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Using remotely sensed solar radiation data for reference evapotranspiration estimation at a daily time step

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16 Abstract

17 Solar radiation is an important climatic variable for assessing reference evapotranspiration 18 (E_{θ}) , but it is seldom available in weather station records. Meteosat satellite images processed 19 with the Heliosat-2 method provide the HelioClim-1 database, which displays spatialized 20 solar radiation data at a daily time step for Europe and Africa. The aim of the present work 21 was to investigate the interest of satellite-sensed solar radiation for E_0 calculation, where air 22 temperature is the sole local weather data available. There were two study areas in Southern 23 France. One (Southwest, SW) is characterized by oceanic climate and the other (Southeast, 24 SE) by Mediterranean climate. A data set of daily values for 19 weather stations spanning five 25 years (2000-2004) was used. First, a sensitivity analysis of the Penman-Monteith formula to 26 climate input variables was performed, using the Sobol' method. It shows that E_0 is mainly 27 governed by solar radiation during summer, and by wind speed during winter. Uncertainties 28 of HelioClim-1 solar radiation data and their repercussions on E_0 formulae were evaluated, 29 using the FAO-56 Penman-Monteith formulae (PM) and radiation-based methods (Turc, TU; 30 Priestley-Taylor, PT and Hargreaves-Radiation, HR). It was shown that HelioClim-1 data 31 slightly underestimate solar radiation and provide relative RMSE (root mean squared error) of 32 20% of the mean annual value for SW and 14% for SE. The propagation of HelioClim-1 data 33 uncertainties is small in PM but considerable in radiation methods. Four estimation methods 34 were then compared to PM data: the 1985 Hargreaves formula (HT) based on air temperature 35 only; TU, PT and HR, based on air temperature and satellite sensed solar radiation. Radiation 36 methods were more precise and more accurate than HT, with RMSE ranging from 0.52 mm to 37 0.86 mm against 0.67 mm to 0.96 mm. These results suggest that using satellite-sensed solar 38 radiation may improve E_0 estimates for areas where air temperature is the only available 39 record at ground level.

40

41 *Keywords:* evapotranspiration, solar radiation, Penman-Monteith equation, sensitivity
42 analysis, remote sensing.
43

44 **1 Introduction**

45 Reference evapotranspiration (E_0) is an agrometeorological variable widely used in 46 hydrology and agriculture. Together with precipitation, it is a major input in soil water 47 balance models. Several of these models require daily or hourly evapotranspiration data to 48 provide acceptable estimate of plants water requirements (Brisson et al., 1992; Guyot, 1997; 49 Lebon et al., 2003). Penman-Monteith combination method is one of the most accurate

50 methods to evaluate E_0 at different time steps. A standardization of this method has been

51 proposed by the Food and Agriculture Organization (Allen et al., 1998). It is known as FAO-

52 56 Penman-Monteith application, and it can be considered as a worldwide standard. However, 53 it requires numerous weather variables (air temperature, relative humidity, wind speed and 54 solar radiation), which are seldom available in basic meteorological records. Consequently, 55 reference evapotranspiration is often estimated by means of empirical equations based on air 56 temperature, relative humidity, extraterrestrial radiation and/or precipitation (Droogers and 57 Allen, 2002 ; Hargreaves et al., 1985 ; Popova et al., 2005 ; Turc, 1961). Several authors 58 proposed modifications of existing empirical methods (Droogers and Allen, 2002; Gavilan et 59 al., 2006; Pereira, 2004; Pereira and Pruitt, 2004; Popova et al., 2005; Xu and Singh, 2002). 60 The accuracy of these methods remains acceptable when applied at large time and space 61 scales (e.g., a decade and distances larger than 1000 km). However, empirical formulae are 62 limited by their inherent characteristics. The lack of one, or more, climate variable physically 63 related to evaporation and transpiration processes inescapably reduces the accuracy of evapotranspiration estimation. Even if recalibration of empirical factors may improve locally 64 65 the precision of these methods, considerable estimation errors will remain as time variations 66 of missing climate variables are not considered. An example of this statement is the varying 67 behavior of empirical formulae according to the type of climate considered (Jensen et al., 68 1990). Thus, there is little hope that a universal, accurate and robust empirical formula based 69 on a limited set of weather variables will ever be proposed. 70 Choudhury (1997) proposed a method to assess E_0 by means of satellite data, such as remotely sensed solar radiation, air temperature (derived from infrared images and weather station 71 72 measurements) and vapor pressure deficit. This method provides good evapotranspiration 73 estimates for low-resolution applications such as worldwide scale and monthly time step. The 74 accuracy is limited by the high uncertainties provided by satellite sensed vapor pressure 75 estimations. 76 Several methods have been recently proposed to estimate solar radiation (Struzik, 2001). 77 Amongst them, the Heliosat-2 method (Rigollier et al., 2004) has been proved to be 78 reasonably reliable for estimating daily irradiation over Europe and Africa. This method has 79 been used to elaborate a database, HelioClim-1, available at http://www.soda-is.org (Lefèvre 80 et al., 2007). 81 Solar radiation strongly controls evaporation from the land surface. As small uncertainties in 82 solar radiation may have considerable effect on the E_{θ} calculation (Llasat and Snyder, 1998) 83 and as the variations in space of the radiation cannot be captured by pyranometers, which are 84 in any case expensive and fragile devices, it can be assumed that remotely sensed solar 85 irradiation should be useful for E_0 estimation. 86 In this paper, the relevance of remotely sensed solar radiation for computing E_0 at a daily time 87 step is tested and discussed. First, a sensitivity analysis of the Penman-Monteith method to 88 input variables for daily reference evapotranspiration calculation is performed. Then satellite-89 sensed solar radiation data is compared to ground data and error propagations in several E_0 90 methods are evaluated. Finally, the accuracy of several E_{θ} methods based on solar radiation 91 data are compared to the E_{θ} Hargreaves temperature method, to evaluate the benefits provided 92 by the use of satellite-sensed solar radiation, for areas where air temperature is the only 93 ground-measured available data.

94

95 2 Methods

96 *2.1 Study areas*

97 The study was performed in two regions of France (figure 1). One is located in the Southwest

98 of France (hereafter referred to as SW). It is mostly flat and is characterized by a temperate

99 climate under the influence of the Atlantic Ocean. Rainfalls range from 800 mm to 1800 mm

100 per year; the average value for the area is 1000 mm per year. Summer is dry (mean of 60 mm

101 per month), and autumn and winter are wet (approximately 100 mm per month). From 1971

- to 2000, monthly means of temperatures varied from 5 °C in the winter to 20 °C in the
- summer. The second area is the Southeast of France (hereafter referred to as SE). It exhibits
- 104 marked orography due to the Southern Alps. The climate is Mediterranean, with hot and dry
- summers (20 mm to 40 mm of rainfall per month and an average maximum temperature over
- 106 30 °C) and mild and wetter winters (40 mm to 100 mm per month with mean temperature
- 107 between 0 $^{\circ}$ C and 5 $^{\circ}$ C).
- 108
- 109 2.2 Data
- 110 2.2.1 Ground station data

111 Data was collected from 19 INRA-Agroclim weather stations. Eight are situated in Southwest 112 area and 11 are located in Southeast area (table 1 and figure 1). All stations are Cimel[®] 113 automatic weather stations, equipped with humidity and thermal sensors under a cylinder type 114 disc shelter (80 mm x 150 mm), cup anemometer and class 2 pyranometer. Minimum and 115 maximum temperature, minimum and maximum relative humidity, solar irradiation and wind 116 speed at 2 meters high at a daily time step were used. Average daily temperature is the mean 117 of minimum and maximum daily temperatures values. The study was performed on a five 118 year (2000-2004) data set.

119

120 2.2.2 Satellite sensed solar radiation

121 Remotely sensed solar irradiation was collected from the HelioClim-1 database available at 122 http://www.soda-is.org. This database has been obtained by the application of the Heliosat-2 123 method to Meteosat satellite images. The Heliosat-2 method is based on the principle of the 124 construction of a *cloud index* for each given pixel of satellite images (Cano *et al.*, 1986; 125 Rigollier et al., 2004). This index is obtained by calculating ground and cloud albedos from 126 time-series of images acquired in a broadband channel spanning visible and near-infrared 127 bands. A clear-sky index is then derived from the cloud index. Irradiation is obtained by 128 multiplying this clear-sky index by the irradiation that should be observed under clear-sky 129 conditions; the latter is estimated by means of the model of Rigollier et al. (2000). The 130 precision of the method depends mostly on the cloud cover: relative uncertainties are lower 131 during clear sky days (Rigollier et al., 2004 ; Lefèvre et al., 2007). 132 The HelioClim-1 database provides daily irradiation data for Europe and Africa. It has been 133 constructed from a data set of reduced spatial resolution, called ISCCP-B2 data, that was 134 created for the International Satellite Cloud Climatology Project (ISCCP) to better handle and 135 exploit the wealth of information provided by the Meteosat series of satellites. The B2 data set 136 is produced from Meteosat images by firstly performing a time sampling that reduces the

- 137 frequency of observation to the standard meteorological synoptic 3-h intervals, starting at
- 138 0000 UTC. Secondly, the higher-resolution data in the visible channel are averaged to match
- the lower resolution of infrared channel data (i.e. an image of 2500 x 2500 pixels with a resolution of 5 km). Finally, a spatial sampling is performed by taking 1 pixel over 6 in each
- 141 direction (i.e. 1 pixel each 30 km), starting with the south-easternmost pixel. For each
- 142 remaining pixel, the irradiation was calculated every 3 h and integrated to provide daily
- 143 irradiation. The HelioClim-1 database contains daily irradiation for these pixels (Lefevre et
- al., 2007). The irradiation data for any location are obtained by interpolating the daily values
- available at the nine closest pixels using inverse distance squared method (Lefèvre *et al.*,
- 146 2002). Daily irradiation data were collected for the location of the 19 weather stations for the147 period 2000-2004.
- 148
- 149 2.3 Reference evapotranspiration methods
- 150 2.3.1 The FAO Penman-Monteith method

The Penman-Monteith method combines energy balance and mass transfer concepts (Penman, 151

152 1948) with stomatal and surface resistance (Monteith, 1981).

153 Recently, the FAO proposed a standard parameterization of the Penman-Monteith method for

154 estimating the evaporation from a well-irrigated, homogenous, 0.12 m grass cover considered

155 as a "reference crop" (Allen et al., 1998). This method, hereafter referred as PM, is now used

- worldwide and the international agronomy community considers it as a standard. The FAO 156
- 157 Penman-Monteith reference evapotranspiration (mm) is calculated as follows: 000

158
$$E_{PM} = \frac{0.408\Delta(R_n) + \gamma \frac{900}{(T+273)} u_2(e_s - e_a)}{\Delta + \gamma (1 + 0.34u_2)}$$
(1)

where Δ is the slope of the saturation vapor pressure curve at air temperature [kPa °C⁻¹], γ is 159

160

the psychrometric constant [kPa °C⁻¹], T is the average air temperature [°C], u_2 is the wind speed measured at 2 m above ground surface [m s⁻¹], e_s and e_a are the saturation and the actual 161

162 vapor pressure [kPa], respectively, and
$$R_n$$
 is the net radiation [MJ m⁻²], calculated as follows :
163 $R_n = R_{nn} - R_{nl}$ (2)

$$K_n = K_{ns} - K_{nl} \tag{2}$$

where R_{ns} is the net shortwave radiation [MJ m⁻²] given by : 164 165

$$R_{ns} = (1-a)R_s \tag{3}$$

166 and R_{nl} is the net longwave radiation [MJ m⁻²] given by :

167
$$R_{nl} = \sigma \left[\frac{T_{\max,K}^4 + T_{\min,K}^4}{2} \right] \left(0.34 - 0.14 \sqrt{e_a} \right) \left(1.35 \frac{R_s}{R_{so}} - 0.35 \right)$$
(4)

where R_s is the global solar radiation [MJ m⁻²], a is the albedo of the hypothetical grass 168 reference crop, set to 0.23, $T_{\max,K}$ and $T_{\min,K}$ are the maximum and minimum air temperature 169 [K], respectively, and R_{so} is the clear-sky solar radiation [MJ m⁻²], given by : 170

171
$$R_{sa} = (0.75 + 2z10^{-5})R_{a}$$
(5)

172 where z is the station elevation above sea level [m] and R_a is the extraterrestrial radiation [MJ m⁻²]. Undefined components used in equations (2), (3), (4) and (5) have the same 173 174 signification and units as in equation (1).

The actual vapor pressure [kPa], used in equations (1) and (4) is calculated as follows: 175

176
$$e_{a} = \frac{e^{\circ}(T_{\min})\frac{RH_{\max}}{100} + e^{\circ}(T_{\max})\frac{RH_{\min}}{100}}{2}$$
(6)

where $e^{\circ}(T_{min})$ and $e^{\circ}(T_{max})$ are the saturation vapor pressure at minimum and maximum air 177

178 temperature [kPa], respectively, RH_{min} is the minimum relative humidity and RH_{max} is the

179 maximum relative humidity.

181

180 The slope of saturation vapor pressure curve at air temperature is given by :

$$\Delta = \frac{4098[e^{\circ}(T)]}{(T+237.2)^2}$$
(7)

- where $e^{\circ}(T)$ is the saturation vapor pressure at average air temperature and T as the same 182
- 183 signification and units as in equation (1).
- 184 PM or other Penman-Monteith versions have been proved to be among the most precise and

185 accurate models for daily reference evapotranspiration prediction under different climatic

- 186 conditions when compared to lysimetric measurements (Allen et al., 1989; Hargreaves and
- 187 Allen, 2003 ; Garcia et al., 2004 ; Pereira, 2004; Pereira and Pruitt, 2004).
- 188 In this paper, E_{PM} is considered as the reference value against which other empirical methods
- 189 will be compared. This choice is motivated by the fact that most of the applications based
- 190 upon reference evapotranspiration, such as irrigation schemes, hydrological studies or water
- 191 balance modelling, use calculated E_0 rather than lysimetric measurements.

192

2.3.2 Empirical methods

194 In this study, radiation methods, *i.e.* empirical methods that calculate E_0 with air temperature 195 and solar radiation, are singled out, in order to test the relevance of using remotely sensed 196 solar radiation for E_0 estimates.

197 Three radiation methods and one temperature method were compared to *PM*.

198 Hargreaves radiation method (hereafter referred as to *HR*, Hargreaves and Samani, 1982) was

199 established in 1975 from a regression with lysimeter data collected at Davis (California, USA)

and the product of temperature and solar radiation, for a five day time step. The followingprediction equation was then proposed:

202
$$E_{HR} = 0.0135 \frac{R_s}{\lambda} (T + 17.8)$$
(8)

where λ is the latent heat of vaporization = 2.45 MJ kg⁻¹ at 20 °C (as λ is very stable, this 203 204 value was used in the current study), and other components having the same signification and 205 units as in equations (1) and (3). Hargreaves radiation method has seldom been tested, despite 206 encouraging results (Hargreaves and Allen, 2003). As solar radiation has rarely been 207 available, Hargreaves proposed a modified version of this method, so that reference 208 evapotranspiration could be estimated with minimum and maximum air temperature only 209 (Hargreaves et al., 1985). This method is known as the 1985 Hargreaves temperature method 210 (hereafter referred to as HT):

211
$$E_{HT} = 0.0023 \frac{R_a}{\lambda} (T + 17.8) \sqrt{(T_{\text{max}} - T_{\text{min}})}$$
(9)

where T_{\min} and T_{\max} are the minimum and the maximum air temperature, respectively [°C]. and undefined components having the same signification and units as in equations (1), (5) and

(8). Local calibrations of the empirical coefficient (0.0023), based upon regional wind speed

and air temperature, were recently proposed (Gavilan *et al.*, 2006).

216

217 The Turc radiation method (hereafter referred to as TU; Turc, 1961), initially developed for

218 10-day periods, provides good results for a humid environment (Jensen et al., 1990).

219 Reference evapotranspiration is calculated as follows:

220
$$E_{TU} = 0.013 \left(23.88 R_s + 50 \right) \left(\frac{T}{T + 15} \right)$$
(10)

221 where R_s and T have the same signification and units as in equations (1) and (3).

222 The Priestley-Taylor method (hereafter referred as PT, Priestley and Taylor, 1972), unlike

radiation methods presented above, is mostly based on physical principles. The *PT* method is derived from energy balance concepts and the hypothesis that (at least for short vegetation) fluxes over land are mostly governed by radiative rather than advected energy. Thus, E_0 is

given by:

227

$$E_{PT} = \alpha \frac{\Delta}{\Delta + \gamma} R_n \tag{11}$$

where α is an empirical and unitless coefficient, set to 1.26, and R_n , Δ and γ have the same signification and units as in equation (1). To avoid the use of minimum and maximum relative humidity for E_{PT} calculation (E_{PT} is calculated with air temperature and solar radiation only), the actual vapour pressure e_a , required for R_n calculation (equation (4)) is estimated from minimum air temperature only:

233
$$e_a = e^{\circ}(T_{\min}) = 0.611 \exp\left[\frac{17.27T_{\min}}{T_{\min} + 237.3}\right]$$
(12)

where e_a and T_{\min} have the same significance and units as in equations (6) and (9).

- Equation (12) follows the recommendations in Allen *et al.* (1998) to compute e_a when relative humidity is missing.
- 237 *PT* method has been used and tested in many studies, and has shown to be reliable in humid
- 238 climate conditions for evaporation (Xu and Singh, 2000) and reference evapotranspiration
- 239 (Jensen *et al.*, 1990) estimations. Local adjustments of α are necessary in numerous cases (Xu
- and Singh, 2002; Bois *et al.*, 2005; Fisher *et al.*, 2005), and a calculation method for α based
- on surface and aerodynamic resistance parameters was proposed by Pereira (2004). A
- recalibration of α to increase the precision of *PT* estimates, is discussed in the results section,
- but the results presented in this paper focus on the *PT* method with α set to 1.26, as
- recalibration of empirical formulae is not the main objective of the present sutdy.
- 245

246 *2.4 Sensitivity analysis*

247 2.4.1 The Sobol' method

248 To estimate the relative participation of climate variables to *PM* model output, a sensitivity 249 analysis was performed. There are several approaches available for sensitivity analysis studies 250 (see Frey and Patil, 2002 or Saltelli et al., 2006 for reviews). For the present work, the Sobol' 251 based variance method was used (Sobol', 1993). This method allows evaluating the sensitivity 252 of a model to interaction between input variables. It consists of numerous simulations of the 253 models using two independent samples of N repetitions (rows) and k input variables 254 (columns), retrieved from existing data or randomly generated data from the probability 255 distribution function of each k input variable. One or several variables in the first sample are 256 substituted by the same variable(s) taken from the second sample. For each of the $(2^{k}-1)$ 257 possible combinations of variable substitutions between the two samples, N runs of the model 258 are computed. The sensitivity of the model to input variables is based on so-called sensitivity 259 or Sobol' indices, which are calculated on the principle of the decomposition of the total 260 variance V of the model output, in response to individual or simultaneous variations of the k261 model inputs:

262
$$V = \sum_{i} V_{i} + \sum_{i < j} V_{ij} + \sum_{i < j < m} V_{ijm} + \dots + V_{1,2,\dots,k}$$

263 Where V_i is the model output variance in response to variation of the *i*th input variable, V_{ij} is 264 the model output variance in response to the simultaneous variation of the *i*th and the *j*th 265 model input, and so-on. Then, sensitivity indices are calculated as follows:

$$S_i = \frac{V_i}{V} \tag{1}$$

$$S_{Ti} = \frac{V_i + \sum_j V_{ij} + \sum_{j < m} V_{ijm} + \dots + V_{i,j\dots,k}}{V}$$
(15)

where *j* and *m* are the *j*th and the *m*th model input variables, and
$$i \neq j \neq m$$
. S_i is called the first
order sensitivity index. It measures the sensitivity of the model to the input variable X_i . S_{Ti} is
called the total sensitivity index. It measures the impact of variations of the *i*th model input on
the model output, including all the possible interactions with other input variations. For more
details about the Sobol' method, see Saltelli (2002).

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274 2.4.2 Sensitivity analysis of PM reference evapotranspiration formula

A major constraint, when trying to perform a sensitivity analysis, is the interdependency of input variables. Considering the Penman-Monteith FAO-56 formula, required input data are

277 minimum and maximum air temperature, minimum and maximum relative humidity, solar

278 radiation and wind speed. Minimum and maximum air temperature and relative humidity, if

279 picked randomly in a data set, will lead to nonsense computations, i.e. having a minimum air

(13)

4)

280 temperature or relative humidity value higher than the maximum. To solve this problem

average air temperature and relative humidity and their daily amplitudes were calculated prior
 to elaborating the two random data sets required for Sobol' method:

$$T = \frac{T_{\min} + T_{\max}}{2} \quad ; \quad RH = \frac{RH_{\min} + RH_{\max}}{2} \tag{16} ; (17)$$

284 and

283

285

$$\Delta T = T_{\text{max}} - T_{\text{min}} \quad ; \quad \Delta RH = RH_{\text{max}} - RH_{\text{min}} \tag{18} ; (19)$$

where *T* and *RH* are the daily average air temperature [°C] and the daily average relative humidity [%], ΔT [°C] and ΔRH [%] are their daily amplitude, and T_{\min} , T_{\max} , RH_{\min} and *RH*_{max} having the signification and units as in equations (6) and (9). Once random samples are created, *T*, *RH*, ΔT and ΔRH are used to retrieve minimum and maximum air temperature and relative humidity daily values, inverting the equations (16), (17), (18) and (19).

291 A major requirement of sensitivity analysis is the choice of the input data set. The aim of the 292 present SA is to retrieve the climate variables which PM model is most sensitive to, according 293 to different climatic conditions, i.e. Oceanic and Mediterranean climates. It is assumed that 294 the climate stations within both study areas (8 for SW and 11 for SE) provide a good sample 295 of the spatial variation of climatic conditions. To take into account the variability of climate 296 during the year, sensitivity analyses were performed for each month. That is, the input data set 297 for Sobol' SA is generated for a given month, according to the probability distribution 298 function (PDF) of each input data, recorded at the stations of a given study area (SW or SE). 299 For each month and each area, Sobol' SA was assessed as follows (figure 2): (a) empirical 300 PDF of each input variable were fitted to empirical distributions of the data sets recorded at 301 the (8 or 11) climate stations area during 2000 to 2004, using a Gaussian Kernel fitting 302 function with R statistical software (R Development Core Team, 2007); (b) Two samples 303 were generated by quasi-random sampling with 10000 repetitions; (c) Several model outputs 304 and variance decomposition were computed using Sobol' algorithm of the package sensitivity 305 of R statistical software; (d) First order and total sensitivity indexes and their monthly 306 evolution were then compared. Note that for step (b), one could propose the use of the 307 original data record rather than random sample generations. However, the number of available 308 data for each month was not sufficient for the statistical robustness of the analysis.

309

316

2.5 Statistical indices used for satellite sensed solar radiation and empirical E₀ formulae evaluations

312 The reference data used to evaluate satellite-sensed solar radiation were pyranometer records

313 at ground level. For evapotranspiration, *PM* (equation (1)), using pyranometer records, was

314 used as a reference data for empirical formulae evaluation. For each day *i*, the difference

315 between reference and estimated data was calculated as follows :

$$D_i = Est_i - Ref_i \tag{20}$$

317 where D is the difference (or "error") [mm],
$$Est_{i}$$
 is the satellite-sensed solar radiation or the

318 E_0 estimated with an empirical method and Ref_i is the reference data. The units are MJ m⁻² or 319 mm according to the type of data evaluated.

- 320 The accuracy of each method is given by the bias (or mean error):
- $bias = \frac{1}{n} \sum_{i=1}^{n} D_i$ (21)

The unit of *bias* is mm or MJ m⁻², according to the type of data evaluated, and *n* is the number of days.

324 The precision is given by the root mean squared error (RMSE):

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} D_i^2}$$
(25)

325

326

327

328 **3 Results and discussion**

329 *3.1 Sensitivity analysis of* PM *formula*

330 Sensitivity of E_0 computation using PM method in Southwest area (Oceanic climate). The 331 results of monthly sensitivity analyses computed using Southwest area data show clear 332 seasonal trends (figure 3A). During the winter period (from November to February), wind 333 speed is the main source of variation in E_0 values calculated using PM method (e.g. 38% of E_0 334 total variance in January, table 2). Then come relative humidity and air temperature (32% and 335 17% of E_0 total variance in January, respectively). Solar radiation, daily amplitude of air 336 temperature and daily amplitude of relative humidity have little impact on evapotranspiration 337 process during winter. This trend changes during March and October. From April to 338 September, E_{θ} is mostly sensitive to solar radiation (up to 74% of E_{θ} total variance in May, 339 and 70% in July). From May to July, PM formula is not very sensitive to RH, U_2 , ΔRH and 340 ΔT . Mean daily air temperature participate from 11% to 15% of E_0 variance, from May to 341 September. Total sensitivity indices show that, when added to other variables variations, air 342 temperature has a greater impact on E_{θ} variability during summer, and wind speed has a 343 greater impact during winter (figure 3B). 344 Sensitivity of E_0 computation using PM method in Southeast area (Mediterranean climate). 345 The sensitivity of *PM* formula to climate input variables in Mediterranean climate conditions 346 is very close to the one observed for Oceanic climate. Wind speed as a major impact on E_{θ} 347 calculation during winter and solar radiation is clearly the most influent variable during 348 summer (figures 3C and 3D, table 2).

Errors populations were also analyzed by means of coefficient of determination (R^2) .

The present analysis highlights the great sensitivity of this Penman-Monteith formula to solar radiation during summer period, when E_0 reaches its highest values, and when its calculation is critical for irrigation process and ecological modelling. These results were obtained for

352 Mediterranean and Oceanic climate, at medium latitudes. They are consistent with former

353 uncertainty and sensitivity analyses performed in Mediterranean climate (Llasat and Snyder,

1998 ; Rana and Katerji, 1998). A recent work published by Gong et al. (2006) on a large

range of climatic conditions in Southern China leads to similar results, except for relative humidity which had a greater impact on E_0 during winter than it has been shown in the

357 present study.

358 Considering the results of Penman-Monteith sensitivity to solar radiation, it seems reasonable

to evaluate the benefits of satellite sensed solar radiation to E_0 calculation when no solar

360 radiation ground records are available. This point is studied and discussed in the next section.

361

362 *3.2 Remotely sensed solar radiation performances*

363 Table 3 shows the annual error statistics of solar radiation and E_0 data calculated with

364 HelioClim-1 data instead of pyranometer radiation data. HelioClim-1 underestimates daily

- 365 irradiation (figures 4A and 4D). The bias is twice as important for Southwest area (-
- 1.87 MJ m^{-2}) as it is for Southeast area (-1.07 MJ m⁻²). RMSE is also higher for SW (20% of
- the annual solar irradiation) than for SE (14%). Although the uncertainty, in absolute value, is 1.2
- larger during summer period (Figure 5A), the RMSE are 15% (SW) and 10% (SE) of R_s
- 369 pyranometer value in July, whereas they reach 26% (SW) and 18% (SE) in January, as
- 370 irradiation is larger during summer.
- These errors are consistent with those observed in Northern Europe, during former
- 372 evaluations of HelioClim-1 database (Lefèvre et al., 2007). When no pyranometer data is

373 available, daily satellite sensed solar radiation should be preferred to temperature-based 374 estimations: for both areas, daily irradiation RMSE are 3 to 4 times smaller than those 375 obtained by Hunt et al. (2000) in Ontario (Canada), with empirical formulae based on air 376 temperature. Moreover, HelioClim-1 irradiation may be as precise as pyranometer 377 measurements where weather stations are not steadily maintained or not equipped with 378 accurate devices: uncertainty reported varies from 5 to 25%, according to the class of material 379 and the metrology experts (Llasat and Snyder, 1998; Droogers and Allen, 2002). 380 There are several sources of uncertainties when comparing satellite data to very local 381 measurements, such as weather station records. This point has been widely discussed by 382 Zelenka et al. (1999). First, it is difficult to compare pixel data, corresponding to a surface, 383 with a discrete measurement, such as pyranometer weather station records. Another category 384 of uncertainties comes from the spatial (1 pixel each 30 kilometer) and temporal (3 hours) 385 resolutions of the initial data set used to create the HelioClim-1 database. In addition, the 386 spatial interpolation method generates its intrinsic uncertainties. The Heliosat-2 method itself, used to elaborate the HelioClim-1 database, also participate to uncertainties of satellite sensed 387 388 irradiation data (e.g. the algorithm limits). The uncertainties inherent to the ISCCP-B2 data 389 set could be avoided by applying the Heliosat-2 method to each original Meteosat pixel and 390 for every hour. The HelioClim-2 database was created in that respect but begins only in 2004 391 and could not be used in this study.

392

393 3.3 Propagation of satellite sensed solar radiation errors in E_0 formulae

394 Replacing pyranometer measurement by Heliosat-2 estimations (*i.e.* HelioClim-1 data) 395 induces little error for reference evapotranspiration calculation using the Penman-Monteith 396 model (table 3). Estimation errors are higher for middle range E_0 values (figure 4B and 4E). 397 This could be explained by the fact that most of the errors occur for partially cloudy days, due 398 to uncertainties in retrieving daily solar radiation with Heliosat-2 method for this type of 399 weather (Rigollier et al., 2004). In both areas, E_{PM} is slightly underestimated. For SW, biases 400 vary from -0.34 mm to 0.01 mm, according to the season (figure 5B). The annual RMSE 401 value remains low (11% of E_0 mean value). In SE area, E_{PM} bias is negligible (-0.20 mm to 402 0.01 mm, figure 5C). Relative RMSE in SE is 7% of E_0 mean value, which is lower than in 403 SW. Heliosat-2 method is more successful for clear sky days, which could explain the 404 difference between the two regions, as clear sky situations occur more frequently in SE than 405 SW. Relative errors of E_{PM} calculated with HelioClim-1 are lower during summer (9% for 406 SW and 5% for SE, in July). Again, the better performance of Heliosat-2 method for clear sky 407 days could explain this seasonal trend, as clear sky situations are more numerous during 408 summer than during the other seasons. Yet, higher relative errors could have been expected: 409 sensitivity analyses have shown that solar radiation has the greatest impact on PM model

- 410 during summer (i.e. when evapotranspiration reaches its maximum) in Oceanic or
- 411 Mediterranean climates (see section 3.1).
- 412 Errors are higher when pyranometer data is replaced by HelioClim-1 data in radiation
- 413 methods, i.e. *HR*, *TU* and *PT* (figure 4C and 4F, table 3). Biases are mostly negative.
- 414 Sensitivity to solar radiation errors is higher for radiation methods than for *PM* because
- 415 radiation methods do not include advective effects on the evapotranspiration process and thus
- 416 are mainly governed by radiative transfers. The largest error propagation can be observed for
- 417 the Hargreaves radiation method (table 3, figures 5B and 5C).
- 418
- 419 3.4 Empirical formulae performance
- 420 Daily E_0 values of 4 empirical methods were compared to reference evapotranspiration
- 421 computed with *PM*. HelioClim-1 solar radiation was used for radiation methods, whereas

422pyranometer data was used for PM, as it was considered here as the "control" method. Data423sources used for E_0 calculations are shown in table 4.424In both areas, Hargreaves temperature method (HT) gave the highest uncertainties for the425annual period (table 5). During summer, formulae using satellite-sensed solar radiation426improve considerably E_0 estimation compared to HT estimates based solely on local air427temperature. Figures 6A and 6B show an obvious seasonal trend of HT errors, which is

428 related to the variations in sensitivity of E_0 to the different input variables of *PM*: during

- summer, when E_0 is mainly governed by solar radiation, estimates based upon air temperature only are thus less accurate.
- 431 Evapotranspiration calculated with satellite-sensed solar radiation is mainly underestimated.
- 432 For both climates, all radiation methods show biases similar to those induced by replacement
- 433 of pyranometer data by satellite-sensed solar radiation (between -0.4 mm and -0.2 mm, table 3
- and 5): this suggests that the underestimation observed is mainly due to the propagation of
- 435 HelioClim-1 data bias within radiation methods, rather than wrong calibration of empirical
- 436 coefficients used in these formulae.
- 437 In the Southwest area, *PT* data is strongly correlated to *PM* data ($R^2 = 0.938$, table 5). It is
- 438 also the formula providing the lowest E_0 RMSE during summer and for the whole year (figure

439 6A). Turc and Hargreaves radiation method performances are almost the same. The

440 performance of *TU* is slightly better than other formulae from September to November. It has 441 been shown in former studies that the Turc method provides good results in humid

- 442 environment (Jensen et al., 1990; Turc, 1961), whereas Hargreaves radiation method has
- 443 been established from arid or semi-arid climate data analysis (Hargreaves and Allen, 2003).
- 444 These differences between those two formulae did not emerge from the current study, in
- 445 Southwest oceanic climate. Hargreaves temperature method provided the lowest RMSE and
- the lowest bias (in absolute value), from January to April. However, this temperature-based
- 447 method was the least accurate method for SW, when considering summer and annual periods 448 (DMSE = 0.67 mm, $P^2 = 0.804$ for the sub-size super-
- 448 (RMSE = 0.67 mm, R²=0.894, for the whole year). *HT* overestimated E_0 (a mean error of 449 0.32 mm).
- For the Southeast area, all empirical formulae showed poorer performances when compared to the Southwest region (figure 6B). The higher wind speed and the lower relative humidity in
- 452 SW throughout the year might explain these differences (results not shown). *HR* provided the
- 453 most precise E_0 estimates for the whole year (RMSE= 0.77 mm, i.e. 25% of E_0 mean annual
- 454 value). The best correlation with *PM* values is provided by *PT*. The Priestley-Taylor formula
- 455 performed better than every other formula during summer, but showed considerable bias and
- 456 RMSE during winter. The lowest bias (in absolute value) is provided by *HT*, which showed in 457 contrast high RMSE (0.96 mm, i.e. 31% of the annual mean).
- 458 These results suggest that using satellite sensed-solar radiation within empirical formulae
- 459 improve the accuracy of E_0 estimates during summer and for the whole year, although
- 460 reference evapotranspiration remains underestimated in most cases.
- 461

462 4 Conclusions

The present work focused on the role of solar radiation data in reference evapotranspiration
calculation at daily time steps. A sensitivity analysis of the Penman-Monteith model showed
that solar radiation strongly governs reference evapotranspiration during summer, for Oceanic
and Mediterranean climates at medium latitude. The use of satellite-sensed solar radiation

- 467 taken from HelioClim-1 database for E_0 calculation was evaluated. It was shown that
- 468 HelioClim-1 data underestimates solar radiation at daily time step, for Oceanic and
- 469 Mediterranean climates in France. The RMSE ranges from 14 to 20% of the annual solar
- 470 radiation. The error propagation is considerable in radiation-based methods, as these
- 471 equations are linearly linked to solar radiation input.

- 472 Amongst the numerous studies concerning reference evapotranspiration estimates with
- 473 limited climatic data, few considered daily time step. When temperature data is the sole
- 474 climate variable available, Hargreaves temperature method is often used or recommended and
- 475 provides relative RMSE ranging from 20% to 30% of the mean annual value, depending on
- the type of climate (Droogers and Allen, 2002; Hargreaves and Allen, 2003). In the present
- 477 work, we found that using satellite sensed global radiation via PT or HR methods improves E_0
- estimates, compared to Hargreaves temperature method. With these empirical solar radiation based methods, relative annual RMSE ranges from 22% to 28%, according to the method and
- based methods, relative annual RMSE ranges from 22% to 28%, according to the method and
 the type of climate, humid-Oceanic or semi-arid-Mediterranean. Hargreaves temperature
- 481 method, however, produced annual RMSE of 28% of the annual mean for Oceanic climate
- 482 and 31% for Mediterranean climate. The difference in precision between radiation and
- Hargreaves temperature method reaches its maximum during summer, when the E_0 process is mainly governed by solar radiation. In contrast, *HT* showed smaller uncertainties than
- 485 radiation methods with HelioClim-1 data during winter.
- 486 These results suggest that during summer, using empirical radiation methods with satellite 487 sensed solar radiation from the HelioClim-1 database to estimate E_0 should be preferred to 488 *UT*, when air temperature is the only supjlable mean dat weather stations
- 488 *HT*, when air temperature is the only available record at weather stations.
- 489 These observations need to be verified in other climatic conditions, and especially in arid 490 climates, where E_0 estimation is crucial for water management. This could be easily done
- 490 chinates, where E_0 estimation is crucial for water management. This could be easily done 491 using HelioClim-1 database, as it provides data for a large surface of the globe, i.e. from
- 492 Northern Europe to South-Africa.
- 493

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601







Fig 3. SA monthly indices









(mm) fssoileH _{M9} 3

R_s Heliosat (MJ/m²)





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Fig. 1. Spatial distribution of the 19 meteorological stations used in the study. SW: Southwest area, SE: Southeast area.

Fig. 2. General scheme of Sobol' sensitivity analysis. PDF = Probability Distribution Function. x_i = the *i*th variable of the model's *k* input variables. y = the model output.

Fig. 3. Monthly variations of first order and total sensitivity indices of climate input variables of PM model, for reference evapotranspiration calculation. A and B: Southwest area (SW); C and D: Southeast area (SE).

Fig. 4. Scatter plots of pyranometer and HelioClim-1 data. **A**, **B**, **C**: Southwest area (SW). **D**, **E**, **F**: Southeast area (SE). R_s : daily solar irradiation ; E_{PM} : E_0 daily value with Penman-Monteith (*PM*) method ; E_{TU} : E_0 daily value with Turc (*TU*) method. — : (1:1) curve ; ----: linear fitting curve.

Fig. 5. Errors induced by the use of daily HelioClim-1 data for irradiation (**A**), and E_0 estimates (**B**: Southwest area, **C**: Southeast area). *PM*: Penman-Monteith, *PT*: Priestley-Taylor, *TU*: Turc, *HR*: Hargreaves radiation, *HT*: Hargreaves temperature. : RMSE ; ----: Bias.

Fig. 6. Monthly variations of RMSE resulting from the comparison of daily E_0 between Penman-Monteith and estimation formulae (*PT*: Priestley-Taylor, *TU*: Turc, *HR*: Hargreaves radiation, *HT*: Hargreaves temperature). A: Southwest area ; **B**: Southeast area.

# code	Site	Latitude N (°)	Longitude W (°)	Elevation (m)	$\frac{\text{Mean }E_{\theta}}{(\text{mm }\text{d}^{-1})^{\text{a}}}$	$\mathbf{N}^{\mathbf{b}}$
	South West					
1	BERGERAC	44.855	-0.521	33	2.34	1783
2	BOURRAN	44.334	-0.413	60	2.43	1606
3	CADAUJAC	44.753	0.554	20	2.36	1827
4	LATRESNE	44.780	0.478	63	2.54	1826
5	LUXEY	44.226	0.491	101	2.30	1818
6	SAINT LAURENT-DE-LA-PREE	45.990	1.033	3	2.46	1827
7	SAINT MARTIN DE HINX	43.576	1.269	64	2.29	1826
8	VILLENAVE D'ORNON	44.789	0.578	25	2.55	1827
	South East					
1	AVIGNON	43.916	-4.876	24	3.27	1827
2	BELLEGARDE	43.781	-4.477	61	3.15	1762
3	FOURQUES	43.692	-4.595	3	3.41	1826
4	FREJUS	43.434	-6.717	3	3.13	1827
5	GRUISSAN	43.137	-3.121	40	3.04	1827
6	LES-SAINTES-MARIES-DE-LA-MER	43.580	-4.499	1	3.23	1827
7	MONTPELLIER	43.647	-3.874	50	2.60	1613
8	ROUJAN	43.491	-3.321	78	2.45	774
9	SAINT-MARCEL-LES-VALENCE	44.977	-4.930	190	2.97	1827
10	SAINT-GILLES	43.714	-4.412	72	3.15	1775
11	SALON DE PROVENCE	43.646	-5.014	68	3.27	1604

Table 1 List of weather stations used in the study

^a E_0 was calculated with Penman-Monteith model (*i.e. PM*). ^b Number of available E_0 values (days) on the period 2000-2004. Maximum is 1827. Lower N values means that data used to calculate E_0 with Penman-Monteith model (*i.e.* temperature, relative humidity, wind speed or solar radiation) were unavailable on certain days.

Table 2

First order sensitivity indices of *PM* method to climate variables. The values between brackets correspond to the relative par of total E_0 variance explained by each input variable. Figures in bold correspond to the highest sensitivity index of each month.

-	Month	Т	ΔT	R_s	RH	∆RH	U_2
South-West	January	0.14 (17%)	0.02 (3%)	0.05 (6%)	0.27 (32%)	0.03 (4%)	0.32 (38%)
	April	0.19 (20%)	0.03 (3%)	0.44 (48%)	0.11 (12%)	0.03 (4%)	0.12 (13%)
	July	0.13 (13%)	0.02 (2%)	0.73 (70%)	0.05 (5%)	0.01 (1%)	0.09 (9%)
South-East	January	0.14 (17%)	0.03 (3%)	0.04 (5%)	0.24 (28%)	0.02 (2%)	0.36 (44%)
	April	0.18 (17%)	0.07 (7%)	0.55 (54%)	0.09 (9%)	0.01 (1%)	0.12 (12%)
	July	0.15 (14%)	0.04 (4%)	0.73 (71%)	0.03 (3%)	0.01 (1%)	0.06 (6%)

Table 3

Bias and RMSE resulting from the use of Helioclim-1 data instead of pyranometer data for daily solar irradiation and daily E_0 estimates, using Penman-Monteith or radiation methods. Values between brackets are the ratio of the statistical index with the mean reference value (pyranometer solar radiation, and evapotranspiration calculated with pyranometer data).

South-West						South-East				
-	Mean Bias		RMSE	RMSE N ^a		Bias	RMSE	N ^a		
R_S (MJ m ⁻²)	13.48	-1.87 (-14%)	2.67 (20%)	14566	15.83	-1.07 (-7%)	2.16 (14%)	18997		
E_{PM} (mm)	2.41	-0.14 (-6%)	0.25 (11%)	14308	3.10	-0.08 (-3%)	0.21 (7%)	18448		
E_{TU} (mm)	2.38	-0.27 (-11%)	0.41 (17%)	14308	2.87	-0.16 (-6%)	0.35 (12%)	18448		
E_{PT} (mm)	2.34	-0.22 (-9%)	0.39 (17%)	14308	2.77	-0.14 (-5%)	0.34 (12%)	18448		
E_{HR} (mm)	2.52	-0.33 (-13%)	0.49 (19%)	14308	3.09	-0.20 (-6%)	0.41 (13%)	18448		

^a Number of values.

Table 4						
Sources of climate	variables used for	or reference ev	vapotranspiration	calculations in	section 3	3.4.

Method	Acronym	Temperature	Solar radiation	Relative Humidity	Wind speed
Temperature Method	HT	Ground ^a			
Dedletter Metheda	PT	Ground	Sat ^b		
Radiation Methods	HR	Ground	Sat		
	TU	Ground	Sat		
Penman-Monteith Method	РМ	Ground	Ground	Ground	Ground

^a Ground : climate variable measured with the weather station devices. ^b Sat : Helioclim-1 data (for solar radiation).

Table 5

Summary of statistical indexes of E_0 estimation methods, at daily time step. Values between brackets represent the bias and the RMSE divided by *PM* mean values (relative bias and relative RMSE). R^2 is the coefficient of determination; N_{SW} and N_{SE} are the number of observations for Southwest and Southeast area, respectively. Figures in bold correspond to the best performance in E_0 estimates, according to the index considered.

		Southwest (Oceanic climate)			Southeast (Mediterranean climate)			
	Method	R ² Bias (mm)		RMSE (mm)	R ²	Bias (mm)	RMSE (mm)	
January	HT	0.150	0.08 (11%)	0.34 (49%)	0.044	-0.12 (-12%)	0.56 (81%)	
(N _{SW} =1189)	TU	0.205	-0.15 (-22%)	0.37 (54%)	0.227	-0.23 (-23%)	0.53 (77%)	
(N _{SE} =1577)	PT	0.112	-0.29 (-42%)	0.43 (63%)	0.097	-0.57 (-59%)	0.76 (110%)	
	HR	0.053	-0.16 (-23%)	0.42 (62%)	0.255	-0.17 (-18%)	0.49 (72%)	
April	HT	0.668	0.17 (6%)	0.62 (22%)	0.348	-0.30 (-9%)	1.01 (36%)	
(N _{SW} =1153)	TU	0.830	-0.66 (-23%)	0.80 (28%)	0.672	-0.66 (-19%)	0.96 (34%)	
(N _{SE} =1481)	PT	0.816	-0.46 (-16%)	0.63 (22%)	0.672	-0.53 (-15%)	0.87 (31%)	
	HR	0.825	-0.57 (-20%)	0.77 (27%)	0.678	-0.51 (-15%)	0.90 (32%)	
July	HT	0.624	0.56 (13%)	0.96 (22%)	0.217	-0.53 (-9%)	1.32 (30%)	
(N _{SW} =1236)	TU	0.866	-0.42 (-10%)	0.65 (15%)	0.549	-0.77 (-13%)	1.19 (27%)	
(N _{SE} =1497)	PT	0.868	-0.05 (-1%)	0.50 (11%)	0.576	-0.30 (-5%)	0.93 (21%)	
	HR	0.869	-0.13 (-3%)	0.67 (15%)	0.560	-0.18 (-3%)	0.97 (22%)	
Year	HT	0.894	0.32 (-13%)	0.67 (28%)	0.804	-0.20 (-6%)	0.96 (31%)	
(N _{SW} =14308)	TU	0.914	-0.30 (-12%)	0.58 (24%)	0.880	-0.40 (-13%)	0.84 (27%)	
(N _{SE} =18448)	PT	0.938	-0.29 (-12%)	0.52 (22%)	0.890	-0.47 (-15%)	0.86 (28%)	
	HR	0.906	-0.21 (-9%)	0.59 (24%)	0.882	-0.21 (-7%)	0.77 (25%)	