MET v4.1.0 with the previous version

v4.0.3 is presented, assessed by comparison at validation sites and spatially. At last, I outline the benefits from the new version and evaluate the impact for the possible applications exploiting those results.

C.1. Changes from LSA-SAF MET v4.0.3 (V0) to v4.1.0 (V1)

The main change in model input is the use of LSA-SAF LAI and FVC, with the method proposed in chapter 3. In addition, to avoid any inconsistency in the surface albedo used, a ten-days per-pixel climatology is built to provide a background signal that is combined with the daily albedo for input of the model. Moreover, over Europe, the snow cover product, LSA-SAF SC2, is used: if snow is detected, a snow tile is created to compute a sublimation rate for snow, with an adapted albedo, set to 0.90, leaving only 10% of the energy available for net radiation at the surface. The albedo of snow is known to decrease with time due the ageing effect. However, the information of the snow age is not made available in a straightforward manner. Snow albedo is provided by the LSA-SAF albedo variable, however, while there is a clear rise of albedo due to snow, the values are still too low compared to what it is actually observed.

In practice, to leave as much as possible those new changes outside the evapotranspiration model, three algorithms have been built to create a database that could be used by the ET model the same way it ingested ECOCLIMAP-I. The new designed processes flow is therefore composed of three steps, according to their frequency of use. The first one is done occasionnally, the second on a daily basis and the last one every 30 minutes, the ET algorithm.

First, a static database is built and contains the land cover map projected and aggregated in the MSG/SEVIRI view with the 5 dominant tiles labels and occupation fraction, and averages of the annual cycle for vegetation properties, as shown in the flowchart of Figure C.1. From four years of daily data (2007 to 2010), a 10-days-varying climatology of LAI and ALBEDO (36 files) as well as theirs standard deviation are created, using the method exposed in Ghilain et al. (2012). Additional information

needed are also integrated. The tree heights distribution is assigned pixel by pixel using ECOCLIMAP-I database. For each pixel and for each vegetation tile composing it, the relative position of the nearest 'homogeneous' pixel, occupied by more than 80% of the plant function type of interest, is stored. The static database implemented in the operational system is therefore composed of 10 layers containing the tile labels and their respective occupation fractions, 72 layers with monthly varying backup LAI and their standard deviation, 24 layers with monthly varying background albedo and their standard deviation, and at last 10 layers with the position of the nearest homogeneous pixels for each tile.

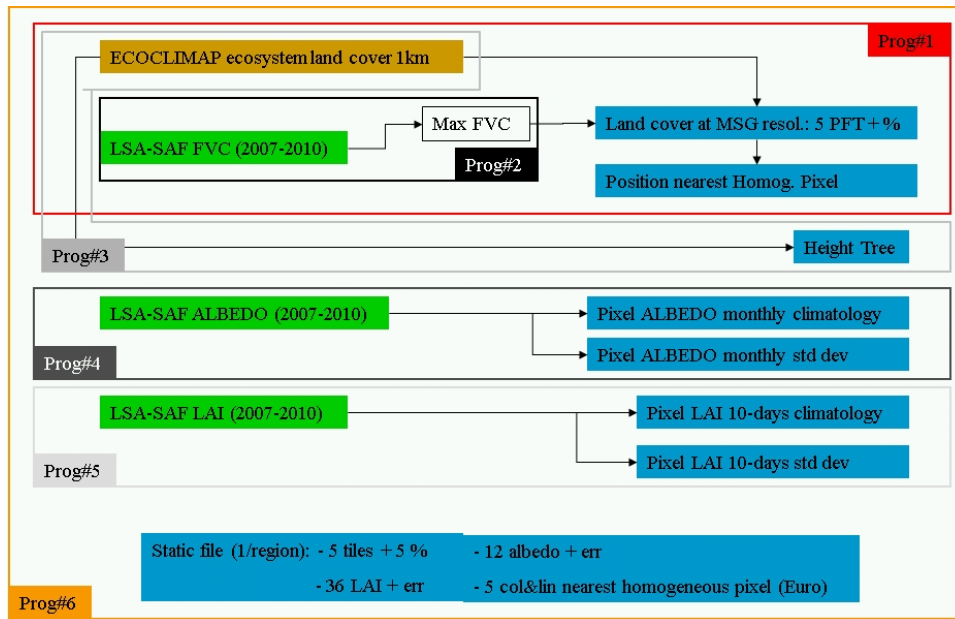


Figure C.1.: **Flowchart of the static database building.**

The second algorithm is used on a daily basis to provide the vegetation database necessary for the ET algorithm execution. It takes as input the static database described above, and the daily maps of LAI, albedo, fractional vegetation cover, snow cover (for Europe) and optionally the broadband emissivity maps (Figure C.2). The snow cover map from LSA-SAF is first used to update the land cover map. A pixel is set to 100% of snow if the snow cover is labelled 'Total snow cover'. If the label is 'Partial snow cover', it is assumed that the pixel is covered by 50% of snow and the tile percentages are divided by two. LAI fields are processed as described in the previous section, making use of the daily product, the background climatology and the value of the nearest homogeneous pixel. The daily albedo is combined with the background albedo signal

pixelwise using the same interpolation procedure set-up for LAI, but without making use of the nearest homogeneous pixel. Emmissivity is then either directly taken from LSA-SAF EMMAPS product or computed from the fractional vegetation cover as a weighted contribution of bare soil and vegetation components, assuming emissivities of 0.96 and 0.99 respectively. Because of the computational time of ET algorithm processing must remain well below 15 minutes, a maximum of 4 tiles is retained. Cover fractions initially for 5 tiles are equally redistributed among the 4 dominant tiles. The daily database is structured the same way it was with ECOCLIMAP-I database, with 8 layers of tile labels and occupation fractions, a sea/ocean mask used to screen out of the process the pixels falling out of land, the LAI, fractional vegetation cover and roughness lengths corresponding to each tile, an albedo and an emissivity per pixel.

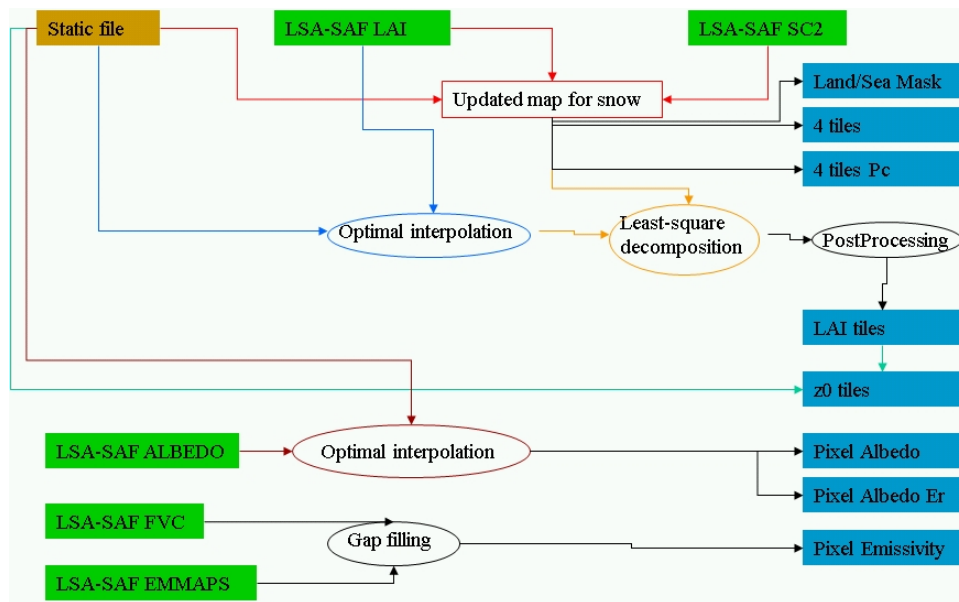


Figure C.2.: **Flowchart for building the daily vegetation database to be used by the ET algorithm, making use of the variables generated by LSA-SAF on a daily basis.**

Several modifications have been applied to the model itself, mainly by adjusting some internal parameters. First, the soil heat flux (G) parameterization has been revised. In the version presented in chapter 2, the formulation of Chebhouni et al. (1996) gave good results over Europe. However, it has been shown by comparing it to groundbased observations that it lead to clear underestimation of ET estimates in sparsely vegetated areas that can be found in Africa. Therefore, a simpler approach has been adpoted, leaving the modelling improvement of that variable to a later date. G is parameterized as

a fixed fraction of R_{net} (10% if $R_n > 0$, 40% otherwise) (Figure C.3).

Taking into account the change of magnitude of part of LAI values given by LSA-SAF LAI, the minimum stomatal resistance has been re-calibrated for forests and grasslands.

In order to reproduce better the response of bare soil evaporation to surface soil moisture, the Jarvis function f_2 for bare soil has been modified by enlarging the range of soil moisture for which bare soil evaporation is sensitive (Figure C.3). The introduction of this formulation change allowed a better capture the drying effect observed in semi-arid areas.

Structurally, the land cover map has been allowed to be dynamic in order to be updated by the snow fraction. A snow tile, previously absent from the scheme, has been introduced in the model, allowing a separate energy budget at the surface and a specific calculation of snow sublimation. In Figure C.3, an example of the land cover map update is shown for 2007-12-25 over Europe. Greenland, the Alps, the Eastern part of Turkey, and a large part of at the eastern border of MSG/SEVIRI field of view have, at least temporarily, their dominant tile set to 'snow'.

Specific attention has been drawn onto the wetlands, where usually a significant proportion of the landscape is composed of waterbodies fraction in the ECOCLIMAP-I land cover map. In the first version, the proportion occupied by 'open-air' water had been neglected, leading to possible underestimation of ET. A water tile has therefore been introduced and an evaporation from water bodies is calculated at a potential rate. The stomatal resistance is set to zero in the model equations, and standard values for roughness lengths are chosen. In Figure C.3, I represent for Europe the fraction occupied by the water tile in each MSG/SEVIRI pixel. Major impact is foreseen in the wetland areas in Poland and in Scandinavia.

At last, the root fraction to compute soil average soil moisture for transpiration has been corrected in sparsely vegetated area.

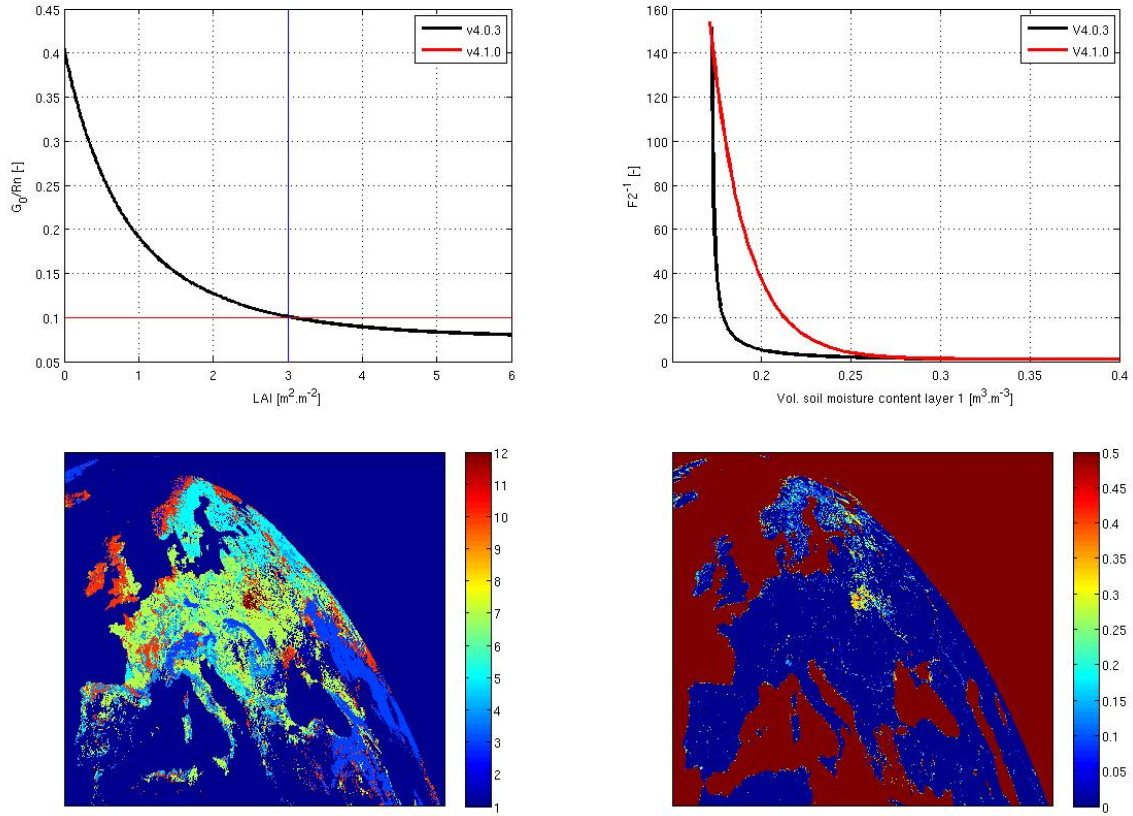


Figure C.3.: 1) Change in formulation of soil heat flux between both versions of MET, 2) change in Jarvis f_2 function to increase the range of sensitivity of bare soil evaporation to soil water stress, 3) daily updated land cover map, with snow covered regions (blue). Example: 25/12/2007, 4) water tile percentage over Europe. (wetlands and rice fields)

C.2. Validation of LSASAF MET v4.1.0

As for LSA-SAF MET v4.0.3, the validation is decomposed into three complementary parts: a comparison with ground observations, a comparison to output of a coupled and an off-line global land surface model (ECMWF and GLDAS), and at last a consistency check with LSA-SAF land surface temperature.

C.2.1. Ground-based validation

A set of datasets have been acquired for the period 2007-03-01 to 2007-12-31 across Europe. Half-hourly measurements of instantaneous surface latent heat flux have been taken by eddy covariance method (CarboEurope, CarboAfrica, AMMA) or by a profile method (BE-AWS). In-situ set-ups intent to provide local observations of surface turbulent fluxes over different ecosystems: coniferous, broadleaf or mixed forests, grasslands, croplands, wetlands, savannahs, under different climatic regimes. Sites considered for the validation are given in Table C.1.

Station	PFT	Climate	Station	PFT	Climate	Station	PFT	Climate
NL-Loo	ENF	T	DE-Hai	DBF	T	BE-Hum	G	T
DE-Wet	ENF	T	FR-Fon	DBF	T	NL-Cab	G	T
DE-Tha	ENF	T	DK-Sor	DBF	T	FR-Laq	G	T
IT-Ren	ENF	M	FR-Hes	DBF	T	BE-Buz	G	T
SE-Nor	ENF	B	It-Non	DBF	M	IE-Dri	G	T
FI-Hyy	ENF	B	ES-LMa	DBF	M	BE-Beit	G	T
FI-Sod	ENF	B	FR-Pué	DBF	M	PT-Toj	G	M
IL-Yat*	ENF	M	IT-Ro2	DBF	M	CG-Tch*	G	E
FI-Kaa*	W	B	IT-Col	DBF	M	ML-Ago	G	S-A
SD-Dem	S	S-A	IT-Czp*	DBF	M	BE-Lon	C	T
BE-Vie	MF	T	IT-Lec	DBF	M	GE-Geb	C	T
BE-Jal	MF	T	BE-Die	G	T	FR-Lam	C	T

Table C.1.: In-situ datasets used for the validation of METv4.1.0. PFT= ENF (evergreen-needle forest), DBF (deciduous broad-leaf), MF (mixed forest), C (non-irrigated crops), G (grassland), W (wetland), S (savannah). Climate = T (temperate), B (boreal), M (mediterranean), S-A (semi-arid), E (equatorial). *Stations foreseen, but not included yet.

The LSA-SAF MET v4.1.0 pixel estimate of LE is compared to measurements. Data have been screened to remove unreliable observations or periods of rain. Only good quality flag observations have been retained and observations during and just after rain events (up to 2 hours after rain) have been filtered out. In some cases, observations are not filtered because precipitation rates are not known, and no quality flag associated.

Statistical scores computed are the standard deviation of both observations and simulated LE, the root mean square difference between both datasets (RMSD), and the correlation coefficient, for each site. As the three scores are related, there exists

a way to present a synthesis of the results in Taylor diagrams (Taylor, 2001). To synthesize information from all sites, the standard deviations from all simulations have been normalized by the standard deviation by each individual dataset. Visually, the distance between the observation and the simulation point gives an idea about the relative performance compared to other points: the closer, the better.

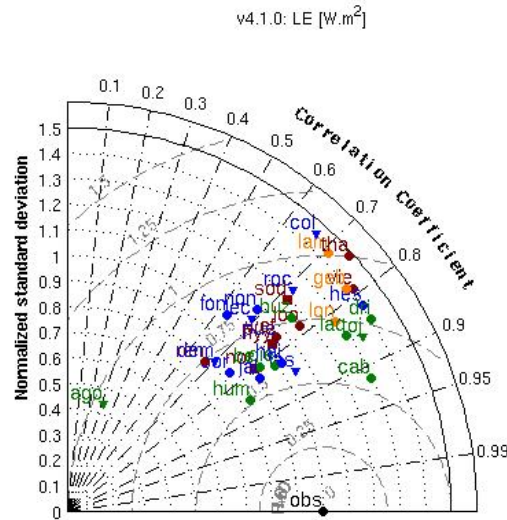


Figure C.4.: **Statistical scores of the comparison between local observations and LSASAF MET v4.1.0 LE estimates, presented in a Taylor diagram. Each colored point represents the comparison for a set of data at a in-situ validation site. Codes of colour indicate the PFT locally observed through the experimental set-up: grass (green), blue (DBF), dark red (ENF), crops (orange).**

The correlation coefficient is mostly (20 on 28 sites) comprised between 0.7 and 0.85, with 7 datasets less than 0.7 and 1 dataset above 0.9 (Figure C.4). It shows that the diurnal cycles and the seasonal variation of LE are well simulated. Globally, higher correlation is found over grassland sites than forested sites or cropland, except for the Agoufou site. In average, the results show no systematic bias (see normalized standard deviation), which varies between -20% to +50% of the mean observed LE. 16 over 26 datasets display a bias less than 20%, while 10 others are between 30% and 50%. A systematic effect is visible for grasslands: the variability with BE-AWS observations tends to be underestimated, while for the FLUXNET sites, it is overestimated, which could be possibly explained by a difference in the in-situ measurement technique. Simulated LE over grassland seems to reproduce best the short time scale dynamics over grassland sites (lowest dispersion)

than forests. For cropland sites, the performance of the model is difficult to assess, as differences of spatial scales induce lots of differences in the seasonal dynamics in patchy landscapes. Therefore, at the exception of the ML-Ago site where the difference can be due to wrong identification of dry periods in the soil moisture dataset used, the model has been shown to be able to reproduce the observed variations of LE for very contrasted sites across Europe, sampling Mediterranean, Temperate and Boreal climates, including large variations in precipitation regimes.

C.2.2. Comparison with other operational products

LSASAF MET v4.1.0 estimates are compared to ET rates computed by GLDAS and ECMWF IFS for 2007, as in Ghilain et al. (2011). All results are aggregated to the coarsest resolution of GLDAS, i.e. 3h average at 1° spatial resolution. Occurrence histograms over each window and each month have been computed, and global time series comparisons have been carried out in the same line. A selection of histograms comparisons are shown in Figure C.6, while mean ET bias of LSA-SAF MET v4.1.0 to ECMWF and GLDAS over 2007 is shown in Figure C.5.

Each LSA-SAF window is analyzed separately. For Europe, it appears from the spatial analysis (Figure C.5) that LSASAF MET v4.1.0 matches well with ECMWF and GLDAS for Temperate Western Europe, while it gives a median ET between ECMWF and GLDAS for Southern Europe (Spain, Greece, Turkey). Ukrainian ET estimates are lower in LSASAF MET v4.1.0 than ECMWF and in a lesser extent than GLDAS. From the temporal analysis (Figure C.6), LSASAF MET v4.1.0 gives results compatible with ECMWF and GLDAS, with however a lower median value than ECMWF, and maximum values between ECMWF and GLDAS.

For North Africa (NAfr), large differences appear between the 3 models estimates, with a closer agreement of LSASAF MET with GLDAS than with ECMWF, particularly from the sub-Saharan zone to the equator. ECMWF ET tend to be higher than LSASAF for the equatorial forest, as well as for the Sahel. The mean monthly values tend to be the same as those of GLDAS, and systematically lower than ECMWF. In addition, LSASAF MET seems to be limited to a threshold towards high evaporation rates.

For Southern Africa (SAfr), significant differences are found in South Africa and Namibia. Otherwise differences are relatively small. Histograms of the 3 models results are similar for April. In May, MET v4.1.0 is closer to ECMWF than to GLDAS. Again, as for NAfr, the mean monthly values tend to be the same as those of GLDAS, and systematically lower than ECMWF. In addition, LSASAF MET seems to be limited to a threshold towards high evaporation rates.

For South America (SAm), significant differences with ECMWF, and with GLDAS in a lesser extent, over the Amazonian forest are observed.

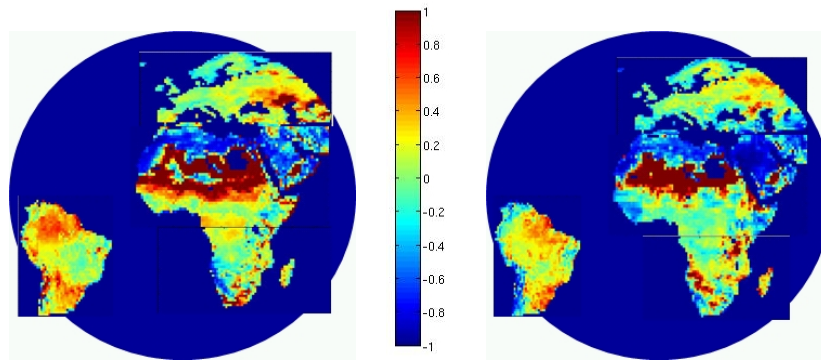


Figure C.5.: European $1^\circ \times 1^\circ$ maps of the mean relative bias [-100%, 100%] between ECMWF and LSA SAF MET (left) and between GLDAS and LSA SAF MET (right). Red: GCM > LSA-SAF MET, Blue: GCM < LSA-SAF MET.

Compared to the results of chapter 2, the changes introduced in the new model (V1) leads to a reduced bias with ECMWF for some regions (Spain and some parts of the sub-saharian region, mainly). A comparison of the histograms for the 2 versions reveals that over Africa, a higher mean is obtained with the new version compared to the baseline version of chapter 2 over the african continent, while the distribution for July over Europe is almost unchanged.

C.2.3. Comparison of the modeled skin temperature and LSASAF LST

LSA-SAF LST is not used in the current version of the LSA-SAF MET algorithm; nevertheless, it should be consistent with the skin temperature (T_{skin}) generated by the

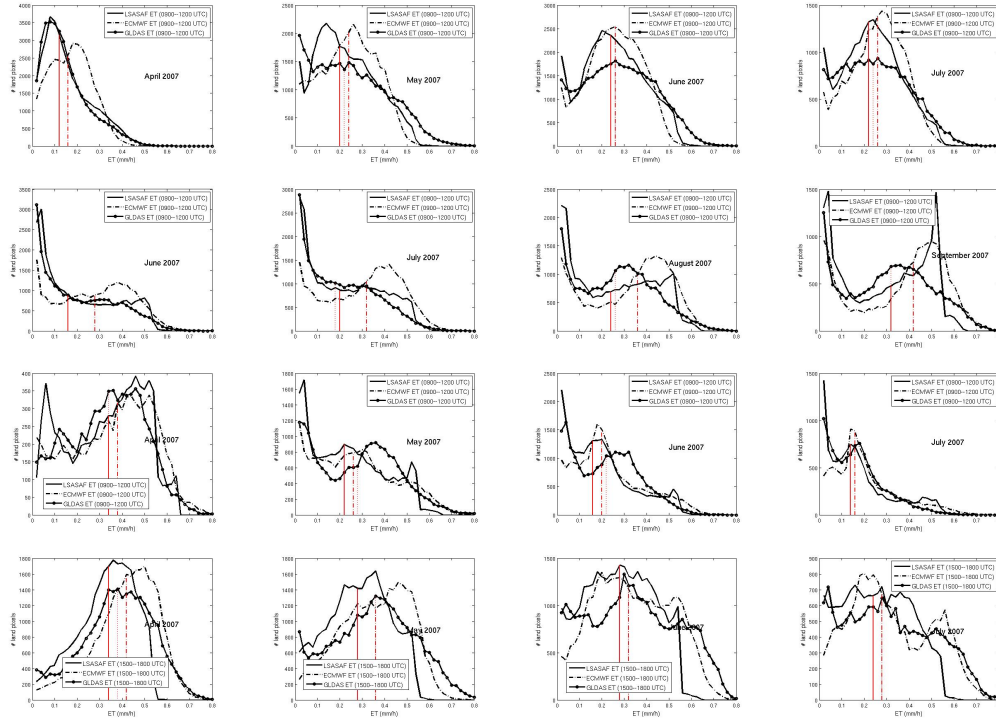


Figure C.6.: **ET occurrence histograms of GLDAS, ECMWF and LSASAF MET v4.1.0 (1° spatial res. aggregated, average 9 to 12 UTC) over a) Euro from April to July 2007, b) NAfr from June to September 2007, c) Safr from April to July 2007 and d) Same from April to July 2007 (15-18 UTC).**

MET algorithm. It is important from a user's point of view to rely on a consistent portfolio of products based on data acquired by the same sensor. A way to assess this consistency is by comparing LSA-SAF LST to the *skin temperature*, T_{skin} computed by MET algorithm at a selected set of locations. The computed *skin temperature* is neither a radiative temperature nor an aerodynamic temperature, but a mixture of both definitions. Physical interpretation of LST, derived by split-window technique, is not straightforward. While LST and T_{skin} correspond to different concepts and therefore are not expected to be equal, we expect a coherent evolution between both. Comparisons of time series are shown for the pixels encompassing some measurement sites used in this section.

The comparisons of half-hourly temperatures show a good agreement between both estimates during the daytime, with an increasing difference with the highest values (Figure C.7). Dispersion is about 5°C, with events (correlation with wind speed regime) presenting very large differences. Two explanations of this dispersion are possible: at

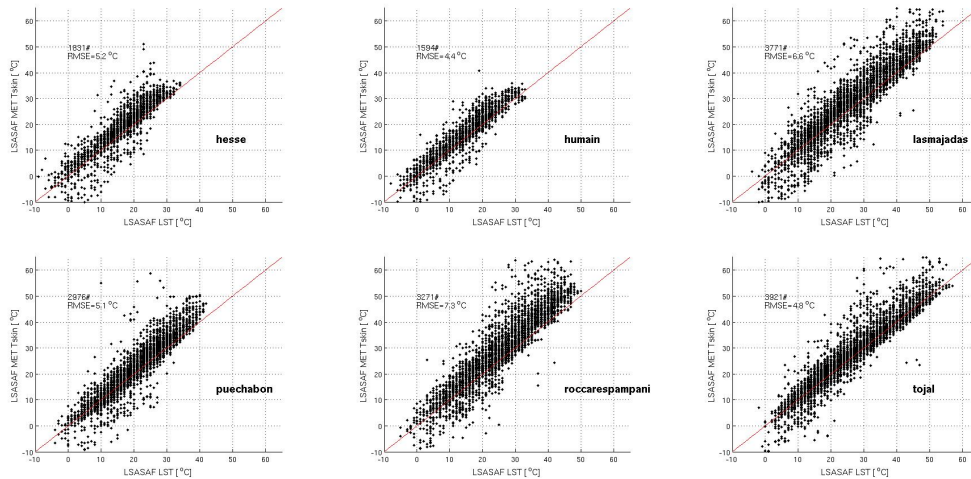


Figure C.7.: Comparison of LSASAF LST and LSASAF MET modeled Tskin for a set of locations (Las Majadas del Tietar, Tojal, Roccarespampani, Puechabon, Hesse, Humain). The line represents the unity. RMSE is indicated in addition to the number of observations used.

first, LST has been reported with an error between 2 and 3 K, Tskin could certainly have the same order of accuracy, leading sometimes to large dispersion. Another explanation can be a difference (more or less systematic by location) in phase between the two variables, leading to some kind of hysteresis curve, widening the spread. The second possible explanation will be carefully checked for the next version of the model integrating the developments of this thesis, and modelling (soil heat flux) could possibly be altered depending on the result.

C.3. Comparison of both versions of LSA-SAF MET at validation sites

Common datasets are selected for both versions, and comparison is carried out on the same time slots against ground measurements of LE. The correlation coefficient is slightly improved overall (Figure C.8), even if a bit more dispersed. Negative bias is lessened for most stations, but a positive bias is introduced in some grassland (Cab, Dri, Laq, Toj) and forest (Col, Vie, Hes) sites over Europe. For African sites, bias is largely

reduced, but the correlation coefficient is almost unchanged. Improvements are mainly seen for grassland and ENF sites, as well as for sites affected by soil water availability, while results over DBF are sometimes deteriorated (Figure C.8, and Table C.2).

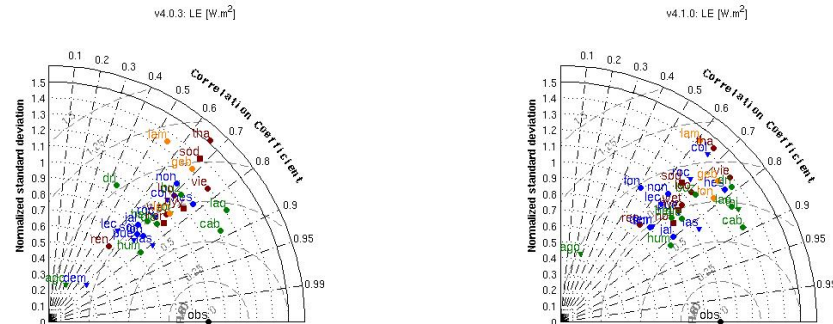


Figure C.8.: Statistical scores as in Figure C.4, presented for v4.0.3 and v4.1.0 over the same dataset of comparison.

Stat	Bias		R		RMSD		NS		Stat	Bias		R		RMSD		NS	
	v1	v2	v1	v2	v1	v2	v1	v2		v1	v2	v1	v2	v1	v2	v1	v2
Loo	8	5	0.71	0.78	59	53	0.33	0.46	Pue	-32	-7	0.73	0.77	60	51	0.33	0.50
Wet	-4	-5	0.75	0.77	59	59	0.49	0.50	Ro2	11	29	0.72	0.71	63	81	0.45	0.13
Tha	42	26	0.67	0.74	85	67	<0	<0	Col	23	44	0.70	0.67	59	85	0.23	<0
Ren	-68	-33	0.64	0.68	126	107	0.16	0.39	Lec	-4	13	0.63	0.69	73	73	0.38	0.34
Nor	-17	-16	0.77	0.80	67	61	0.53	0.59	Die	-22	-12	0.74	0.82	70	61	0.48	0.62
Hyy	6	0	0.77	0.77	54	49	0.48	0.53	Hum	-55	-32	0.80	0.85	88	68	0.41	0.65
Sod	18	6	0.69	0.72	50	36	<0	0.28	Cab	17	17	0.89	0.92	48	48	0.63	0.65
Dem	-67	-33	0.71	0.70	103	77	<0	0.36	Laq	36	23	0.85	0.85	78	73	0.38	0.47
Vie	38	41	0.77	0.79	63	68	<0	<0	Buz	18	11	0.72	0.76	80	75	0.31	0.40
Jal	-3	0	0.68	0.82	77	58	0.44	0.67	Dri	-23	33	0.45	0.84	78	67	<0	0.21
Hai		0		0.82		50		0.64	Beit	-28	-19	0.71	0.80	77	66	0.39	0.58
Fon	-18	-2	0.75	0.62	66	81	0.53	0.27	Toj	19	18	0.75	0.86	57	56	0.43	0.46
Sor	-17	-14	0.71	0.76	81	72	0.48	0.56	Ago	-56	-34	0.42	0.31	112	99	<0	<0
Hes	49	57	0.78	0.82	76	83	0.06	<0	Lon	20	36	0.75	0.82	60	68	0.42	0.23
Non	45	12	0.68	0.68	94	81	0.00	0.30	Lam	47	33	0.55	0.71	102	86	<0	<0
LMa	-16	-5	0.81	0.85	60	55	0.62	0.69	Geb	65	47	0.69	0.78	99	79	<0	<0

Table C.2.: Statistical scores of LE simulations against in-situ observations: comparison of v4.0.3 and 4.1.0. Bias and RMSD are given in $W.m^{-2}$, correlation coefficient (R) and Nash-Sutcliffe index (NS) are dimensionless.

C.4. Conclusion

Major impacts have been noticed for semi-arid areas in Africa (Sahel, Nile delta), and Middle East (Iraq) and in a lesser extend in Europe (Iberian Peninsula, Italy, Greece, Turkey). The added-value of the new version relies on several key points. The model is more based on MSG/SEVIRI, as it relies on the vegetation parameters retrieved from

MSG. It therefore allow a better day-to-day monitoring using MSG derived vegetation parameters, and snow cover maps. Continuity and consistency of time series is ensured, as background information for vegetation and surface albedo is derived from a 4 years climatology on LSASAF products. Overall, the changes made on the evapotranspiration model, including the use of the vegetation parameters from LSA-SAF, allow a better estimation in semi-arid areas. This has been demonstrated by comparison with in-situ observations over Spain and Africa. In this study, we could analyze new datasets not available for the study of chapter 2 and covering regions with high dispersion among the models (LSA-SAF, ECMWF and GLDAS). This demonstrated that LSA-SAF new model is able to better estimate evapotranspiration in part of those regions. A future analysis should prospect the regions still lacking a ground reference to resolve large dispersion of models results.

Bibliography

- ALADIN International Team, 1997. The ALADIN project: Mesoscale modelling seen as a basic tool for weather forecasting and atmospheric research. *WMO Bull.* 46, 317–324.
- Albergel, C., Calvet, J.C., Mahfouf, J.F., Rüdiger, C., Barbu, A.L., Lafont, S., Roujean, J.L., Walker, J.P., Crapeau, M., Wigneron, J.P., 2010. Monitoring of water and carbon fluxes using a land data assimilation system: a case study for southwestern France. *Hydrol. Earth Syst. Sci.* 14, 1109–1124.
- Albergel, C., de Rosnay, P., Gruhier, C., Munoz-Sabater, J., Hasenauer, S., Isaksen, L., Kerr, Y., Wagner, W., 2012. Evaluation of remotely sensed and modelled soil moisture products using global ground-based in situ observations. *Remote Sens. Environ.* 118, 215–226.
- Allen, R., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration - Guidelines for computing crop water requirements. FAO-Food and Agriculture Organization of the United Nations.
- Alton, P.B., 2011. How useful are plant functional types in global simulations of the carbon, water, and energy cycles? *J. Geophys. Res.* 116 (G1). Doi: 10.1029/2010JG001430.
- Anderson, M.C., Norman, J.M., Mecikalski, J.R., Otkin, J.A., Kustas, W.P., 2007. A climatological study of evapotranspiration and moisture stress across the continental united states based on thermal remote sensing: 1. model formulation. *J. Geophys. Res.* 112 (D11). Doi: 10.1029/2006JD007507.
- Arboleda, A., Ghilain, N., Gellens-Meulenberghs, F., 2011. Eumetsat's lsa-saf evapotranspiration: comparisons of operational product to observations and models at hydrological basins scale, *Proc. EUMETSAT user's conference*, 7 pp., June 2011, Oslo, Norway.
- Aubinet, M., Chermanne, B., Vandenhaute, M., Longdoz, B., Yernaux, M., Leitat, E., 2001. Long term carbon dioxide exchange above a mixed forest in the Belgian Ardennes. *Agr. Forest Meteorol.* 108 (4), 293–315.
- Aubinet, M., Grelle, A., Ibrom, A., Rannik, U., Moncrieff, J., Foken, T., Kowalski, A., Martin, P., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grünwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., Vesala, T., 2000. Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology. *Advances in Ecological Research* 30, 113–175.

- Bacour, C., Baret, F., Béal, D., Weiss, M., Pavageau, K., 2006. Neural network estimation of LAI, fAPAR, fCover and LAIxCab from top of canopy MERIS reflectance data: principles and validation. *Remote Sens. Environ.* 105 (4), 313–325. Doi: 10.1016/j.rse.2006.07.014.
- Baldocchi, D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Evans, R., Fuentes, J., Goldstein, A., Katul, G., Law, B., Lee, X., Mahli, Y., Meyers, T., Munger, W., Oechel, W., Paw, K.T., Pileggard, K., Schmid, H.P., Valentini, R., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2001. Fluxnet: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. *B. Am. Meteorol. Soc.* 82, 2415–2434.
- Balsamo, G., Albergel, C., Beljaars, A., Boussetta, S., Cloke, H., Dee, D., Dutra, E., Munoz-Sabater, J., Pappenberger, F., de Rosnay, P., Stockdale, T., Vitart, F., 2013. ERA-Interim/Land: a global land water resources dataset. *Hydrol. Earth Syst. Sci. Discuss.* 10, 14705–14745.
- Balsamo, G., Viterbo, P., Beljaars, A., van den Hurk, B., Hirshi, M., Betts, A.K., Scipal, K., 2009. A revised hydrology for the ECMWF model: Verification from field site to terrestrial water storage and impact in the integrated forecast system. *J. Hydrometeor.* 10 (3), 623–643.
- Baret, F., Hagolle, O., Geiger, B., Bicheron, P., Miras, B., M.Huc, Berthelot, B., f. Nino, M.Weiss, Samain, O., Roujean, J., M.Leroy, 2007. LAI, FAPAR, and FCover CYCLOPES global products derived from Vegetation. Part 1: principles of the algorithm. *Remote Sens. Environ.* 110 (3), 305–316. Doi: 10.1016/j.rse.2007.02.018.
- Bartalis, Z., Wagner, W., Naeimi, V., Hasenauer, S., Scipal, K., Bonekamp, H., Figa, J., Anderson, C., 2007. Initial soil moisture retrieval from the METOP-A Advanced Scatterometer. *Geophysical Research Letters* 34 (L20). Doi: 10.1029/2007GL031088.
- Bartholomé, E., Belward, A.S., 2005. GLC2000: a new approach to global land cover mapping from earth observation data. *Int. J. Remote Sens.* 26, 1959–1977.
- Bastiaanssen, W.G.M., Menenti, M., Feddes, R.A., Holtslag, A.A.M., 1998. The surface energy balance algorithm for land (sebal): Part 1 formulation. *J. Hydrol.* 212, 198–212.
- Beljaars, A.C.M., Bosveld, F.C., 1997. Cabauw data for the validation of land surface parameterization schemes. *J. Climate* 10, 1172–1193.
- Beljaars, A.C.M., Viterbo, P., 1994. The sensitivity of winter evaporation to the formulation of aerodynamic resistance in the ECMWF model. *Bound.-Lay. Meteorol.* 71 (1-2), 135–149.
- Ben-Ami, Y., Koren, I., Rudich, Y., Artaxo, P., Martin, S.T., Andreae, M.O., 2010. Transport of North African dust from the Bodélé depression to the Amazon Basin: a case study. *Atmos. Chem. Phys.* 10, 7533–7544.
- Bernier, N.B., Belair, S., 2012. High horizontal and vertical resolution limited-area model: Near-surface and wind energy forecast applications. *J. Applied Meteorology and Climatology* 51, 1061–1078.

- Bicheron, P., Ambrey, V., Bourg, L., Petit, D., Huc, M., Miras, B., Brockmann, C., Hagolle, O., Delwart, S., Ronera, F., Leroy, M., Arino, O., 2011. Geolocation assessment of MERIS GlobCover orthorectified products. *IEEE T. Geosci. Remote* 49, 2972–2982.
- Bicheron, P., Huc, M., Henry, C., Bontemps, S., et al., 2008. GLOBCOVER: Products Description Manual. GLOBCOVER Manual GLOBCOVER-PDM-I2.2.
- Bicheron, P., Leroy, M., Brockmann, C., Krämer, U., Miras, B., Huc, M., Nino, F., Defourny, P., Vancutsem, C., Arino, O., Ranéra, F., Petit, D., Amberg, V., Berthelot, B., Gross, D., 2006. Globcover : a 300m global land cover product for 2005 using envisat/meris time series, in: *Proceedings of the Recent Advances in Quantitative Remote Sensing Symposium*, Valencia, Spain.
- Blyth, E., Best, M., Cox, P., Essery, R., Boucher, O., Harding, R., Prentice, C., Vidale, P.L., Woodward, I., 2006. Jules: a new community land surface model. *Global Change Newsletter* 66, 9–11.
- Bonan, G.B., Levis, S., Kergoat, L., Oleson, K.W., 2002. Landscapes as patches of plant functional types: An integrated concept for climate and ecosystem models. *Global Biogeochem. Cy.* 16 (2), 1021. Doi: 10.1029/2000GB001360.
- Bontemps, S., Herold, M., Kooistra, L., van Groenestijn, A., Hartley, A., Arino, O., Moreau, I., Defourny, P., 2012. Revisiting land cover observations to address the needs of the climate modelling community. *Biogeosciences* 9, 2145–2157.
- Boone, A., de Rosnay, P., Balsamo, G., Beljaars, A., Chopin, F., Decharme, B., Delire, C., Ducharme, A., Gascoin, S., Grippa, M., Guichard, F., Gusev, Y., Harris, P., Jarlan, L., Kergoat, L., Mougin, E., Nasonova, O., Norgaard, A., Orgeval, T., Ottlé, C., Pocard-Leclercq, I., Polcher, J., Sandholt, I., S. Saux-Picart, S., Taylor, C., Xue, Y., 2009. The AMMA Land Surface Model Intercomparison Project (ALMIP). *Bull. Amer. Meteorol. Soc.* 90 (12), 1865–1880. Doi: 10.1175/2009BAMS2786.1.
- Brut, A., Rüdiger, C., Lafont, S., Roujean, J., Calvet, J., Jarlan, L., Gibelin, A., Albergel, C., Lemoigne, P., Soussana, J., Klumpp, K., Guyon, D., Wigneron, J.P., Ceschia, E., 2009. Modelling LAI at regional scale with ISBA-A-gs: comparison with satellite-derived LAI over southwestern france. *Biogeosciences* 6, 1389–1404. Doi: 10.5194/bg-6-1389-2009.
- Bultot, F., Dupriez, G.L., 1976a. Conceptual hydrological model for an average-sized catchment area, i. concepts and relationships. *J. Hydrol.* 29 (3-4), 251–272.
- Bultot, F., Dupriez, G.L., 1976b. Conceptual hydrological model for an average-sized catchment area, ii. estimate of parameters, validity of model, applications. *J. Hydrol.* 29 (3-4), 273–292.
- Carrer, D., Roujean, J.L., Meurey, C., 2010. Comparing operational MSG/SEVIRI land surface albedo products from Land SAF with ground measurements and MODIS. *IEEE T. Geosci. Remote* 48, 1714–1728.

- Champeaux, J.L., Masson, V., Chauvin, F., 2005. ECOCLIMAP: a global database of land surface parameters at 1 km resolution. *Meteorol. Applications* 12 (1), 29–32. Doi: 10.1017/S1350482705001519.
- Chehbouni, A., Qi, J., Seen, D.L., Kerr, Y., Dedieu, G., Moran, S., Daubas, M., Monteny, B.M., 1996. Estimation of real evaporation, in: *Proc. Int. workshop on Remote Sensing and Water Resources*, 10 pp., 30 November 1996, Montpellier, France.
- Chesters, D., 1998. The scientific basis for the advanced geosynchronous studies program. Technical Report. NASA. <http://goes.gsfc.nasa.gov/text/agscience.html>.
- Cooley, H.S., Riley, W.J., Torn, M.S., He, Y., 2005. Impact of agricultural practice on regional climate in a coupled land surface mesoscale model. *J. Geophys. Res.* 110 (D3). Doi: 10.1029/2004JD005160.
- Courault, D., Seguin, B., Olioso, A., 2005. Review on estimation of evapotranspiration from remote sensing data: from empirical to numerical modelling approaches. *Irrigation and Drainage Systems* 19 (3-4), 223–249. Doi: 10.1007/s10795-005-5186-0.
- Crow, W., Berg, A.A., Cosh, M.H., Loew, A., Mohanty, B.P., Panciera, R., De Rosnay, P., Ryu, D., Walker, J., 2012. Upscaling sparse ground-based soil moisture observations for the validation of coarse-resolution satellite soil moisture products. *Reviews of Geophysics* 50 (2). Doi: 10.1029/2011RG000372.
- Defourny, P., Mayaux, P., Herold, M., Bontemps, S., 2012. Global land-cover map validation experiences: Toward the characterization of quantitative uncertainty, in: Giri, C.P. (Ed.), *Remote Sensing of Land Use and Land Cover: Principles and Applications*. CRC Press 2012, pp. 207–224.
- Delworth, T.L., Manabe, S., 1988. The influence of potential evaporation on the variabilities of simulated soil wetness and climate. *J. Climate* 1 (5), 523–547.
- Dirmeyer, P.A., 2011. A history and review of the global soil wetness project (gswp). *J. Hydrometeorol.* 12, 729–749.
- Dolman, A.J., de Jeu, R.A.M., 2010. Evaporation in focus. *Nature Geoscience* 3, 296.
- Dolman, A.J., Moors, E.J., Elbers, J.A., Snijders, W., 1998. Evaporation and surface conductance of three temperate forests in the Netherlands. *Ann. For. Sci.* 55, 255–270.
- Dorigo, W.A., Wagner, W., Hohensinn, R., Hahn, S., Paulik, C., Xaver, A., Gruber, A., Drusch, M., Mecklenburg, S., van Oevelen, P., Robock, A., Jackson, T., 2011. The International Soil Moisture Network: a data hosting facility for global in situ soil moisture measurements. *Hydrol. Earth Syst. Sci.* 15, 1675–1698.
- Dorigo, W.A., Zurita-Milla, R., Wit, A.J.W.D., Brazile, J., Singh, R., Schaepman, M.E., 2006. A review on reflective remote sensing and data assimilation techniques for enhanced agroecosystem modeling. *Int. J. Appl. Earth Obs.* 9 (2), 165–193. Doi: 10.1016/j.jag.2006.05.003.

- Drusch, M., Scipal, K., de Rosnay, P., Balsamo, G., Andersson, E., Bougeault, P., Viterbo, P., 2009. Towards a kalman filter based soil moisture analysis system for the operational ECMWF integrated forecast system. *Geophys. Res. Lett.* 36 (10). Doi: 10.1029/2009GL037716.
- Durgun, Y.O., Gilliams, S., Tychon, B., Djaby, B., Duveiller, G., 2014. Improving remote sensing derived dry matter productivity by adding water limitation factor, in: *GV2M: Global vegetation monitoring and modeling*, Avignon, France. Oral presentation.
- Edwards, J.M., 2009. Simulation of land surface temperatures: comparison of two climate models and satellite retrievals. *Geosci. Model Dev.* 2, 123–136.
- Foken, T., Aubinet, M., Finnigan, J.J., Leclerc, M.Y., Mauder, M., Pau, U., 2011. Results of a panel discussion about the energy balance closure correction for trace gases. *Bull. Amer. Meteorol. Soc.* 92 (4), 13–18.
- Foken, T., Wichura, B., 1996. Tools for quality assessment of surface-based flux measurements. *Agric. For. Meteorol.* 78, 83–105.
- Frank, J.M., Massman, W.J., Ewers, B.E., 2013. Underestimates of sensible heat flux due to vertical velocity measurement errors in non-orthogonal sonic anemometers. *Agr. Forest Meteorol.* 171, 72–81.
- Freitas, S.C., Trigo, I.F., Bioucas-Dias, J.M., Göttsche, F., 2010. Quantifying the uncertainty of land surface temperature retrievals from SEVIRI/meteosat. *IEEE T. Geosci. Remote* 48, 523–534.
- Garcia, M., I. Sandholt, P.C., Ridler, M., Mougins, E., Kergoat, L., Timouk, F., Fensholt, R., Domingo, F., 2014. Actual evapotranspiration in drylands derived from in-situ and satellite data: Assessing biophysical constraints. *Remote Sens. Environ.* 131, 103–118.
- García-Haro, F.J., Camacho-de Coca, F., Meliá, J., Martínez, B., 2005a. Operational derivation of vegetation products in the framework of the LSA SAF project, in: *Proceedings of the EUMETSAT Meteorological Satellite Conference*, EUMETSAT, p. 116.
- García-Haro, F.J., Sommer, S., Kemper, T., 2005b. Variable multiple endmember spectral mixture analysis (VMESMA). *Int. J. Remote Sens.* 26, 2135–2162.
- Garcia-Haro, J., Verger, A., Camacho, F., Melia, J., 2008. LSA-SAF Product User Manual: Vegetation parameters (FVC, LAI, FAPAR), PUM-VEGA v2.1. Technical Report. LSA-SAF.
- Garrigues, S., Lacaze, R., Baret, F., Morisette, J.T., Weiss, M., Nickeson, J.E., Fernandes, R., Plummer, S., Shabanov, N.V., Myneni, R.B., Knyazikhin, Y., Yang, W., 2008. Validation and intercomparison of global leaf area index products derived from remote sensing data. *J. Geophys. Res.* 113 (G2). Doi: 10.1029/2007JG000635.
- Ge, J., 2009. On the proper use of satellite-derived leaf area index in climate modeling. *J. Climate* 22 (16), 4427–4433. Doi: 10.1175/2009JCLI2868.1.

- Geiger, B., Carrer, D., Franchistéguy, L., Roujean, J., Meurey, C., 2008a. Land surface albedo derived on a daily basis from Meteosat Second Generation observations. *IEEE T. Geosci. Remote* 46, 3841–3856.
- Geiger, B., Meurey, C., Lajas, D., Franchistéguy, L., Carrer, D., Roujean, J.L., 2008b. Near real-time provision of downwelling shortwave radiation estimates derived from satellite observations. *Meteorol. Appl.* 15, 411–420.
- Gellens-Meulenberghs, F., 2000. Evapotranspiration and surface heat fluxes over Belgium: outcome and perspectives. *Agronomie* 20, 857–868.
- Gellens-Meulenberghs, F., 2005. Sensitivity tests of an energy balance model to choice of stability functions and measurement accuracy. *Bound.-Lay. Meteorol.* 115, 453–471.
- Gellens-Meulenberghs, F., Arboleda, A., Ghilain, N., 2007. Towards a continuous monitoring of evapotranspiration based on MSG data, in: Owe, M., Neale, C. (Eds.), *Remote Sensing for Environmental Monitoring and Change Detection*. IAHS Publ. volume 316, pp. 228–234.
- Gentine, P., Entekhabi, D., Chehbouni, A., Boulet, G., Duchemin, B., 2007. Analysis of evaporative fraction diurnal behaviour. *Agr. Forest Meteorol.* 143, 12–29.
- Ghent, D., Kaduk, J., Remedio, J., Balzter, H., 2011. Data assimilation into land surface models: the implications for climate feedbacks. *Int. J. Remote Sens.* 32 (3), 617–632.
- Ghilain, N., Arboleda, A., Gellens-Meulenberghs, F., 2011. Evapotranspiration modelling at large scale using near-real time MSG SEVIRI derived data. *Hydrol. Earth Sys. Sci.* 15 (3), 771–786.
- Ghilain, N., Arboleda, A., Sepulcre-Canto, G., Batelaan, O., Ardo, J., Gellens-Meulenberghs, F., 2012. Improving evapotranspiration in land surface models by using biophysical parameters derived from MSG/SEVIRI satellite. *Hydrol. Earth Sys. Sci.* 16, 2567–2583.
- Ghilain, N., Gellens-Meulenberghs, F., 2014. Impact of land cover map resolution and geolocation accuracy on evapotranspiration simulations by a land surface model. *Remote Sensing Letters Submitted*.
- Gibelin, A.L., Calvet, J.C., Roujean, J.L., Jarlan, L., Los, S.O., 2006. Ability of the land surface model ISBA-A-gs to simulate leaf area index at the global scale: Comparison with satellites products. *J. Geophys. Res.* 111 (D18). Doi: 10.1029/2005JD006691.
- Gil, M., Garrido, A., Hernandez-Mora, N., 2013. Direct and indirect economic impacts of drought in the agri-food sector in the Ebro River basin (Spain). *Nat. Hazards Earth Syst. Sci.* 13, 2679 – 2694.
- Gillies, K.K., Carlson, T.N., 1995. Thermal remote sensing of surface soil water content with partial vegetation cover for incorporation into climate models. *J. Applied Meteorol.* 34, 745–756.

- Göckede, M., Foken, T., Aubinet, M., Aurela, M., Banza, J., Bernhofer, C., Bonnefond, J., Brunet, Y., Carrara, A., Clement, R., Dellwik, E., Elbers, J., Eugster, W., Fuhrer, J., Granier, A., Grünwald, T., Heinesch, B., Janssens, I.A., Knohl, A., Koeble, R., Laurila, T., Longdoz, B., Manca, G., Marek, M., Markkanen, T., Mateus, J., Mateucci, G., Mauder, M., Migliavacca, M., Minerbi, S., Moncrieff, J., Montagnani, L., Moors, E., Ourcival, J.M., Papale, D., Pereira, J., Pilegaard, K., Pita, G., Rambal, S., Rebmann, C., Rodrigues, A., Rotenberg, E., Sanz, M.J., Sedlak, P., Seufert, G., Siebicke, L., Soussana, J.F., Valentini, R., Vesala, T., Verbeeck, H., Yakir, D., 2008. Quality control of CarboEurope flux data-part i: Coupling footprint analyses with flux data quality assessment to evaluate sites in forest ecosystems. *Biogeosciences* 5, 433–450.
- Göckede, M., Markkanen, T., Hasager, C.B., Foken, T., 2006. Update of footprint-based approach for the characterisation of complex measurement sites. *Boundary-Layer Meteorology* 118 (3), 635–655.
- Göckede, M., Rebmann, C., Foken, T., 2004. A combination of quality assessment tools for eddy covariance measurements with footprint modelling for the characterisation of complex sites. *Agric. For. Meteorol.* 127, 175–188.
- Gokmen, M., Vekerdy, Z., Lubczynski, M.W., Timmermans, J., Batelaan, O., Verhoef, W., 2013. Assessing groundwater storage changes using rs-based evapotranspiration and precipitation at a large semi-arid basin scale. *J. Hydrometeorol.* 14 (6), 1733–1753. Doi: 10.1175/JHM-D-12-0156.1.
- Gond, V., Bartholomé, E., Ouattara, F., Nonguierma, A., Bado, L., 2004. Surveillance et cartographie des plans d'eau et des zones humides et inondables en région arides avec l'instrument VEGETATION embarqué sur SPOT-4. *Int. J. Remote Sensing* 25 (5), 987–1004.
- Göttsche, F., 2013. Validation of land surface temperature products with 5 years of permanent in-situ measurements in 4 different climate regions, in: Proc. 'EUMETSAT Meteorological Satellite conference', EUMETSAT.
- Goulden, M.L., Miller, S.D., da Rocha, H.R., Menton, M.C., de Freitas, H.C., Figueira, A.M.E.S., de Sousa, C.A.D., 2004. Diel and seasonal patterns of tropical forest CO₂ exchange. *Ecol. Appl.* 14, 42–54.
- Granier, A., Biron, P., Lemoine, D., 2000. Water balance, transpiration and canopy conductance in two beech stands. *Agr. Forest Meteorol.* 100, 291–308.
- Grippa, M., Kergoat, L., Frappart, F., Araud, Q., Boone, A., de Rosnay, P., Lemoine, J.M., Gascoin, S., Balsamo, G., Ottlé, C., Decharme, B., Saux-Picart, S., Ramillien, G., 2011. Land water storage variability over West Africa estimated by Gravity Recovery and Climate Experiment (GRACE) and land surface models. *Water Resour. Res.* 47 (5). Doi: 10.1029/2009WR008856.
- Gu, Y., Bélair, S., Mahfouf, J.F., Deblonde, G., 2006. Optimal interpolation analysis of leaf area index using MODIS data. *Rem. Sens. Environ.* 104 (3), 283–296. Doi: 10.1016/j.rse.2006.04.021.

- Hamdi, R., Degrauwe, D., Termonia, P., 2012. Coupling the town energy balance (TEB) scheme to an operational limited-area NWP model: Evaluation for a highly urbanized area in Belgium. *Weather and Forecasting* 27, 323–344.
- Harris, K., O'Hagan, A., Quegan, S., 2010. The impact of satellite-derived land cover uncertainty on carbon cycle calculations. *IEEE Geosciences and Remote Sensing Letters* 15, 771–786.
- Hsieh, C.I., Katul, G.G., Chi, T.W., 2000. An approximate analytical model for footprint estimation of scalar fluxes in thermally stratified atmospheric flows. *Advances in Water Resources* 23, 765–772.
- Hunsberger, C., Evans, T.P., et al., 2012. The fifth global environmental outlook report, chapter 3: land. UNEP. 32 pp., Available online at http://www.unep.org/geo/pdfs/geo5/GEO5_report_C3.pdf.
- Idso, S., 1981. A set of equations for the full spectrum and 8- and 14- micron and 10.5- to 12.5 thermal radiation from cloudless skies. *Wat. Res. Res.* 17, 295–304.
- Immerzeel, W.W., Droogers, P., 2008. Calibration of a distributed hydrological model based on satellite evapotranspiration. *J. Hydrol.* 349 (3-4), 411–424.
- Ineichen, P., Barroso, C.S., Geiger, B., Hollmann, R., Marsouin, A., Mueller, R., 2009. Satellite application facilities irradiance products: hourly time step comparison and validation over Europe. *Int. J. Remote Sens.* 30 (21), 5549–5571. Doi: 10.1080/01431160802680560.
- Jaeger, J.A.G., Soukup, T., Madrinan, L.F., Schwick, C., Kienast, F., 2011. Landscape fragmentation in Europe. EEA report.
- Jarlan, L., Balsamo, G., Lafont, S., Beljaars, A., Calvet, J.C., Mougin, E., 2008. Analysis of leaf area index in the ECMWF land surface model and impact on latent heat and carbon fluxes: Application to West Africa. *J. Geophys. Res.* D 113 (D24). Doi: 10.1029/2007JD009370.
- Jarvis, P.G., 1976. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. *Phil. Trans. Roy. Soc. London B.* 273 (927), 593–610.
- Jiang, L., Kogan, F.N., Guo, W., Tarpley, J.D., Mitchell, K.E., Ek, M.B., Tian, Y., Zheng, W., Zou, C.Z., Ramsay, B.H., 2010. Real-time weekly global green vegetation fraction derived from advanced very high resolution radiometer-based NOAA operational global vegetation index (GVI) system. *J. Geophys. Res.* 115 (D11). Doi: 10.1029/2009JD013204.
- Jimenez, C., Prigent, C., Aires, F., 2009a. Towards an estimation of global land surface heat fluxes from multisatellite observations. *J. Geophys. Res.* 114 (D6). Doi: 10.1029/2008JD011392.
- Jimenez, C., Prigent, C., Mueller, B., Seneviratne, S.I., McCabe, M.F., Rossow, W.B., Balsamo, G., Betts, A.K., Dirmeyer, P.A., Fisher, J.B., Jung, M., Kanamitsu, M., Reichle, R.H., Reichstein, M., Rodell, M.,

- Sheffield, J., Tu, K., Wang, K., 2009b. Global intercomparison of 12 land surface heat flux estimates. *J. Geophys. Res.* 116 (D2). Doi: 10.1029/2010JD014545.
- Jimenez, M.A., Mira, A., Cuxart, J., Luque, A., Alonso, S., Guijarro, J.A., 2008. Verification of a clear-sky mesoscale simulation using satellite-derived surface temperatures. *Mon. Wea. Rev.* 12, 5148–5161. Doi: 10.1175/2008MWR2461.1.
- Joffre, R., Rambal, S., Romane, F., 1996. Local variations of ecosystem functions in a Mediterranean evergreen oak woodland. *Ann. For. Sci.* 53, 561–570.
- Jung, M., Henkel, K., Herold, M., Churkina, G., 2006. Exploiting synergies of global land cover products for carbon cycle modeling. *Rem. Sens. Environ.* 101, 534–553.
- Kabsch, E., Olesen, F.S., Prata, F., 2008. Initial results of the land surface temperature (LST) validation with the Evora, Portugal, ground-truth station measurements. *Int. J. Remot. Sens.* 29, 5329–5345.
- Kahan, D.S., Xue, Y., Allen, S.J., 2006. The impact of vegetation and soil parameters in simulations of surface energy and water balance in the semi-arid sahel: A case study using SEBEX and HAPEX-Sahel data. *J. Hydrol.* 320 (1-2), 238–259. Doi: 10.1016/j.hydrol.2005.07.011.
- Kalma, J.D., McVicar, T.R., McCabe, M.F., 2008. Estimating land surface evapotranspiration: A review of methods using remotely sensed surface temperature data. *Surveys in Geophysics* 29 (4-5), 421–469. Doi: 10.1007/s10712-008-9037-z.
- Kaptué Tchunte, A.T., De Jong, S.M., Roujean, J.L., Favier, C., Mering, C., 2011. Ecosystem mapping at the African continent scale using a hybrid clustering approach based on 1-km resolution multi-annual data from SPOT/VEGETATION. *Rem. Sens. Environ.* 115 (2), 452–464. Doi: 10.1016/j.rse.2010.09.015.
- Kaptué Tchunte, A.T., Roujean, J.L., Faroux, S., 2010. ECOCLIMAP-II: an ecosystem classification and land surface parameter database of Western Africa at 1 km resolution for the African Monsoon Multidisciplinary Analysis (AMMA) project. *Rem. Sens. Environ.* 114 (5), 961–976. Doi: 10.1016/j.rse.2009.12.008.
- Kato, H., Rodell, M., Beyrich, F., Cleugh, H., van Gorsel, E., Liu, H., Meyers, T.P., 2007. Sensitivity of land surface simulations to model physics, parameters and forcings, at four CEOP sites. *J. Meteor. Soc. Japan* 85A, 187–204.
- Kergoat, L., Grippa, M., Baille, A., Lacaze, R., Mougin, E., Ottlé, C., Pellarin, T., Polcher, J., de Rosnay, P., Roujean, J.L., Sandholt, I., Taylor, C., Zin, I., Zribi, M., 2011. Remote sensing of the land surface during the African Monsoon Multidisciplinary Analysis (AMMA). *Atmospheric Science Letters* 12 (1), 129–134. Doi: 10.1002/asl.325.

- Kochendorfer, J.P., Meyers, T.P., Frank, J.M., Massman, W.J., Heuer, M.W., 2012. How well can we measure the vertical wind speed? implications for fluxes of energy and mass. *Boundary-Layer Meteorol.* 145 (2), 383–398.
- Koster, R.D., Houser, P.R., Engman, E.T., Kustas, W.P., 1999. Remote sensing may provide unprecedented hydrological data. *Eos Trans. AGU* 80 (4), 156–156.
- Kouadio, L., Duveiller, G., Djaby, B., Jarroudi, M.E., Defourny, P., Tychon, B., 2012. Estimating regional wheat yield from the shape of decreasing curves of green area index temporal profiles retrieved from MODIS data. *International Journal of Applied Earth Observation and Geoinformation* 18, 111–118.
- Krajnovic, B., 2012. Analysis of precipitation and the values of the linear trend of precipitation in the area of Dinarides of Bosnia and Herzegovina for the period 2001-2010. *BALWOIS 2012*, Orhid, Republic of Macedonia.
- Kroon, P.S., 2004. De Sluiting van de oppervlakte energiebalans in Cabauw gedurende TEBEX (1995-1996), TR-261, 63 pp. Technical Report. KNMI.
- Kutsch, W., Hanan, N., Scholes, R.J., McHugh, I., Kubheka, W., Eckhardt, H., Williams, C., 2008. Response of carbon fluxes to water relations in a savanna ecosystem in South Africa. *Biogeosciences* 5, 1797–1808. Doi: 10.5194/bg-5-1797-2008.
- Lacaze, R., Balsamo, G., Baret, F., Calvet, J., Camacho, F., d’Andrimont, R., Pacholczyk, P., Poilvé, H., Smets, B., Tansey, K., Trigo, I., Wagner, W., 2010. Geoland2 - towards an operational GMES land monitoring core service: first results of the biogeophysical parameters core mapping service, in: *Abstract book of the Recent advances in quantitative remote sensing (RAQRS): 3rd international symposium (27 September - 1 October 2010, Torrent, Spain, p. 116.*
- Leng, P., Song, X., Li, Z.L., Ma, J., Zhou, F., Li, S., 2014. Bare surface soil moisture retrieval from the synergistic use of optical and thermal infrared data. *International J. Remote Sens.* 35 (3), 988–1003.
- Leuning, R., Gorsel, E.V., Massman, W.J., Isaac, P.R., 2012. Reflections on the surface energy imbalance problem. *Agr. Forest Meteorol.* 156, 65–74.
- Lhomme, J.P., Elguero, E., 1999. Examination of evaporative fraction diurnal behaviour using a soil-vegetation model coupled with a mixed-layer model. *Hydrol. Earth Syst. Sci.* 3, 259–270.
- Li, Z.L., Tang, R., Wan, Z., Bi, Y., Zhou, C., Tang, B., Yan, G., Zhang, X., 2009. A review of current methodologies for regional evapotranspiration estimation from remotely sensed data. *Sensors* 9 (5), 3801–3853. Doi: 10.3390/s90503801.
- Loveland, T.R., Reed, B.C., Brown, J.F., Ohlen, D.O., Zhu, Z., Yang, L., 2000. Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. *Int. J. Remote Sens.* 21, 1303–1330.

- Lu, L., Shuttleworth, J., 2002. Incorporating NDVI-derived LAI into the climate version of RAMS and its impact on regional climate. *J. Hydrometeorol.* 3 (3), 347–362.
- Macauley, M.K., 2009. Earth observations in social science research for management of natural resources and the environment: Identifying the landsat contribution. *The Journal of Terrestrial Observation* 1 (2), 31–51.
- Massari, C., Brocca, L., Barbetta, S., Papathanasiou, C., Mimikou, M., Moramarco, T., 2013. Using globally available soil moisture indicators for flood modelling in Mediterranean catchments. *Hydrol. Earth Syst. Sci. Discuss.* 10, 10997–11033.
- Masson, V., Champeaux, J.L., Chauvin, F., Meriguet, C., Lacaze, R.A., 2003. Global database of land surface parameters at 1-km resolution in meteorological and climate models. *J. Climate* 16, 1261–1282.
- Mellab, K., 2009. PROBA-V spacecraft and vegetation instrument presentation, PROBA-V International Users Committee, brussels, 14 december 2009.
- Merbold, L., Ardö, J., Arneth, A., Scholes, R.J., Nouvellon, Y., de Grandcourt, A., Archibald, S., Bonnefond, J.M., Boulain, N., Brueggemann, N., Bruemmer, C., Cappelaere, B., Ceschia, E., El-Khidir, H.A.M., El-Tahir, B.A., Falk, U., Lloyd, J., Kergoat, L., Dantec, V.L., Mougin, E., Muchinda, M., Mukelabai, M.M., Ramier, D., Rounsard, O., Timouk, F., Veenendaal, E.M., Kutsch, W.L., 2009. Precipitation as driver of 20 carbon fluxes in 11 African ecosystems. *Biogeosciences* 6, 1027–1041.
- Meyers, T.P., Hollinger, S.E., 2004. An assessment of storage terms in the surface energy balance of maize and soybean. *Agr. Forest Meteorol.* 125, 105–115.
- Miglietta, F., Gioli, B., Brunet, Y., Hutjes, R.W.A., Matese, A., Sarrat, C., Zaldei, A., 2009. Sensible and latent heat flux from radiometric surface temperatures at the regional scale: methodology and evaluation. *Biogeosciences* 6, 1975–1986.
- Miller, J., Barlage, M., Zeng, X., Wei, H., Mitchell, K., Tarpley, D., 2006. Sensitivity of the NCEP/Noah land surface model to the MODIS green vegetation fraction data set. *Geophys. Res. Letters* 33 (L13). Doi: 10.1029/2006GL026636.
- Mougin, E., Hiernaux, P., Kergoat, L., Grippa, M., de Rosnay, P., Timouk, F., Dantec, V.L., Demarez, V., Lavenu, F., Arjounin, M., Lebel, T., Soumaguel, N., Ceschia, E., Mougnot, B., Baup, F., Frappart, F., Frison, P., Gardelle, J., Gruhier, C., Jarlan, L., Mangiarotti, S., Sanou, B., Tracol, Y., Guichard, F., Trichon, V., Diarra, L., Soumaré, A., Koité, M., Dembélé, F., Lloyd, C., Hanan, N., Damesin, C., Delon, C., Serça, D., Galy-Lacaux, C., Seghieri, J., Becerra, S., Dia, H., Gangneron, F., Mazzega, P., 2009. The AMMA-CATCH Gourma observatory site in mali: Relating climatic variations to changes in vegetation, surface hydrology, fluxes and natural resources. *J. Hydrol.* 375 (1-2), 14–33. Doi: 10.1016/j.jhydrol.2009.06.045.

- Mu, Q., Heinsch, F., Zhao, M., Running, S.W., 2007. Development of a global evapotranspiration algorithm based on MODIS and global meteorology data. *Remote Sens. Environ.* 111, 519–536.
- Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models, part I-A discussion of principles. *J. Hydrol.* 10 (3), 282–290. Doi: 10.1016/0022-1694(70)90255-6.
- Njoku, E.G., Entekhabi, D., 1996. Passive microwave remote sensing of soil moisture. *J. Hydrology* 184, 101–129.
- Njoku, E.G., Jackson, V., Lakshmi, V., Chan, T., Nghiem, S.V., 2003. Soil moisture retrieval from AMSR-E. *IEEE T. Geosci. Remote* 41, 215–229.
- Noilhan, J., Planton, A., 1989. A simple parameterization of land surface processes for meteorological models. *Mon. Wea. Rev.* 117 (3), 536–549.
- Oleson, K., Bonan, G., 2000. The effects of remotely sensed plant functional type and leaf area index on simulations of boreal forest surface fluxes by the NCAR land surface model. *J. Hydrometeorol.* 1 (5), 431–446.
- Owe, M., de Jeu, R., Holmes, T., 2008. Multisensor historical climatology of satellite-derived global land surface moisture. *J. Geophys. Res.* 113 (F1). Doi: 10.1029/2007JF000769.
- Pauwels, V.R.N., Wood, E., 2000. The importance of classification differences and spatial resolution of land cover data in the uncertainty in model results over boreal ecosystems. *J. Hydrometeorol.* 1 (3), 255–266.
- Pedinotti, V., Boone, A., Decharme, B., Crétaux, J., Mognard, N., Panthou, G., Papa, F., Tanimoun, B.A., 2012. Evaluation of the ISBA-TRIP continental hydrologic system over the niger basin using in situ and satellite derived datasets. *Hydrol. Earth Syst. Sci.* 16, 1745–1773.
- Pekel, J.F., Bartholomé, E., Clerici, M., 2010. Assessing the use of LSA-SAF VEGA data for environmental monitoring in Africa: fractional cover and natural vegetation condition assessment, in: *LSA-SAF 4th user workshop*, Toulouse.
- Pereira, J.S., Mateus, J.A., Aires, L.M., Pita, G., Pio, C., David, J.S., Andrade, V., David, J.B.T.S., Paçao, T.A., Rodrigues, A., 2007. Net ecosystem carbon exchange in three contrasting mediterranean ecosystems-the effect of drought. *Biogeosciences* 4, 791–802.
- Price, J.C., 1980. The potential of remotely sensed thermal infrared data to infer surface soil moisture and evaporation. *Water Resour. Res.* 16, 787–795.
- Prigent, C., Aires, F., Rossow, W.B., Robock, A., 2005. Sensitivity of satellite microwave and infrared observations to soil moisture at a global scale: Relationship of satellite observations to in situ soil moisture measurements. *J. Geophys. Res.* 110 (D11). Doi: 10.1029/2004JD005094.

- Proud, S.R., Fensholt, R., Rasmussen, L.V., Sandholt, I., 2011. Rapid response flood detection using MSG geostationary satellite. *International Journal of Applied Earth Observation and Geoinformation* 13 (4), 536–544. Doi: 10.1016/j.jag.2011.02.002.
- Quaife, T., Quegan, S., Disney, M., Lewis, P., Lomas, M., Woodward, F.I., 2008. Impact of land cover uncertainties on estimates of biospheric carbon fluxes. *Global Biogeochemical Cycles* 22 (4). Doi: 10.1029/2007GB003097.
- Ramillien, G., Famiglietti, J.S., Wahr, J., 2008. Detection of continental hydrology and glaciology signals from GRACE: a review. *Surveys in Geophysics* 29 (4), 361–374.
- Rebmann, C., Göckede, M., Foken, T., Aubinet, M., Aurela, M., Berbigier, P., Bernhofer, C., Buchmann, N., Carrara, A., Cescatti, A., Ceulemans, R., Clement, R., Elbers, J., Granier, A., Grünwald, T., Guyon, D., Havrankova, J., Heinesch, B., Knohl, A., Laurila, T., Longdoz, B., Marcolla, B., Markkanen, T., Miglietta, F., Moncrieff, J., Montagnani, L., Moors, E.J., Nardino, M., Ourcival, J.M., Rambal, S., Rannik, U., Rotenberg, E., Sedlak, P., Unterhuber, G., Vesala, T., Yakir, D., 2005. Quality analysis applied on eddy covariance measurements at complex forest sites using footprint modelling. *Theor. Appl. Climatol.* 80, 121–141.
- Rebmann, C., Zeri, M., Lasslop, G., Mund, M., Kolle, O., Schulze, E.D., Feigenwinter, C., 2010. Treatment and assessment of the CO₂-exchange at a complex forest site in Thuringia, Germany. *Agr. Forest Meteorol.* 150 (5), 684–691. Doi: 10.1016/j.agroformet.2009.11.001.
- Redelsperger, J.L., Thorncroft, C., Diedhiou, A., Lebel, T., Parker, D., Polcher, J., 2006. African monsoon, multidisciplinary analysis (AMMA): An international research project and field campaign. *Bull. Amer. Meteorol. Soc.* 87 (12), 1739–1746.
- Reithmaier, L.M., Göckede, M., Markkanen, T., Knohl, A., Churkina, G., Rebmann, C., Buchmann, N., Foken, T., 2006. Use of remotely sensed land use classification for a better evaluation of micrometeorological flux measurement sites. *Theor. Appl. Climatol.* 84, 219–233.
- Rodell, M., Famiglietti, J.S., Chen, J., Seneviratne, S.I., Viterbo, P., Holl, S., Wilson, C.R., 2004a. Basin scale estimates of evapotranspiration using grace and other observations. *Geophys. Res. Lett.* 31 (20).
- Rodell, M., Houser, P.R., 2004. Updating a land surface model with MODIS derived snow cover. *J. Hydrometeorol.* 5 (6), 1064–1075.
- Rodell, M., Houser, P.R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin, J.K., Walker, J.P., Lohmann, D., Toll, D., 2004b. The Global Land Data Assimilation System. *B. Am. Meteorol. Soc.* 85 (3), 381–394. Doi: 10.1175/BAMS-85-3-381.
- Romaguera-Albentosa, M., Krol, M.S., Salama, M.S., Hoekstra, A.Y., Su, Z., 2012. Determining irrigated areas and quantifying blue water use in europe using remote sensing meteosat second generation (MSG)

- products and global land data assimilation system (GLDAS) data. Photogrammetric engineering and remote sensing 78, 861–873.
- Rosema, A., 1993. Using METEOSAT for operational evapotranspiration and biomass monitoring in the Sahel region. *Remote Sens. Environ.* 46, 27–44.
- Roulin, E., 2002. Assimilating latent heat fluxes from meteorological geostationary satellite data in a hydrological model at the scale of 20,000 km^2 , in: EGS XXVII General assembly, Nice, France.
- Samain, O., Kergoat, L., Hiernaux, P., Guichard, F., Mougin, E., Timouk, F., Lavenu, F., 2008. Analysis of the in situ and MODIS albedo variability at multiple time scales in the Sahel. *J. Geophys. Res.* 113 (D14). Doi: 10.1029/2007JD009174.
- Schmid, H.P., 1994. Source areas for scalars and scalar fluxes. *Boundary-Layer Meteorol.* 67, 293–318.
- Sepulcre-Canto, G., 2013. Assessment of the EUMETSAT LSA-SAF evapotranspiration product for agricultural drought monitoring in Europe, in: 5th LSA-SAF user workshop, Karlsruhe, Germany.
- Sepulcre-Cantó, G., Gellens-Meulenberghs, F., Arboleda, A., Duveiller, G., De Wit, A., Eerens, H., Djaby, B., Defourny, P., 2013. Estimating crop specific evapotranspiration using remote sensing imagery at various spatial resolutions for improving crop growth modeling. *Int. J. Remote Sens.* 34 (9-10), 3274–3288. Doi: 10.1080/01431161.2012.716911.
- Simmons, A., Uppala, S., Dee, D., Kobayashi, S., 2006. ERA-Interim: New ECMWF reanalysis products from 1989 onwards. *ECMWF Newsletter* 10, 26–35.
- Sjöström, M., Ardö, J., Eklundh, L., El-Tahir, B.A., EL-Khidir, H.A.M., Pilesjö, P., Seaquist, J., 2009. Evaluation of satellite based indices for primary production estimates in a sparse savanna in the sudan. *Biogeosciences* 6, 129–138.
- Song, X., Leng, P., Li, X., Li, X., Ma, J., 2013. Retrieval of daily evolution of soil moisture from satellite-derived land surface temperature and net surface shortwave radiation. *International J. Remote Sens.* 34 (9-10), 3289–3298.
- Steenmans, C., 2002. The CORINE land cover inventory. Available online at <http://www.gmes.info/pages-principales/library/forum-and-events/3rd-gmes-forum/plenary-session-2/>.
- Stisen, S., Sandholt, I., Noergaard, A., Fensholt, R., Jensen, K.H., 2008. Combining the triangle method with thermal inertia to estimate regional evapotranspiration - Applied to MSG-SEVIRI data in the Senegal River basin. *Rem. Sens. Environ.* 112 (3), 1242–1255. Doi: 10.1016/j.rse.2007.08.013.
- Stöckli, R., Lawrence, D.M., Niu, G.Y., Oleson, K.W., Thornton, P.E., Yang, Z.L., Bonan, G.B., Denning, A.S., Running, S.W., 2008. Use of FLUXNET in the Community Land Model development. *J. Geophys. Res.* 113 (G1). Doi: 10.1029/2007JG000562.

- Stoy, P.C., Mauder, M., Foken, T., Marcolla, B., Boegh, E., Ibrom, A., Arain, M.A., Arneth, A., Aurela, M., Bernhofer, C., Cescatti, A., Dellwik, E., Duce, P., Gianelle, D., van Gorsel, E., Kiely, G., Knohl, A., Margolis, H., McCaughey, H., Merbold, L., Montagnani, L., Papale, D., Reichstein, M., Saunders, M., Serrano-Ortiz, P., Sottocornola, M., Spano, D., Vaccari, F., Varlagin, A., 2013. A data-driven analysis of energy balance closure across FLUXNET research sites: the role of landscape scale heterogeneity. *Agr. Forest Meteorol.* 171, 137–152.
- Su, H., Wood, E.F., McCabe, M.F., Su, Z., 2007. Evaluation of remotely sensed evapotranspiration over the CEOP EOP-1 reference sites. *J. Meteorol. Soc. Jpn.* 85, 439–459.
- Su, Z., 2002. The Surface Energy Balance System (SEBS) for estimation of turbulent heat fluxes. *Hydrol. Earth Syst. Sci.* 6, 85–99.
- Su, Z., Dorigo, W., Fernandez-Prieto, D., Van Helvoirt, M., Hungershoefer, K., deãJeu, R., Parinussa, R., Timmermans, J., Roebeling, R., Schröder, M., Schulz, J., Van der Tol, C., Stammes, P., Wagner, W., Wang, L., Wang, P., Wolters, E., 2010. Earth observation water cycle multi-mission observation strategy (WACMOS). *Hydrol. Earth Syst. Sci. Discuss.* 7, 7899–7956.
- Suni, T., Berninger, F., Vesala, T., Markkanen, T., Pertti, H., Makela, A., Ilvesniemi, H., Hanninen, H., Nikinmaa, E., Huttula, T., Laurila, T., Aurela, M., Grelle, A., Lindroth, A., Arneth, A., Shibistova, O., Lloyd, J., 2003. Air temperature triggers the recovery of evergreen boreal forest photosynthesis in spring. *Global Change Biology* 10, 1410–1426.
- Tang, Y., Lean, H.W., Bornemann, J., 2013. The benefits of the Met Office variable resolution NWP model for forecasting convection. *Meteorol. Appl.* 20 (4), 417–426.
- Taylor, C., de Jeu, R.A.M., Guichard, F., Harris, P.P., Dorigo, W., 2012. Afternoon rain more likely over drier soils. *Nature* 489, 423–426.
- Taylor, K.E., 2001. Summarizing multiple aspects of model performance in a single diagram. *J. Geophys. Res.* 106 (D7). Doi: 10.1029/2000JD900719.
- Tedeschi, V., Rey, A., Manca, G., Valentini, R., Jarvis, P.G., Borghetti, M., 2006. Soil respiration in a mediterranean oak forest at different developmental stages after coppicing. *Global Change Biology* 12 (1), 110–121. Doi: 10.1111/j.1365-2486.2005.01081.x.
- Tian, Y., Dickinson, R.E., Zhou, L., Zeng, X., Dai, Y., Myneni, R.B., Knyazikhin, Y., Zhang, X., Friedl, M., Yu, H., Wu, W., Shaick, M., 2006. Comparison of seasonal and spatial variations of LAI and fraction of absorbed photosynthetically active radiation from Moderate Resolution Imaging Spectroradiometer (MODIS) and Common Land Model. *J. Geophys. Res.* 109 (D1). Doi: 10.1029/2003JD003777.
- Tian, Y., Zhang, Y., Knyazikhin, Y., Myneni, R.B., Glassy, J.M., Dedieu, G., Running, S.W., 2000. Prototyping of MODIS LAI and FPAR algorithm with LASUR and LANDSAT data. *IEEE T. Geosci. Remote* 38 (5), 2387–2401.

- Timmermans, J., van der Tol, C., Verhoef, A., Wang, L., van Helvoirt, M., Verhoef, W., Su, Z., 2010. Quantifying the uncertainty in estimates of surface atmosphere fluxes by evaluation of SEBS and SCOPE models, in: Proc. 'Earth Observation and Water Cycle Science', ESA.
- Timmermans, W.J., Su, Z., Oliso, A., 2009. Footprint issues in scintillometry over heterogeneous landscapes. *Hydrol. Earth Syst. Sci.* 13, 2179–2190.
- Timouk, F., Kergoat, L., Mougin, E., Lloyd, C.R., Ceschia, E., Cohard, J.M., de Rosnay, P., Hiernaux, P., Demarez, V., Taylor, C.M., 2009. Response of surface energy balance to water regime and vegetation development in a Sahelian landscape. *J. Hydrology* 375 (1-2), 1–43. Doi: 10.1016/j.jydrol.2009.04.022.
- Trigo, I.F., Barroso, C., Viterbo, P., Freitas, S.C., Monteiro, I.T., 2010. Estimation of downward longwave radiation at the surface combining remotely sensed data and NWP data. *J. Geophys. Res.* 115 (D24). Doi: 10.1029/2010JD013888.
- Trigo, I.F., DaCamara, C.C., Viterbo, P., Roujean, J.L., Olesen, F., Barroso, C., de Coca, F.C., Carrer, D., Freitas, S.C., Garcia-Haro, J., Geiger, B., Gellens-Meulenberghs, F., Ghilain, N., Melia, J., Pessanha, L., Siljamo, N., Arboleda, A., 2011. The Satellite Application Facility on Land Surface Analysis. *Int. J. Remote Sens.* 32, 2725–2744.
- Trigo, I.F., Monteiro, I.T., Olesen, F., Kabsch, E., 2008. An assessment of remotely sensed land surface temperature. *J. Geophys. Res.* 113 (D17). Doi: 10.1029/2008JD010035.
- Turner, K., Georgiou, S., Clarck, R., Brouwer, R., Burke, J., 2004. FAO water report 27: Economic valuation of water resources in agriculture: from the sectoral to a functional perspective of natural resources management. Technical Report. FAO.
- Van Achteren, T., Dierckx, W., Sterckx, S., Livens, S., Saint, G., 2014. Proba-V - A SPOT-VGT successor mission, product definition and specifications. *International Journal of remote sensing* 35 (5).
- van den Hurk, B., Viterbo, P., Los, S., 2003. Impact of leaf area index seasonality on the annual land surface evaporation in a global circulation model. *J. Geophys. Res.* 108 (D6). Doi: 10.1029/2002JD002846.
- van den Hurk, B.J.J.M., Viterbo, P., Beljaars, A.C.M., Betts, A.K., 2000. Offline validation of the ERA40 surface scheme. ECMWF Technical Memorandum 295. 41 pp.
- Van Doninck, J., Peters, J., De Baets, B., De Clercq, E., Ducheyne, E., Verhoest, N.E.C., 2011. The potential of multitemporal Aqua and Terra MODIS apparent thermal inertia as a soil moisture indicator. *Int. J. Appl. Earth Obs.* 13, 934–941.
- Verger, A., Camacho, F., Garcia-Haro, F.J., Meliá, J., 2009. Prototyping of Land-SAF leaf area index algorithm with VEGETATION and MODIS data over Europe. *Remote Sens. Environ.* 113 (11), 2285–2297. Doi: 10.1016/j.rse.2009.06.009.

- Veroustraete, F., Li, Q., Verstraeten, W.W., Chen, X., Bao, A., Dong, Q., Liu, T., Willems, P., 2012. Soil moisture content retrieval based on apparent thermal inertia for Xinjiang province in China. *Int. J. Remot. Sens.* 33, 3870–3885.
- Verstraeten, W.W., Veroustraete, F., van der Sande, C.J., Grootaers, I., Feyen, J., 2006. Soil moisture retrieval using thermal inertia, determined with visible and thermal spaceborne data, validated for european forests. *Remote Sens. Environ.* 101, 299–314.
- Viterbo, P., Beljaars, A.C.M., 1995. An improved land surface parameterization scheme in the ECMWF model and its validation. *J. Climate* 8 (11), 2716–2748.
- W. H. Brutsaert, 1982. *Evaporation in the Atmosphere - Theory, History, and Applications*. Kluwer Academic, D. Reidel publishers, Dordrecht, The Netherlands.
- Wagner, W., Naeimi, V., Scipal, K., de Jeu, R., Martinez-Fernandez, J., 2007. Soil moisture from operational meteorological satellites. *Hydrogeol. J.* 15, 121 – 131.
- Wan, Z.M., Dozier, J., 1996. A generalized split-window algorithm for retrieving land-surface temperature from space. *IEEE T. Geosci. Remote* 34 (4), 892–905.
- Wang, K., Wang, P., Li, Z., Sparrow, M., Cribb, M., 2007. A simple method to estimate evapotranspiration from a combination of net radiation, vegetation indices and temperatures. *J Geophys. Res.* 112 (D15). DOI: 10.1029/2006JD008351.
- Wang, Z.M., Batelaan, O., De Smedt, F., 1996. A distributed model for water and energy transfer between soil, plants and atmosphere (WetSpa). *Phys. Chem. Earth* 21 (3), 189–193.
- Ward, H.C., Evans, J.G., Hartogensis, O.K., Moene, A.F., Bruin, H.A.R.D., Grimmond, C.S.B., 2013. A critical revision of the estimation of the latent heat flux from two-wavelength scintillometry. *Q. J. Roy. Meteor. Soc.* 139 (676), 1912–1922.
- Wesely, M.L., Hart, R.L., 1985. *Variability of short-term eddy correlation estimates of mass exchange*. D. Reidel, Dordrecht.
- Williams, M., Richardson, A.D., Reichstein, M., Stoy, P.C., Peylin, P., Verbeeck, H., Carvalhais, N., Jung, M., Hollinger, D.Y., Kattge, J., Leuning, R., Luo, Y., Tomelleri, E., Trudinger, C.M., Wang, Y.P., 2009. Improving land surface models with FLUXNET data. *Biogeosciences* 6, 1341–1359.
- Wilson, K.B., Goldstein, A.H., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., Bernhofer, C., Ceulemans, R., Dolman, H., Field, C., Grelle, A., Law, B., Meyers, T., Moncrieff, J., Monson, R., Oechel, W., Tenhunen, J., Valentini, R., Verma, S., 2002. Energy balance closure at FLUXNET sites. *Agr. Forest Meteorol.* 113, 223–243.

- Wipfler, E.L., Metselaar, K., van Dam, J.C., Feddes, R.A., van Meijgaard, E., van Uft, L.H., van den Hurk, B., Zwart, S., Bastiaanssen, W.G.M., 2011. Seasonal evaluation of the land surface scheme HTESSEL against remote sensing derived energy fluxes of the Transdanubian region in Hungary. *Hydrol. Earth Sys. Sci.* 15, 1257–1271.
- Wolfe, R.E., Nishihama, M., Fleig, A.J., Kuyper, J.A., Roy, D.P., Storey, J.C., Patt, F.S., 2002. Achieving sub-pixel geolocation accuracy in support of MODIS land science. *Rem. Sens. Environ.* 83 (1-2), 31–49.
- Wood, E.F., Jimenez, C., Seneviratne, S.I., McCabe, M., 2010. Satellite-based retrievals of global evapotranspiration, and a report on the GEWEX Landflux initiative, in: *Proc. 'Earth Observation and Water Cycle Science'*, ESA. p. 674.
- Xie, P., Arkin, P.A., 1997. Global precipitation: a 17 years monthly analysis based on gauge observations, satellite estimates, and numerical model output. *Bull. Amer. Meteor. Soc.* 78, 2539–2558.
- Yang, W., Huang, D., Tan, B., Stroeve, J.C., Shabanov, N.V., Knyazikhin, Y., Nemani, R.R., Myneni, R.B., 2006a. Analysis of leaf area index and fraction of PAR absorbed by vegetation products from the Terra MODIS sensor: 2000-2005. *IEEE Trans. Geosci. Remot. Sens.* 44 (7), 1829–1842. Doi: 10.1109/TGRS.2006.871214.
- Yang, W., Shabanov, N., Huang, D., Wang, W., Dickinson, R., Nemani, R., Knyazikhin, Y., Myneni, R., 2006b. Analysis of leaf area index products from combination of MODIS Terra and Aqua data. *Remote Sens. Environ.* 104 (3), 297–312. Doi: 10.1016/j.rse.2006.04.016.
- Zhao, W., Li, A., 2013. A downscaling method for improving the spatial resolution of AMSR-E derived soil moisture product based on MSG-SEVIRI data. *Remote Sens.* 5, 6790–6811.

Publications & Communications

Articles in peer-review journals

Published articles

- **N. Ghilain**, F. De Roo & F. Gellens-Meulenberghs (2014), Evapotranspiration monitoring with Meteosat Second Generation satellites: improvement opportunities from moderate spatial resolution satellites for vegetation, *Int. J. Remot. Sens.*, 35(7), 2654-2670.
- **N. Ghilain**, A. Arboleda, G. Sepulcre-Canto, O. Batelaan, J. Ardö & F. Gellens-Meulenberghs (2012), Improving evapotranspiration in a land surface model using biophysical variables derived from MSG/SEVIRI satellite, *Hydrol. Earth Syst. Sci.*, 16, 2567-2583.
- **N. Ghilain**, A. Arboleda & F. Gellens-Meulenberghs (2011), Evapotranspiration modelling at large scale using near-real time MSG SEVIRI derived data, *Hydrol. Earth Syst. Sci.*, 15, 771-786.
- I. F. Trigo, C. C. DaCamara, P. Viterbo, J.-L. Roujean, F. Olesen, C. Barroso, F. Camacho-de Coca, D. Carrer, S. C. Freitas, J. Garcia-Haro, B. Geiger, F. Gellens-Meulenberghs, **N. Ghilain**, J. Melia, L. Pessanha, N. Siljamo & A. Arboleda (2013), The Satellite Application Facility on Land Surface Analysis, *Int. J. Remote Sens.*, 32, 2725-2744.

Articles in review or in preparation

- **N. Ghilain**, A; Arboleda, I. F. Trigo, O. Batelaan & F. Gellens-Meulenberghs (2014), Tracking down soil moisture from MSG SEVIRI: fulfilling the promises of geostationary satellites, in preparation.
- **N. Ghilain** & F. Gellens-Meulenberghs (2014), Impact of land cover map resolution and geolocation accuracy on evapotranspiration simulations by a land surface model, submitted to Remote Sensing Letters.

Conference proceedings

- **N. Ghilain**, A. Arbeda & F. Gellens-Meulenberghs (2013), Evapotranspiration monitoring in semi-arid areas using MSG/SEVIRI derived data: improvements from the use of leaf area index and land surface temperature, Proceedings of EUMETSAT's user conference.
- A. Arboleda, **N. Ghilain** & F. Gellens-Meulenberghs (2012), EUMETSAT's LSA-SAF evapotranspiration products: status and perspectives, Proceedings of EUMETSAT's user conference.
- **N. Ghilain**, A. Arboleda & F. Gellens-Meulenberghs (2012), Monitoring evapotranspiration at sub-kilometer scale: downscaling MSG/SEVIRI images using moderate resolution remote sensing derived data, Proceedings of the 32nd EARSEL Symposium.
- A. Arboleda, **N. Ghilain** & F. Gellens-Meulenberghs (2011), EUMETSAT's LSA-SAF evapotranspiration: comparisons of operational product to observations and models at hydrological basisns scale, Proceedings of EUMETSAT's user conference.
- F. Gellens-Meulenberghs, **N. Ghilain** & A. Arboleda (2011), Land surface evapotranspiration as seen from Meteosat second generation satellites: LSA-SAF developments and perspectives, Proceedings (peer-reviewed) of the IGARSS conference, 4 pp.

- F. Gellens-Meulenberghs, A. Arboleda and **N. Ghilain** (2008), Evapotranspiration assessment by LSA-SAF: methodology, status of validation and plans for near future, Proceedings of EUMETSAT user's conference, 8 pp.
- **N. Ghilain**, A. Arboleda, F. Gellens-Meulenberghs (2008), Improvement of a surface energy balance model by the use of MSG-SEVIRI derived vegetation parameters, Proceedings of EUMETSAT user's conference, 7 pp.
- F. Gellens-Meulenberghs, A. Arboleda and **N. Ghilain** (2007), Towards a continuous monitoring of evapotranspiration based on MSG data, Remote Sensing for Environmental Monitoring and Change Detection, M. Owe and Ch. Neale eds., IAHS Publ., 316, p. 228-234.
- F. Gellens-Meulenberghs, A. Arboleda and **N. Ghilain** (2006), Status of development of the LSA-SAF evapotranspiration product, Proceedings of the 2nd LSA-SAF Training Workshop, 10 pp.
- A. Arboleda, **N. Ghilain** and F. Gellens-Meulenberghs (2005), The LSA-SAF evapotranspiration product-first results with MSG, Proceedings of EUMETSAT user's conference, 7 pp.

Peer-reviewed scientific reports

- **N. Ghilain**, F. De Roo & F. Gellens-Meulenberghs (2012), PROBA-VET project (Application of high spatial resolution vegetation information for large scale evapotranspiration monitoring): final report, PROBA-V preparatory program, 22 pp.
- N. Ghilain, A. Arboleda & F. Gellens-Meulenberghs (2009), LSA-SAF MET evapotranspiration product: Validation report.
- **N. Ghilain**, A. Arboleda & F. Gellens-Meulenberghs (2008), LSA-SAF MET evapotranspiration product: Validation report, 67 pp.
- A. Arboleda, **N. Ghilain** & F. Gellens-Meulenberghs (2008), LSA-SAF MET evapotranspiration product: Product User Manual, 17 pp.

- **N. Ghilain**, A. Arboleda & F. Gellens-Meulenberghs (2008), LSA-SAF MET evapotranspiration product: Algorithm Theoretical Basis Document.
- **N. Ghilain** (2004, Forcing of the TVM atmospheric model developed in perturbations mode, Master Thesis.

Conference abstracts

- **N. Ghilain**, A. Arboleda & F. Gellens-Meulenberghs (2013), Evapotranspiration monitoring in semi-arid areas using MSG/SEVIRI derived data: improvements from the use of leaf area index and land surface temperature, EUMETSAT's user conference, Vienna, Austria, September 2013 (oral presentation).
- F. Gellens-Meulenberghs, **N. Ghilain** & A. Arboleda (2011), Evapotranspiration assessment constrained by MSG SEVIRI derived data, iLEAPS conference, 2011.
- **N. Ghilain**, F. De Roo & F. Gellens-Meulenberghs (2012), , Belgian Earth Observation days, Brugge, Belgium, September 2012 (oral presentation).
- **N. Ghilain** and A. Arboleda and F. Gellens-Meulenberghs (2012), Monitoring of evapotranspiration at sub-kilometer scale: downscaling MSG/SEVIRI images using moderate resolution remote sensing derived data, 32nd EARSEL conference, Mykonos, Greece, May 2012 (oral presentation).
- **N. Ghilain**, F. De Roo, A. Arboleda & F. Gellens-Meulenberghs (2012), Impact on evapotranspiration of land cover and biophysical parameters derived from EO at different spatial resolution, 2nd Terrabites symposium, Frascati, Italy, February 2012.
- **N. Ghilain**, A. Arboleda, G. Sepulcre-Canto, O. Batelaan, J. Ardö & F. Gellens-Meulenberghs (2012), Improving evapotranspiration in land surface models by using biophysical parameters derived from MSG/SEVIRI satellite, EGU annual general assembly, Vienna, Austria, April 2012.
- **N. Ghilain**, F. De Roo, A. Arboleda & F. Gellens-Meulenberghs (2012), LSA-SAF evapotranspiration products based on MSG/SEVIRI: improvement opportunities

from moderate spatial resolution satellites sensors for vegetation (SPOT-VGT, MODIS, PROBA-V), EGU annual general assembly, Vienna, Austria, April 2012.

- **N. Ghilain**, A. Arboleda & F. Gellens-Meulenberghs (2009), Use of geostationary satellite imagery in optical and thermal bands for the estimation of soil moisture status and land evapotranspiration, European Geophysical Union, Vienna, 20-24 April 2009.
- A. Arboleda, **N. Ghilain** & F. Gellens-Meulenberghs (2008), LSA-SAF evapotranspiration over Europe and Africa: current results and comparison at different scales, European Geophysical Union, Vienna, 14-18 April.
- F. Gellens-Meulenberghs, **N. Ghilain**, A. Arboleda, S. Hasenauer & W. Wagner (2008), A combination of land surface modelling and remote sensing: synergy between LSA-SAF and H-SAF for soil moisture retrieval, European Geophysical Union, Vienna, 14-18 April.
- **N. Ghilain**, A. Arboleda & F. Gellens-Meulenberghs (2007), Using MSG-SEVIRI derived vegetation parameters in an energy balance model: methodology and impact on surface heat fluxes, European Geophysical Union, Vienna, 16-20 April.
- F. Gellens-Meulenberghs, W. Wagner, A. Arboleda, **N. Ghilain**, C. Kuenzer & S. Hasenauer (2007), Toward assimilation of METOP-ASCAT derived superficial soil moisture into a MSG-SEVIRI driven land surface model: a first LSA-SAF-H-SAF activity, European Geophysical Union, Vienna, 14-18 April.
- **N. Ghilain**, A. Arboleda & F. Gellens-Meulenberghs (2005), Derivation of evapotranspiration over Europe using MSG data in the framework of the LSA-SAF project, Stereo Project Scientific Meeting "Agriculture and vegetation at local scale", Habay-la-Neuve, Belgique, 20 Septembre.
- **N. Ghilain**, A. Arboleda & F. Gellens-Meulenberghs (2005), Assessment of the evapotranspiration and surface fluxes in the framework of the LSA-SAF: methodology and first results, European Geophysical Union, Vienna, 24-29 April.

Lectures

- **N. Ghilain:** LSA-SAF evapotranspiration and possible applications, Application of remote sensing data for drought monitoring: Introduction to EUMETSAT Land SAF products, organized by the World Meteorological Organization in Brdo, Slovenia, 11-15 November 2013.
- **N. Ghilain**, A. Arboleda and F. Gellens-Meulenberghs: Suivi de l' évapotranspiration par MSG, Cours sur l' utilisation des produits satellitaires aux applications agrométéorologiques, organized by EUMETSAT and WMO in Niamey, Niger, November 2012.
- **N. Ghilain** and A. Arboleda, Session 4: Evapotranspiration, EUMETRAIN LSA-SAF Week, organized by EUMETSAT, on-line platform, November 2011.
- **N. Ghilain:** Evapotranspiration monitoring from remote sensing: a large scale application, VUB workshop for masters students in hydrology, April 2011.

Successful project proposals

- PROBA-VET project, duration: 1 year, call: PROBA-V preparatory program, funding body: Belgian Science Policy.
- EVA3M project, duration: 1 year, call: STEREO-II program, funding body: Belgian Science Policy.