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Daily evapotranspiration at sub-kilometre spatial resolution by combining observations from geostationary and polar-orbit satellites

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ABSTRACT

Evapotranspiration (ET) estimates based on remote sensing are constrained by the spatial and temporal resolution of spaceborne observations. Therefore, the choice to be made is whether modelling at high temporal resolution with geostationary satellites at the cost of the spatial detail, or spatially detailed instantaneous modelling at overpass-time with polar-orbit satellites. This study aimed at exploiting the strength of both modelling approaches and derive daily ET estimates with cell size ≤ 1.0 km. The study was conducted in four sites with different land cover arrangements and catalogued as wetlands. The methodological approach was based on the algorithm behind the operational ET product of the Satellite Application Facility on Land Surface Analysis (LSA-SAF) initiative. The examined period comprised the end of the Spot-Végétation (Spot-V) mission and the first year of Proba-V operational modus. Two aspects were investigated: 1. The adequacy of combining observations from geostationary and Spot-V and Proba-V satellite missions for obtaining the target product; and, 2. The intercompatibility of ET estimates based on Spot-V and Proba-V so that continuous series over the operational period of both missions could be built. The comparison of simulated ET with *in situ* measured fluxes (eddy covariance) showed that the introduction of more spatial detail through polar-satellite observations resulted in the reduction of bias and root-mean-square error in ET estimates, as compared with estimations where Earth observation data were taken from geostationary satellites only. Moreover, the signals derived from Spot-V and Proba-V exhibited similarity during the period of operational overlap; especially in non-cultivated surfaces. This suggests that continuity objective of these two missions can be exploited in the estimation of ET time series.

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1. Introduction

Terrestrial evapotranspiration (ET) is a major process in the Earth's water cycle. It involves a volume of water equivalent to 60–65% of precipitation (Brutsaert 1982) and is composed by water evaporated from upper soil layers, waterbodies, water intercepted by plant canopies

and, mainly, by plant transpiration (Jasechko et al. 2013). At global scale, ET is a key element of the climate system as it represents an energy transfer process with cooling effects on the Earth's surface. At local and regional scales, ET is a fundamental parameter in applications related to, for instance, agriculture production (Bhattacharya et al. 2011; Chen et al. 2015; Ko and Piccinni 2009; Sepulcre-Cantó et al. 2013; Tadesse et al. 2015; Wei et al. 2015), drought detection and mapping (Sepulcre-Cantó et al. 2014; Zha et al. 2010), water catchment management (González-Dugo et al. 2013; Wu et al. 2014), urban studies (Gkatsopoulos 2017; Litvak and Pataki 2016), amongst other.

Spaceborne Earth observation systems are often the only source of data delivered at regular time steps and with large spatial coverage. Therefore, the exploitation of the growing pool of remote sensing data has been a core concern in ET research for years. Various research endeavours have produced modelling proposals with different degrees of participation of remotely sensed data in the forcing (e.g. Banstiaanssen et al. 1998; Ghilain, Arboleda, and Gellens-Meulenberghs 2011; Mallick et al. 2014; Mu et al. 2007). Since no remote observation is a direct indicator of ET, research has been oriented towards the estimation of ET determinants from the optical, near-infrared and thermal electromagnetic regions so that they can constitute the forcing of mathematical models (Nouri et al. 2013).

Ecosystem monitoring can benefit from ET estimates complying with two conditions: frequent data generation to reveal time-varying features (trends, anomalies) and sufficient spatial detail to resolve landscape units. These conditions are, however, seldom present in the same ET product. In consequence, the choice of remote sensing data sources represents often a trade-off between spatial and temporal detail. Geostationary satellites deliver data at high temporal rate and enable the derivation of sub-daily ET estimates. This is a valuable aspect as weather conditions can vary substantially in the course of the day. However, the spatial detail is insufficient to resolve homogeneous units in fragmented landscapes, which hampers their exploitation in ecosystem monitoring (Ghilain, De Roo, and Gellens-Meulenberghs 2014), on the other hand, can supply more spatial detail but their cyclic revisit time ranges from 1 to 2 days (at its best) to several days at more or less fixed overpass times.

This study addresses the question whether observations from both, geostationary and polar-orbit satellites, could be combined to obtain daily estimates of ET (ET_d) at moderate spatial resolution. The target spatial resolutions of the simulations were about 1.0 km and about 0.3 km which correspond to the native cell size of Spot-Végétation (Spot-V) and Proba-V grids, respectively. The Proba-V mission, launched in 2013, is intended to carry forward the series of spaceborne observations conducted by Spot-V between 1998 and May 2014. The notion of continuity was also present in the design of the more recent Sentinel-3 satellite (European Space Agency 2012) and represents the possibility of studying ET patterns across a long period. This aspect motivated the choice of the study period which covered the last year of the Spot-V mission and the first year of Proba-V operational modus.

The ET calculations were based on the algorithm behind the ET product set in operation in the framework of the Satellite Application Facility on Land Surface Analysis (LSA-SAF) (Trigo et al. 2011). The LSA-SAF ET product is driven by -amongst other source observations by the Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard the Meteosat Second Generation Satellite (MSG) (Ghilain, Arboleda, and Gellens-Meulenberghs 2011). The ET estimates are generated in near-real time with a time step of 30 min and are freely disseminated. Validation exercises (Royal

Meteorological Institute of Belgium 2011) and independent studies (e.g. Hu, Jua, and Menenti 2014; Jovanovic et al. 2014; Minacapilli et al. 2016; Petropoulos et al. 2016; Sepulcre-Cantó et al. (2013), (2014)) report good agreement between the LSA-SAF ET estimates and validation datasets.

The study areas contained wetlands, fragile ecosystems characterized by the permanent high level of humidity at or near the surface at depths lower than six metres (Millenium Ecosystem Assessment 2005). Monitoring these ecosystems is of particular relevance in virtue of their ecological value as a habitat of many (often unique) species of fauna and flora and as providers of valuable services to society (Zedler and Kercher 2005).

2. Methods

2.1. The ET algorithm

The algorithm implemented in this study followed to a large extent the principles and methods behind the operational LSA-SAF ET product (Ghilain, Arboleda, and Gellens-Meulenberghs 2011; Royal Meteorological Institute of Belgium 2010; Trigo et al. 2011). In the LSA-SAF implementation, the algorithm operates over the gridded surface of the MSG satellite imagery covering Europe, Africa and Eastern South-America. In this study, the algorithm was slightly adapted to be implemented onto the Spot-V and Proba-V grids (about 1.0 and 0.3 km cell size) and to ingest more detailed information on land cover. As in the LSA-SAF implementation, the actual calculation of the partition in surface heat fluxes occurred at the level of subcell units of homogeneous land cover called *tiles*. Each cell contained up to 4 tiles and the estimated cell values resulted from the weighted aggregation of the results at tile level. The notion of tiles and a number of parameterization criteria were adopted from the Tiled ECMWF (European Centre for Medium-Range Weather Forecast) Scheme for Surface Exchanges over Land (TESSEL) Soil-Vegetation-Atmosphere transfer (SVAT) model (Van den Hurk et al. 2000; Viterbo and Beljaars 1995) and further adapted by Ghilain, Arboleda, and Gellens-Meulenberghs (2011).

Table 1 presents the basic set of formulae for the calculation of surface energy fluxes. Equation (1) is the general expression of the energy balance whereby R_{net} results from adding the net short and long wave segments of solar radiation hitting the Earth's surface (Equation (2)). The Equations (3)–(5) show the determinant role of canopy and aerodynamic resistances as well as humidity and temperature gradients in the partition of R_{net} into sensible, latent and ground heat fluxes. The canopy resistance varies in the course of the growing season as it follows the dynamics of vegetation growth, soil moisture status, solar radiation, and atmospheric moisture deficit. The aerodynamic resistance is related to the atmospheric stability which is formulated as a function of friction velocity and the Obukhov's stability length. More details in the formulation of r_c and r_a are given in Ghilain, Arboleda, and Gellens-Meulenberghs (2011).

At each time step, a system of equations had to be solved iteratively. In the iteration process, an estimate of surface or *skin* temperature (T_{skin} in Equations (2–4)) was generated. This feature in the algorithm made it possible to estimate ET without having satellite-based land surface temperature data in the forcing, as explained in Ghilain, Arboleda, and Gellens-Meulenberghs (2011), *i.e.* ET could be estimated in all weather conditions. The estimation procedure of T_{skin} is different than that of remotely sensed

Table 1. Basic equations for the estimation of the energy balance components.

Surface energy balance:

$$R_{\text{net}} = H + (\text{LE}) + G \quad (1)$$

where:

$$R_{\text{net}} = (1 - \alpha)S_d + \epsilon(L_d - \sigma T_{\text{skin}}^4) \quad (2)$$

$$\text{LE} = \frac{\lambda \rho_a}{(r_a + r_c)} [q_{\text{sat}}(T_{\text{skin}}) - q_a(T_a)] \quad (3)$$

$$H = \frac{\rho_a}{r_a} [c_p(T_{\text{skin}} - T_a) - gz_a] \quad (4)$$

$$G = \beta R_{\text{net}} \quad (5)$$

R_{net}	Net radiation	H	Sensible heat flux
LE	Latent heat flux	G	Heat flux into the ground
α	Albedo	S_d	Downwelling shortwave radiation
ϵ	Emissivity	L_d	Downwelling longwave radiation
σ	Stephan-Boltzmann constant	ρ	Air density
r_a	Aerodynamic resistance	r_c	Canopy resistance
q_a	Specific humidity	T_{skin}	Skin temperature
q_{sat}	Specific humidity at saturation	g	Gravity
T_a	Air temperature	β	Fraction of R_{net} stored in the ground (function of Leaf Area Index (LAI) Chehbouni et al. (1997))
z_a	Roughness height	λ	Latent heat of vaporization
c_p	Heat capacity at constant pressure		

land surface temperature. Nevertheless, both quantities have correlated well in validation exercises conducted in the framework of the LSA-SAF ET product across different ecosystems (Royal Meteorological Institute of Belgium 2011).

The forcing comprised data obtained from satellite platforms, meteorological forecasts and land cover-related parameters. Details on these data sources are provided in the following sections. The time step of the simulations was 30 min which corresponds to the temporal resolution of the forcing variables based on geostationary satellite observations. The target spatial resolution was about 1.0 km and about 0.3 km which corresponds to the cell size of the Spot-V and Proba-V grids, respectively (Proba-V products are also generated at 1.0 km and 100.0 m spatial resolutions). The studied period was 2013 and 2014 which frames the end of Spot-V mission and the start of Proba-V operations. Therefore, the 1.0 km simulations encompassed the two studied years while the 0.3 km was only possible from 2014 onwards. The half-hourly ET estimates were aggregated over the length of one day to obtain the target product, ET_d.

2.1.1. Spaceborne datasources

The forcing variables derived from Earth observation platforms were S_d , L_d , Leaf Area Index (LAI) and α . The radiation terms S_d , L_d were taken from dedicated operational LSA-SAF products based on MSG-SEVIRI observations trigo1. These parameters are continuously generated over the MSG grid at a time step of 30 min. These products were taken at their original temporal resolution in order to capture the diurnal fluctuations in solar radiation reaching the Earth's surface.

The LAI data at 1.0 km resolution was obtained from both the Spot-V and Proba-V LAI products generated in the framework of the Copernicus Global Land programme (Gio-Global Land Component Lot1 consortium 2014). As for LAI data at 0.3 km resolution, no operational LAI product existed at the time this study was conducted. LAI at 0.3 km was derived through an empirical relationship having the Normalized Difference Vegetation Index (NDVI) (Wolters et al. 2014) as covariate. Such empirical relationship was derived from a regression analysis performed on historical records of Spot-V NDVI-LAI pairs (Gio-Global Land Component Lot1 consortium 2014) taken at approximately 2500 random points over different ecosystem types across Europe. The NDVI-LAI pairs covered the period 2000–2013 (about 36 values per year on each point). The resulting empirical relationship was $LAI = 0.1532017 \exp(3.838(NDVI))$ (coefficient of determination R^2 : 0.656, p -value < 0.005).

The α values were obtained from the MCD43B3 and MCD43A3, the combined albedo products at, respectively, 0.5 and 1.0 km spatial resolutions, derived from the Moderate-resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua satellites. These MODIS products were reprojected from their original sinusoidal projection and nearest neighbour resampled to match the 0.3 and 1.0 km target grids.

The Spot-V-Proba-V and MODIS products are made available at a time step of 10 and 8 days, respectively. Daily values were obtained through linear interpolation and used in the simulations at sub-daily time steps.

2.1.2. Land cover

A number of important modelling parameters are associated to the surface land cover. These parameters indicate the way the biophysical environment interacts with meteorological phenomena in shaping the actual evaporated and transpired water flux. The major source of land cover-related parameters was the Ecoclimap database (Masson et al. 2003). This dataset provides information on the distribution and extent of ecosystem types at the global scale. The database distinguishes 215 ecosystem types at a spatial resolution of 1.0 km. Ecoclimap supports the tile approach and contains information on the tile composition of each ecosystem type as well as the occupation fraction of each tile in the cell.

In the LSA-SAF ET product, the resolution of Ecoclimap is degraded to match the MSG grid. In each cell, the bare soil and the 3 dominant vegetation tiles are identified to perform the energy balance calculations (Ghilain, Arboleda, and Gellens-Meulenberghs 2011). When modelling over the Spot-V grid, an Ecoclimap class was assigned to each Spot-V cell by overlaying both grids and selecting the Ecoclimap class with the highest overlap degree. The fraction of vegetation cover within each cell varies in the course of the growing season as the function of LAI.

The cells in the Proba-V grid are smaller than those in the Ecoclimap database grid. This impeded a 1:1 association between cells in both grids which implied that more spatial detail in the definition of the landscape units was needed. Finer detail in the definition of landscape units was achieved by adopting the CORINE (Coordination of Information on the Environment) land cover (CLC) (100.0 m spatial resolution) (Europe Environment Agency 2009) as the main source on the location, extent and shape of those units. Each CLC class present in the study sites was then associated to the corresponding Ecoclimap class and its associated parameters. The tiles composition and occupation fraction within a Proba-V could then be established on the basis of the parameters in the Ecoclimap database and the conduction of standard spatial overlay procedure.

2.1.3. Meteorological data

As in the LSA-SAF ET product, the meteorological forcing was obtained from weather forecasts produced by the ECMWF. The operational ECMWF weather forecasts were regularly produced at a global scale at a time step of 3 h in the considered period. The data were resampled to match the temporal resolution of the LSA-SAF radiation products. The meteorological forcing in the model was composed by air and dew point temperatures, wind speed, atmospheric pressure, and water volume and temperature for 4 soil layers.

The diagram in Figure 1 gives a summary overview of the datasets involved in the derivation of daily ET at 1.0 and 0.3 km spatial resolution.

As shown in Figure 1, the forcing was composed by datasets at different spatial and temporal resolutions. Such setting was intended to better account for the actual variability in space and time of the ET drivers. For instance, meteorological variables and solar radiation terms may safely be assumed to be somewhat uniform across an area covering several 0.3–1.0 km cells but their variability in diurnal patterns justifies sub-daily sampling rates. On the other hand, LAI and other land cover-related parameters

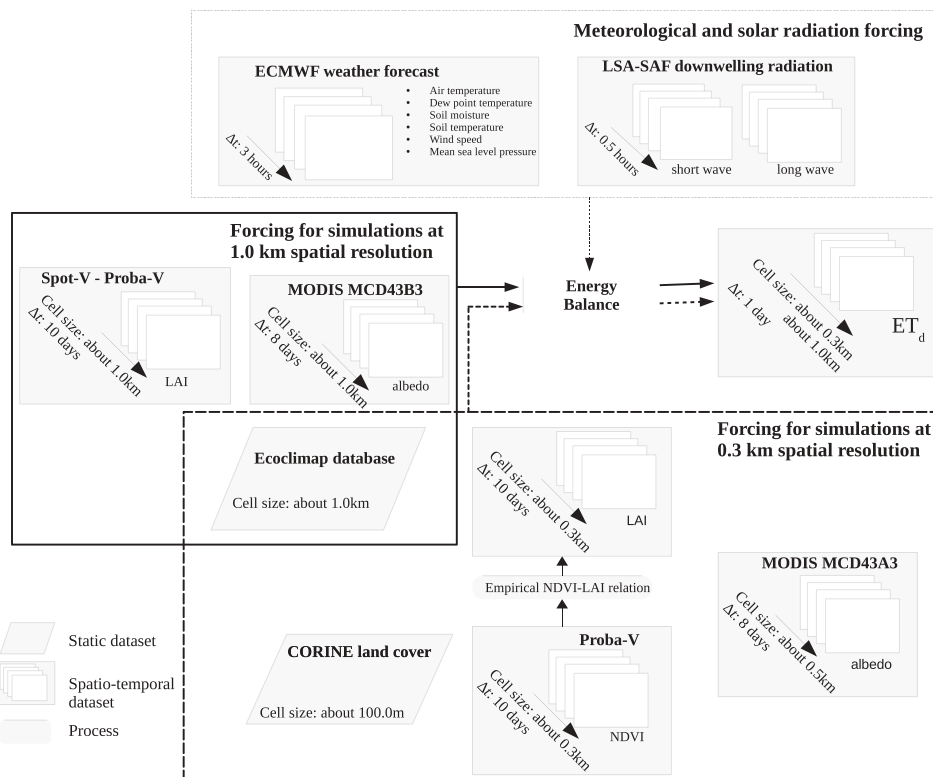


Figure 1. Diagram representation of spaceborne, meteorological, and land cover-related data to derive daily ET at about 1.0 and 0.3 km spatial resolution. Rectangles delimited by full and dashed lines indicate datasets used for simulations at, respectively, 1.0 and 0.3 km spatial resolution. Datasets framed in dash-dot lines are meteorological and solar radiation datasets used in all simulations.

can naturally vary within a radius of tens or hundreds of metres (depending on landscape heterogeneity) but the temporal frame of importance is rather seasonal or annual.

2.2. Study sites

The ET simulations were run over four study sites included in the global Fluxnet eddy covariance measurement network (Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) 2014). The study sites exhibit different land cover arrangements and are catalogued as wetlands: Anklam, Spreewald, Schechenfilz Nord, and Zarnekow, in Germany. The humidity in these sites has formed peat soils which have undergone different management regimes and exhibit different degrees of peat decomposition (Dettmann et al. 2014). The actual studied area was delimited by the extent of the MSG pixel containing each eddy covariance station. Figure 2 presents a map showing the location of these sites as well as real-colour views of the study areas. Table 2 presents the coordinates and the ecosystem classification at the location of the flux tower according to the Ecoclimap database.

The adoption of the extent of one MSG cell (about 4.0 km –6.0 km spatial resolution) to delimit the studied area enabled the comparison of the simulated ET with the LSA-SAF ET operational product as well as the visual inspection of spatial ET patterns.

The *in situ* measured eddy covariance data covered the period 2013–2014, which encompasses the end of the Spot-V mission and the start of Proba-V operations.

2.3. Statistical analysis

The adequacy of the modelled results was assessed by statistically comparing them to ET_d values derived from half-hourly latent heat measured at the flux towers. The computed statistical parameters were root mean squared error (RMSE), bias, coefficient of determination (R^2) and the Nash-Sutcliffe Index (NSI) (Nash and Sutcliffe 1970).

The consistency in the estimation between the two considered spatial resolutions was verified as well. At each time step, the modelled values at 1.0 and 0.3 km were aggregated over the extent of the MSG cell delimiting the study area. The resulting series were compared against each other and against the LSA-SAF ET product by calculating R^2 and by statistically testing the following hypothesis (H_0): the mean of the difference between two paired ET_d series is equal to zero. This analysis could only be performed for the year 2014.

3. Results and discussion

Table 3 presents a set of statistical parameters on the degree of agreement between the validation datasets and the modelled ET_d at the location of the flux tower at 1.0 and 0.3 km spatial resolutions. For comparison purposes, the statistical scores for the LSA-SAF ET product are also presented.

The figures in Table 3 indicate a general good match between the considered modelling schemes and the validation datasets. The coefficient of determination R^2 was everywhere greater than 0.80 and the NSI ranged between about 0.52 and 0.83. The RMSE values did not exceed 0.72 mm and the bias had a maximum absolute value of about 0.30 mm. The analysis at Schechenfilz Nord did not include the first half of the growing season of 2013. Failures in

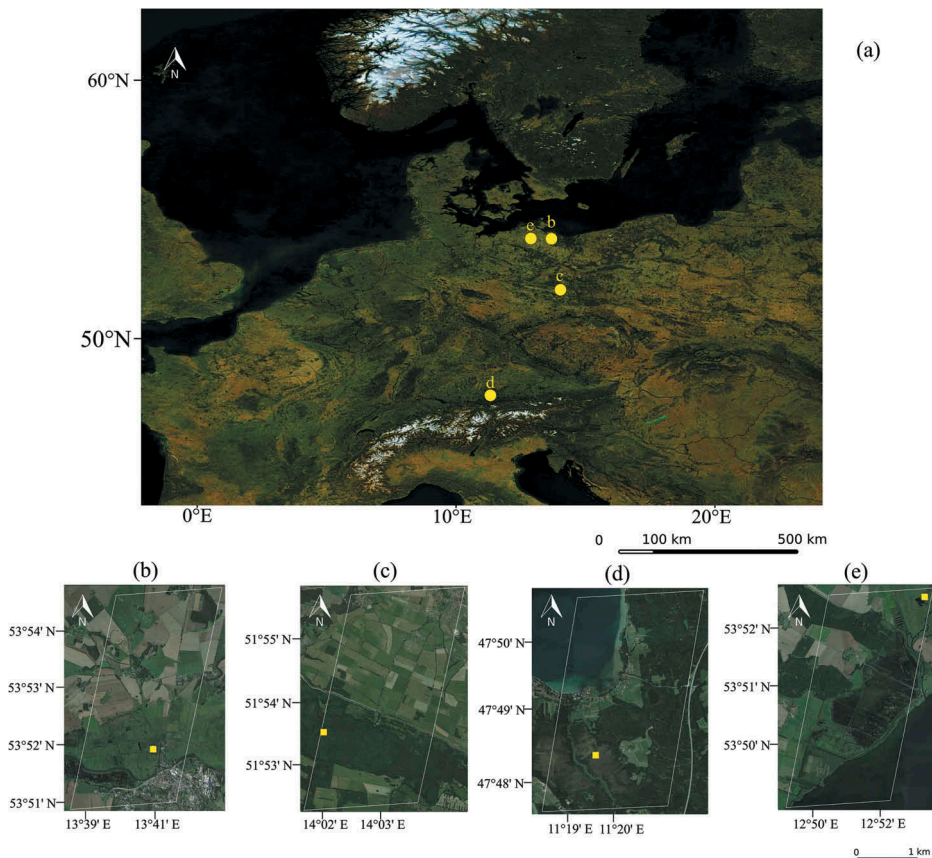


Figure 2. Location (sub-figure (a)) and aerial view of study sites: (b) Anklam, (c) Spreewald, (d) Schechenfilz Nord and (e) Zarnekow. The yellow squares points on the sub-figures (b)–(e) indicate the location of the flux measurement towers and the trapezoidal polygon delimits the area covered by the MSG cell containing the flux tower. Aerial views were extracted from the GoogleEarth® platform.

Table 2. Geographical coordinates and Ecoclimap class at the location of the flux measurement towers in the study sites.

Name	Ecoclimap class	Longitude (°)	Latitude (°)
Anklam	Temperate wetland	13.6834	53.8662
Spreewald	Temperate broad-leaved forest	14.0337	51.8923
Schechenfilz Nord	Peat bog	11.3275	47.8064
Zarnekow	Temperate pasture	12.8890	53.8759

the functioning of the flux tower during that period as reported by Hommeltenberg et al. (2014) might have impacted the evaluation of the performance of the model.

In most of the cases, the simulations either at 1.0 km or 0.3 km slightly outperformed the scores for the LSA-SAF ET product. Spreewald and the simulation at 1.0 km spatial resolution in Zarnekow were exceptions to that. These and other aspects can be further examined in the ET time series plots shown in Figures 3 and 4. These plots show the modelled ET_d by the operational LSA-SAF ET and the estimations conducted over the 1.0 and 0.3 km grids together with the ET_d derived from the flux tower

Table 3. Statistical parameters on the degree of agreement between the validation datasets and the ET_a estimates over the 1.0 and 0.3 km grids and the LSA-SAF ET product.

Site	Grid-model	RMSE	Bias	R ²	NSI	n	Period
Anklam	1.0 km cell	0.5814	−0.0430	0.9006	0.8101	411	2013–2014
	0.3 km cell	0.5768	−0.0176	0.8964	0.8023	191	2014
	LSA-SAF ET	0.6480	−0.1635	0.8945	0.7790	526	2013–2014
Spreewald	1.0 km cell	0.7245	−0.3063	0.8047	0.5293	426	2013–2014
	0.3 km cell	0.6805	−0.1927	0.8085	0.6104	254	2014
	LSA-SAF ET	0.5575	0.2709	0.9191	0.7216	599	2013–2014
Schechenfliz Nord	1.0 km cell	0.5634	0.1276	0.9138	0.8147	369	2013–2014
	0.3 km cell	0.5805	−0.1509	0.9246	0.8293	247	2014
	LSA-SAF ET	0.7984	−0.0156	0.8015	0.6233	598	2013–2014
Zarnekow	1.0 km cell	0.6763	0.2174	0.8925	0.7490	417	2013–2014
	0.3 km cell	0.5757	0.1400	0.8969	0.7900	245	2014
	LSA-SAF ET	0.6467	0.2783	0.9093	0.7630	505	2013–2014

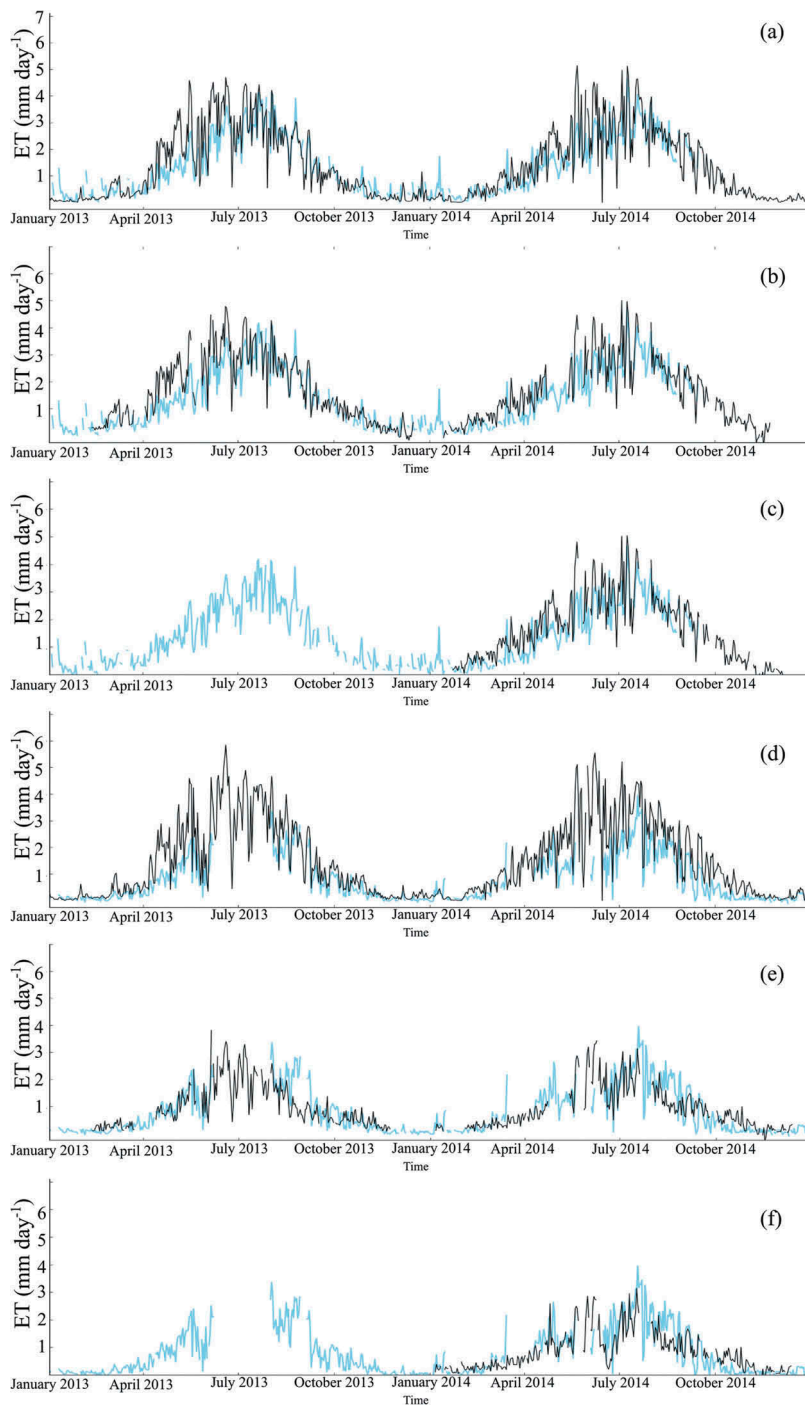


Figure 3. Time series of daily evapotranspiration at the location of the flux tower in Anklam (a)–(c) and Spreewald (d)–(f) as derived from flux tower measurements (sky blue line) and as modelled (black line) by the LSA-SAF ET product ((a) and (d): Anklam and Spreewald, respectively), over the grid of about 1.0 km spatial resolution ((b) and (e): Anklam and Spreewald, respectively) and over the grid of about 0.3 km spatial resolution ((c) and (f): Anklam and Spreewald, respectively).

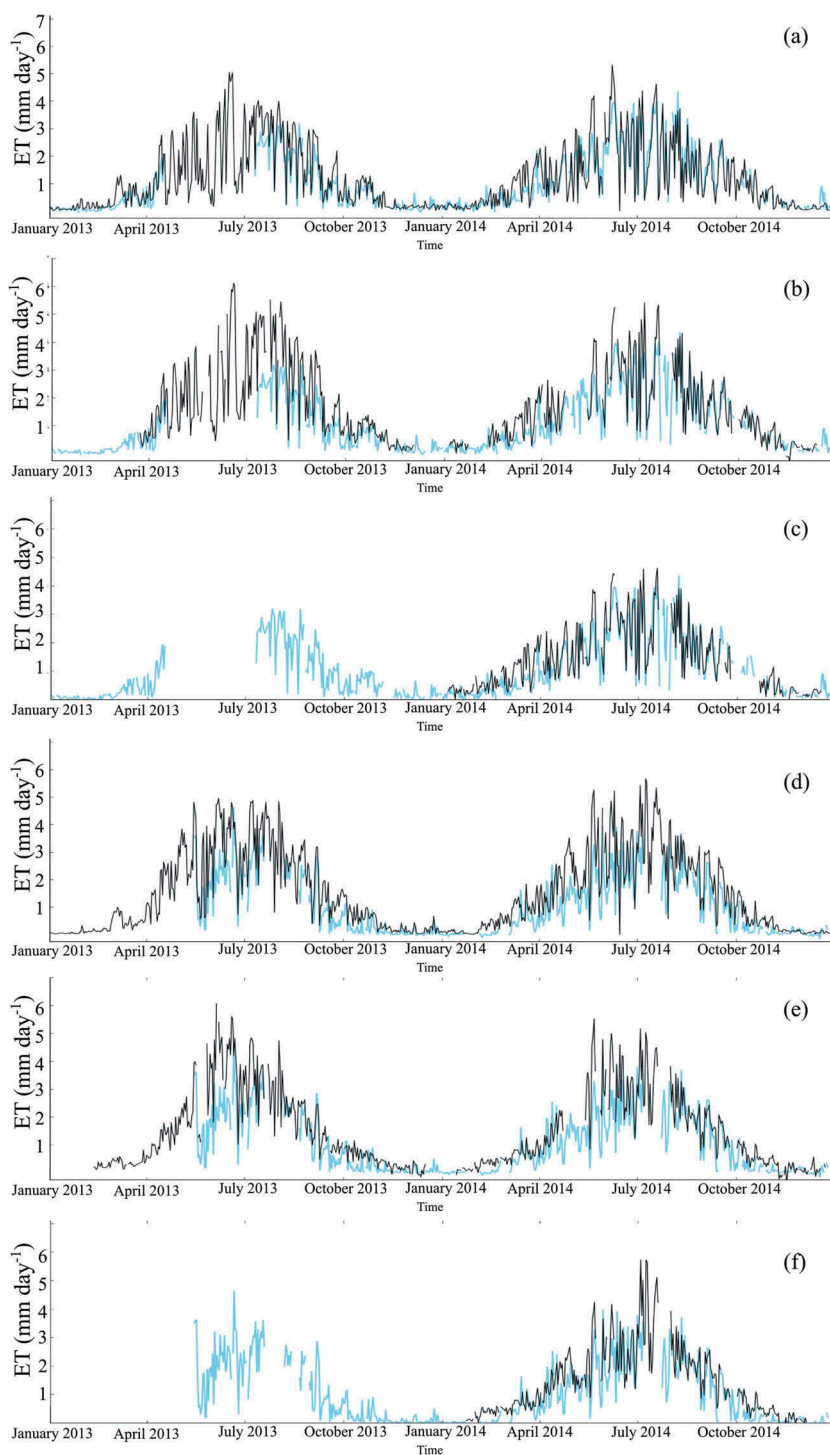


Figure 4. Time series of daily evapotranspiration at the location of the flux tower in Schechenfilz Nord (a)–(c) and Zarnekow (d)–(f) as derived from flux tower measurements (sky blue line) and as modelled (black line) by the LSA-SAF ET product ((a) and (d): Schechenfilz Nord and Zarnekow, respectively), over the grid of about 1.0 km spatial resolution ((b) and (e): Schechenfilz Nord and Zarnekow, respectively) and over the grid of about 0.3 km spatial resolution ((c) and (f): Schechenfilz Nord and Zarnekow, respectively).

measurements. The modelled values in the plots correspond to the cell where the flux tower was located.

These results showed that geostationary and polar-orbit satellite platforms can function synergetically to model ET_d . On the basis of the figures presented in Table 3, one may intuitively conclude that every step towards more spatial detail in the simulations will lead to lower RMSE and bias values. That was the case in this study; except for Spreewald where the simulations at 1.0–0.3 km, though satisfactory, did not lead to lower RMSE and/or higher R^2 or NSI than the LSA-SAF ET product. This indicates that there is still room for better exploiting currently available satellite datasets and improve ET_d simulations at the target spatial resolution. An avenue of improvement could be the adaptation of model parameter to the enhanced spatial detail of the simulations. The eddy covariance tower in this site is located in the middle of a forested wetland and the standard parameterization for broad-leaved forests might not account optimally for the high level of water content and the concomitant soil hydraulics in this ecosystem (Dettmann et al. 2014).

3.1. ET_d spatial patterns within the MSG cell

The extraction of ET_d patterns for landscape elements that can not be resolved at the spatial resolution of MSG was a major goal in this study. The plots of Figure 5 represent time series of modelled ET_d across the 1.0 and 0.3 km grids within the MSG cell. Although the accuracy of modelled ET_d away the footprint of the flux tower could not be assessed, the LSA-SAF ET algorithm has been calibrated and validated in a large diversity of conditions and climates (Royal Meteorological Institute of Belgium 2011).

Each line in the plots of Figure 5 depicts the modelled ET_d pattern for one 1.0–0.3 km cell within one MSG cell. The actual number of 1.0 km–0.3 km cells within one MSG cell depends on the latitude of the location under consideration. Each MSG cell in the study areas in this paper contained about 40 cells with a size of about 1.0 km and over 270 cells with a size of about 0.3 km. The coloured indication of land cover for each line shows that the signals form recognizable clusters of land cover type with different degrees of internal variability.

The signals in Figure 5 depict ET patterns that are likely to occur in each land cover class. For instance, the ET_d values in the urban classes in Anklam were most of the time surpassed by vegetated classes. This contrasted with the temperate wetlands class having most of the time the highest ET_d rate, except during the period of full crop development when the ET_d rate in the latter class surpassed the others. The temperate pastures in Spreewald exhibited higher ET_d rate during the simulation period as compared to other classes in the neighbourhood. As it can be expected, the open water areas in Schechenfilz Nord and Zarnekow exhibited higher ET_d rates with respect to the vegetated areas. The peat bogs in Schechenfilz Nord exhibited higher ET_d rates than the forest classes in that site.

Figure 6 presents sequences of ET_d maps that allow a spatial view on the results for the four study sites as modelled over the 1.0 and 0.3 km grids for a few dates in 2014, the first year for which modelling at both considered spatial resolutions was possible. These maps illustrate the dynamics and diversity of ET_d spatial patterns within a MSG cell as well as the difference in spatial detail between 1.0 and 0.3 km grids. The maps in Figure 6 show, for instance, that the period of intensive crop growth in Anklam in the beginning of the season caused the highest ET_d rates to be located in the northern half of that MSG cell. The wetland area, located in the southern half of the MSG cell,

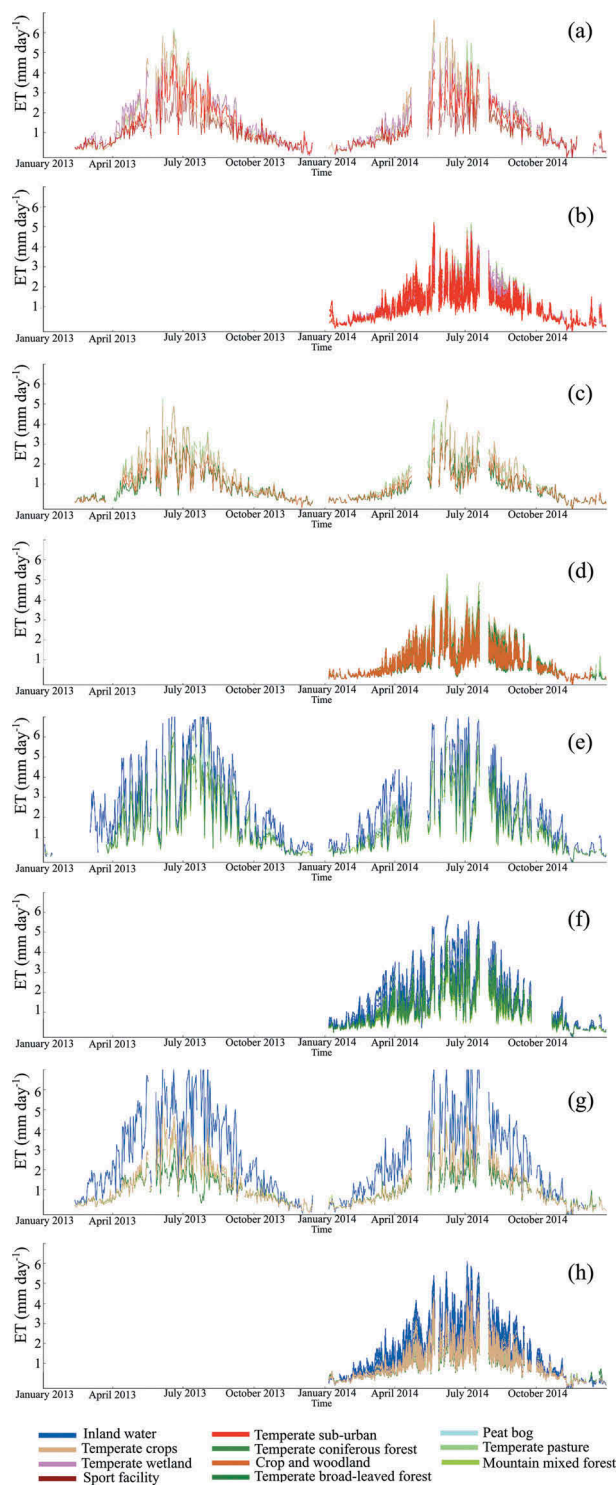


Figure 5. Daily evapotranspiration signals as modelled over the grid of about 1.0 km (2013–2014) and over the grid of about 0.3 km (2014) across the extent of one MSG cell. The colours indicate the Ecoclimap class. Anklam (a)–(b), Spreewald (c)–(d), Schechenfilz Nord (e)–(f) and Zarnekow (g)–(h).

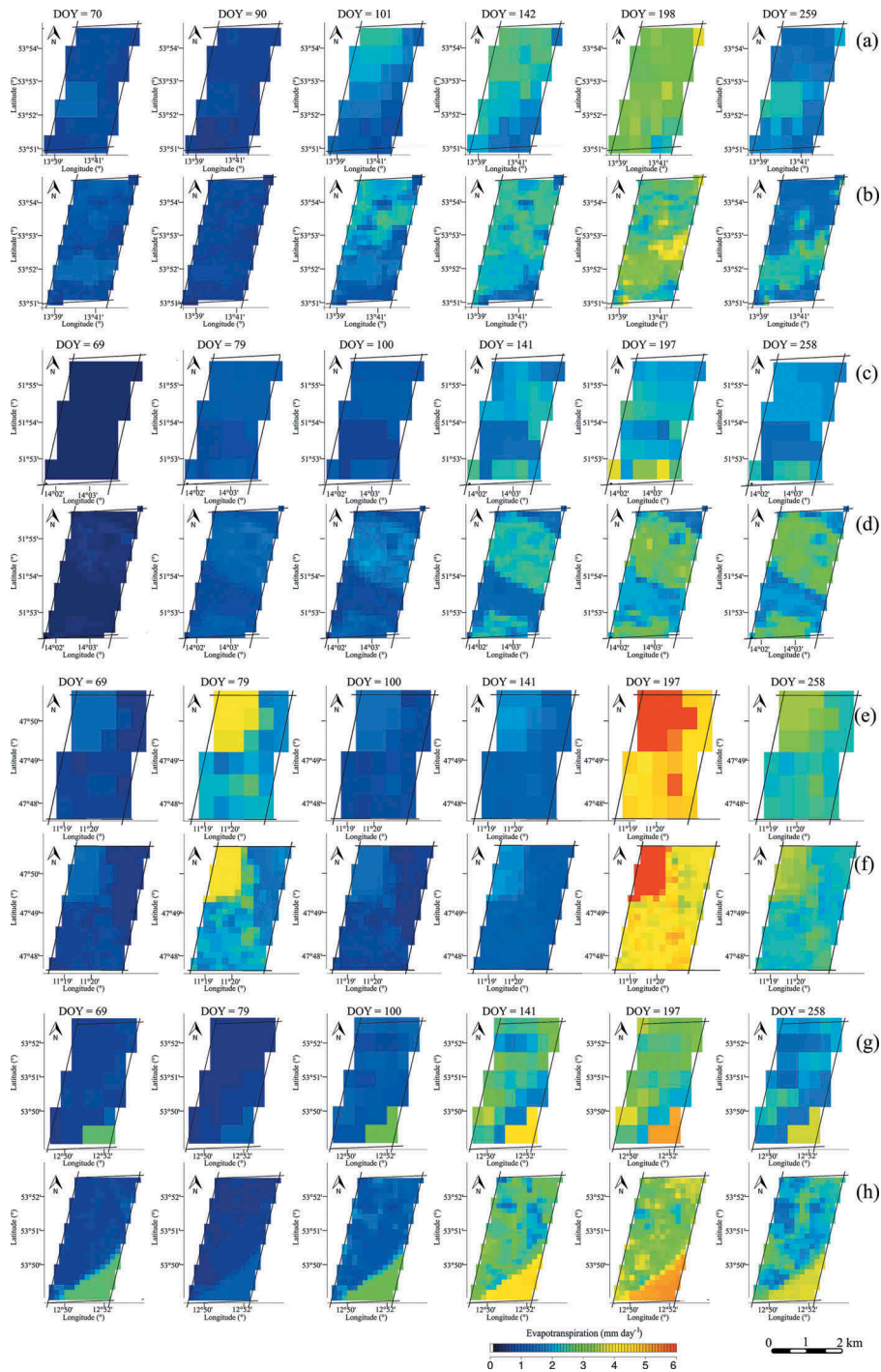


Figure 6. Daily evapotranspiration maps over the grids of 1.0 and 0.3 km spatial resolution across the extent of one MSG cell containing for different days of the year (DOY) in 2014. Anklam (a)–(b), Spreewald (c)–(d), Schechenflz Nord (e)–(f) and Zarnekow (g)–(h).

exhibited above-average ET_d rates during a large part of the year. Likewise, the cropped area in Spreewald, located in the northern half of the MSG cell, exhibited the highest ET_d rates throughout the year. The open water areas form a clearly noticeable pattern in the Zarnekow and Schechenfilz Nord maps. The maps of Schechenfilz Nord also show the high ET_d rates of the peat bogs located to the south of the lake.

The plots and maps of [Figures 5 and 6](#) pictured the variety of ET_d patterns within the boundaries of a MSG cell. This is an aspect of importance for ecosystem monitoring as the landscape structure within a MSG cell can be complex, as can be inferred from the real colour views in [Figure 2](#).

3.2. Missions compatibility

The plots and map sequences presented in the previous section suggested the possibility of coupling ET_d estimates at 1.0 and 0.3 km to construct time series covering the operational period of consecutive Earth observation missions. As mentioned above, ensuring the continuity in spaceborne observations has been an important aspect in the preparation of the Proba-V and Sentinel-3 missions. A first appraisal of the correspondence between 1.0 and 0.3 km simulations during the missions overlap period is illustrated in the plot of [Figure 7](#). This plot contrasts the ET_d estimated at the location of the flux tower at 1.0 and 0.3 km spatial resolutions. The series exhibited a high correlation which suggests that both missions could jointly supply forcing data to study ET_d patterns at one particular location across mission operational periods. Similar evidences of compatibility have been found when testing the compatibility between Spot-V and Proba-V NDVI for crop prediction in North Africa (Meroni et al. 2016).

[Figure 8](#) shows the results of aggregating the modelled values over the extent of the MSG cell. These results are shown in the form of panels containing scatterplots, the values of R^2 and the result of the hypothesis test.

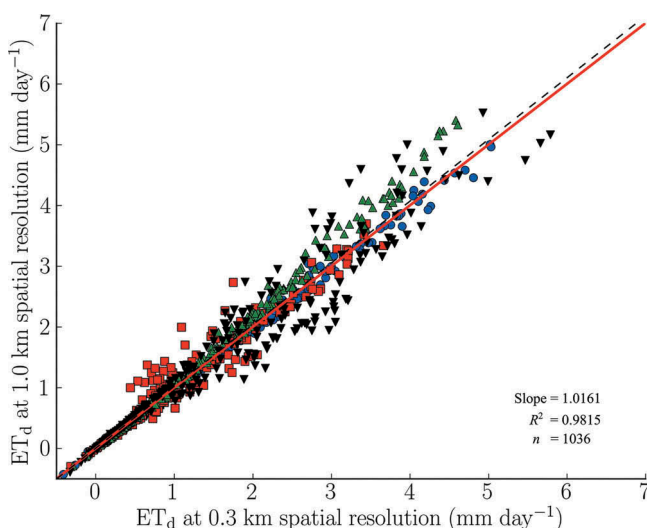


Figure 7. Daily evapotranspiration estimates as modelled at spatial resolutions of about 1.0 and 0.3 km at the location of the flux tower in Anklam (dot), Spreewald (square), Schechenfilz Nord (triangle) and Zarnekow (inverted triangle).

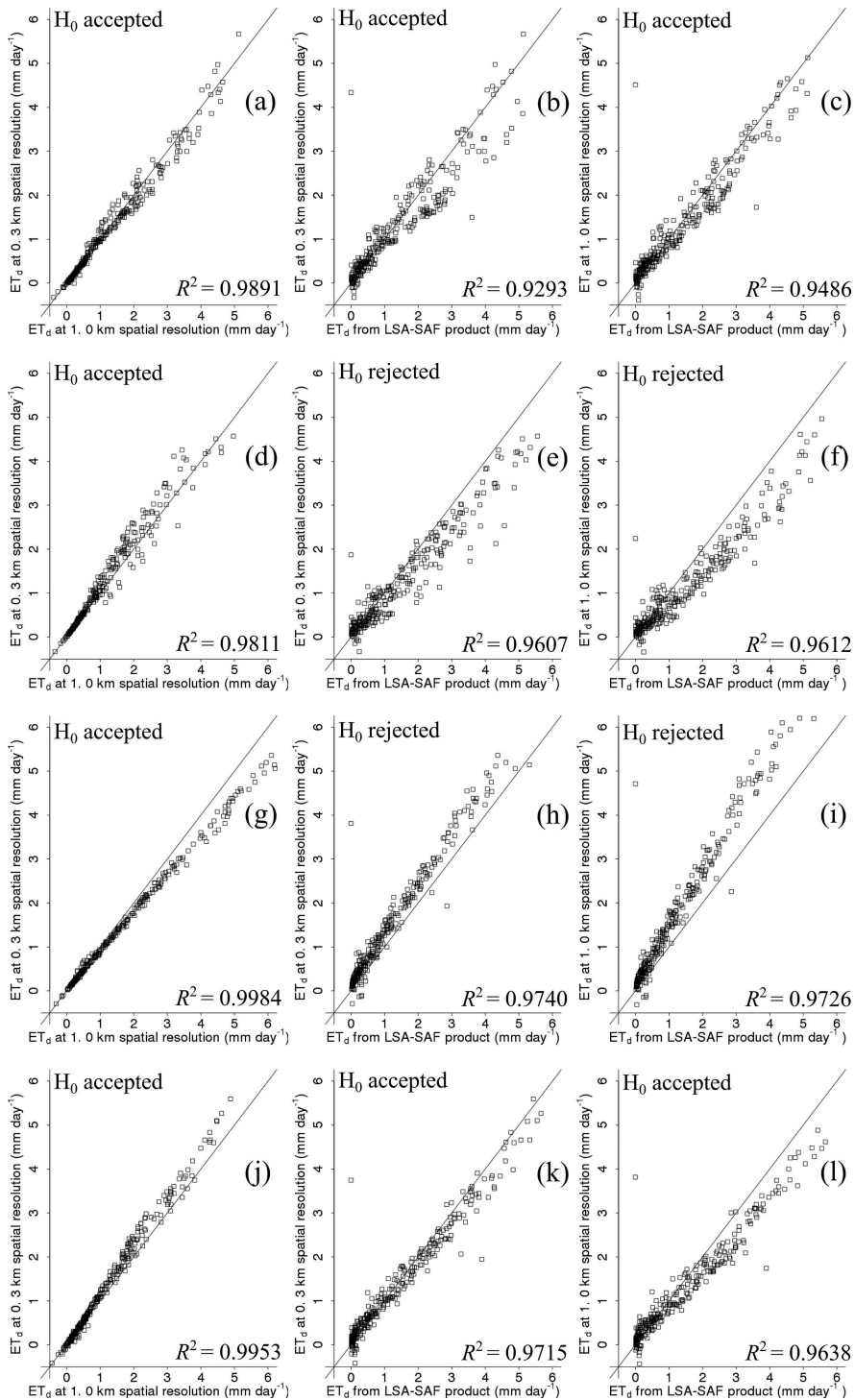


Figure 8. Scatterplots of paired series of daily evapotranspiration as modelled for 2014 in the LSA-SAF ET product and the implementations over grids of about 1.0 and 0.3 km spatial resolution. Plots (a)–(c), (d)–(f), (g)–(i) and (j)–(l) correspond to Anklam, Spreewald, Schechenfilz Nord, and Zarnekow, respectively. The plots indicate the result of evaluating the hypothesis $H_0: \mu = 0$ with 0.05 significance where μ is the mean difference between two paired series of ET_d .

All point clouds in [Figure 8](#) were highly correlated ($R^2 > 0.92$; p – value < 0.05). The test of hypothesis led to accept the H_0 in all cases where simulations over the 0.3 and 1.0 km grids were compared to each other. When LSA-SAF ET was compared to the aggregated simulations over 1.0 and 0.3 km grids, the H_0 was accepted in two of the four study sites (Anklam and Zarnikow). The latter result is not surprising given the large difference in spatial detail of the forcing between the LSA-SAF ET product and the 0.3 and 1.0 km simulations. In addition, the algorithm behind the ET_d estimates is non-linear and thus the additivity property is not satisfied.

The possibility of connecting the operational periods of consecutive satellite missions is beneficial for ecosystem monitoring. In this respect, the comparison of ET_d simulations over the 0.3 and 1.0 km grids at the location of the flux towers ([Figure 7](#)) suggested the possibility of building ET_d time series for a particular location across the operational life of both platforms. Such a possibility is rooted in the similarity in optical sensitivity of both sensors and in the fact that both simulations shared crucial forcing variables. This might explain as well why the aggregated 0.3 and 1.0 km ET_d values across a larger area exhibited high correlation and no statistical difference in the estimated values, as shown in [Figure 8](#). This is an important result towards the construction of ET_d time series covering the operational periods of satellite platforms despite differences in spatial resolution.

4. Conclusions

The main purpose of this study was to test the feasibility of combining the strengths of polar-orbit and geostationary satellites for deriving ET_d estimates at moderate spatial resolution (≤ 1.0 km). The obtained results led to the following general conclusions:

- (1) The seasonal LAI and albedo signatures at the spatial resolution of Spot-V, Proba-V and MODIS imagery can interact synergetically with meteorological and radiation forcing delivered at high temporal resolution for deriving ET_d estimates at moderate spatial resolution.
- (2) Such modelling strategy led in most of the cases to ET_d estimates exhibiting lower error and bias as compared with estimates over the grid of a geostationary satellite.
- (3) The characteristics Spot-V and Proba-V sensors have in common represent the possibility of estimating ET_d for periods covering the operations of both sensors. Since Proba-V also is designed as preparation mission for Sentinel-3 mission, the potential for studying long-term ET_d patterns and/or implement an operational service on the basis of these missions is real.

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References

- Bastiaanssen, W. G. M., M. Menenti, R. A. Feddes, and A. A. M. Holtslag. 1998. "A Remote Sensing Surface Energy Balance Algorithm for Land (SEBAL)." *Journal of Hydrology* 212/213: 198–212.
- Bhattacharya, B., K. Mallick, R. Nigam, K. Dakore, and A. M. Shekh. 2011. "Efficiency Based Wheat Yield Prediction in a Semi-Arid Climate Using Surface Energy Budgeting with Satellite Observations." *Agricultural and Forest Meteorology* 151 (10): 1394–1408.
- Brutsaert, W. 1982. *Evaporation into the Atmosphere Theory, History and Applications*. Dordrecht, Holland: D. Reidel Publishing Company.
- Chehbouni, A., J. Qi, D. Lo Seen, Y. H. Kerr, G. Dedieu, S. Moran, M. Daubas, and B. M. Monteny. 1997. "Estimation of Real Evaporation." In *International Workshop on Remote Sensing and Water Resources*. Montpellier, France: Food and Agriculture Organization.
- Chen, R., S. Kang, X. Hao, F. Li, T. Du, R. Qiu, and J. Chen. 2015. "Variations in Tomato Yield and Quality in Relation to Soil Properties and Evapotranspiration under Greenhouse Condition." *Scientia Horticulturae* 197: 318–328.
- Dettmann, U., M. Bechtold, E. Frahm, and B. Tiemeyer. 2014. "On the Applicability of Unimodal and Bimodal Van Genuchten Mualem Based Models to Peat and Other Organic Soils under Evaporation Conditions." *Journal of Hydrology* 515: 103–115.
- European Environment Agency. 2009. "CORINE Land Cover 2000." <http://www.eea.europa.eu/themes/landuse/clc-download>
- European Space Agency. 2012. "Sentinel-3: ESA's Global Land and Ocean Mission for GMES Operational Services." Noordwijk, The Netherlands: ESA Communications. https://sentinels.copernicus.eu/documents/247904/351187/S3_SP-1322_3.pdf
- Ghilain, N., A. Arboleda, and F. Gellens-Meulenberghs. 2011. "Evapotranspiration Modelling at Large Scale Using Near-Real Time MSG SEVIRI Derived Data." *Hydrology and Earth System Sciences* 15: 771–786.
- Ghilain, N., F. De Roo, and F. Gellens-Meulenberghs. 2014. "Evapotranspiration Monitoring with Meteosat Second Generation Satellites: Improvement Opportunities from Moderate Spatial Resolution Satellites for Vegetation." *International Journal of Remote Sensing* 35 (7): 2654–2670.
- Gio-Global Land Component Lot1 consortium. 2014. "GIOGL1 ATBD GEOV1." Copernicus Programme. http://land.copernicus.eu/global/sites/default/files/products/GIOGL1_ATBD_LAIV1_11.10.pdf
- Gkatsopoulos, P. 2017. A Methodology for Calculating Cooling from Vegetation Evapotranspiration for Use in Urban Space Microclimate Simulations. *Procedia Environmental Sciences* 38: 477–484. Sustainable synergies from Buildings to the Urban Scale.
- González-Dugo, M. P., S. Escuin, C. F. Cano, V. Cifuentes, F. L. M. Padilla, J. L. Tirado, N. Oyonarte, P. Fernández, and L. Mateos. 2013. "Monitoring Evapotranspiration of Irrigated Crops Using Crop Coefficients Derived from Time Series of Satellite Images. II. Application on Basin Scale." *Agricultural Water Management* 125: 92–104.
- Hommeltemberg, J., M. Mauder, M. Drösler, K. Heidbach, P. Werle, and H.-P. Schmid. 2014. "Ecosystem Scale Methane Fluxes in a Natural Temperate Bog-Pine Forest in Southern Germany." *Agricultural and Forest Meteorology* 198–199: 273–284.
- Hu, G., L. Jua, and M. Menenti. 2014. "Comparison of MOD16 and LSA-SAF MSG Evapotranspiration Products over Europe for 2011." *Remote Sensing of Environment* 156: 510–526.
- Jasechko, S., Z. Sharp, J. Gibson, S. J. Birks, Y. Yi, and P. Fawcett. 2013. "Terrestrial Water Fluxes Dominated by Transpiration." *Nature* 496 (7445): 347–350.

- Jovanovic, N., C. García, R. Bugan, I. Teich, and C. García Rodríguez. 2014. "Validation of Remotely-Sensed Evapotranspiration and NDWI Using Ground Measurements at Riverlands, South Africa." *Water SA* 40 (2): 211–220.
- Ko, J., and G. Piccini. 2009. "Corn Yield Responses under Crop Evapotranspiration-Based Irrigation Management." *Agricultural Water Management* 96 (5): 799–808.
- Litvak, E., and D. Pataki. 2016. "Evapotranspiration of Urban Lawns in a Semi-Arid Environment: An in Situ Evaluation of Microclimatic Conditions and Watering Recommendations." *Journal of Arid Environments* 134: 87–96.
- Mallick, K., A. J. Jarvis, E. Boegh, J. Fisher, D. Drewry, K. Tu, S. Hook, et al. 2014. "A Surface Temperature Initiated Closure (STIC) for Surface Energy Balance Fluxes." *Remote Sensing of Environment* 141: 243–261.
- Masson, V., J.-L. Champeaux, F. Chauvin, C. Meriguet, and R. Lacaze. 2003. "A Global Database of Land Surface Parameters at 1-Km Resolution in Meteorological and Climate Models." *Journal of Climate* 16 (9): 1261–1282.
- Meroni, M., D. Fasbender, R. Balaghi, M. Dali, M. Haffani, I. Haythem, J. Hooker, et al. 2016. "Evaluating NDVI Data Continuity between SPOT-VEGETATION and PROBA-V Missions for Operational Yield Forecasting in North African Countries." *IEEE Transactions on Geoscience and Remote Sensing* 54 (2): 795–804.
- Millenium Ecosystem Assessment. 2005. "Ecosystems and Human Well-Being Synthesis." Technical Report. World Resources Institute. ISBN 1-59726-040-1. <http://www.millenniumassessment.org/documents/document.356.aspx.pdf>
- Minacapilli, M., S. Consoli, D. Vanella, G. Ciraolo, and A. Motisi. 2016. "A Time Domain Triangle Method Approach to Estimate Actual Evapotranspiration: Application in A Mediterranean Region Using MODIS and MSG-SEVIRI Products." *Remote Sensing of Environment* 174: 10–23.
- Mu, Q., F. A. Heinsch, M. Zhao, and S. W. Running. 2007. "Development of a Global Evapotranspiration Algorithm Based on MODIS and Global Meteorology Data." *Remote Sensing of Environment* 111 (4): 519–536.
- Nash, J. E., and J. V. Sutcliffe. 1970. "River Flow Forecasting through Conceptual Models Part I -A Discussion of Principles." *Journal of Hydrology* 10 (3): 282–290.
- Nouri, H., S. Beecham, F. Kazemi, A. M. Hassanli, and S. Anderson. 2013. "Remote Sensing Techniques for Predicting Evapotranspiration from Mixed Vegetated Surfaces." *Hydrology and Earth System Sciences Discussions* 10: 3897–3925.
- Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC). 2014. "FLUXNET Portal." Accessed January 15, 2014. <http://fluxnet.ornl.gov/>
- Petropoulos, G., G. Ireland, S. Lamine, H. Griffiths, N. Ghilain, V. Anagnostopoulos, M. North, P. Srivastava, and H. Georgopoulou. 2016. "Operational Evapotranspiration Estimates from SEVIRI in Support of Sustainable Water Management." *International Journal of Applied Earth Observation and Geoinformation* 49: 175–187.
- Royal Meteorological Institute of Belgium. 2010. "Algorithm Theoretical Basis Document Evapotranspiration (MET) Product Daily MET (DMET) Product." LSA-SAF. <http://landsaf.meteo.pt>.
- Royal Meteorological Institute of Belgium. 2011. "Validation Report Evapotranspiration (ET) Products: LSA-16(MET), LSA-17(DMET)." LSA-SAF. <http://landsaf.meteo.pt>
- Sepulcre-Cantó, G., F. Gellens-Meulenberghs, A. Arboleda, G. Duveiller, A. De Wit, H. Eerens, B. Djaby, and P. Defourny. 2013. "Estimating Crop-Specific Evapotranspiration Using Remotesensing Imagery at Various Spatial Resolutions for Improving Crop Growth Modelling." *International Journal of Remote Sensing* 34 (9–10): 3274–3288.
- Sepulcre-Cantó, G., J. Vogt, A. Arboleda, and T. Antofie. 2014. "Assessment of the EUMETSAT LSA-SAF Evapotranspiration Product for Drought Monitoring in Europe." *International Journal of Applied Earth Observation and Geoinformation* 30: 190–202.
- Tadesse, T., G. Senay, G. Berhan, T. Regassa, and S. Beyene. 2015. "Evaluating A Satellite-Based Seasonal Evapotranspiration Product and Identifying Its Relationship with Other Satellite-Derived Products and Crop Yield: A Case Study for Ethiopia." *International Journal of Applied Earth Observation and Geoinformation* 40: 39–54.

- Trigo, I., C. Dacamara, P. Viterbo, J.-L. Roujean, F. Olesen, C. Barroso, F. Camacho-de Coca, et al. 2011. "The Satellite Application Facility for Land Surface Analysis." *International Journal of Remote Sensing* 32 (10): 2725–2744.
- Van den Hurk, B., P. Viterbo, A. Beljaars, and A. Betts. 2000. *Offline validation of the ERA40 surface scheme*. Technical Report 295. ECMWF. Technical memorandum.
- Viterbo, P., and A. Beljaars. 1995. "An Improved Land Surface Parameterization Scheme in the ECMWF Model and Its Validation." *Journal of Climate* 8: 2716–2748.
- Wei, Z., P. Paredes, Y. Liu, C. Wei, and L. Pereira. 2015. "Modelling Transpiration, Soil Evaporation and Yield Prediction of Soybean in North China Plain." *Agricultural Water Management* 147: 43–53.
- Wolters, E., W. Dierckx, J. Dries, and E. Swinnen. 2014. "PROBA-V Products User Manual." VITO. http://proba-v.vgt.vito.be/sites/default/files/Product_User_Manual.pdf
- Wu, B., L. Jiang, N. Yan, C. Perry, and H. Zeng. 2014. "Basin-Wide Evapotranspiration Management: Concept and Practical Application in Hai Basin, China." *Agricultural Water Management* 145: 145–153.
- Zedler, J., and S. Kercher. 2005. "WETLAND RESOURCES: Status, Trends, Ecosystem Services, and Restorability." *Annual Review of Environment and Resources* 30 (1): 39–74.
- Zha, T., A. Barr, G. van der Kamp, T. A. Black, J. H. McCaughey, and L. Flanagan. 2010. "Interannual Variation of Evapotranspiration from Forest and Grassland Ecosystems in Western Canada in Relation to Drought." *Agricultural and Forest Meteorology* 150 (11): 1476–1484.