International Journal of Applied Earth Observation and Geoinformation 30 (2014) 190–202

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag

Assessment of the EUMETSAT LSA-SAF evapotranspiration product for drought monitoring in Europe

Guadalupe Sepulcre-Canto[a,*], Jürgen Vogt[a], Alirio Arboleda[b], Tiberiu Antofie[a]

[a] European Commission, DG Joint Research Centre, Institute for Environment and Sustainability, Via E. Fermi 2749, 21027 Ispra, Italy
[b] Royal Meteorological Institute of Belgium, Avenue circulaire 3, 1180 Brussels, Belgium

ARTICLE INFO

Article history:
Received 19 September 2013
Accepted 31 January 2014
Available online 14 March 2014

Keywords:
Evapotranspiration
Water stress
Drought
LSA-SAF
EUMETSAT
EDO

ABSTRACT

Evapotranspiration is a key parameter for water stress assessment as it is directly related to the moisture status of the soil-vegetation system and describes the moisture transfer from the surface to the atmosphere. With the launch of the Meteosat Second Generation geostationary satellites and the setup of the Satellite Application Facilities, it became possible to operationally produce evapotranspiration data with high spatial and temporal evolution over the entire continents of Europe and Africa. In the frame of this study we present an evaluation of the potential of the evapotranspiration (ET) product from the EUMETSAT Satellite Application Facility on Land Surface Analysis (LSA-SAF) for drought assessment and monitoring in Europe.

To assess the potential of this product, the LSA-SAF ET was used as input for the ratio of ET to reference evapotranspiration (ET_0), the latter estimated from the ECMWF interim reanalysis. In the analysis two case studies were considered corresponding to the drought episodes of spring/summer 2007 and 2011. For these case studies, the ratio ET/ET_0 was compared with meteorological drought indices (SPI, SPEI and Sc-PDSI for 2007 and SPI for 2011) as well as with the anomalies of the fraction of absorbed photosynthetic active radiation (fAPAR) derived from remote sensing data. The meteorological and remote sensing indicators were taken from the European Drought Observatory (EDO) and the CARPATCLIM climatological atlas.

Results show the potential of ET/ET_0 to characterize soil moisture variability, and to give additional information to fAPAR and to precipitation distribution for drought assessment. The main limitations of the proposed ratio for drought characterization are discussed, including options to overcome them. These options include the use of filters to discriminate areas with a low percentage vegetation cover or areas that are not in their growing period and the use of evapotranspiration without water restriction (ET_{wwr}), obtained as output of the LSA-SAF model instead of ET_0. The ET/ET_{wwr} ratio was tested by comparing its accumulated values per growing period with the winter wheat yield values per country published by Eurostat. The results point to the potential of using the remote sensing based LSA-SAF evapotranspiration and the ET/ET_{wwr} ratio for vegetation monitoring at large scale, especially in areas where data is generally lacking.

Introduction

Drought can be defined as the result of a shortage of precipitation that limits plant water availability to such an extent that ecosystem productivity is reduced. In the specific case of agricultural areas this can lead to yield reductions implying in some cases important economic consequences. Other impacts, less easy quantifiable in terms of economic losses, include increased fire risks in forests and other (semi-)natural ecosystems and long-term environmental impacts like soil erosion or desertification.

In case of limited water availability in the soil, the evapotranspirative loss of the vegetation exceeds the supply of water from the soil producing what is defined as water stress. Plants react to water stress by (partially) closing their leaf stomata in order to reduce the loss of water by transpiration. The term evapotranspiration (ET) describes the combined effect of water loss from the soil surface by evaporation and water loss from the vegetation by transpiration.

* Corresponding author. Tel.: +39 0332785712.
E-mail addresses: guadalupe.sepulcre@outlook.com (G. Sepulcre-Canto), juergen.vogt@jrc.ec.europa.eu (J. Vogt), alirio.arboleda@meteo.be (A. Arboleda), tiberiu.antofie@jrc.ec.europa.eu (T. Antofie).

http://dx.doi.org/10.1016/j.jag.2014.01.021
0303-2434/

Traditional methods for identifying water stress rely on punctual observations (like leaf water potential or stomatal conductance) that are time consuming and have the limitation of the number of observations that can be done in a time window narrow enough to consider them homogeneous. These limitations explain the interest of spatially resolved information on water stress (Sepulcre-Canto et al., 2006; Berni et al., 2009).

Evapotranspiration is a key parameter for water stress assessment as it describes the water transfer from the surface and vegetation canopy to the atmosphere, integrating environmental factors like meteorological conditions and soil moisture status. Several methods have been developed to obtain evapotranspiration estimates from remote sensing data, but most of them have been applied at regional scale (see Verstraeten et al., 2008, for a review). The repeated measurement of surface variables such as the surface temperature, the surface albedo or the percentage vegetation cover and their injection into models of the surface energy balance enable a more detailed mapping and monitoring of water stress. The latent heat flux is of particular interest in this context, since it represents the link between the energy and the water budget equations. It is directly related to the moisture status of the soil-vegetation system and its integration over time yields the daily rate of evapotranspiration. Many surface energy balance studies using remote sensing data have been performed during the last decades. In particular, research has focused on the determination of the partitioning of energy into the sensible and latent heat fluxes at the surface.

Physically-based approaches model the sensible heat flux by a resistance scheme. One of the first approaches was developed by Choudhury et al. (1986). The method has been subsequently improved in order to be applied to heterogeneous surfaces (e.g., Kustas et al., 1989; Kustas, 1990; Sugita and Brutsaert, 1990), to obtain daily quantities (e.g., Hall et al., 1992; Diak and Whipple, 1993; Anderson et al., 1997), and to better account for different surface cover types and for the fraction of bare soil (e.g., Norman et al., 1995; Lhomme, 1997; Kustas and Norman, 1997). Soil-Vegetation-Atmosphere-Transfer (SVAT) models are more complex, giving a detailed description of soil and vegetation canopy processes, like water, turbulent and radiation transfer mechanisms or physiological processes like stomatal regulation (see Olioso et al., 1999 for a review on the use of remote sensing in SVAT models).

During recent years, new efforts have been undertaken in order to develop global and continental evapotranspiration products from remote sensing imagery. One of the few available operational products is the evapotranspiration product by the EUMETSAT Satellite Application Facility on Land Surface Analysis (LSA-SAF) based on the SEVIRI sensor onboard the Meteosat Second Generation geostationary satellites (MSG-SEVIRI). The benefits of using LSA-SAF products are their spatial coverage (Europe, Africa and parts of South America) and the fact that they are produced operationally in near-real time (every 30 min in the case of ET), which is fundamental for drought early warning. In addition, geostationary satellites provide homogeneous images over their entire field of view, such as the entire European continent. The model used to obtain this product is based on the specific parameterizations of the TESSEL SVAT scheme (van den Hurk et al., 2000; Balsamo et al., 2009), using a combination of remote sensing data (MSG-SEVIRI) and atmospheric model outputs (Ghilain et al., 2011).

ET by itself is not a water stress indicator as, in addition to water availability, it is influenced by many other factors like wind speed or solar radiation. That is the reason why ET is commonly normalized by the reference or by the potential evapotranspiration in order to characterize water stress. This is, for example, the theoretical basis of the Crop Water Stress Index (CWSI, Idso et al., 1981; Jackson et al., 1981), largely used in agriculture for assessing water stress and for irrigation scheduling, and of the soil water requirement satisfaction index proposed by the Food and Agriculture Organization (Doorenbos and Pruitt, 1977) for estimating water needs and forecasting yield losses due to water stress. Common approaches for drought monitoring using ET also include the computation of the anomalies of ET for the estimation of the Evapotranspiration Deficit Index (ETDI) (Narasimhan and Srinivasan, 2005), or of anomalies of the ratio between evapotranspiration and potential evapotranspiration for the estimation of the Evaporative Stress Index (ESI) (Anderson et al., 2011). For the calculation of anomalies, long time series of data are, however, needed in order to arrive at a statistically robust characterization of normal conditions.

The main goal of this study is to assess the potential of using remote sensing based evapotranspiration for drought monitoring in Europe within the framework of the European Drought Observatory (EDO) (http://edo.jrc.ec.europa.eu). In particular, the ET assessed is the EUMETSAT LSA-SAF product.

EDO is an initiative of the European Commission's Joint Research Centre that aims to integrate drought information at European level in order to provide a drought monitoring tool that encompasses continental, national, regional and local scales. Apart from specific indicators provided by different institutions that reflect local conditions, a set of standardized indicators are produced to enable a homogeneous analysis over the entire European continent. These indicators are based on data coming from meteorological observations as well as from remote sensing data and distributed hydrological models. Currently, the only remote sensing based indicator included in EDO is the anomaly of the fraction of Absorbed Photosynthetic Active Radiation (fAPAR) obtained from the VEGETATION sensor on board the SPOT satellite. fAPAR is considered a good indicator to assess drought impacts on vegetation because of its sensitivity to water stress (Gobron et al., 2005) that affects the capacity of vegetation to intercept solar radiation and therefore the vegetation growth rate. Since a reduction in plant transpiration is expected before a visible reduction in the vegetation growth rate and the response in plant transpiration is also expected to be faster under recovery conditions (Hsiao, 1973), a water stress indicator based in ET would be a very useful complementary information for drought assessment. The fact that the LSA-SAF ET product is based on geostationary satellite imagery adds the benefits of homogeneity and high temporal resolution.

Because the objective of EDO is to assess drought operationally at European level and for all ecosystem types, the water stress indicator proposed in this study is the ratio between evapotranspiration (ET) and the reference evapotranspiration (ET_0). In addition, the ratio between ET and ET without water restriction (ET_{wwr}) was also tested, both obtained from the EUMETSAT LSA-SAF ET SVAT model.

Materials and methods

Imagery retrieval and processing

The evapotranspiration product used in this study is the daily ET product operationally produced in the framework of the EUMETSAT Satellite Application Facility on Land Surface Analysis (LSA-SAF). The model used is a simplified Soil-Vegetation-Atmosphere-Transfer (SVAT) scheme that uses as input a combination of remote sensing data and atmospheric model outputs (Ghilain et al., 2011). These inputs include other LSA-SAF products from MSG-SEVIRI (the Albedo, the Downwelling Surface Shortwave Flux and the Downwelling Surface Longwave Flux), meteorological data coming from the ECMWF numerical weather prediction model, and the ECOCLIMAP database (Masson et al., 2003) for identifying and characterizing the land cover. In the model, each pixel is considered a mix of homogeneous tiles representing particular land cover types. The cover types can be: bare soil and rocks, deciduous, coniferous and evergreen broadleaf trees, rainfed and irrigated crops and natural herbaceous. For each pixel, a maximum of 4 tiles (3 vegetation tiles plus bare soil) are allowed. The energy balance equations are solved at tile level and the global pixel value is obtained through the weighted contribution of each tile. The evapotranspiration product retrieved in this way has been validated using ground truth data and other model outputs with positive results by Ghilain et al. (2012).

ET data was downloaded from the EUMETSAT's LSA-SAF webpage (http://landsaf.meteo.pt/). It has a spatial resolution of 3–5 km (depending on the latitude and distance to nadir view) and is distributed with one day of delay. The product is available operationally since 2012, but the developers provided images for 2007 and 2011 for this study. These data, in order to be compared with the other indicators used in EDO were accumulated every 10 days. Each month was split in 3 periods (named dekads): from the 1st to the 10th day, from the 11th to the 20th day, and from the 21st day to the end of the month.

10-day ET_0 data for Europe were further obtained from the FOODSEC Meteodata Distribution Page (http://marswiki.jrc.ec.europa.eu/datadownload/index.php). These data consist in reference evapotranspiration (FAO Penman-Monteith equation) obtained from ECMWF ERA INTERIM weather prediction data at 0.25° resolution (Meteoconsult, 2013). Therefore, the same meteorological data source was used as input to the ET model as well as input to the ET_0 equations.

ET data was resampled to 0.25° for the case of 2007, while keeping it in its original spatial resolution for 2010 and 2011. The 2007 data were resampled in order to eliminate artifacts observed due to the absence, at that time, of an interpolation algorithm for the meteorological data (originally at 0.25°) used as input to the SVAT model. This interpolation algorithm was only introduced in 2010 homogenizing the resolution of the input data and eliminating the artifacts. Finally, the ratio ET/ET_0 was calculated. ET/ET_0 varies between 0 and values slightly higher than 1. In areas covered by a vegetation canopy values close to 1 indicate that the plant water demand is satisfied (fully satisfied when the value is 1 for the reference crop), while values close to 0 indicate canopy water stress (0 corresponding to absence of evapotranspiration).

For the period from April to July 2011, ET_{wwr} was estimated using the configuration of the SVAT corresponding to soil water saturation, thus allowing normalizing ET by the ET of the corresponding land cover under ideal water conditions. These two evapotranspiration products were obtained with the most recent version of the ET algorithm. In this version, daily LSA-SAF Leaf Area Index (LAI) and Fraction of Vegetation Cover (FVC) products are combined with ECOCLIMAP land cover data in order to derive a daily vegetation characteristics database. The main advantage of using the LAI/FVC products is that they reflect a vegetation status closer to reality, as compared to ECOCLIMAP, where vegetation characteristics vary on a monthly basis (Gilahin et al., 2012). To obtain ET_{wwr}, the algorithm was run with exactly the same input as for real ET but assuming no water-shortage.

Assessment of the drought detection capabilities

To assess the performance of the ratio ET/ET_0 under drought conditions, two different case studies were analyzed. These case studies corresponded to the drought periods of spring/summer 2007 and spring/summer 2011.

In the case of 2007, ET/ET_0 results were compared with maps of the Standardized Precipitation Index (SPI), the Standardized Precipitation-Evapotranspiration Index (SPEI) and the self-calibrating Palmer Drought Severity Index (Sc-PDSI). These maps were obtained from data provided by the CARPATCLIM project (http://www.carpatclim-eu.org). The CARPATCLIM project through the CARPACLIM atlas provides daily meteorological variables and monthly drought indicators from 1961 to 2010 at 10 km spatial resolution. The atlas covers an area of 600,000 km^2 in south-eastern Europe (Fig. 1). Finally, the ET/ET_0 maps were contrasted with those maps of the fraction of Absorbed Photosynthetic Active Radiation (fAPAR) anomalies obtained in the EDO system. In the case of 2011, the results of the ET/ET_0 ratio were compared to the SPI and the fAPAR anomalies produced routinely by EDO for all of Europe.

SPI (McKee et al., 1993) is one of the most widely used meteorological drought indicators, being a statistical indicator that compares the total precipitation received at a particular location during an accumulation period, with the long-term precipitation distribution for the same period of time at that location. The accumulation periods used in this study were 1 and 3 months (named SPI-1 and SPI-3, respectively). In EDO a reference period of 30 years (1981–2010) is used. In this case, SPI is obtained from the interpolation of SPI values calculated from observed meteorological point data. An SPI between −1 and 1 indicates near normal conditions, from −1 to −1.5 moderate drought, from −1.5 to −2 severe drought and if it is lower than −2, extreme drought.

The nature of the two drought events chosen as case studies was different in terms of intensity and continuity of the precipitation deficits. In the 2007 case a very short but extreme precipitation deficit was observed in April while in 2011 mild precipitation deficits were observed during the months of March, April and May. That is the reason why in the analysis of 2007 the SPI-1 is used (that means accumulating one month of information), and in 2011 the SPI-3 is used (accumulating three months of information).

The SPEI (Vicente-Serrano et al., 2010) is an index that uses the difference between precipitation and potential evapotranspiration; the last calculated as a function of the air temperature (Thornthwaite, 1948). This difference represents a simple climatic water balance which, similar to the SPI, is calculated at different time scales to obtain the SPEI. As in the case of SPI, SPEI between −1 and 1 indicates near normal conditions, from −1 to −1.5 moderate drought, from −1.5 to −2 severe drought and if it is lower than −2, extreme drought.

Sc-PDSI (Wells et al., 2004) is based on a modified version of the Palmer Drought Severity Index (PDSI), first introduced by Palmer (1965) with the intent to measure the spatial and temporal moisture variability related to local normal conditions. The index is based on the supply-and-demand concept of a complex water budget system and calculated using precipitation and temperature records as well as soil characteristics of the site. The Sc-PDSI focuses on the anomalies of the soil moisture computed as a difference between the actual precipitation and the amount of precipitation needed to maintain a normal soil moisture level. The Sc-PDSI is commonly ranging from −4 to +4. A Sc-PDSI between 2 and −2 indicates near normal conditions, from −2 to −3 moderate drought, from −3 to −4 severe drought and if it is lower than −4, extreme drought.fAPAR represents the fraction of the solar energy which is absorbed by the vegetation. fAPAR is currently obtained from the VEGETATION sensor on board SPOT satellite using the MERIS Global Vegetation Index (MGVI) algorithm (Gobron et al., 2004). fAPAR anomalies are obtained routinely in the EDO system on a 10-daily basis. The reference period for the baseline statistics is 1999 to 2011. The fAPAR anomalies are commonly ranging from −3 to +3, negative values indicating a reduction of photosynthetic activity compared to the average and consequently a potential vegetation water stress.

Further, in the case of 2011, the evolution of the ET/ET_0 ratio for one of the main affected regions during this drought episode (France) was compared with the evolution during a year when the precipitation distribution was normal (i.e., 2012).

Finally the performance of the ratio between evapotranspiration and evapotranspiration without water restriction was tested,

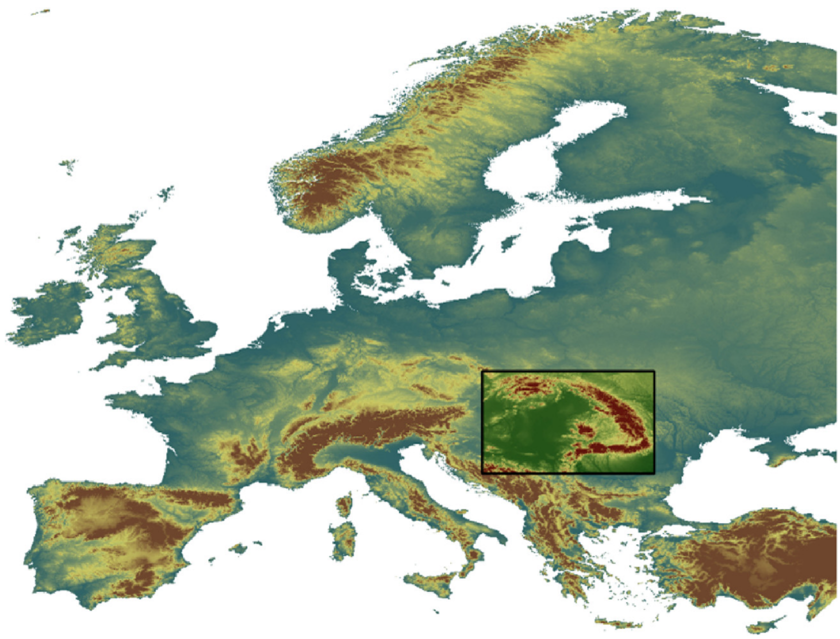

Fig. 1. Map of the European and CARPATCLIM study areas. The CARPATCLIM project area is delimited by a black square.

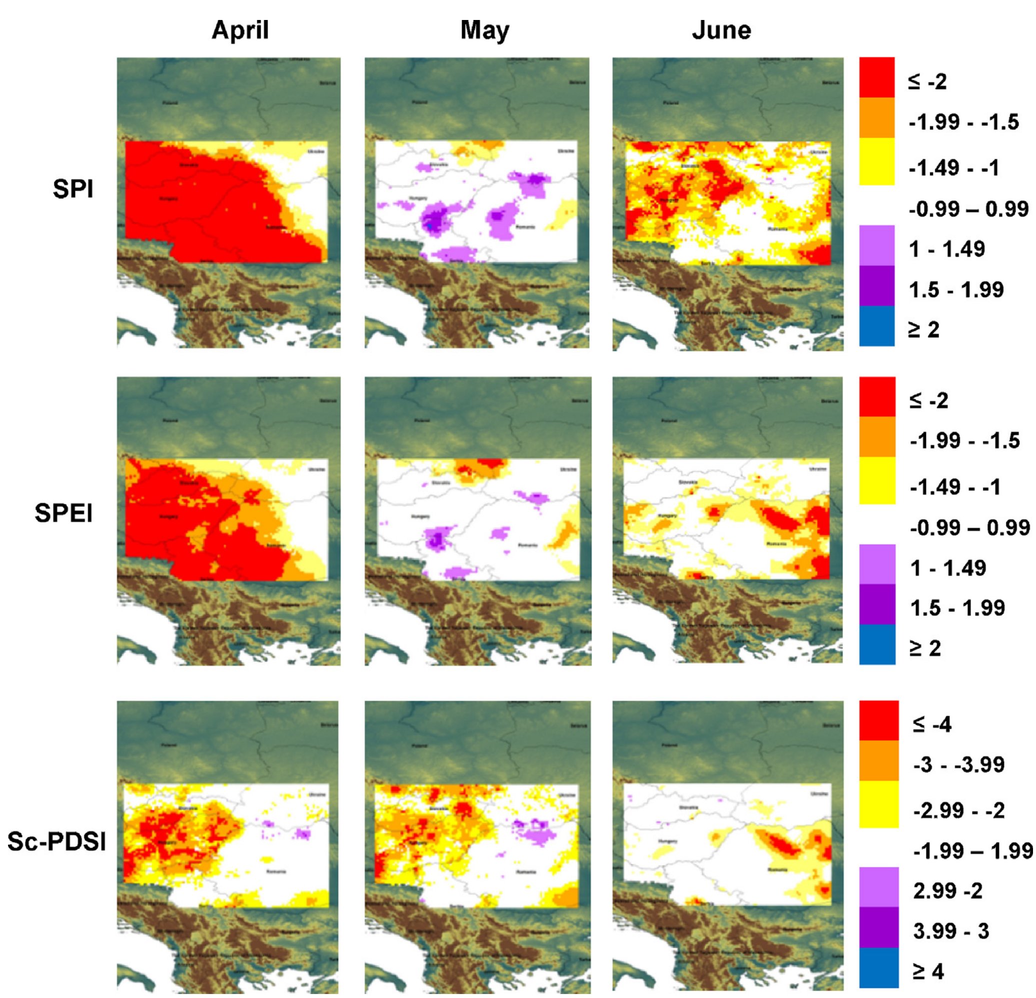

Fig. 2. SPI-1, SPEI-1, and Sc-PDSI images of the CARPATCLIM project area from April to June 2007.

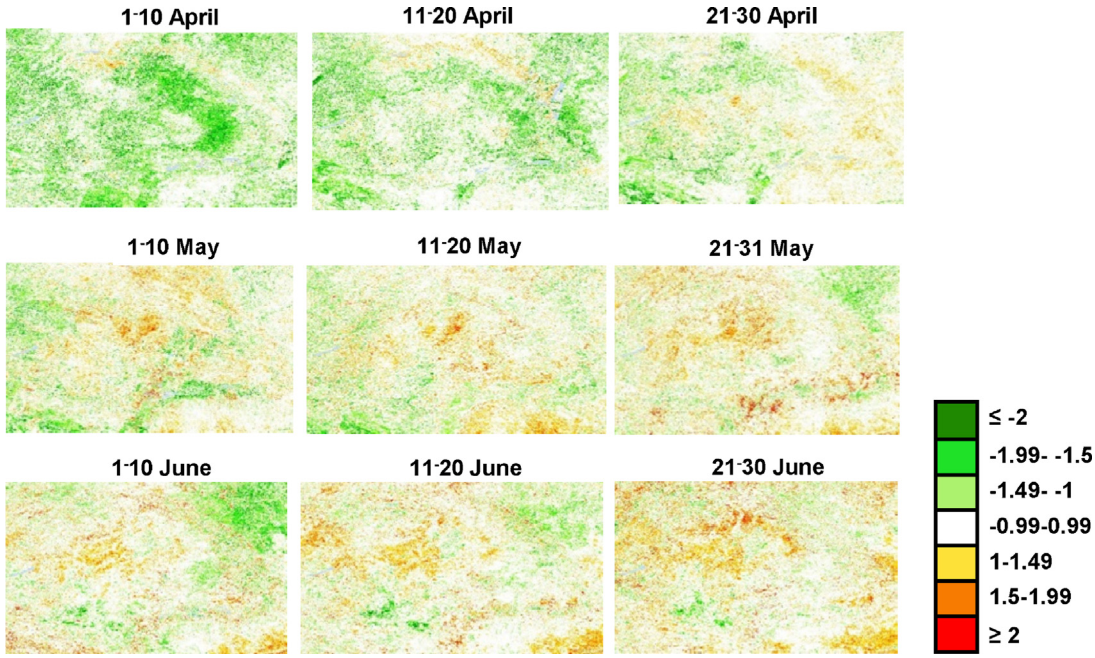

Fig. 3. fAPAR anomalies of the CARPATCLIM project area from April to June 2007, based on VEGETATION data at 1.0 km spatial resolution.

comparing qualitatively the maps obtained for all of Europe with those of ET/ET_0 and SPI for the period spring/summer 2011. The potential of this ratio was also assessed quantitatively relating the accumulated values per growing period by country with the relative winter wheat yield production (kg/ha) (Doorenbos and Kassam, 1979) obtained from the values provided for each country by Eurostat (http://epp.eurostat.ec.europa.eu). Winter wheat is the most important cereal produced in Europe and its active growing period begins in spring, being harvested from the end of May-beginning of June in the southern countries to end of July-beginning of August in the Northern countries of Europe. To obtain this relationship, the ratio was accumulated from April to the end of July and the relative yield production was obtained as an approximation, dividing the yield values of 2011 by the maximum yield of the last 10 years.

Vegetation filtering

As the interest of this study was to identify vegetation water stress for drought monitoring, different vegetation filters were applied in order to minimize the soil influence and/or remove areas where the indicator response is not relevant for drought assessment.

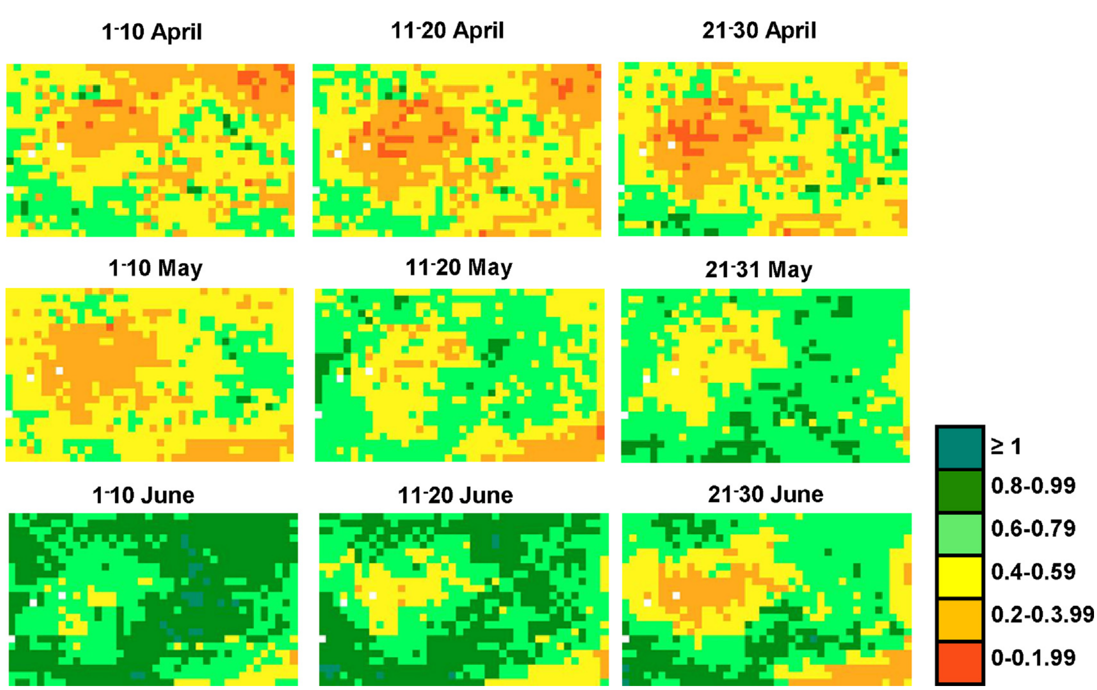

Fig. 4. ET/ET_0 of the CARPATCLIM project area from March to June 2007, based on MSG-SEVIRI data resampled at 0.25° spatial resolution.

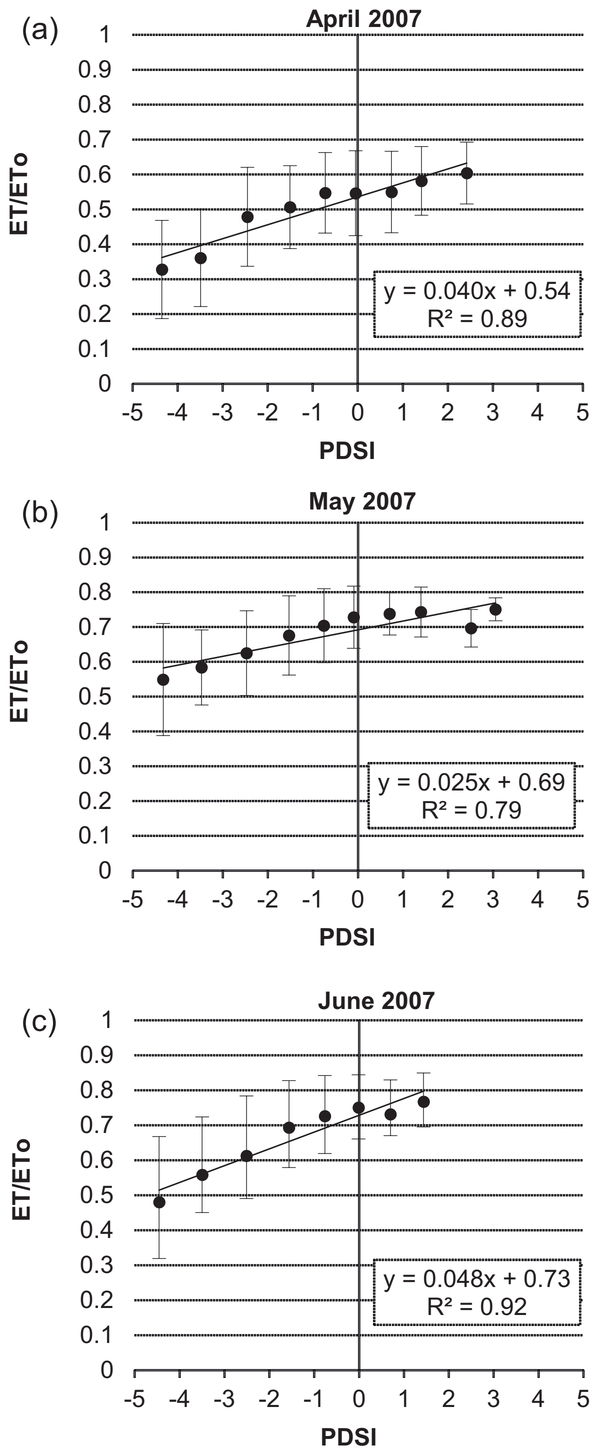

Fig. 5. Relationship between ET/ET_0 and Sc-PDSI mean values for (a) April 2007, (b) May 2007 and (c) June 2007. Vertical bars indicate one standard deviation.

i) **Phenology filter**, consisting in eliminating all the pixels that are outside the vegetation growing period, using the phenological indicators of beginning of the growing period and end of the growing period derived from remote sensing data (Ivits et al., 2012).
ii) **fAPAR filter**, consisting in eliminating the pixels that have an fAPAR value lower than the long-term annual mean value of fAPAR for this pixel (taking into account all the time series, in this case from 1999 to 2011) (Carrão et al., 2013).
iii) **ECOCLIMAP filter**, consisting in eliminating the pixels for which the principal tile in the ECOCLIMAP land cover database is bare soil or rocks. The ECCOCLIMAP database (Masson et al., 2003) has a 1 km resolution. The filtering was done discarding the MSG-SEVIRI pixels occupied by these classes in more than 1/3 of their extension.
iv) **FVC filter**, consisting in filtering all the pixels with a fraction of percentage of vegetation cover (FVC) lower than 50%. The threshold of 50% was chosen arbitrarily. For that, the LSA-SAF product of FVC was used (LSA-SAF, 2008). This product, also derived daily from SEVIRI imagery, has the same spatial and temporal resolution than the ET product.

Results

Case studies

Case study 2007

In 2007, the Carpathian Region (Fig. 1) was affected by a heat wave in spring and summer. In April, June and July there were deficits of precipitation in different regions, the most pronounced being in April and affecting all the countries of the area. As an example of the consequences of this drought episode, the cereal production decreased in Romania by ca. 50% from the mean value of the previous 5 years (http://epp.eurostat.ec.europa.eu/).

Fig. 2 shows the SPI-1, SPEI-1 and Sc-PDSI for April to June 2007 from the CARPATCLIM climate atlas (http://www.carpatclim-eu.org). The maps show how Romania among other countries in the Carpathian area suffered extreme drought conditions in the month of April with SPI and SPEI values lower than −2 approximately in 50% of the area. As shown by the SPI, during May the country received normal or near normal precipitation and again in June, some areas (this time, in a smaller extension) received less than normal precipitation. The pattern of Sc-PDSI differs from the pattern of SPI and SPEI especially in May, giving information about the soil moisture deficit. This soil moisture deficit occurring in parts of Hungary, Slovakia, Serbia or the south of Romania, continued until June even if the countries received normal or above normal precipitation amounts in the month of May.

The images of the fAPAR anomalies (Fig. 3) begin to show the impacts of the drought conditions on the vegetation cover from the last 10 days of April. More pronounced impacts can be seen during the months of May and June, with values in general, not lower than −2 standard deviations. The ratio between ET and ET_0 (Fig. 4), however, shows the effect of the warm and dry weather from the beginning of April and reflects clearly the effects of the recovery conditions that occurred in May. The average growing period in Romania begins at the end of March; consequently the area suffered an extreme deficit of precipitation at the beginning of the growing period. As a result, the development of the vegetation was lower than the normal for all the vegetative cycle, as can be seen in the anomalies of fAPAR. The ratio ET/ET_0 on the contrary reflects the climatological conditions of May leading to a recovery of the vegetation water availability, showing its usefulness as complementary information to fAPAR for evaluating the vegetation status.

The results of a spatial comparison of the ET/ET_0 ratio with the different meteorological indices shown in Fig. 2 are summarized in Table 1. The relationships are obtained between the ET/ET_0 from the last dekad of the months of April, May and June and the different indices of each of the corresponding months. The correlation coefficients obtained were significant ($p < 0.05$) for all the cases except for the relationship with SPI in June. The best correlation was obtained with the Sc-PDSI index, related not only to precipitation distribution as the SPI but also to soil moisture variability. The highest correlation coefficient was obtained for the Sc-PDSI in

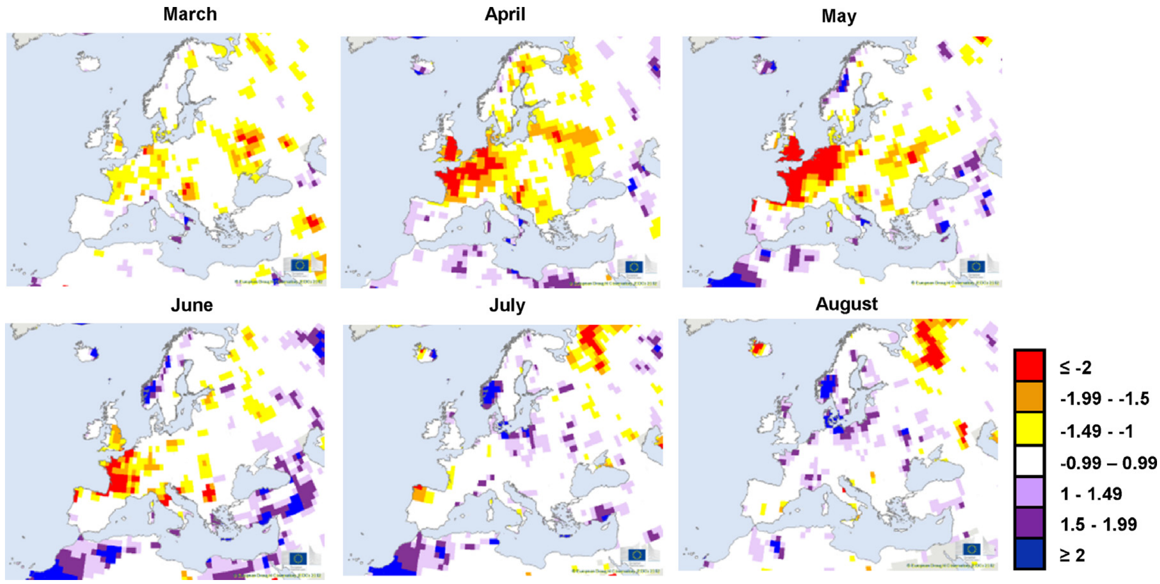

Fig. 6. SPI-3 images of Europe from March to August 2011.

the month of April yielding an $R = 0.5$. Additionally, Fig. 5 shows the relationship between ET/ET_0 and Sc-PDSI, for April, May and June, based on the mean values obtained for each of the PDSI classes described in Alley (1984), where the near normal class is subdivided in 5 classes, slightly wet with values from 1 to 1.99, incipient wet spell from 0.5 to 0.99, near normal from −0.49 to 0.49, incipient drought from −0.99 to −0.5 and mild drought from −1.99 to −1. In this case, the determination coefficients obtained were $R^2 = 0.89$ in April, 0.79 in May and 0.92 in June. These results indicate the capability of the ratio ET/ET_0 to identify soil moisture variability and therefore, to identify extended soil moisture deficits. Nevertheless more in-depth research is needed in order to set meaningful thresholds for identifying drought intensities. Further analyzing Fig. 5, it can be noticed how for the months of May and June, mean ET/ET_0 values lower than 0.6 correspond to the classes of moderate, severe or extreme drought according to the Sc-PDSI classification, values between 0.6 and 0.7 to moderate and mild drought, and values above 0.7 to incipient, normal or wet classes. Nevertheless for April, the ET/ET_0 mean values obtained for each Sc-PDSI class are lower than those for the months of May and June. This could be due to the fact that April is the beginning of the growing period and the vegetation canopy probably covers the soil only partially, consequently the ET/ET_0 pixels include a significant portion of bare soil information.

Case study 2011

Another significant drought episode occurred in spring 2011. During this period, southern England, western Germany, the Netherlands, Belgium and the north-western areas of France received considerably less precipitation than what is climatologically expected (EDO, 2011).

The SPI-3 (Fig. 6) shows how the precipitation deficit began in March identifying some areas with moderate drought (SPI-3 with values from −1.5 to −1). These drought conditions became more severe in April and even more in May with values lower than −2 in western Germany, the Netherlands, Belgium and the North of France. Also the drought conditions that existed in March over Ukraine, Belarus and the Baltic countries persisted into May. The situation turned to normal conditions in some of the areas in June and over almost all the continent in July.

Despite the precipitation deficit, the fAPAR (Fig. 7) shows positive anomalies in April, indicating a vegetation development higher than normal for this month probably due to an earlier start of the growing season as a result of exceptionally high temperatures. The anomalies of fAPAR began to turn into negative values in the second dekad of May for some of the affected areas, extending over the entire affected area in June and retreating slowly in July, indicating improving conditions of the vegetation canopy. Values lower than −2 persisted over extended areas from the last dekad of May to the second dekad of July.

The corresponding ratio ET/ET_0, from April to the end of July 2011 is shown in Fig. 8. These images show good correspondence between the areas where SPI is lower than −1 or −2 indicating moderate or extreme drought (Fig. 6) and the areas with a value of the ET/ET_0 ratio lower than 0.6 or 0.4 from the second and more evidently form the third dekad of May. ET/ET_0 shows the effects of the recovery conditions in the last 10 days of July. In general, the spatial and temporal pattern of the ET/ET_0 ratio is coherent with the fAPAR anomalies (Fig. 7).

Despite the good correspondence of the spatial patterns of ET/ET_0 and drought conditions in areas where there is a high percentage of vegetation cover, the relationship in areas with low vegetation cover or outside the growing period is worse or missing. This can, for example, be seen for the Iberian Peninsula (Fig. 8), where the values of ET/ET_0 in June are lower than 0.4 even though the country received normal precipitation amounts (Fig. 6). Such values fall into the normal climatic range for this region and therefore do not represent exceptional drought conditions. Due to the absence of long enough time series of ET/ET_0 it is, however, not yet possible to calculate statistically robust anomalies. A solution to avoid confusion in these areas could be filtering by taking into

Table 1
Correlation coefficients obtained from the spatial comparison between the ET/ET_0 map of the last dekad of each month and the indices, SPI, SPEI and ScPDSI for the CRAPATCLIM area.

R ($n = 960$)	ET/ET_0		
	April	May	June
SPI	0.25	0.11	–
SPEI	0.24	0.11	0.20
ScPDSI	0.50	0.44	0.45

– $p > 0.05$

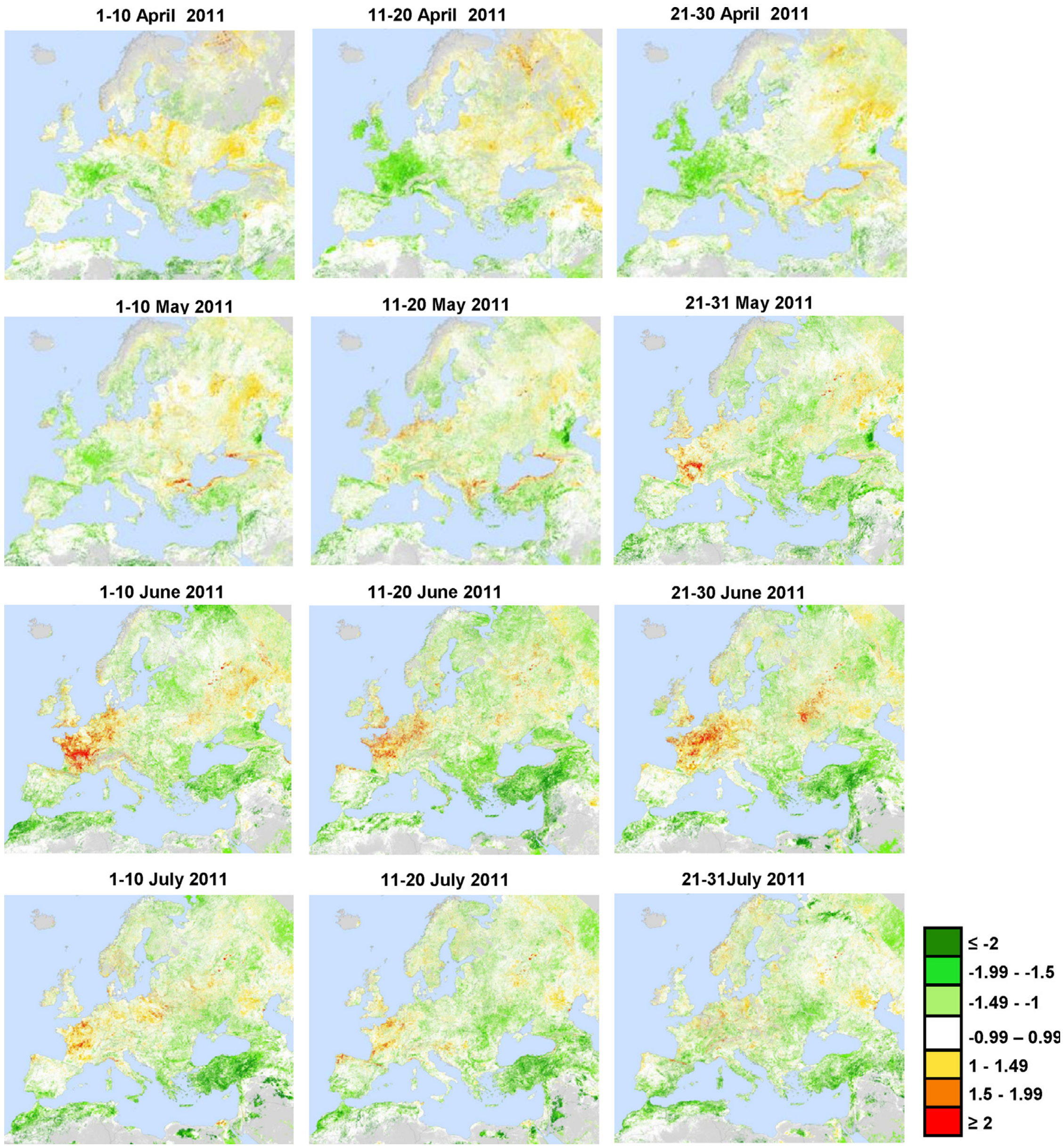

Fig. 7. 10-daily fAPAR anomalies of Europe from April to July 2011.

account the beginning and the end of the growing period or by using the percentage of vegetation cover as a basis. Results of using different filters are discussed in Vegetation Filtering Section.

Another possible approach could be the comparison of actual ET/ET_0 values to values from a known year with normal conditions. A particular example for France can be seen in Fig. 9, where a comparison with images of the same periods in 2011 and 2012 is shown. During 2012 the country received a normal quantity of precipitation. This example shows clearly how the ratio ET/ET_0 reflects the effects of the drought conditions for 2011.

Vegetation filtering

The ET/ET_0 ratio, has to be interpreted with care and is a useful drought indicator only in areas with sufficient vegetation cover and during seasons that are not normally arid. In order to avoid misinterpretations when using ET/ET_0 for drought characterization, it is proposed the use of adequate filters to discriminate areas with little vegetation cover or exclude the usually arid season.

The different filters proposed in Vegetation Filtering Section were applied, showing that the ECOCLIMAP and the vegetation cover filters are the most restrictive, while the phenology filter is the least restrictive. For the latter one should take into account that even during the growing period a low percentage vegetation cover can introduce non-negligible effects of bare soil information. This effect of bare soil is more important when the temperatures are high and therefore the evaporative demand is high. In general, the filter based on the percentage vegetation cover masks all areas where low values of the ET/ET_0 ratio are not due to drought conditions but due to the absence of vegetation. It is also a dynamic filter that changes with the vegetation development status. Fig. 10 shows the complete sequence of ET/ET_0 images of Europe obtained for spring/summer 2011 with a filter based on a threshold of 50% of vegetation cover applied. Comparing these filtered ET/ET_0 maps with the SPI-3 maps from the same period (Fig. 6), the spatial pattern of yellow to reddish colors is more coherent with actual drought conditions than in the ET/ET_0 maps without applying any filter (Fig. 8).

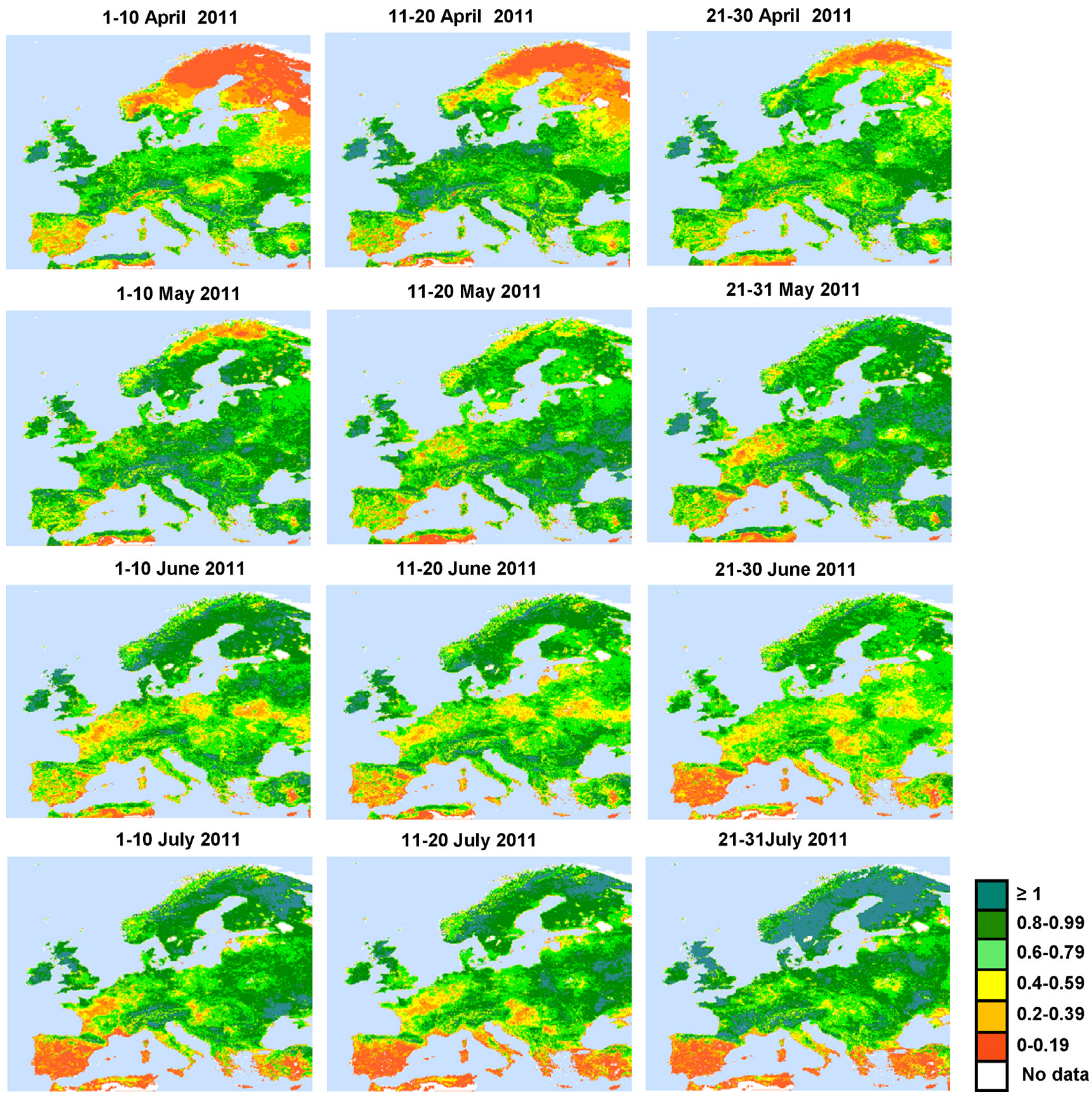

Fig. 8. ET/ET_0 images obtained for each dekad from April to July 2011.

Use of ET_{wwr}

Conceptually, the ratio between ET and ET_0 is indicative of the climatic water demand in relation to the soil moisture supply. ET_0 is obtained from meteorological information (air temperature, wind speed and air humidity) only, using the Penman-Monteith equation. By calculating the ratio ET/ET_0, ET is normalized by the meteorological conditions. By modifying the SVAT model and using the parameterization corresponding to soil saturation, the result is the evapotranspiration without water restriction (ET_{wwr}). Replacing ET_0 with ET_{wwr} as divisor of the ratio, adds information on the land cover characteristics, allowing to obtain an indication of the vegetation water demand in relation to the soil moisture supply when working in vegetated areas.

One example of the behavior of this ratio for Europe for the last dekads of April, May, June and July 2011 is shown in Fig. 11. The values and spatial distribution obtained are very close to those of the ratio ET/ET_0 (Fig. 8), also showing the effects of the drought conditions in the most affected areas. Main differences are found in Scandinavia in April where most of the areas were still covered by snow. As in the case of ET/ET_0, the ratio between ET and ET_{wwr} shows low values in the Mediterranean regions from June onwards, that do not correspond to drought conditions per se but to the effect of the evaporation due to the generally arid climate and reduced percentage of vegetation cover during the Mediterranean summer.

The accumulated values of this new ratio were related with yield production of the main cereal of Europe, the winter wheat. This was done, as an example to test the potential of this ratio in the agricultural domain, a specific case of ecosystem. Following this idea, the accumulated values of the ratio from April to July (corresponding to the winter wheat growing period), were compared with the relative winter wheat yield production (kg/ha) by country. The accumulated values were obtained from the ten available 10-daily images of ET and ET_{wwr}, filtered eliminating the pixels with a fraction of vegetation cover lower than the 50% as suggested in the previous section. The first dekad of April and the first of July were not produced due to a lack of data. The result of the comparison is shown in Fig. 12. The resulting coefficient of determination of 0.41 suggests the potential using the remote sensing based LSA-SAF ET and ET_{wwr} for vegetation monitoring at large scales, in particular for agricultural areas. One specific example of this potential would be for areas covered by a determinate crop, where the corresponding ratio could be considered as proxy of the FAO ET/ET_x, where ET_x is defined as the maximum ET or ET when the crop water requirements are fully met (Smith and Steduto, 2012). The ratio ET/ET_x is commonly used to forecast yield production using the FAO parameterizations (Doorenbos and Kassam, 1979).

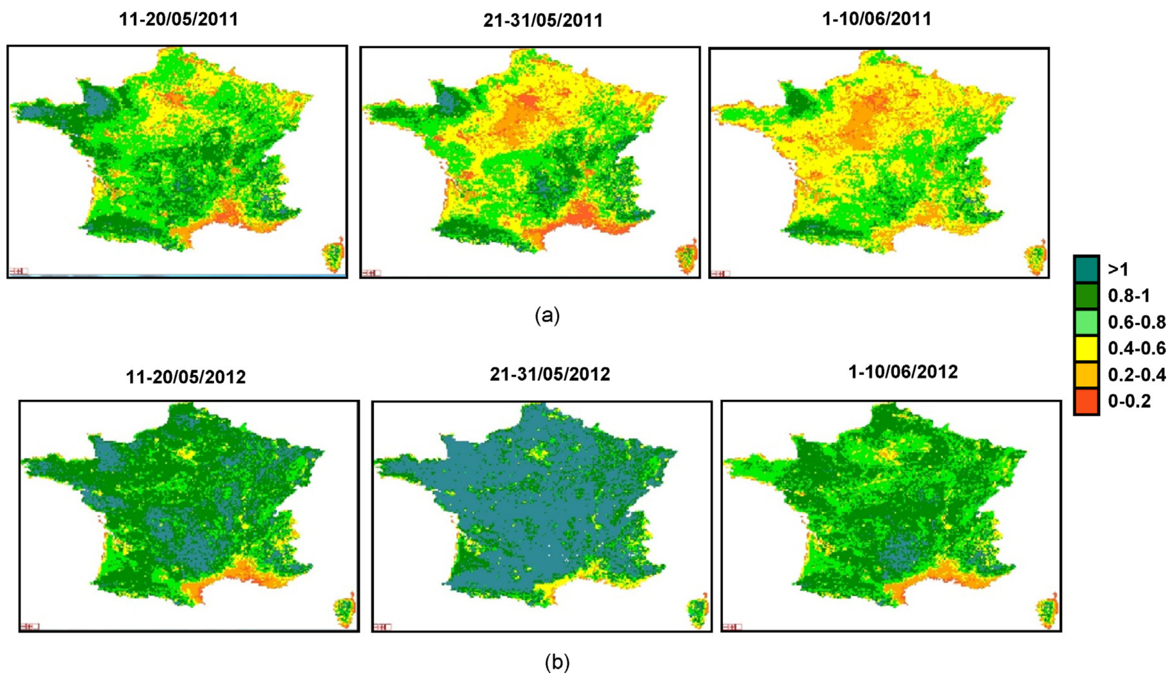

Fig. 9. ET/ET_0 images of France, obtained (a) from the second dekad of May to the first dekad of June 2011, and (b) from the second dekad of May to the first dekad of June 2012.

Discussion

Evapotranspiration (ET) is an important parameter that gives information about the exchange of water and energy between soil, plant and atmosphere. Moreover, it integrates environmental factors like meteorological conditions and the soil moisture status. The retrieval of evapotranspiration rates over extended areas is, however, a complex task, requiring spatially resolved information for a number of variables. In this study ET is obtained with a model that uses remote sensing and meteorological data as inputs. The

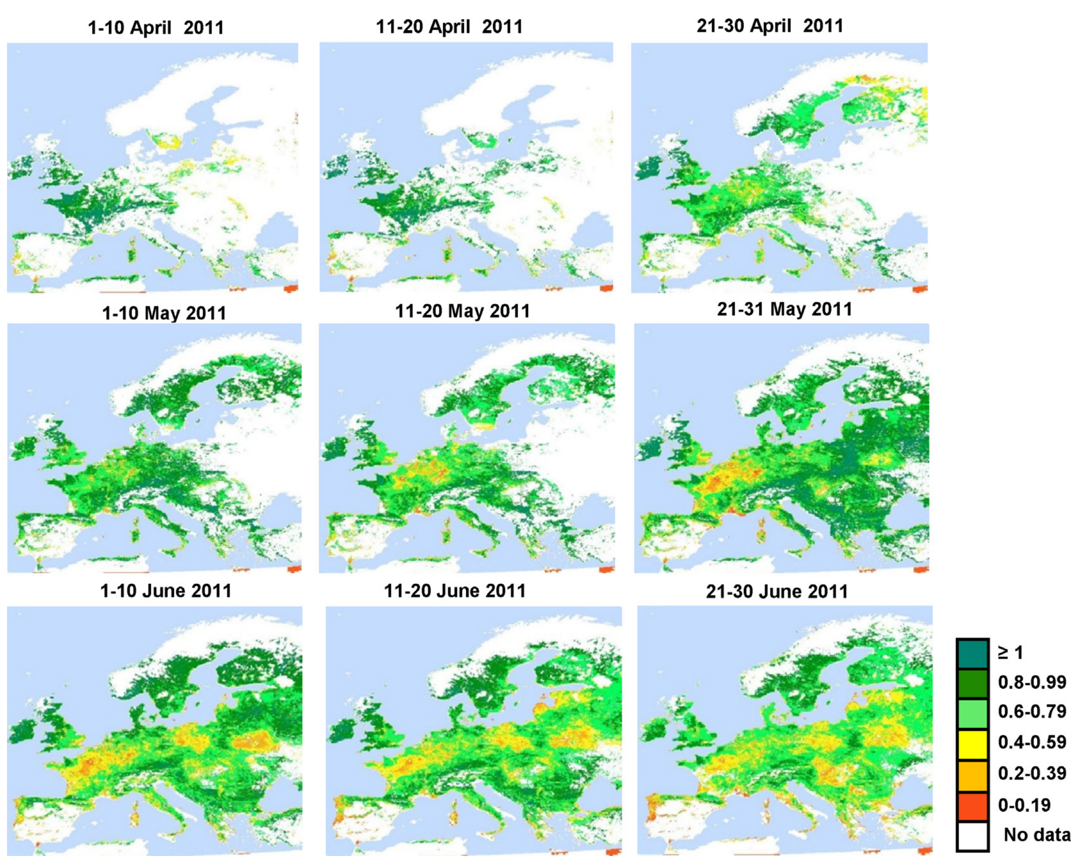

Fig. 10. ET/ET_0 images of Europe obtained for spring 2011 masked with a filter of 50% vegetation cover (white areas have been masked).

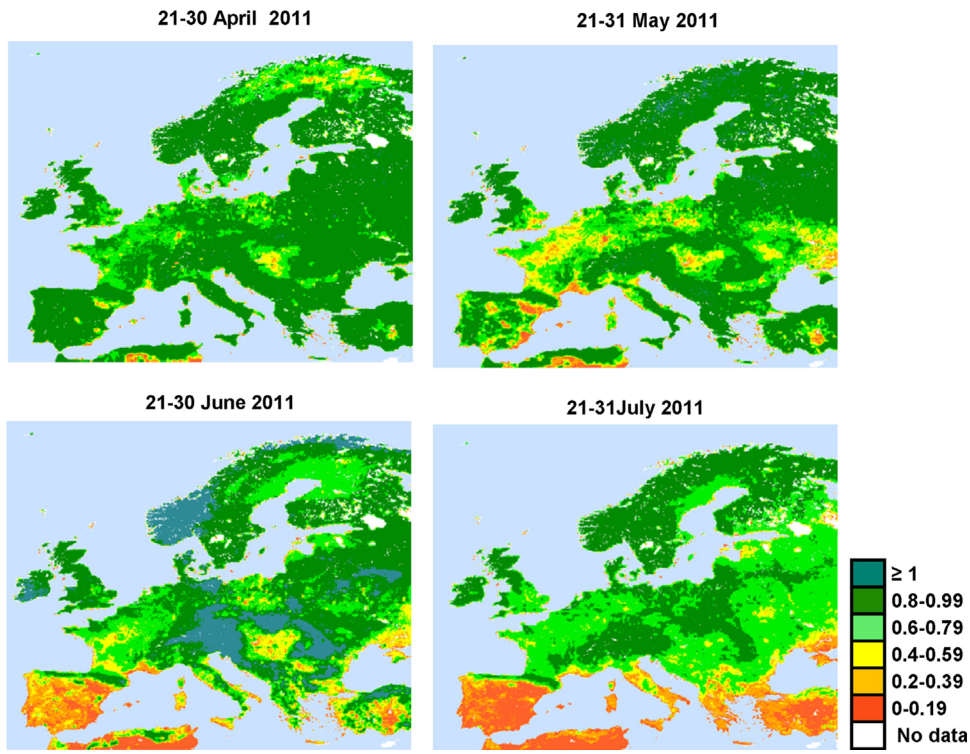

Fig. 11. ET/ET_{wwr} images of Europe obtained for spring/summer 2011.

result is therefore dependent on a large number of variables that add uncertainty to the value. However the evapotranspiration product used has been extensively validated using ground truth data and compared to other model outputs (Ghilain et al., 2012).

The ratio between evapotranspiration (ET) and reference evapotranspiration (ET_0) reflects the climatic demand in relation to the soil water supply. Several studies demonstrated the potential of using anomalies of ET/ET_0 for drought monitoring in the US, but at present, as the ET product of EUMETSAT is very new (half hour images have been produced operationally since 2010, daily images since 2012), we lack a long-term database for the robust calculation of anomalies. Nevertheless, the results obtained in the two case studies analyzed, indicate that, in absence of time series of data long enough to characterize normal conditions, ET/ET_0 gives relevant information for drought monitoring.

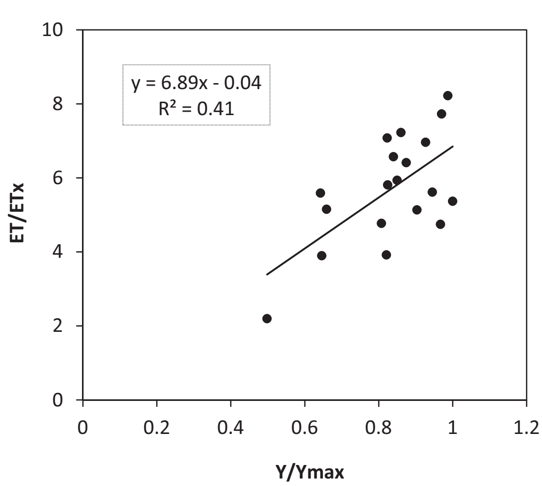

Fig. 12. relationship between the accumulated ratio between ET and ET_{wwr} (filtered with 50% vegetation cover) and relative yield production for 19 European countries in 2011.

The ET/ET_0 ratio, however, has to be interpreted with care. Despite the good correspondence found between spatial patterns of ET/ET_0 and drought conditions in areas where there is a high percentage of vegetation cover, the values obtained in areas of low vegetation cover or during arid seasons do not necessarily represent the effects of drought conditions. These values are not necessarily wrong, falling into the normal climatic range for the region. Due to the absence of long enough time series of ET/ET_0 it is, however, not yet possible to calculate statistically robust anomalies that would take into account this normal climatic variability. As an alternative, different filters were tested in order to mask areas with unreliable information due to arid conditions or seasonally low vegetation cover. The strategy was filtering with respect to the growing period, the land cover classification, or the percentage of vegetation cover. In general, the filter based on the percentage of vegetation cover was the most restrictive but also the one that seemed to eliminate most of the problematic areas. This can be explained considering that this filter eliminates the pixels with more than 50% of bare soil which will strongly affect the final value of the ET/ET_0 ratio, decreasing the values radically when temperatures and evaporative demand are high. Future research will be focused in removing the soil influence by working directly with transpiration instead of evapotranspiration.

Conclusions

This paper assesses the potential of using the ratio ET/ET_0 for drought detection and monitoring in Europe by means of two case studies, corresponding to two drought episodes with different characteristics.

The first case study corresponds to the spring/summer 2007 in the Carpathian region. The ratio ET/ET_0 was compared spatially with the drought indices of SPI, SPEI and Sc-PDSI, showing the best relationship for Sc-PDSI, with a correlation coefficient of 0.5 for the month of April. Sc-PDSI is an index related with soil moisture variations, indicating, that ET/ET_0 gives additional information to

SPI and SPEI that rely on precipitation and temperature measurements only. In addition, the determination coefficients obtained between ET/ET_0 and Sc-PDSI yielded $R^2 = 0.89$ in April, 0.79 in May and 0.92 in June, based on the mean values for each of the PDSI classes. These relations indicate the capability of the ratio ET/ET_0 to identify soil moisture variability and therefore, to identify ecosystem drought. The correspondence between Sc-PDSI and the mean values of ET/ET_0 depends of the month under analysis, suggesting that future work should also focus on setting the thresholds of ET/ET_0 for distinguishing drought from non-drought conditions. In this case study, characterized by a short and very intense precipitation deficit, the qualitative temporal comparison between ET/ET_0 and the anomalies of fAPAR showed a faster response of the ratio to drought conditions.

The second case study corresponds to the spring/summer 2011 for the entire European continent. In general, and for both case studies, ET/ET_0 showed a coherent behavior compared to SPI and fAPAR, being able to identify areas under water stress conditions when they have a high vegetation cover percentage. Particularly for France (one of the most affected countries), ET/ET_0 showed to be able to give a clear answer to the drought conditions reported in 2011 when comparing with a year in which the country received normal precipitation. Discrepancies were shown in areas with low vegetation cover or during arid seasons. A proposed method to avoid these cases is filtering the areas were the percentage of vegetation cover is lower than 50%.

ET/ET_0 can be produced operationally as it is based on three products operationally produced and freely available, ET and fractional vegetation cover (FVC) distributed by EUMETSAT and ET_0 by MARS-JRC. Nevertheless, the SVAT model used to obtain ET can be modified to obtain ET_{wwr} as a new product. To test this product, the ET/ET_{wwr} ratio was obtained for the spring/summer 2011 period. The behavior of this ratio was very similar to the ET/ET_0 and therefore in general coherent with drought conditions with the limitations explained above. Nevertheless, once filtering the pixels with a vegetation cover lower than 50%, the comparison between its accumulated values and the relative winter wheat yield production (kg/ha) by country yielded a coefficient of determination of $R^2 = 0.41$. This determination coefficient indicates the potential of using the remote sensing based LSA-SAF evapotranspiration and the ET_{wwr} for vegetation monitoring at large scale in general, and agricultural areas in particular, which is of great interest for areas where local data is generally lacking.

Acknowledgements

The authors would like to acknowledge the CARPATCLIM project for sharing the meteorological data, Eva Ivits for sharing the phenological indicator imagery, Andrew Singleton for facilitating the SPI computation at the weather stations and Carmelo Cammalleri for his review. We further acknowledge the help of the LSA-SAF colleagues in providing the MSG-SEVIRI data for this study and the JRC-MARS unit for the ET_0 data. The authors would also like to acknowledge our JRC colleagues involved in the development of the European Drought Observatory.

References

Alley, W.M., 1984. The Palmer Drought Severity Index: Limitations and assumptions. Journal of Climate and Applied Meteorology 23, 1100–1109.

Anderson, M.C., Hain, C., Wardlow, B., Pimstein, A., Mecikalski, J.R., Kustas, P., 2011. Evaluation of Drought Indices Based on Thermal Remote Sensing of Evapotranspiration over the Continental United States. Journal of Climate 24, 2025–2044.

Anderson, M.C., Norman, J.M., Diak, G.R., Kustas, W.P., Mecikalski, J.R., 1997. A two-source time-integrated model for estimating surface fluxes using thermal infrared remote sensing. Remote Sensing of Environment 60, 195–216.

Balsamo, G., Viterbo, P., Beijaars, A., van den Hurk, B., Hirschi, 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. Journal of Hydrometeorology 10 (3), 623–643.

Berni, J.A.J., Zarco-Tejada, P.J., Sepulcre-Cantó, G., Fereres, E., Villalobos, F.J., 2009. Mapping canopy conductance and CWSI in olive orchards using high resolution thermal remote sensing imagery. Remote Sensing of Environment 113, 2380–2388.

Carrão, H., Sepulcre, G., Horion, S., Barbosa, P., 2013. A multitemporal and non-parametric approach for assessing the impacts of drought on vegetation greenness: a case study for Latin America. EARSeL eProceedings 12 (1), 8–24.

Choudhury, B.J., Reginato, R.J., Idso, S.B., 1986. An analysis of infrared temperature observations over wheat and calculation of latent heat flux. Agricultural and Forest Meteorology 37, 75–88.

Doorenbos, J., Kassam, A.H., 1979. Yield response to water, FAO Irrigation and Drainage Paper No. 33. FAO, Rome, Italy.

Doorenbos, J., Pruitt, W.O., 1977. Crop water requirements, FAO Irrigation and Drainage Paper No. 24. FAO, Rome, Italy.

Diak, G.R., Whipple, M.S., 1993. Improvements to models and methods for evaluating the land-surface energy balance and effective roughness using radiosonde reports and satellite-measured skin temperature data. Agricultural and Forest Meteorology 63, 189–218.

European Drought Observatory, Drought News in Europe: Situation in May 2011, available at: http://edo.jrc.ec.europa.eu/documents/news/EDODroughtNews201105.pdf, last access 17 September 2013.

Ghilain, N., Arboleda, A., Gellens-Meulenberghs, F., 2011. Evapotranspiration modelling at large scale using near-real time MSG SEVIRI derived data. Hydrology and Earth System Sciences 15, 771–786.

Ghilain, N., Arboleda, A., Sepulcre-Cantò, G., Batelaan, O., Ardö, J., Gellens-Meulenberghs, F., 2012. Improving evapotranspiration in a land surface model using biophysical variables derived from MSG/SEVIRI satellite. Hydrology and Earth System Sciences 16, 2567–2583.

Gobron, N., Aussedat, O., Pinty, B., Taberner, M., Verstraete, M.M., 2004. Medium Resolution Imaging Spectrometer (MERIS) - An optimized FAPAR Algorithm - Theoretical Basis Document, EUR Report No. 21386.

Gobron, N., Pinty, B., Mélin, F., Taberner, M., Verstraete, M.M., Belward, A., Lavergne, T., Widlowski, J.-L, 2005. The state vegetation in Europe following the 2003 drought. International Journal Remote Sensing Letters 26 (9), 2013–2020.

Hall, F.G., Huemmrich, K.F., Goetz, S.J., Sellers, P.J., Nickerson, J.E., 1992. Satellite remote sensing of surface energy balance: success, failures and unresolved issues in FIFE. Journal of Geophysics Research 97, 19061–19089.

Hsiao, T.C., 1973. Plant responses to water stress. Annual Review of Plant Physiology 24, 519–570.

Idso, S.B., Jackson, R.D., Pinter, P.J., Reginato, R.J., Hatfield, J.L., 1981. Normalizing the stress-degree-day parameter for environmental variability. Agricultural and Forest Meteorology 24, 45–55.

Ivits, E., Cherlet, M., Toth, G., Sommer, S., Mehl, W., Vogt, J., Micale, F., 2012. Combining satellite derived phenology with climate data for climate change impact assessment. Global and Planetary Change, http://dx.doi.org/10.1016/j.gloplacha.2012.03.010.

Jackson, R.D., Idso, S.B., Reginato, R.J., Pinter, P.J., 1981. Canopy temperature as a crop water stress indicator. Water Resources Research 17, 1133–1138.

Kustas, W.P., 1990. Estimates of evapotranspiration with a one- and two-layer model of heat transfer over partial canopy cover. Journal of Applied Meteorology 29, 704–715.

Kustas, W.P., Choudhury, B.J., Moran, M.S., Reginato, R.J., Jackson, R.D., Gay, L.W., Weaver, H.L., 1989. Determination of sensible heat flux over sparse canopy using thermal infrared data. Agricultural and Forest Meteorology 44, 197–216.

Kustas, W.P., Norman, J.M., 1997. A two-source approach for estimating turbulent fluxes using multiple angle thermal infrared observations. Water Resources Research 33 (6), 1495–1508.

Lhomme, J.P., 1997. Towards a rational definition of potential evaporation. Hydrology and Earth System Science 1 (2), 257–264.

LSA-SAF: Product User Manual (PUM) Vegetation Parameters (FVC, LAI, FAPAR), PUM_VEGAv2.1, available at: http://landsaf.meteo.pt/, 2008.

Masson, V., Champeaux, J.L., Chauvin, F., Meriguet, C.H., Lacaze, R.A., 2003. Global database of land surface parameters at 1 km resolution in meteorological climate models. Journal of Climate 16, 1261–1282.

McKee, T.B., Doesken, N.J., Kleist, J., 1993. The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th Conference of Applied Climatology, Anaheim, CA, American Meterological Society, pp. 179–184.

Meteoconsult, Meteorological data from ECMWF models, available at: http://marswiki.jrc.ec.europa.eu/agri4castwiki/index.php/Meteorological_data_from_ECMWF_models, last access 17 September 2013.

Narasimhan, B., Srinivasan, R., 2005. Development and evaluation of soil moisture deficit index (SMDI) and evapotranspiration deficit Index (ETDI). Agricultural and Forest Meteorology 133, 69–88.

Norman, J.M., Kustas, W.P., Humes, K.S., 1995. Source approach for estimating soil and vegetation energy fluxes in observations of directional radiometric surface-temperature. Agricultural and Forest Meteorology 77 (3–4), 263–293.

Olioso, A., Chauki, H., Courault, D., Wigneron, J.P., 1999. Estimation of evapotranspiration and photosynthesis by assimilation of remote sensing data into SVAT models. Remote Sensing of Environment 68, 341–356.

Palmer, W.C., 1965. Meteorological drought. U. S. Department of Commerce. Weather Bureau Research Paper., pp. 45–58.

Smith, M., Steduto, P., 2012. Yield response to water: the original FAO water production function, FAO Irrigation and drainage paper No. 66. FAO, Rome, Italy.

Sugita, M., Brutsaert, W., 1990. Regional surface fluxes from remotely sensed skin temperature and lower boundary layer measurements. Water Resources Research 26, 2937–2944.
Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geographical Review 38, 55–94.
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 No. 295, 41 pp.
Verstraeten, W.W., Veroustraete, F., Feyen, J., 2008. Assessment of evapotranspiration and soil moisture content across different scales of observation. Sensors 8, 70–117.
Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2010. A multi-scalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index–SPEI. Journal of Climate 23 (7), 1696–1718.
Wells, N., Goddard, S., Hayes, M.J., 2004. A self-calibrating Palmer Drought Severity Index. Journal of Climate 17, 2335–2351.