Reference crop evapotranspiration estimated from geostationary satellite imagery.

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ABSTRACT
A revised Makkink formula is presented to estimate the Reference Crop Evapotranspiration (ET_0), as defined by the FAO, requiring incoming solar radiation and air temperature only and allowing operational ET_0 mapping with geostationary satellite (MSG) imagery. For 2008 daily MSG-ET_0 compare well with 'ground-truth' data collected over well-watered 'FAO-grass'. The project is carried out in the context of the LSF SAF project (http://landsaf.meteo.pt/). It is argued that solar radiation must be preferred over measured net radiation as input variable for ET_0 calculations.

INTRODUCTION
The method proposed by Allen et al. (1998) to determine evaporative demands of agricultural crops is currently considered the most accurate. It is based on the concept that crop water requirements can be estimated from the reference crop evapotranspiration, ET_o, multiplied by a crop-factor. ET_o is the evapotranspiration under the same meteorological conditions from an extensive hypothetical grass crop with specified characteristics. The methodology requires input data gathered over horizontal extensive surface similar to the hypothetical grass. Such sites are rare in most semi-arid regions. The objective of this study to present the first results of a project aiming to develop an alternative methodology to estimate ET_o from geostationary satellite images and additional information provided by operational weather forecasts from the European Centre for Medium-range Weather Forecasts (ECMWF). Our methodology requires daily values of downward solar radiation (R_s) obtained from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) radiometer onboard Meteosat Second Generation (MSG) and the air temperature at 2 m extracted from ECMWF initial fields. It should be stressed that our method does not mean to replace that of Allen et al. (1998). In contrast, this approach is highly recommended.

THEORY AND APPROACH
Per definition ET_o is the evapotranspiration under the given meteorological conditions from a hypothetical grass reference crop with specific characteristics, namely a fixed surface resistance of 70 s m^{-1}, a height of 0.12 m and an albedo of 0.23. The reference surface closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground. The fixed surface resistance of 70 s m^{-1} implies a moderately dry soil surface resulting from about a weekly irrigation frequency. Here we will deal with daily ET_o values. Allen et al. (1998) provides guidelines on how to calculate ET_o from standard weather data. It concerns an application of the Penman-Monteith equation (hereafter denoted as PMFAO). In this study we will adopt PMFAO with ignoring soil heat flux and using estimated net radiation with the expression proposed by Allen et al. (1998) from maximum and minimum temperature, water vapor and R_s. The reason why we prefer estimated R_n over direct measurements will be explained in the Appendix.

The best-known approximation of ET_o is the Priestley-Taylor formula (PT) (Priestley and Taylor, 1972), requiring net radiation and temperature as input. Experience shows that for well-watered grass daily net radiation is highly correlated with R_s. This leads to the revised Makkink equation (MAK) proposed by De Bruin (1987):

$$ET_{MAK} = c_{mak} \frac{86400}{\lambda} \frac{\Delta}{\Delta+\gamma} R_s = \frac{86400}{\lambda} f(T,p) R_s \qquad \text{(mm day}^{-1}\text{)} \qquad (1)$$

where Δ is the slope of the saturation water vapor pressure -temperature curve (kPa °C^{-1}), γ the psychometric constant (kPa °C^{-1}), λ is the latent heat of vaporization and c_{mak} an empirical constant. For the growing season in moderate climate zones it is found that $c_{mak} \approx 0.7$ (rounded value). Stewart et al. (1999), Watts et al. (2000), Garatuza et al., (1998), Schüttemeyer (2005) and Schüttemeyer et al. (2007), Choudhury and de Bruin (1998), Temesgen (2009) and De Bruin et al. (2010) report successful applications of MAK, also in semi-arid regions. But, other studies show that in arid and advective conditions both MAK and PT tends to underestimate ET_o (Allen et al., 1998; Berengena and Gavilán, 2005; Irmak et al. 2008).

Using a data set gathered near Cordoba (latitude: 37º 51' N; longitude: 4º 51' W; altitude: 110 m a.m.s.l.) over well-watered 'FAO-grass' plot (Berengena and Gavilán, 2005) we found a new revised MAK (MAKNEW) by replacing $f(T,p)$ in equation 1 with

$$f_2(T,p) = a(p)T + b(p) \qquad (2)$$

where $a(p) = \left[\frac{d(MAK(T,p))}{dT}\right]_{T=12,p}$, i.e. the derivative of MAK to T at T = 12 ^{0}C and the prevailing pressure and. Next, $b(p)$ is chosen such that MAKNEW equals MAK at T = 12 ^{0}C.

The pressure dependency is due to the fact that γ is proportional to p (see also de Bruin et al., 2010). For a motivation why MAKNEW must be preferred over PT see the Appendix.

RESULTS AND DISCUSSIONS

Figure 1 shows ET_o estimated with new revised MAK using R_s and T obtained from MSG imagery and ECMWF fields (for details see Trigo et al., 2010), compared with the corresponding PMFAO values obtained with data collected over well-watered grass at the location near Cordoba. Results reveal a good agreement between the two time-series. Note that PMFAO compares very well with corresponding lysimter data in this location (Berengena and Gavilán, 2005).

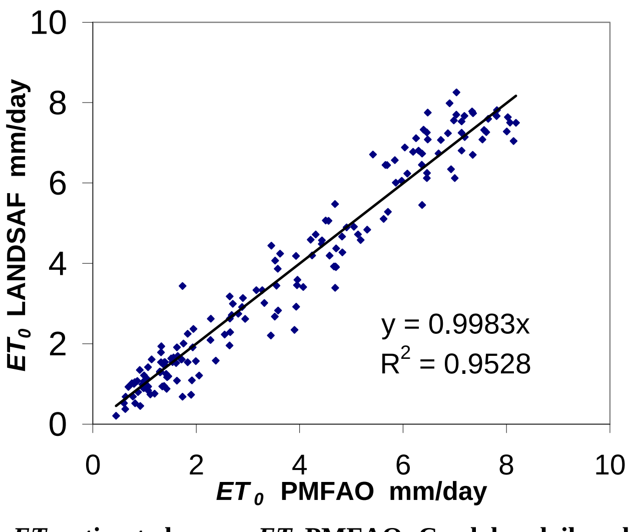

Figure 1. ET_o estimated versus ET_o PMFAO: Cordoba, daily values, 2008

Daily accumulated solar radiation, R_s, is obtained through the integration of instantaneous values, estimated every 30-minute from SEVIRI/MSG data provided the Satellite Applications Facility (LSA SAF, Trigo et al, 2010). During the study period (year 2008), daily R_s values were still being provided as demonstration products by the LSA SAF, and since we restrict the analysis to days for which all 48

MSG slots were available, this study is based on a satellite-based ET_o time-series with a total of NNN points. Daily R_s is currently produced, distributed and archived operationally by the LSA SAF, and therefore the number of missing data has been significantly reduced.

It can be concluded that the novel MAKNEW formula yields fairly accurate estimates of ET_o using MSG-R_s and ECMWF *T2* as input. These results reveal that reasonably accurate estimates of ET_o can be obtained from R_s and *T* only for strongly advective conditions also. But it should be noted that we fitted the constants *a* and *b* using the same data set as we used in Figure 1. More extensive tests of MAKNEW will be performed in the near future.

APPENDIX

ET_o is defined for an hypothetical well-watered grass. Evaporation tends to lower the surface temperature and thus to reduce the outgoing longwave radiation. This explains why net radiation of an irrigated grass field is lower than that of an adjacent dry field. In tropical regions

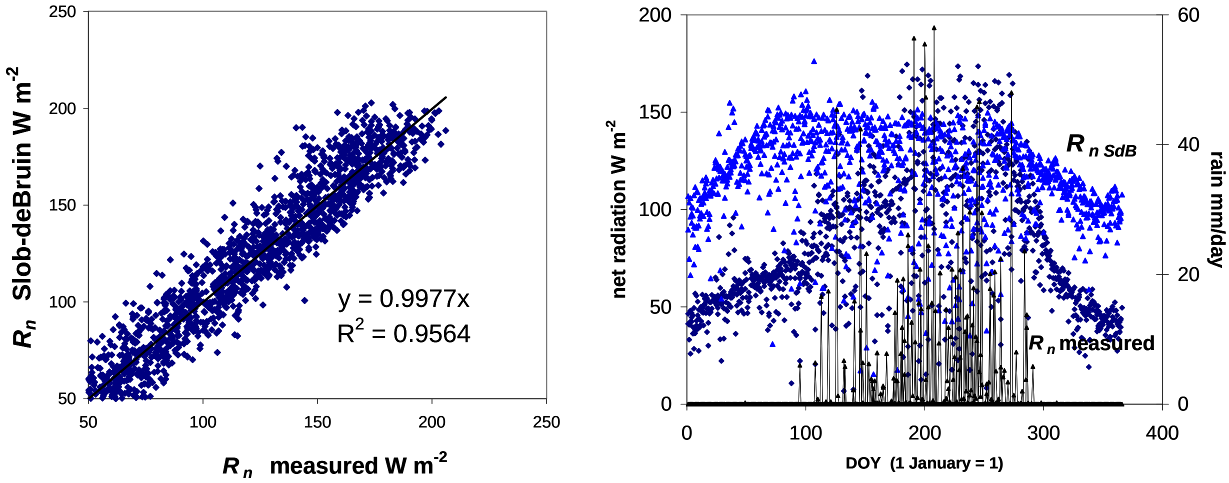

Figure 2 Test R_n Slob-de Bruin Zaragoza (left panel); Diurnal course of R_n measured and R_n estimated with Slob-de Bruin and rainfall 2008, Burkina Faso (right panel). All daily values.

this difference can be significant. This feature is illustrated in Figure 2: in the right panel, for a location in Burkina Faso, the annual cycle of the daily measured net radiation of bare soil is depicted together with rainfall and net radiation estimated for well-watered 'FAO-grass' using a formula proposed by De Bruin (1987) as special application of the Slob-approximation for net longwave radiation requiring R_s as only input. A test of the latter is given in the left panel. It is seen that in the dry season the differences between measured and estimated net radiation are huge. This example shows that the soil moisture status of the surface affects net radiation. This motivated us to adopt PMFAO with estimated net radiation and to prefer MAKNEW over PT.

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