



A time domain triangle method approach to estimate actual evapotranspiration: Application in a Mediterranean region using MODIS and MSG-SEVIRI products

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ABSTRACT

In this study, spatially distributed estimates of regional actual evapotranspiration (ET) were obtained using a revised procedure of the so called “triangle method” to parameterize the Priestley–Taylor ϕ coefficient. In the procedure herein proposed, named Time-Domain Triangle Method (TDTM), the triangular feature space was parameterized considering pairs of T_s –VI values obtained by exploring, for each pixel, only their temporal dynamics. This new method was developed using time series products provided by MODIS and MSG-SEVIRI sensors. Moreover the proposed procedure does not depend on ancillary data, and it is only based on remotely sensed vegetation indices and day–night time land surface temperature differences.

Two different test areas located in Sicily were selected for testing and validating the approach. Satellite ET rates were validated versus directly measured fluxes of mass (ET) obtained by eddy covariance (EC) towers during the observation period 2010–2012.

The proposed approach predicts daily ET rates with an acceptable level of accuracy for practical purposes; therefore, the TDTM can be considered as a simple and effective tool to easily estimate, at regional scale, spatial and temporal changes of this key-variable related to water resource management, agriculture, ecology and climate change.

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1. Introduction

Evapotranspiration (ET) is a key variable that plays a strategic role in the fields of water resource management, agriculture, ecology and climate change (Sobrinho, Gómez, Jiménez-Muñoz, & Oliso, 2007; Chirouze et al., 2014). For most of the Mediterranean regions (southern part of Europe), which are usually characterized by semiarid climates and chronic water scarcity, agriculture is the major user of water resources, and hence has significant impacts on water quantity. In these regions, the availability of water is a major limitation on crop production due to insufficient rainfall to compensate the evaporative losses by crops (i.e. more than 80% of the annual available water is lost through evapotranspiration) (Chehbouni et al., 2008). There is therefore a need to rationalize the use of irrigation via monitoring ET process. In particular, continuous and accurate estimation of spatial and temporal ET variations at regional scale is of paramount importance for improving water resources management, drought detection, climate change simulation and mitigation (Wang & Liang, 2008). Although ET at the local

scale can be accurately estimated from detailed ground-based observations (i.e. eddy covariance, EC; Bowen ratio, BR, etc.), it is much more critical for regional authorities to monitor water allocation and use at the irrigation district or watershed scales. At the regional scale, sufficient ground-point observations, necessary to explore the spatial variability of ET, are often not available; moreover, despite the spatial variability of the footprint area of EC technique (e.g. one of the most used methods for measuring latent heat flux density), its measurement might be considered as an average over the footprint and quite variable in time (Wang & Jia, 2013). Therefore, current field-based measurements cannot capture hydrological processes with adequate reliability over large areas.

Spatially distributed remote sensing data can permit reliable descriptions of the observed surface at most scales, ranging from plot to region, and across wide temporal scales depending on the overpass time of remote sensing platforms (Chirouze et al., 2014).

The use of remote sensing to estimate ET is presently being developed to retrieve large-scale distribution of land surface parameters such as temperature, albedo, and vegetation indices (Li et al., 2009; Minacapilli et al., 2009; Consoli & Vanella, 2014a), which are essential inputs to remotely sensed ET models application at the regional scale (Tang, Li, & Tang, 2010).

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The use of remote sensing to estimate ET is presently being developed along two approaches: (i) land surface energy balance (EB) methods, which include applications of the Penman–Monteith (P–M) equation, using visible and near infrared spectral bands and ancillary meteorological data (Idso, Schmugge, Jackson, & Reginato, 1975; Moran, 1989; Norman, Kustas, & Humes, 1995; Chavez, Neale, Hipps, Prueger, & Kustas, 2005; Allen, Tasumi, & Trezza, 2007; González-Dugo et al., 2009; Consoli & Vanella, 2014a); (ii) a reflectance-based vegetation index (VI) approach that relies on the ability of vegetation indices (VI_s), derived from surface reflectance data to trace the crop growth and estimate the basal crop coefficient (K_{cb}) (Minacapilli, Iovino, & D'Urso, 2008; Glenn, Nagler, & Huete, 2010). This second method determines spatially distributed values of K_{cb} that capture field-specific crop development and are used to adjust daily reference ET (ET_0) estimated from local weather station data (González-Dugo et al., 2013; Consoli & Vanella, 2014b). The main advantage of the VI-based methods is that satellite images in the reflective bands of the spectrum are more readily available than the thermal band data, and generally at higher spatial resolution. However, unless coupled to a soil water balance, this method cannot account for evapotranspiration rate changes due to water stress conditions. In contrast, surface temperature-based methods can readily capture stress effects without requiring ancillary rainfall data and soil hydraulic and texture properties (Anderson, Norman, Mecikalski, Otkin, & Kustas, 2007; González-Dugo et al., 2009; Consoli & Vanella, 2014b).

Remotely sensed ET models based on the classic “residual solution” of the surface energy balance, SEB, can be applied using two main schematizations, i.e., “single source” (Bastiaanssen, Menenti, Feddes, & Holtslang, 1998) or “dual source” (Norman et al., 1995). Numerous authors have provided detailed descriptions of these models since 1990s (Kustas & Norman, 1996; Glenn, Huete, Nagler, Hirschboeck, & Brown, 2007; Kalma, McVicar, & McCabe, 2008; Li et al., 2009; Kustas & Anderson, 2009; Minacapilli et al., 2009; Consoli & Vanella, 2014a). For example, well known SEB models, such as SEBAL (surface energy balance algorithm for land, Bastiaanssen et al., 1998) and METRIC (mapping evapotranspiration at high resolution with internalized calibration, Allen et al., 2007), join the use of remote sensing information with ancillary data to derive sensible heat flux (H), net radiation, (R_n), soil heat flux, (G) and instantaneous evapotranspiration, the latter as the residual term of the energy balance equation (Bastiaanssen et al., 1998; Boegh, Soegaard, & Thomsen, 2002; Kustas, Perry, Doraiswamy, & Moran, 1994; Norman et al., 2003). These methods estimate surface resistance adopting various schemes and using radiometric surface temperature and ground ancillary weather data.

Other remotely based methodologies require the direct application of the Penman–Monteith equation to estimate regional evapotranspiration (Monteith, 1965). In particular, Mu, Heinsch, Zhao, and Running (2007) proposed a complex model to estimate the crop resistance parameter as a function of Leaf Area Index (LAI) and consequently the monthly crop evapotranspiration using standard MODIS data products coupled with the GMAO climatic database (Ramoelo et al., 2014; Kim, Hwang, Mu, Lee, & Choi, 2012). This approach (Mu et al., 2007; Mu, Zhao, & Running, 2011) was validated using the Ameriflux eddy covariance tower network and adopted by NASA which is presently available as the “MOD16A2-ET” product. However, Ramoelo et al. (2014) expressed concerns on the reliability of “MOD16A2-ET” product to derive crop evapotranspiration data. Questionable product performance can be attributed to both the spatial variability of the retrieval algorithm input data and the coarseness of GMAO climatic database.

The described methods have in common the need of ground-based measurements and ancillary data, (i.e. wind speed, air temperature, solar radiation, vegetation height), thus limiting their operational applications to mapping ET at the regional scale.

Dependence on ancillary data can be addressed using simplified models based on the interpretation of the so-called “triangle method” obtained from T_s – VI_s scatterplots (Carlson, Gillies, & Perry, 1994;

Carlson, Gillies, & Schmugge, 1995; Jiang & Islam, 1999, 2001; Stisen, Sandholt, Nørgaard, Fensholt, & Jensen, 2008).

The method relies on the triangular shape formed by the scatterplots of surface temperature versus vegetation index (VI, such as: normalized difference vegetation index, NDVI, enhanced vegetation index, EVI, fractional cover, F_c), under a wide range of vegetation cover and soil moisture availability, to estimate the evaporative fraction (EF) and ET at the satellite pixel resolution scale. EVI is an optimized index designed to enhance the vegetation signal with improved sensitivity in high biomass regions and to improve the vegetation monitoring.

Several triangle method applications have been successfully applied for ET estimation by combining MODIS and AVHRR data (Venturini, Bisht, Islam, & Jiang, 2004; Batra, Islam, Venturini, Bisht, & Jiang, 2006).

The reliability of the triangle method depends mainly on the parameterization of the dry and wet edges in the T_s – VI feature space. Jiang and Islam (2001, 2003) have identified the wet edge by using the lowest observed clear pixel surface or air temperature in the image scene; whereas the dry edge has been generally defined by a linear interpolation of pixels with minimum VI and maximum surface temperatures (Stisen et al., 2008). Apart from the specific algorithms used, all the proposed methods adopted for dry and wet edge determination share a “triangular feature space”, obtained by plotting T_s – VI values only collected in a given spatial domain, i.e. two single scene images (T_s and VI) captured in the same time. The use of a spatial domain to obtain the “triangle feature space” involves, as main hypothesis, the assumption of uniform atmospheric conditions over the whole image. To meet this hypothesis, the required extension of the explored surface area, used to collect the T_s – VI_s , may be too wide. This assumption is limiting especially when the method is applied at a coarse resolution, such as in regional scale applications, contrasting the need of a large number of pixels to clearly define the key features of the “triangle geometry” (i.e. warm and cold edges). Moreover, the use of only the spatial domain to parameterize the T_s – VI relationship does not take into account the natural crops behaviour (e.g., crop types and phenological variability) related to the atmospheric water demand (e.g., seasonal meteorological variations), and makes the hypothesis of a unique interpretation of the T_s – VI_s space unrealistic. In this view, Carlson (2007) proposed the idea of the “universal triangle”, with a further time dimension.

This study, starting from an existing spatial-domain solution of the “triangle method” introduced by Jiang and Islam (2001) and then by Stisen et al. (2008), aims at developing a new procedure for identifying reliable boundary conditions of the triangle method.

The proposed procedure is based on a pixel by pixel T_s – VI feature space, obtained by exploring the temporal domains over each single image pixel. A single T_s – VI triangle feature space is obtained for each pixel of the image; the triangle contains the whole climatic variability of the T_s – VI_s time series, thus contributing to eliminate the hypothesis of atmospheric homogeneity.

Specifically, through this new method, called Time-Domain Triangle Method (TDTM) the following main objectives were pursued:

- to exploit time series products (T_s , VI_s , and albedo) provided by MODIS satellite sensors to derive the T_s – VI feature space, based on the temporal dynamic of the observed T_s – VI_s pairs;
- to set-up a new parameterization of dry and wet edges over the previously derived T_s – VI feature space;
- to estimate actual regional evapotranspiration by combining the new triangle method approach with MODIS and MSG-SEVIRI products, without using ancillary ground-based data.

The developed procedure for ET estimation was validated through evapotranspiration measurements, carried out using eddy covariance (EC) techniques, in two different test areas in Sicily, during 2010–2012 period. Once the procedure was validated, it was applied over the entire Sicilian region (insular Italy) for mapping ET rates time series.

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