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# Assessment of reference evapotranspiration using remote sensing and forecasting tools under semi-arid conditions

M. Cruz-Blanco, P. Gavilán, C. Santos, I.J. Lorite*

*IFAPA – Centro "Alameda del Obispo", Regional Government of Andalusia, Córdoba, Spain*

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ABSTRACT

Reference evapotranspiration ($ET_o$) assessment at regional scale is a challenge to agricultural and hydrological research requiring the characterization of vast areas to obtain accurate meteorological variables. To account for this, a new approach considering a modified version of the Makkink equation and based on a combination of remotely sensed solar radiation ($R_s$) considering the MSG satellite, and numerical weather forecast of near surface air temperature ($T_{2m}$), was developed. The new approach is referred as Makkink-Advection equation (MAK-Adv).

Once $R_s$ and $T_{2m}$ were validated for the semiarid conditions registered in Southern Spain with very satisfactory results (RMSE = 1.6 MJ m$^{-2}$ d$^{-1}$ and 1.4 °C respectively, with linear regressions with slope = 0.99 and $R^2$ = 0.97), the MAK-Adv approach was calibrated and validated with $ET_o$ measurements from a weighing lysimeter under near-reference conditions in Southern Spain. The new approach has provided accurate daily $ET_o$ estimations compared with lysimeter data (RMSE = 0.50 mm d$^{-1}$, RE = 12.3% and MAE = 0.39 mm d$^{-1}$), and remains accurate during summer time (RMSE = 0.62 mm d$^{-1}$ and RE = 9%), the critical period when accurate $ET_o$ data are essential for a correct agricultural water management.

Once calibrated and validated, and thanks to the use of remotely sensed data, the MAK-Adv approach allowed the $ET_o$ assessment at regional scale. For a semi-arid region located in southern Spain with an area of 87,300 km$^2$, a detailed spatial $ET_o$ assessment was performed, determining $ET_o$ values for the totality of the area with a resolution of about 9 km$^2$ allowing to evaluate the spatial and temporal variability at basin/region scale. This new approach gets over the serious limitations for a correct $ET_o$ assessment when traditional methodologies are not able to provide these data for vast areas, even with the modern weather station networks. Thus, MAK-Adv approach is especially useful for those areas with missing or inaccurate meteorological in situ observations.



## Introduction

Reference evapotranspiration ($ET_o$) is a key component of the hydrological cycle and base to estimate crop water requirements (Allen et al., 1998). $ET_o$ is defined as the evapotranspiration, under the given meteorological conditions, of a reference grass crop with specific characteristics such as an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground (Allen et al., 1998).

The most accurate methodology for $ET_o$ assessment is the use of weighing lysimeters (Malone et al., 2000). Weighing lysimeters have been long used to measure evapotranspiration (Wright, 1982). As such, lysimeters are the standard method to directly measure $ET_o$ (Xu and Chen, 2005; López-Urrea et al., 2006) or crop ET (Yang et al., 2000; Lorite et al., 2012) and therefore the best source of observations for independent validation of $ET_o$ estimates. However the available lysimeter data are very limited and alternative procedures such as Penman–Monteith approach (PM-FAO56) have been developed. Thus, PM-FAO56 has been compared with lysimeter measurements under semi-arid environments (Berengena and Gavilán, 2005; López-Urrea et al., 2006) obtaining very accurate $ET_o$ estimations. This equation is, therefore, considered the standard procedure for $ET_o$ estimation (Allen et al., 1998), leading to a satisfactory performance even under advective conditions (Berengena and Gavilán, 2005). However, the required input data (solar radiation, wind speed, temperature and relative humidity of the air) must be collected under the previously described reference conditions (Allen et al., 1998). This is often not possible or impractical, particularly in semi-arid regions where a

* Corresponding author at: IFAPA – Centro "Alameda del Obispo", Regional Government of Andalucia, Avda. Menendez Pidal s/n, Post Office Box: 3092, 14080 Córdoba, Spain. Tel.: +34 671 532698.

*E-mail addresses:* ignacioj.lorite@juntadeandalucia.es, lorite.torres@gmail.com (I.J. Lorite).

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network of such stations is difficult and costly to maintain, limiting the widespread use of this equation (Pereira and Pruitt, 2004). As a consequence, PM-FAO56 has often been substituted by approaches with lower input requirements such as Hargreaves or Makkink equations (Gavilán et al., 2006; De Bruin et al., 2010) using weather data from weather station networks.

In addition, weather stations networks are usually located close to irrigated areas (Gavilán et al., 2006), and then a correct weather characterization for non-irrigated areas and for hydrological purposes is even more difficult. Furthermore, the number of the weather stations is clearly limited, and vast areas are located far of well-managed weather stations (Voogt, 2006) avoiding a correct weather characterization. For example, Collins (2011) described the huge limitations depicted in Africa caused by low density of weather stations and usually unevenly distributed. An alternative for this limitation has been the use of spatial interpolation approaches (Alves et al., 2013), but several authors indicated the uncertainty in those datasets derived from interpolation methods (Ramirez-Villegas and Challinor, 2012). Thus, the development of new methodologies applied at regional scale and requiring lower cost observations is required, with a high impact on the availability and quality of $ET_o$ estimations over many parts of the globe.

As a potential solution for the necessity of a new tool for $ET_o$ assessment, the contribution of remote sensing must be considered. Remote sensing techniques have contributed in the improvement of water management at basin scale in the last years. The most advanced approaches have been focused on the determination of crop evapotranspiration ($ET_c$), using energy balance models (Galleguillos et al., 2011; Poças et al., 2013) or vegetation indexes (Ghilain et al., 2012). These approaches have provided relevant information for hydrological cycle analysis and agricultural water management, enabling the determination of crop water requirements (Santos et al., 2010), crop yield forecasting (De Wit and van Diepen, 2008), the analysis of the spatial and temporal variability of the vegetation (Stisen et al., 2008; Ghilain et al., 2012) or hydrological analyses (Bailly et al., 2011). For $ET_o$ assessment, although recently De Bruin et al. (2010), Cammalleri and Ciraolo (2013) and Sepulcre-Canto et al. (2014) have demonstrated that geostationary satellite data can be used to determine $ET_o$ values for vast areas, studies have been less numerous, being required further analyses related with new input data methodologies and regional calibration (Cammalleri and Ciraolo, 2013). Furthermore, despite the promising preliminary results concerning the feasibility of $ET_o$ estimation derived from remotely sensed solar radiation from geostationary satellite MSG (De Bruin et al., 2010; Cristobal and Anderson, 2012), a calibration and validation of this empirical approach is still required, particularly under semi-arid conditions.

The main objective of the current study is to evaluate the use of an innovative approach using remotely sensed and ECMWF data for $ET_o$ assessment at regional scale to get over the serious limitations of traditional methodologies for $ET_o$ assessment in vast areas. Equally, an evaluation of the spatial and temporal variability at regional scale and the study of the main factors influencing the quality of the estimations are considered. To carry out these objectives, the introduced methodology considered weighing lysimeter and weather station data under semi-arid conditions in Southern Spain.

## Materials and methods

### *EUMETSAT LSA SAF and ECMWF products*

The EUMETSAT Satellite Applications Facility for Land Surface Analysis (LSA SAF) is part of the SAF network, a set of specialized development and processing centers serving the European Organization for the exploitation of meteorological satellites (EUMETSAT) (Trigo et al., 2011). The main objective of LSA SAF is the development of remote sensing applications relevant to land surface processes and biosphere applications, such as the case of $ET_o$ (Trigo et al., 2011). The main input to $ET_o$ satellite retrievals analyzed here is daily solar radiation at the surface. Within the LSA SAF this corresponds to the so-called daily down-welling surface shortwave radiation flux (DIDSSF) in the wavelength interval 0.3–4 μm (Geiger et al., 2008; Trigo et al., 2011). DIDSSF was determined from the accumulation of 30-min observations provided by the spinning enhanced visible and infrared imager (SEVIRI) radiometer, on board MSG (Schmetz et al., 2002) at a pixel resolution of 3 km at nadir (Trigo et al., 2011).

Air temperature at 2 m ($T_{2m}$) was obtained from the operational forecasts provided by the European Center for Medium-Range Weather Forecasts (ECMWF). The initial 3-hourly $T_{2m}$ forecasts at a resolution of about 25 km were linearly interpolated in time to hourly, and bi-linearly interpolated in space to the SEVIRI/MSG resolution (3 km at nadir). As ECMWF model surface orography and the SEVIRI elevation model showed differences in the pixel altitude caused by the different spatial resolution, the $T_{2m}$ values underwent an adjustment to correct these altitude differences using a constant slope rate of 0.0067 °C m$^{-1}$ (De Bruin et al., 2010). Thus, the $T_{2m}$ values were reduced or increased at the indicated slope rate when the SEVIRI elevation was higher or lower than the ECMWF elevation, respectively. These adjusted $T_{2m}$ values are considered for $ET_o$ estimations by EUMETSAT LSA SAF (Trigo et al., 2010). A detailed full-description of ECMWF data is available in Persson (2011).

The EUMETSAT LSA SAF (Trigo et al., 2011) is planning to generate and distribute $ET_o$ primarily based on solar radiation using MSG satellite measurements and ECMWF forecasts. In the context of the LSA SAF (De Bruin et al., 2010, 2012a; Trigo et al., 2011), such satellite based estimations make use of an empirical procedure based on Makkink equation, yielding $ET_o$ for the whole field of view of the European geostationary satellite MSG. These results will be made available in near-real-time (http://landsaf.meteo.pt) at the MSG pixel resolution (3 km at nadir; Trigo et al., 2011), and cover an area encompassing Africa, most of Europe and part of South America.

### *Experiment setup for lysimeter and meteorological variables collection*

A weighting lysimeter provided reference evapotranspiration data to carry out the calibration and validation process for MAK-Adv approach. It was installed in 1985 and is located in the center of a well-watered grass field with a size of 1.6 ha (Fig. 1), with regular agricultural practices in order to follow the FAO recommendations (Allen et al., 1998), being usually surrounded by fields cultivated with rainfed crops. These grass field characteristics and the weather conditions of the area generated a significant process of heat advection, with values of the ratio between reference evapotranspiration and net radiation (defined as the advection index) around 1.0–1.4 (Berengena and Gavilán, 2005), depicting advection for most of the sampled days (Gavilán and Berengena, 2007). These values indicate clear advection conditions for the grass field where the weighting lysimeter is installed.

The lysimeter facility, described in Berengena and Gavilán (2005), has provided accurate $ET_o$ measurements for the last 20 years (Mantovani et al., 1995; Farahani et al., 2007; Gavilán et al., 2007), constituting a high valuable dataset very uncommon in the world. In order to ensure the quality of the collected data from this facility, its performance was checked once a year by placing known mass pieces on the lysimeter. Measurements were made increasing and decreasing the load on the platform by adding and removing pieces respectively (Gavilán and Berengena, 2007),