Monitoring Evapotranspiration at Sub-Kilometer Scale: Downscaling MSG/SEVIRI Images Using Moderate Resolution Remote Sensing Derived Data

Nicolas Ghilain, Alirio Arboleda and Françoise Gellens-Meulenberghs
Royal Meteorological Institute of Belgium, Brussels, Belgium;
nicolas.ghilain@meteo.be

Abstract. Continental scale evapotranspiration (ET) monitoring with Meteosat Second Generation geostationary satellite is on-going in the context of the Land Surface Analysis – Satellite Application Facility (LSA-SAF). The products are now operational and delivered to users. However, for some applications, higher spatial resolution is needed, as geostationary satellites cannot resolve sub-kilometer structures. In this paper, we explore the new opportunities offered by moderate resolution spaceborne sensors to downscale the LSA-SAF ET product at sub-kilometer range. More specifically, the continuity ensured by SPOT-VGT (1 km) and the future ProbaV satellite (330 m) is under focus. A downscaling scheme has been conceived, and then tested over two heterogeneous sites in Europe and Africa, using MODIS/Terra derived products as surrogates for future ProbaV. It is shown that the total evapotranspiration spatial pattern is globally conserved, but loss of detail can be brought back by the downscaling technique. Compared to typical summer, ground observations, 0.4-0.5 $mm.hr^{-1}$, the downscaled estimate is within an acceptable range, 0.42 $mm.hr^{-1}$. Comparison with downscaled results obtained using SPOT-VGT shows the high potential of the ProbaV satellite compared to SPOT-VGT, regarding the gain of detail with increased spatial resolution.

Keywords. Evapotranspiration, remote sensing, Meteosat, ProbaV.

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 user applications, including water management and agriculture, more and more techniques have been developed, and some automated. However, monitoring ET is still a challenge as no direct observation is possible at large scale [1] and only a combination of modelling and observations can help achieving that goal. In that perspective, spaceborne remote sensing has been seen as a great opportunity.

Recently, EUMETSAT's LSA-SAF [2] has started the distribution of two near-real time products aiming at the monitoring of the ET: instantaneous every half-hour (LSASAF MET) and daily cumulated (LSASAF DMET), over the full field of view (FOV) of SEVIRI instrument on board of the geostationary satellite MSG (Meteosat Second Generation) covering Europe, Africa and Eastern South America [3], [4]. ET is monitored using MSG satellite data at an unprecedented rate (every 30 minutes) and is delivered through an operational continuous service provided by LSA-SAF host center in Lisbon (http://landsaf.meteo.pt). The products are fully documented (updated user manual, validation reports and algorithm theoretical basis document), dissemination is ensured by EUMETSAT and LSA-SAF, and new developments are supported by continuous research.

For some applications, limitation in the use of the LSASAF MET products can be found due to the rather MSG/SEVIRI imager coarse resolution (3.1 km at best). It is especially true for applications in local agriculture practices and water management in small hydrological catchments, where higher spatial resolution is required to get an accurate estimation for adequate decisions. Therefore, combining LSASAF MET products with higher spatial resolution data derived from remote sensing seems an interesting way to benefit from both high time and spatial sampling resolution. Polar satellites usually allow monitoring land surface variables at a finer spatial resolution than geostationary ones. Products derived from moderate resolution sensors is attractive for ET monitoring, as satellites are launched on orbits such that global coverage is secured within 1 to 2 consecutive days, and a fairly good spatial resolution.

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, a service of continuous production of land related variables (http://www.geoland2.eu). SPOT-VGT plays a major role, as 2 successive SPOT satellites allow a continuous global monitoring of the vegetation for about 15 years, at a spatial resolution of ~1 km. However, in 2013 the expected life time of the satellite will be exceeded, and its GMES successor, Sentinel-3, designed to monitor globally the vegetation at a spatial resolution of 300 m, is not expected to be exploited before 2014, leaving a gap in the continuous monitoring. The ProbaV mission has then been set up to act as a gap-filler mission [5], 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.

In order to prepare the way to a possible continuous ET monitoring at sub-kilometer scale using ProbaV satellite data, we propose a method to downscale LSASAF MET at a resolution of 1000 and 300 m using LSA-SAF radiations products along with NDVI and surface albedo derived from moderate spatial resolution satellites. The methodology is then tested on two areas in Europe and Africa, typified by heterogeneous moisture regimes, using MODIS/Terra data as surrogate for the future ProbaV data. Preliminary validation result is given to support the methodological development. The methodology and results are then discussed in the context of a continuous monitoring using SPOT-VGT satellite and its improved successor, ProbaV.

2. Methods

2.1. Material

In this subsection, the satellite products used are shortly described. First, the products derived from MSG/SEVIRI, and at second, those derived from polar orbiters with moderate spatial resolution imaging systems.

2.1.1. LSA-SAF products derived from MSG geostationary satellite

MSG/SEVIRI provides a wealth of information due to its unprecedented observation rate (full FOV scanned every 15 minutes). LSA-SAF operational system produces in near-real time variables related to land surface derived from MSG/SEVIRI data: the land evapotranspiration [3], ET, the land surface temperature (LST), generated every 15 minutes [6], the daily fractional vegetation cover [7], FVC, and the half-hourly downward radiation in the short and infrared wavelength, DSSF [8] and DSLF respectively [9]. All the variables are distributed in the MSG satellite view, and split over 4 main pre-defined geographical areas: Europe (Euro), Northern and Southern Africa (NAfr, and SAfr), and South America (SAme).

2.1.2. Products derived from moderate spatial resolution spaceborne sensors

Products derived from SPOT-VGT are distributed with a resolution of approximately 1 km. MODIS land products are dependently delivered with a spatial resolution from 250 m to 1 km. In this study, the downscaling makes use of the 10/16-days composites of NDVI derived respectively from SPOT-VGT (Geoland2 product at 1 km resolution) and MODIS/Terra, MOD13Q1, at a resolution of 250 m. In addition, surface albedo derived from those sensors is required. Geoland2 surface albedo and MODIS albedo are provided respectively at 1000 m and 500 m spatial resolutions.

2.2. Downscaling method

The proposed downscaling methodology is primarily based on LSASAF MET half-hourly images. As well, ET is computed at moderate spatial resolution. An approximate ET, noted here HR ET first guess, is obtained using a simple model [10]. We suggest two options to downscale LSASAF MET based on the approximate solution (Figure 1): 1) using a per pixel analysis, the distribution of approximate ET inside a MSG pixel is shifted to let match the mean of the distribution with the LSASAF MET estimate, 2) using an area analysis, the distribution of LSASAF MET values is compared to the distribution of approximate values and parameters (mean and variance) from the latter one are adapted. This method is referred as “CDF matching”, and total ET is conserved.

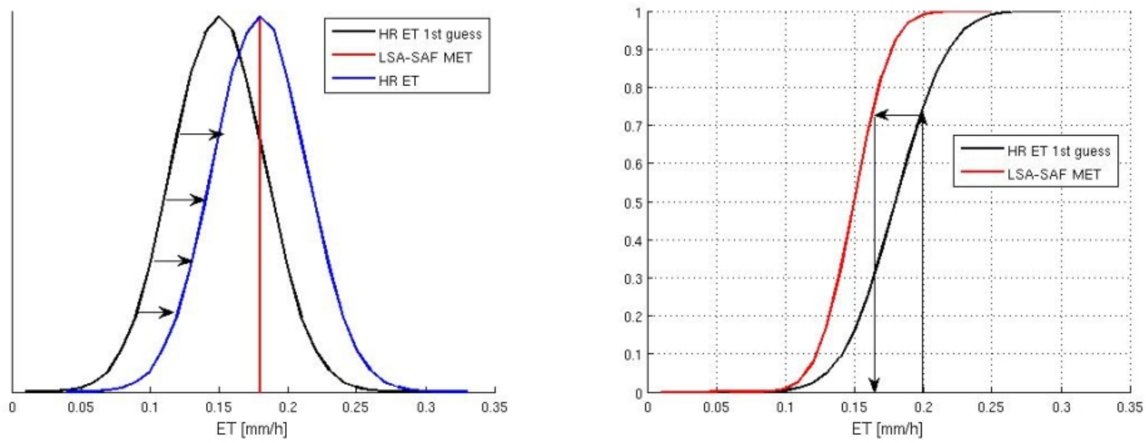

Figure 1: Strategies for combining LSASAF MET and first guess ET estimate at high resolution: (left) per pixel combination by shifting the mean, or (right) matching both cumulative distribution functions.

The simple model from [10] is used for the present study to obtain an approximate distribution of HR ET. The model has been chosen for its easiness of implementation and satisfactory accuracy to complement LSASAF MET. In the nominal configuration, maps of ET can be derived at high resolution according to Equation1, provided that net radiation, a vegetation index (NDVI) and the mean air or surface temperature are available. [10] have analyzed the sensitivity of their model to the input variables and it resulted not as very sensitive to the air/surface temperature. [10] give the following parameters: a_0=0.106, a_1=0.49, a_2=0.0039, if the daytime average surface temperature is used, a_0=0.084, a_1=0.498, a_2=0.0039, if the daytime maximum surface temperature is used.

$$ET = R_{net}.(a_0 + a_1.NDVI + a_2.T_s) \quad (1)$$

In practice, NDVI will be provided by the high-resolution imagery (see previous sub-section). Computation of the net radiation requires albedo, short and long-wave incoming radiation, as well as land surface temperature at the desired resolution. Surface albedo can be derived from high-resolution imagery, LSA-SAF DSSF and DSLF can be statistically downscaled. Because of the need of land surface temperature at high resolution and at a high rate, LSA-SAF LST is downscaled using local linear relations with FVC and NDVI (Agam et al., 2008).

The overall downscaling scheme is shown in Figure 2. LSA-SAF DSLF and DSSF are re-sampled at high-resolution. LSA-SAF LST and LSA-SAF FVC are used to derive local linear relations. Using those relations, high-resolution NDVI (HR NDVI) is used to compute the high-resolution LST (HR LST). From the 3 downscaled LSA-SAF radiation products (HR DSSF and HR DSLF) and high-resolution albedo (HR Albedo), a net radiation is computed at high-resolution. Using the [10] evapotranspiration model, the high-resolution net radiation and NDVI, maps of high-resolution evapotranspiration are derived, and used as a first guess (HR ET 1st guess). At last, LSASAF MET estimates are compared to the first guess high-resolution ET, and the latter ones are adapted using option 1 or 2 to give the final downscaled high resolution ET map (HR ET).

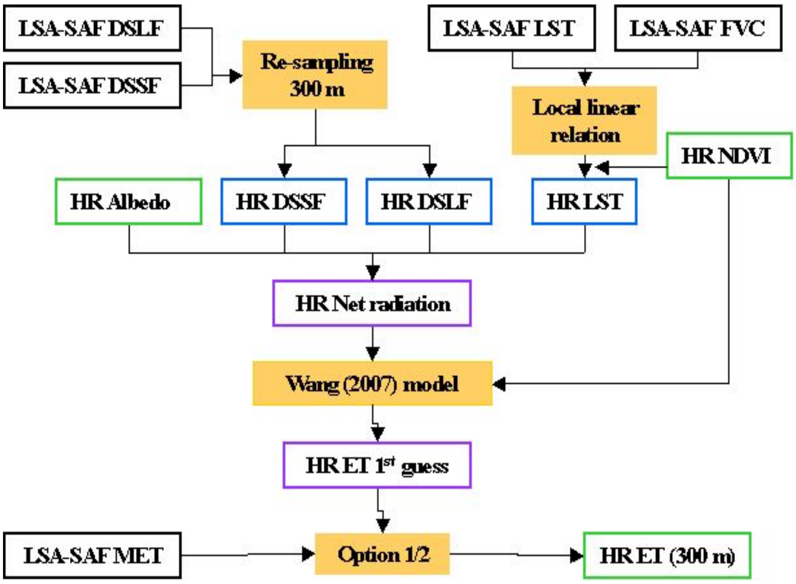

Figure 2: Flowchart of the downscaling procedure to obtain ET at high spatial resolution from LSA-SAF ET and high resolution NDVI. Black boxes denote LSA-SAF products, green boxes are products derived from high resolution satellite data (HR), blue boxes are variables at high resolution obtained by re-sampling or statistical procedures.

2.3. Study areas

Two areas of approximately 30x30 km² (10x10 MSG/SEVIRI pixels) have been chosen for application of the downscaling: 1) Barrax-Albacete Spanish complex agricultural site (39.04°N, 2°W), 2) transition zone along the Nile river (29.40°N, 31.16°E). Those areas have been chosen for their specific heterogeneity: 1) Barrax-Albacete area is mainly composed of dry annual crops (65%, mainly winter cereals (67%) and fallow (33%)), and some dense patches of irrigated crops (35%, mainly corn (65%), but also barley/sunflowers (15%), alfalfa (15%), onions(2%), and vegetables(2%)) [7]; 2) The Nile river area is composed of irrigated and annual crops, with a sharp delimited boundary towards bare land.

3. Results

3.1. Downscaling of LSASAF MET at 300 m spatial resolution

We have focused on clear sky scenes. Given the limited area and the sky condition, interpolation of DSSF and DSLF is not crucial. Both products are re-sampled at 300 m resolution. MODIS NDVI at 250 m is retrieved, collocated with MSG pixels and re-sampled at 300 m resolution. LSA-SAF LST is downscaled at 300 m using LSA-SAF FVC and re-sampled MODIS NDVI. Net radiation is computed, and the HR ET first guess. LSASAF MET is then downscaled at 300 m using option 1 and option 2 separately. Examples of the resulting HR ET for 06/08/2009 at 13:30 UTC are presented in Figure 3.

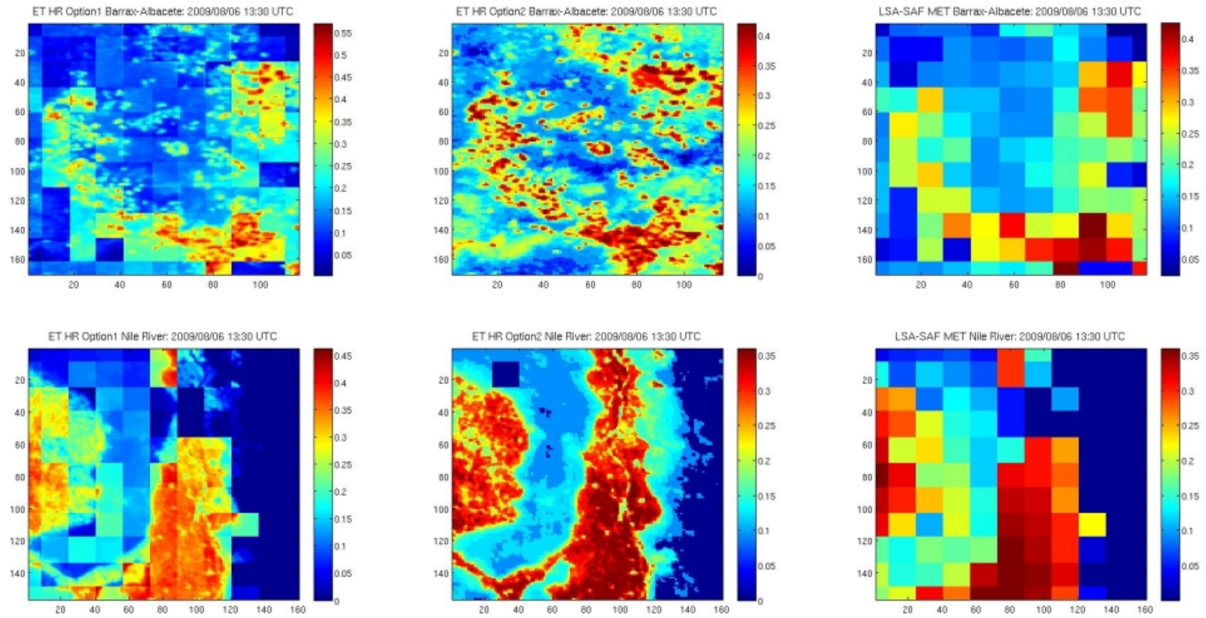

Figure 3: ET [mm.hr^{-1}] for the 2 test areas (06/08/2009 at 13:30 UTC): a) and b) downscaled ET at 300 m resolution using MODIS albedo and NDVI, using method 1, and method 2, c) LSASAF MET operational product.

Calculation of the net radiation seems realistic, with more energy available for vegetated areas than for bare soil. The comparison of LSA-SAF MET maps with first guesses high-resolution ET (not shown here) shows a good spatial agreement for both areas.

The downscaling approach (options 1 and 2) are quite simple procedures that combine information from LSA-SAF MET and HR ET 1st guess. While option 1 is more conservative about the informative content of LSA-SAF ET pixel estimates, option 2 offers an apparent better spatial distribution of ET rates with conservation of minimum, maximum and mean ET over the total area considered. From the application of option 2, summer irrigated crops with the same canopy development (NDVI) give the same amount of ET, which seems reasonable and is not clear from the application of option 1. Let us note that besides spatial resolution consideration, small scale LSA-SAF ET model deficiencies linked to irrigation could explain the differences [12]. With the application of option 2, lost information because of coarse spatial sampling and model deficiencies are given back, especially for small structures. It is probable that further improvements of the LSA-SAF ET algorithm will allow a better correspondence between both downscaling approaches. In the next two sub-sections, only results from the option 2 are retained.

3.2. Preliminary validation

The Barrax area is an excellent test-bed for such type of applications, as recurrent intensive field campaigns have taken place in the past over the region. Several studies have focused on ET [13], [14], [15], and finally anchor stations are still operated nowadays for remote sensing Cal/Val experiments. However, as no intensive measurement campaigns for water fluxes has been carried out, in a period overlapping the LSASAF MET operational production, a preliminary validation of the downscaled ET is done by comparing data derived from typical daily integrated ET estimates over summer irrigated fields in that regions. As reported by the validation study of [16], typical summer ET daily cumulates are between 4 and 5 mm of water for well-watered grass. This is supported by [14], [15], with typical range of 4-6 mm per day for irrigated crops in the same region. Because LSASAF MET gives an instantaneous ET rate averaged over 30 minutes, the daily integrated ET observation needs to be deployed over one typical cloud-free day. From the literature, it is possible to retrieve the diurnal course of ET, by fitting a Gaussian relation depending on the length of the day, given by the latitude, and constrained by the daily integration (Figure 4). Temporal integration over an hour (13:00 to 14:00 UTC) gives a typical range of ET rate of 0.4 to 0.5 $mm.hr^{-1}$, which embeds the maximum ET value of 0.42 $mm.hr^{-1}$ obtained by downscaling. However, it should be noted that the maximum value of ET at high resolution is determined by the range of estimates at coarse resolution. Therefore, maxima might be underestimated using that approximation, unless the considered region encompasses homogeneous extreme pixels.

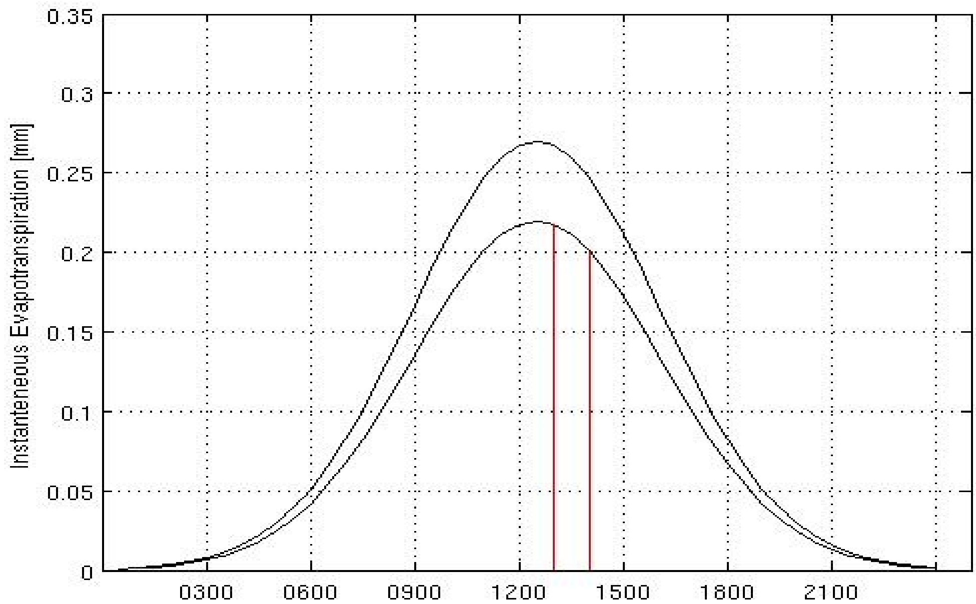

Figure 4: Diurnal course of ET rate (mm per 30 minutes) derived from daily lysimeter measurements at Barrax at Las Tiesas measurement site. Lower and upper curves correspond to daily measurements of 4 and 5 mm of evaporated water (May-June). Red lines delimitate the period chosen for comparison.

3.3. Effect of NDVI spatial resolution on downscaled evapotranspiration

In the context of satellite mission continuity, it is interesting to compare the results at 300 m using MODIS/Terra NDVI to downscaled estimates obtained by using SPOT-VGT derived NDVI at 1000 m. The overall pattern is found in both downscaled images over the Barrax area (Figure 5). However, differences appear in comparing the small structures. Some of those differences can be attributed to the difference in spatial resolution of MODIS and SPOT-VGT for the NDVI product, showing the interesting enhancement of the future ProbaV satellite data compared to SPOT-VGT. However, some differences are not clearly correlated to the spatial sampling, for example a group of irrigated crops are given back when downscaling with MODIS, and not with SPOT-VGT. Possible reasons could be 1) differences in spatial resolution, 2) differences in the sensors spectral characteristics, and 3) differences in the detailed processing of sensor data applied to elaborate NDVI products (time averaging, spatial resampling, atmospheric corrections etc.).

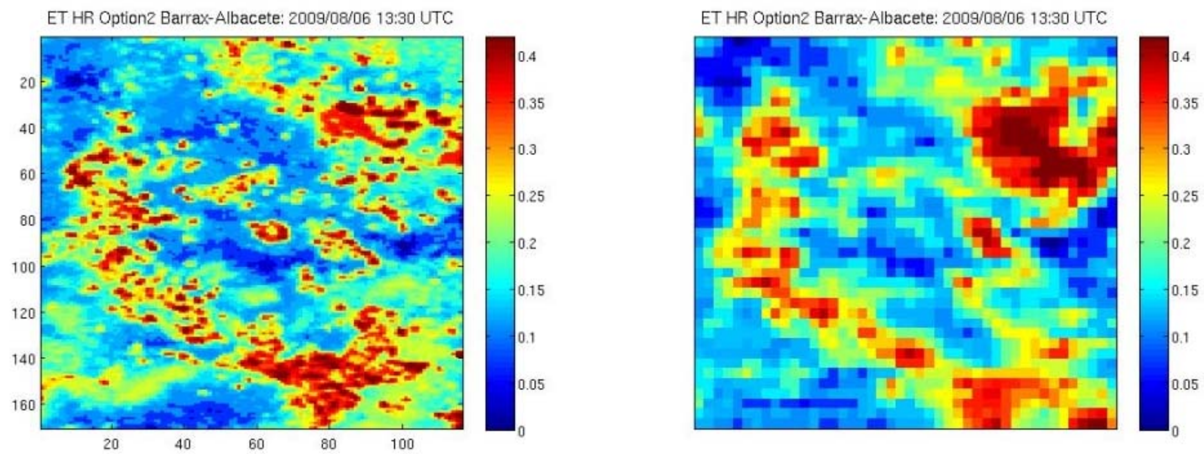

Figure 5: Downscaled LSASAF MET [$mm.hr^{-1}$] with MODIS NDVI (left) and with SPOT-VGT NDVI (right) over the Barrax area for 2009/05/06 at 13:30 UTC.

4. Conclusions

The present study is a first step towards the downscaling of the LSASAF MET evapotranspiration product based on MSG/SEVIRI at higher resolution (300 m). By proposing a downscaling scheme and applying it onto two heterogeneous test sites, we show the possibilities offered by remote sensing at moderate spatial resolution, to monitor ET at high spatial and temporal resolutions, potentially at continental scale. Early validation suggests an agreement of the downscaled ET with typical values observed locally, i.e. 0.4-0.5 $mm.hr^{-1}$, though the maxima might be a bit underestimated due to the CDF matching with the coarse resolution. In the context of continuous ET monitoring at sub-kilometer scale using SPOT-VGT and successors, the effect of NDVI enhanced spatial resolution from 1000 m to 300 m has been demonstrated and shows the potential it has to get useful information at 300 m, potentially compensating loss of accuracy by coarse scale sensors or model deficiencies.

Future research should focus on continental scale application of the downscaling technique, with the production of longer time series. In addition, further ground validation should provide an accuracy assessment of the proposed methodology and drive improved strategies for the synergistic use of geostationary and polar satellite data. At last, application with the real ProbaV data, when available, constitutes a natural extension of this work.

Acknowledgements

PROBA-VET (contract CB/34/18) is part of the ProbaV Preparatory Programme, funded and coordinated by the Belgian Science Policy. Products from MODIS have been acquired through the online Data Pool at the NASA Land Processes Distributed Active Archive Center (LP DAAC), USGS/EROS Center (http://lpdaac.usgs.gov/get_data). Geoland2 products have been provided through the Geoland2 access portal after registration. ("The results of this research has received funding from the European Community's Seventh Framework Program (FP7/2007-2013) under grant agreement n°218795. These products (LAI, NDVI, FAPAR, FCover) are the joint property of INRA, CNES, and VITO under copyright geoland2. They are generated from the SPOT VEGETATION data under copyright CNES and distribution by VITO. The BioPar albedo product was originally developed in the framework of the FP6/CYCLOPES project. It is generated from the SPOT VEGETATION data under copyright CNES and distribution by VITO. The BioPar albedo is available at the address http://www.geoland2.eu."). EUMETSAT's LSA-SAF products can be retrieved from http://landsaf.meteo.pt.

References

[1] Dolman, H. and De Jeu, R., 2010. Evaporation in focus. *Nat. Geosci.*, 3, 296.

[2] Trigo, I. F., DaCamara, C. C., Viterbo, P., Roujean, J.-L., Olesen, F., Barroso, C., Camacho-de Coca, F., Carrer, D., Freitas, S. C., García-Haro, J., Geiger, B., Gellens-Meulenberghs, F., Ghilain, N., Meliá, J., Pessanha, L., Siljamo, N. and Arboleda, A., 2011. The Satellite Application Facility on Land Surface Analysis. *Int. J. Remote Sens.*, 32, pp. 2725-2744, doi: 10.1080/01431161003743199.

[3] Ghilain, N., Arboleda, A. and Gellens-Meulenberghs, F. 2011. Evapotranspiration modelling at large scale using near-real time MSG SEVIRI derived data. *Hydrol. Earth Syst. Sci.*,15, pp. 771-786, DOI: 10.5194/hess-15-771-2011. 011.

[4] Arboleda, A., Ghilain N. and Gellens-Meulenberghs, F., 2011. EUMETSAT's LSA-SAF evapotranspiration: comparisons of operational product to observations and models at hydrological basins scale. *Proceedings of the 2011 EUMETSAT user conference*, Oslo, Norway, 7 pp.

[5] Van Achteren, T., Dierckx, W., Sterckx, S., Livens, S. and Saint, G., 2012. Proba-V, a SPOT-VGT successor mission, product definition and specifications. *32nd EARSeL Symposium, Advances in Geosciences*, this issue.

[6] Trigo, I. F., Monteiro, I. T., Olesen, F. and Kabsch, E., 2008. An assessment of remotely sensed land surface temperature. *J. Geophys. Res.*, 113, D17108, doi:10.1029/2008JD010035.

[7] Verger, A., Camacho, F., García-Haro, F.J. and Meliá, J., 2009. Prototyping of Land-SAF leaf area index algorithm with VEGETATION and MODIS data over Europe. *Remote Sens Environ.*, 113, pp. 2285–2297., DOI:10.1016/j.rse.2009.06.009.

[8] Geiger, B., Meurey, C., Lajas, D., Franchistéguy, L., Carrer, D. and Roujean, J.-L., 2008. Near real-time provision of downwelling shortwave radiation estimates derived from satellite observations. *Meteorol. Appl.*, 15, pp. 411–420. DOI: 10.1002/met.84.

[9] Trigo, I. F., Barroso, C., Viterbo, P., Freitas, S. C. and Monteiro, I. T. 2010. Estimation of Downward Longwave Radiation at the Surface combining Remotely Sensed Data and NWP Data. *J. Geophys. Res.*, 115, D24118, doi:10.1029/2010JD013888.

[10] Wang, K., Wang, P., Li, Z., Cribb, M. and Sparrow, M., 2007. A simple method to estimate actual evapotranspiration from a combination of net radiation, vegetation index, and temperature. *J. Geophys. Res.*, 112, D15107, doi:10.1029/2006JD008351.

[11] Agam, N., Kustas, W. P., Anderson, M. C., Li, F. and Colaizzi, P. D., 2008. Utility of thermal image sharpening for monitoring field-scale evapotranspiration over rainfed and irrigated agricultural regions. *Geophys. Res. Letters*, 35, L02402, doi: 10.1029/2007GL032195.

[12] Gokmen, M., Vekerdy, Z., Lubczynski, M., Batelaan, O. and Verhoef, W., 2012. Assessing groundwater depletion in a semi-arid region using RS-based evapotranspiration and precipitation estimates. Submitted to *J. Hydrol.*

[13] Jochum, M. A. O., de Bruin, H. A. R., Holtslag, A. A. M. and Calera Belmonte, A., 2006. Area-Averaged surface fluxes in a semiarid region with partly irrigated land : lessons learned from EFEDA. *J. Applied Meteorol. Clim.*, 45, pp. 856-874.

[14] Sobrino, J. A., Gomez, M., Jimenez-Muñoz, J.C. and Olioso, A., 2007. Application of a simple algorithm to estimate daily evapotranspiration from NOAA-AVHRR images for the Iberian Peninsula. *Remote Sens. Environ.*, 110, pp. 139-148.
[15] Sobrino, J. A., Gomez, M., Jimenez-Muñoz, J.C., Olioso, A. and Chehbouni, G., 2005. A simple algorithm to estimate evapotranspiration from DAIS data: Application to the DAISEX campaigns. *J. Hydrol.*, 315, pp. 117-125.
[16] de Bruin, H. A. R., Trigo, I. F., Gonzalez Dugo, M. P., Gavilan, P. and Rubio, E., 2008. LSA-SAF estimates of reference crop evapotranspiration. *Presentation at the 3rd Land Surface Analysis SAF Workshop*, Lisbon, 4-6 June 2008.