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Abstract

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

Keywords: evapotranspiration, solar radiation, Penman-Monteith equation, sensitivity analysis, remote sensing.

1 Introduction

Reference evapotranspiration (E_0) is an agrometeorological variable widely used in hydrology and agriculture. Together with precipitation, it is a major input in soil water balance models. Several of these models require daily or hourly evapotranspiration data to provide acceptable estimate of plants water requirements (Brisson et al., 1992 ; Guyot, 1997 ; Lebon et al., 2003). Penman-Monteith combination method is one of the most accurate methods to evaluate E_0 at different time steps. A standardization of this method has been proposed by the Food and Agriculture Organization (Allen *et al.*, 1998). It is known as FAO-

56 Penman-Monteith application, and it can be considered as a worldwide standard. However, it requires numerous weather variables (air temperature, relative humidity, wind speed and solar radiation), which are seldom available in basic meteorological records. Consequently, reference evapotranspiration is often estimated by means of empirical equations based on air temperature, relative humidity, extraterrestrial radiation and/or precipitation (Droogers and Allen, 2002 ; Hargreaves et al., 1985 ; Popova et al., 2005 ; Turc, 1961). Several authors proposed modifications of existing empirical methods (Droogers and Allen, 2002 ; Gavilan et al., 2006 ; Pereira, 2004 ; Pereira and Pruitt, 2004 ; Popova et al., 2005 ; Xu and Singh, 2002). The accuracy of these methods remains acceptable when applied at large time and space scales (e.g., a decade and distances larger than 1000 km). However, empirical formulae are limited by their inherent characteristics. The lack of one, or more, climate variable physically related to evaporation and transpiration processes inescapably reduces the accuracy of evapotranspiration estimation. Even if recalibration of empirical factors may improve locally the precision of these methods, considerable estimation errors will remain as time variations of missing climate variables are not considered. An example of this statement is the varying behavior of empirical formulae according to the type of climate considered (Jensen et al., 1990). Thus, there is little hope that a universal, accurate and robust empirical formula based on a limited set of weather variables will ever be proposed.

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 measurements) and vapor pressure deficit. This method provides good evapotranspiration estimates for low-resolution applications such as worldwide scale and monthly time step. The accuracy is limited by the high uncertainties provided by satellite sensed vapor pressure estimations.

Several methods have been recently proposed to estimate solar radiation (Struzik, 2001). Amongst them, the Heliosat-2 method (Rigollier *et al.*, 2004) has been proved to be reasonably reliable for estimating daily irradiation over Europe and Africa. This method has been used to elaborate a database, HelioClim-1, available at http://www.soda-is.org (Lefèvre *et al.*, 2007).

Solar radiation strongly controls evaporation from the land surface. As small uncertainties in solar radiation may have considerable effect on the E_0 calculation (Llasat and Snyder, 1998) and as the variations in space of the radiation cannot be captured by pyranometers, which are in any case expensive and fragile devices, it can be assumed that remotely sensed solar irradiation should be useful for E_0 estimation.

In this paper, the relevance of remotely sensed solar radiation for computing E_0 at a daily time step is tested and discussed. First, a sensitivity analysis of the Penman-Monteith method to input variables for daily reference evapotranspiration calculation is performed. Then satellite-sensed solar radiation data is compared to ground data and error propagations in several E_0 methods are evaluated. Finally, the accuracy of several E_0 methods based on solar radiation data are compared to the E_0 Hargreaves temperature method, to evaluate the benefits provided by the use of satellite-sensed solar radiation, for areas where air temperature is the only ground-measured available data.

2 Methods

2.1 Study areas

The study was performed in two regions of France (figure 1). One is located in the Southwest of France (hereafter referred to as SW). It is mostly flat and is characterized by a temperate climate under the influence of the Atlantic Ocean. Rainfalls range from 800 mm to 1800 mm per year; the average value for the area is 1000 mm per year. Summer is dry (mean of 60 mm 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 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 30 °C) and mild and wetter winters (40 mm to 100 mm per month with mean temperature between 0 °C and 5 °C).

2.2 Data

2.2.1 Ground station data

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

2.2.2 Satellite sensed solar radiation

Remotely sensed solar irradiation was collected from the HelioClim-1 database available at http://www.soda-is.org. This database has been obtained by the application of the Heliosat-2 method to Meteosat satellite images. The Heliosat-2 method is based on the principle of the construction of a *cloud index* for each given pixel of satellite images (Cano *et al.*, 1986 ; Rigollier *et al.*, 2004). This index is obtained by calculating ground and cloud albedos from time-series of images acquired in a broadband channel spanning visible and near-infrared bands. A clear-sky index is then derived from the cloud index. Irradiation is obtained by multiplying this clear-sky index by the irradiation that should be observed under clear-sky conditions; the latter is estimated by means of the model of Rigollier *et al.* (2000). The precision of the method depends mostly on the cloud cover: relative uncertainties are lower during clear sky days (Rigollier *et al.*, 2004 ; Lefèvre *et al.*, 2007).

The HelioClim-1 database provides daily irradiation data for Europe and Africa. It has been constructed from a data set of reduced spatial resolution, called ISCCP-B2 data, that was created for the International Satellite Cloud Climatology Project (ISCCP) to better handle and exploit the wealth of information provided by the Meteosat series of satellites. The B2 data set is produced from Meteosat images by firstly performing a time sampling that reduces the frequency of observation to the standard meteorological synoptic 3-h intervals, starting at 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 direction (i.e. 1 pixel each 30 km), starting with the south-easternmost pixel. For each remaining pixel, the irradiation was calculated every 3 h and integrated to provide daily 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.*, 2002). Daily irradiation data were collected for the location of the 19 weather stations for the period 2000-2004.

2.3 Reference evapotranspiration methods

2.3.1 The FAO Penman-Monteith method

The Penman-Monteith method combines energy balance and mass transfer concepts (Penman, 1948) with stomatal and surface resistance (Monteith, 1981).
Recently, the FAO proposed a standard parameterization of the Penman-Monteith method for estimating the evaporation from a well-irrigated, homogenous, 0.12 m grass cover considered 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 Penman-Monteith reference evapotranspiration (mm) is calculated as follows:

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

where Δ is the slope of the saturation vapor pressure curve at air temperature [kPa °C^{-1}], γ is 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 vapor pressure [kPa], respectively, and R_n is the net radiation [MJ m^{-2}], calculated as follows :

$$R_n = R_{ns} - R_{nl} \quad (2)$$

where R_{ns} is the net shortwave radiation [MJ m^{-2}] given by :

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

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

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

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

$$R_{so} = (0.75 + 2z10^{-5})R_a \quad (5)$$

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

$$e_a = \frac{e^\circ(T_{\min})\frac{RH_{\max}}{100} + e^\circ(T_{\max})\frac{RH_{\min}}{100}}{2} \quad (6)$$

where e°(T_{min}) and e°($T_{\max}$) are the saturation vapor pressure at minimum and maximum air temperature [kPa], respectively, $RH_{\min}$ is the minimum relative humidity and $RH_{\max}$ is the maximum relative humidity.
The slope of saturation vapor pressure curve at air temperature is given by :

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

where e°(T) is the saturation vapor pressure at average air temperature and T as the same signification and units as in equation (1).
PM or other Penman-Monteith versions have been proved to be among the most precise and accurate models for daily reference evapotranspiration prediction under different climatic conditions when compared to lysimetric measurements (Allen *et al.*, 1989 ; Hargreaves and Allen, 2003 ; Garcia *et al.*, 2004 ; Pereira, 2004; Pereira and Pruitt, 2004).
In this paper, E_{PM} is considered as the reference value against which other empirical methods will be compared. This choice is motivated by the fact that most of the applications based upon reference evapotranspiration, such as irrigation schemes, hydrological studies or water balance modelling, use calculated E_0 rather than lysimetric measurements.

192
193 *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)
200 and the product of temperature and solar radiation, for a five day time step. The following
201 prediction equation was then proposed:

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

203 where λ is the latent heat of vaporization = 2.45 MJ kg^{-1} at 20 °C (as λ is very stable, this
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 $$E_{HT} = 0.0023 \frac{R_a}{\lambda}(T + 17.8)\sqrt{(T_{\max} - T_{\min})} \quad (9)$$

212 where $T_{\min}$ and $T_{\max}$ are the minimum and the maximum air temperature, respectively [°C].
213 and undefined components having the same signification and units as in equations (1), (5) and
214 (8). Local calibrations of the empirical coefficient (0.0023), based upon regional wind speed
215 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 $$E_{TU} = 0.013 \left(23.88 R_s + 50\right)\left(\frac{T}{T + 15}\right) \quad (10)$$

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

227 $$E_{PT} = \alpha \frac{\Delta}{\Delta + \gamma} R_n \quad (11)$$

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

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

234 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.

PT method has been used and tested in many studies, and has shown to be reliable in humid climate conditions for evaporation (Xu and Singh, 2000) and reference evapotranspiration (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.

2.4 Sensitivity analysis

2.4.1 The Sobol' method

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

$$V = \sum_i V_i + \sum_{i<j} V_{ij} + \sum_{i<j<m} V_{ijm} + \cdots + V_{1,2,\ldots,k} \tag{13}$$

Where V_i is the model output variance in response to variation of the ith input variable, V_{ij} is the model output variance in response to the simultaneous variation of the ith and the jth model input, and so-on. Then, sensitivity indices are calculated as follows:

$$S_i = \frac{V_i}{V} \tag{14}$$

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

where j and m are the jth and the mth 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 ith 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).

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 minimum and maximum air temperature, minimum and maximum relative humidity, solar radiation and wind speed. Minimum and maximum air temperature and relative humidity, if picked randomly in a data set, will lead to nonsense computations, i.e. having a minimum air

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:

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

and

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

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).

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

2.5 Statistical indices used for satellite sensed solar radiation and empirical E_0 *formulae evaluations*

The reference data used to evaluate satellite-sensed solar radiation were pyranometer records at ground level. For evapotranspiration, *PM* (equation (1)), using pyranometer records, was used as a reference data for empirical formulae evaluation. For each day *i*, the difference between reference and estimated data was calculated as follows :

$$D_i = Est_i\text{-}Ref_i \qquad (20)$$

where D is the difference (or "error") [mm], $Est_{,i}$ is the satellite-sensed solar radiation or the E_0 estimated with an empirical method and Ref_i is the reference data. The units are MJ m^{-2} or mm according to the type of data evaluated.

The accuracy of each method is given by the bias (or mean error):

$$bias = \frac{1}{n}\sum_{i=1}^{n} D_i \qquad (21)$$

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

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

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

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

3 Results and discussion

3.1 Sensitivity analysis of PM *formula*

Sensitivity of E_0 *computation using* PM *method in Southwest area (Oceanic climate)*. The results of monthly sensitivity analyses computed using Southwest area data show clear seasonal trends (figure 3A). During the winter period (from November to February), wind speed is the main source of variation in E_0 values calculated using *PM* method (e.g. 38% of E_0 total variance in January, table 2). Then come relative humidity and air temperature (32% and 17% of E_0 total variance in January, respectively). Solar radiation, daily amplitude of air temperature and daily amplitude of relative humidity have little impact on evapotranspiration process during winter. This trend changes during March and October. From April to September, E_0 is mostly sensitive to solar radiation (up to 74% of E_0 total variance in May, and 70% in July). From May to July, *PM* formula is not very sensitive to RH, U_2, ΔRH and ΔT. Mean daily air temperature participate from 11% to 15% of E_0 variance, from May to September. Total sensitivity indices show that, when added to other variables variations, air temperature has a greater impact on E_0 variability during summer, and wind speed has a greater impact during winter (figure 3B).

Sensitivity of E_0 *computation using* PM *method in Southeast area (Mediterranean climate)*. The sensitivity of *PM* formula to climate input variables in Mediterranean climate conditions is very close to the one observed for Oceanic climate. Wind speed as a major impact on E_0 calculation during winter and solar radiation is clearly the most influent variable during summer (figures 3C and 3D, table 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 Mediterranean and Oceanic climate, at medium latitudes. They are consistent with former 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 present study.

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

3.2 Remotely sensed solar radiation performances

Table 3 shows the annual error statistics of solar radiation and E_0 data calculated with HelioClim-1 data instead of pyranometer radiation data. HelioClim-1 underestimates daily 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 larger during summer period (Figure 5A), the RMSE are 15% (SW) and 10% (SE) of R_S pyranometer value in July, whereas they reach 26% (SW) and 18% (SE) in January, as irradiation is larger during summer.

These errors are consistent with those observed in Northern Europe, during former 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,
387 used to elaborate the HelioClim-1 database, also participate to uncertainties of satellite sensed
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

pyranometer data was used for *PM*, as it was considered here as the "control" method. Data sources used for E_0 calculations are shown in table 4.

In both areas, Hargreaves temperature method (*HT*) gave the highest uncertainties for the annual period (table 5). During summer, formulae using satellite-sensed solar radiation improve considerably E_0 estimation compared to *HT* estimates based solely on local air temperature. Figures 6A and 6B show an obvious seasonal trend of *HT* errors, which is 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.

Evapotranspiration calculated with satellite-sensed solar radiation is mainly underestimated. For both climates, all radiation methods show biases similar to those induced by replacement 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 HelioClim-1 data bias within radiation methods, rather than wrong calibration of empirical coefficients used in these formulae.

In the Southwest area, *PT* data is strongly correlated to *PM* data ($R^2 = 0.938$, table 5). It is also the formula providing the lowest E_0 RMSE during summer and for the whole year (figure 6A). Turc and Hargreaves radiation method performances are almost the same. The performance of *TU* is slightly better than other formulae from September to November. It has been shown in former studies that the Turc method provides good results in humid environment (Jensen et al., 1990 ; Turc, 1961), whereas Hargreaves radiation method has been established from arid or semi-arid climate data analysis (Hargreaves and Allen, 2003). These differences between those two formulae did not emerge from the current study, in 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 method was the least accurate method for SW, when considering summer and annual periods (RMSE = 0.67 mm, R^2=0.894, for the whole year). *HT* overestimated E_0 (a mean error of 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 SW throughout the year might explain these differences (results not shown). *HR* provided the most precise E_0 estimates for the whole year (RMSE= 0.77 mm, i.e. 25% of E_0 mean annual value). The best correlation with *PM* values is provided by *PT*. The Priestley-Taylor formula performed better than every other formula during summer, but showed considerable bias and RMSE during winter. The lowest bias (in absolute value) is provided by *HT*, which showed in contrast high RMSE (0.96 mm, i.e. 31% of the annual mean).

These results suggest that using satellite sensed-solar radiation within empirical formulae improve the accuracy of E_0 estimates during summer and for the whole year, although reference evapotranspiration remains underestimated in most cases.

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

Amongst the numerous studies concerning reference evapotranspiration estimates with limited climatic data, few considered daily time step. When temperature data is the sole climate variable available, Hargreaves temperature method is often used or recommended and 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 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 the type of climate, humid-Oceanic or semi-arid-Mediterranean. Hargreaves temperature method, however, produced annual RMSE of 28% of the annual mean for Oceanic climate 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 radiation methods with HelioClim-1 data during winter.

These results suggest that during summer, using empirical radiation methods with satellite sensed solar radiation from the HelioClim-1 database to estimate E_0 should be preferred to *HT*, when air temperature is the only available record at weather stations.

These observations need to be verified in other climatic conditions, and especially in arid climates, where E_0 estimation is crucial for water management. This could be easily done using HelioClim-1 database, as it provides data for a large surface of the globe, i.e. from Northern Europe to South-Africa.

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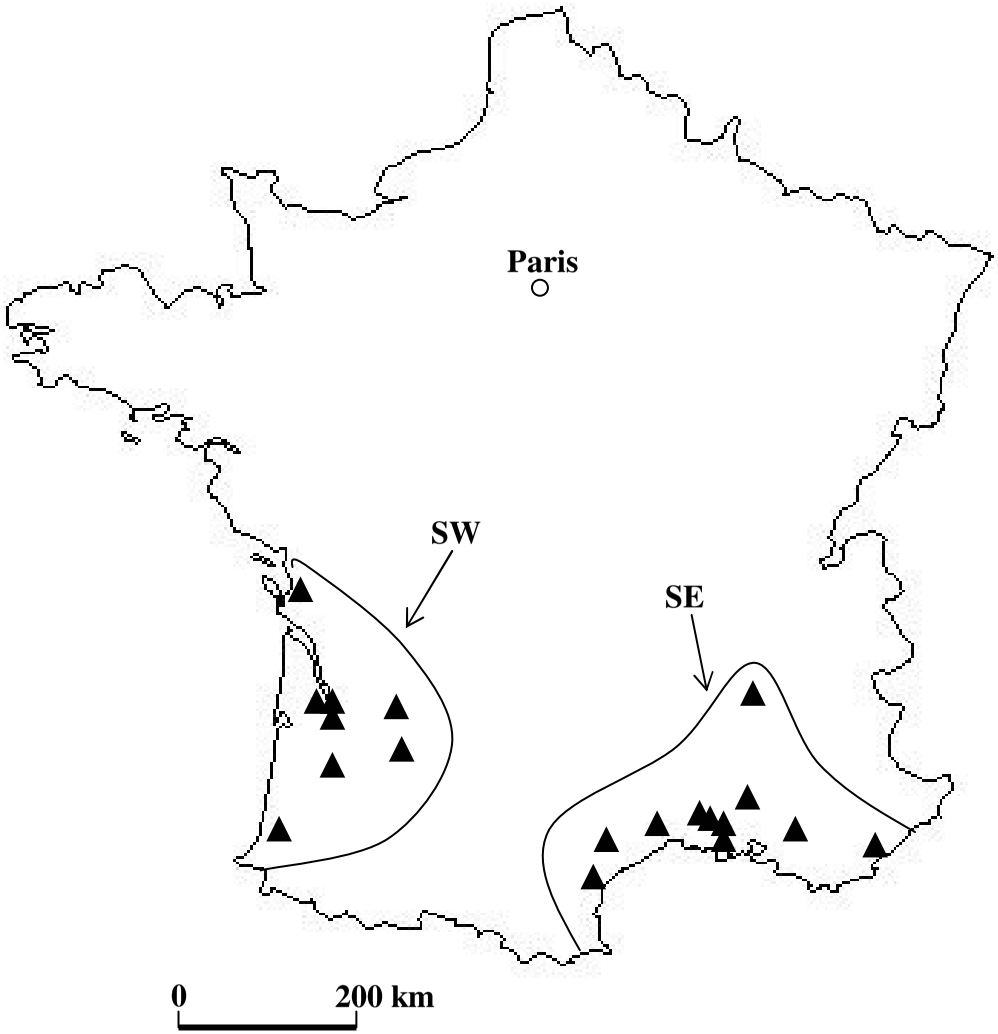
601


Paris
SW
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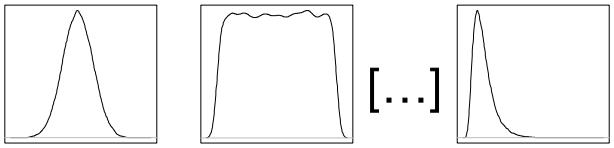
200 km

Input variables *PDF*



x_1 x_2 x_k

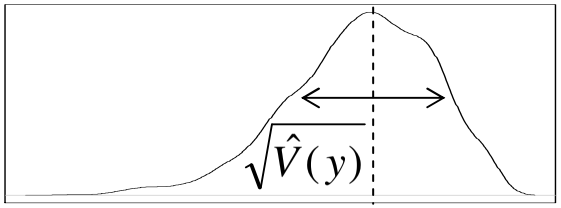
Monte Carlo generations
of two independent random samples
of N repetitions

Input variable $(2^k\text{-}1)$ substitutions

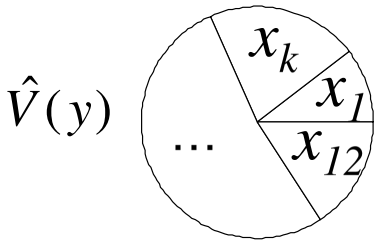
$N(2^k\text{-}1)$ model runs

$y=f(x_1,\ldots,x_i,\ldots,x_k)$

Output empirical *PDF*



Variance partitioning



Sensitivity indexes

S_i , S_{Ti}

Fig 3. SA monthly indices

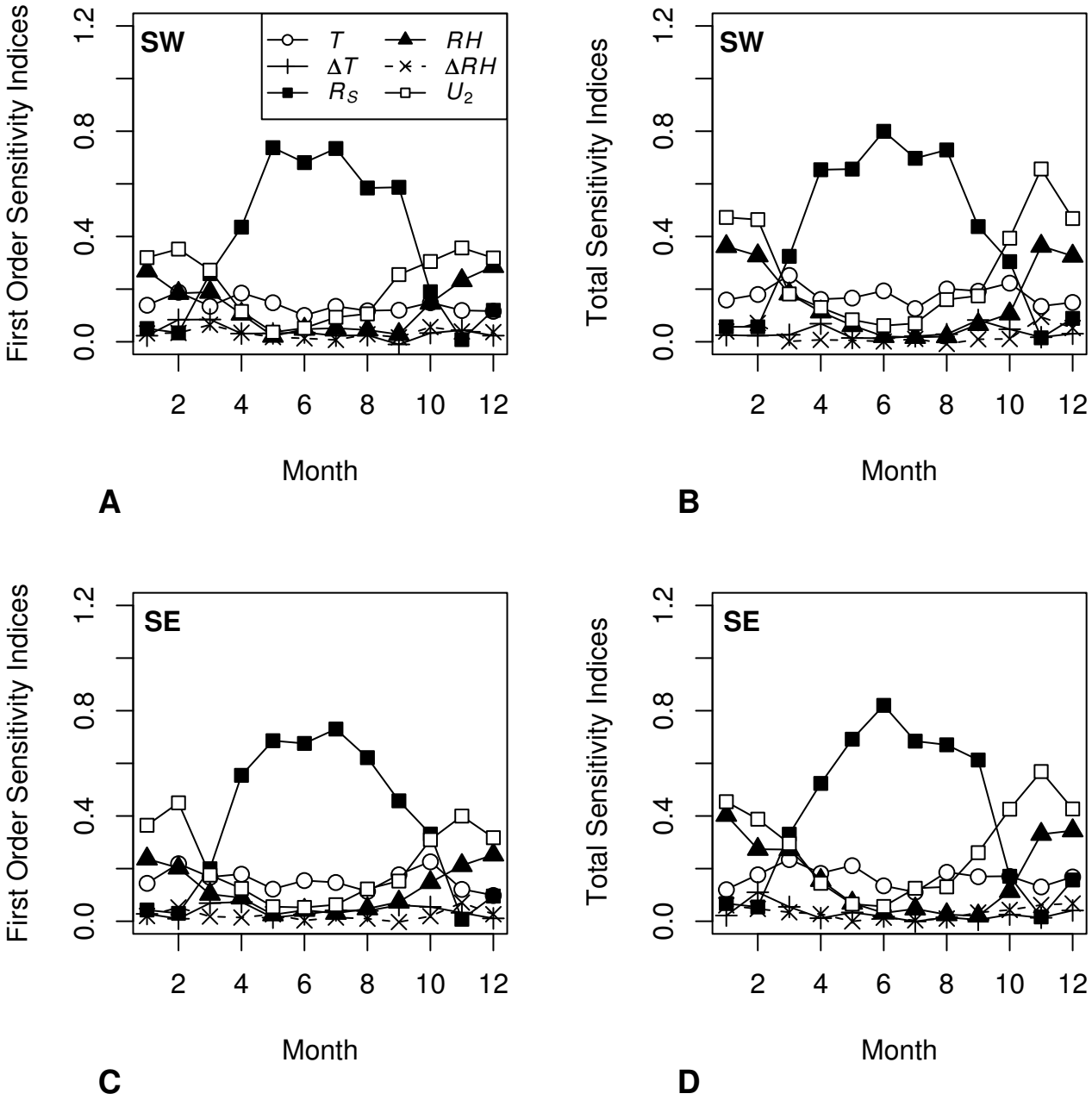


Fig 4. Scatterplots of satellite data vs Pyranometer

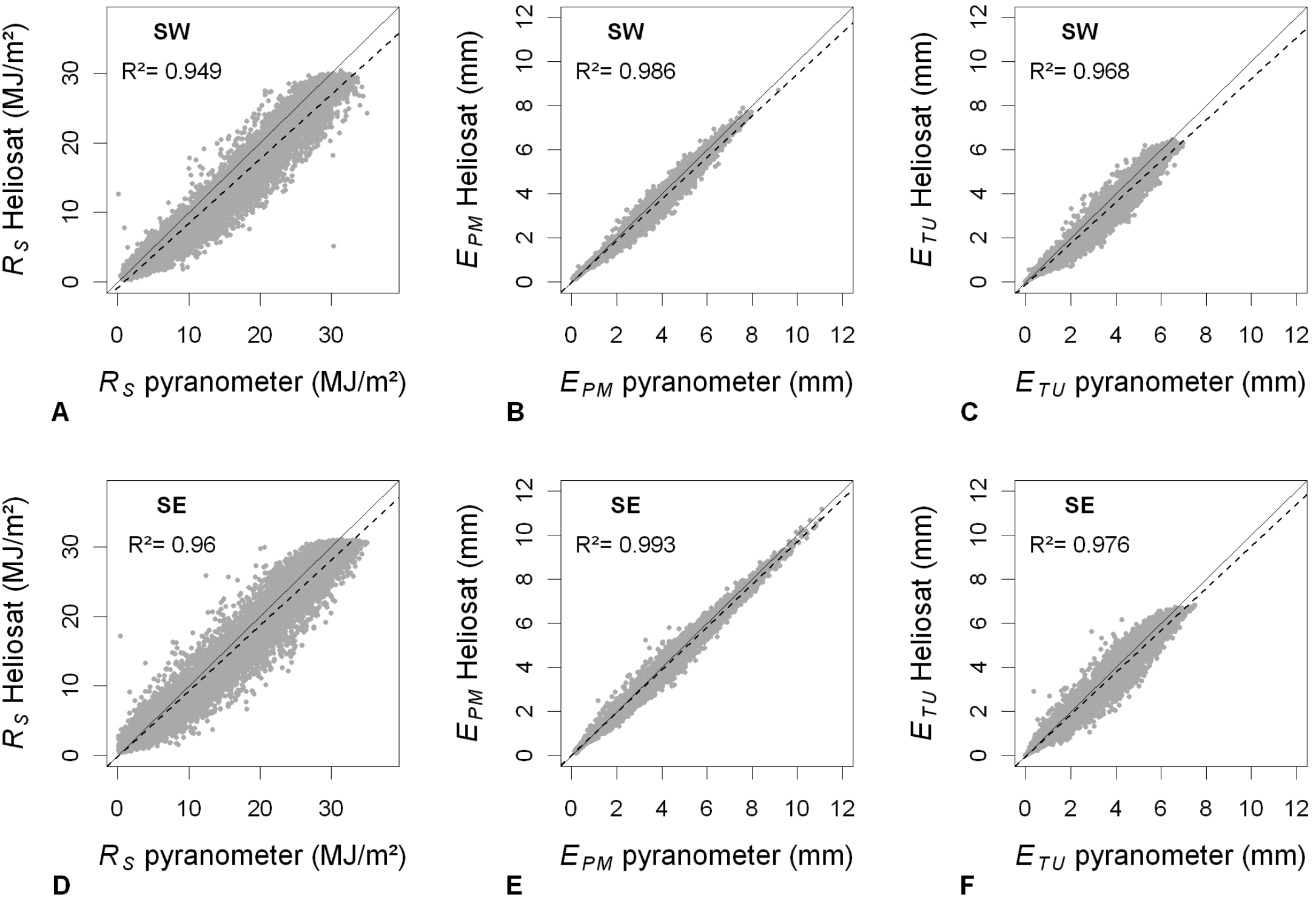


Fig 5. RMSE induced using Helioclim data by month

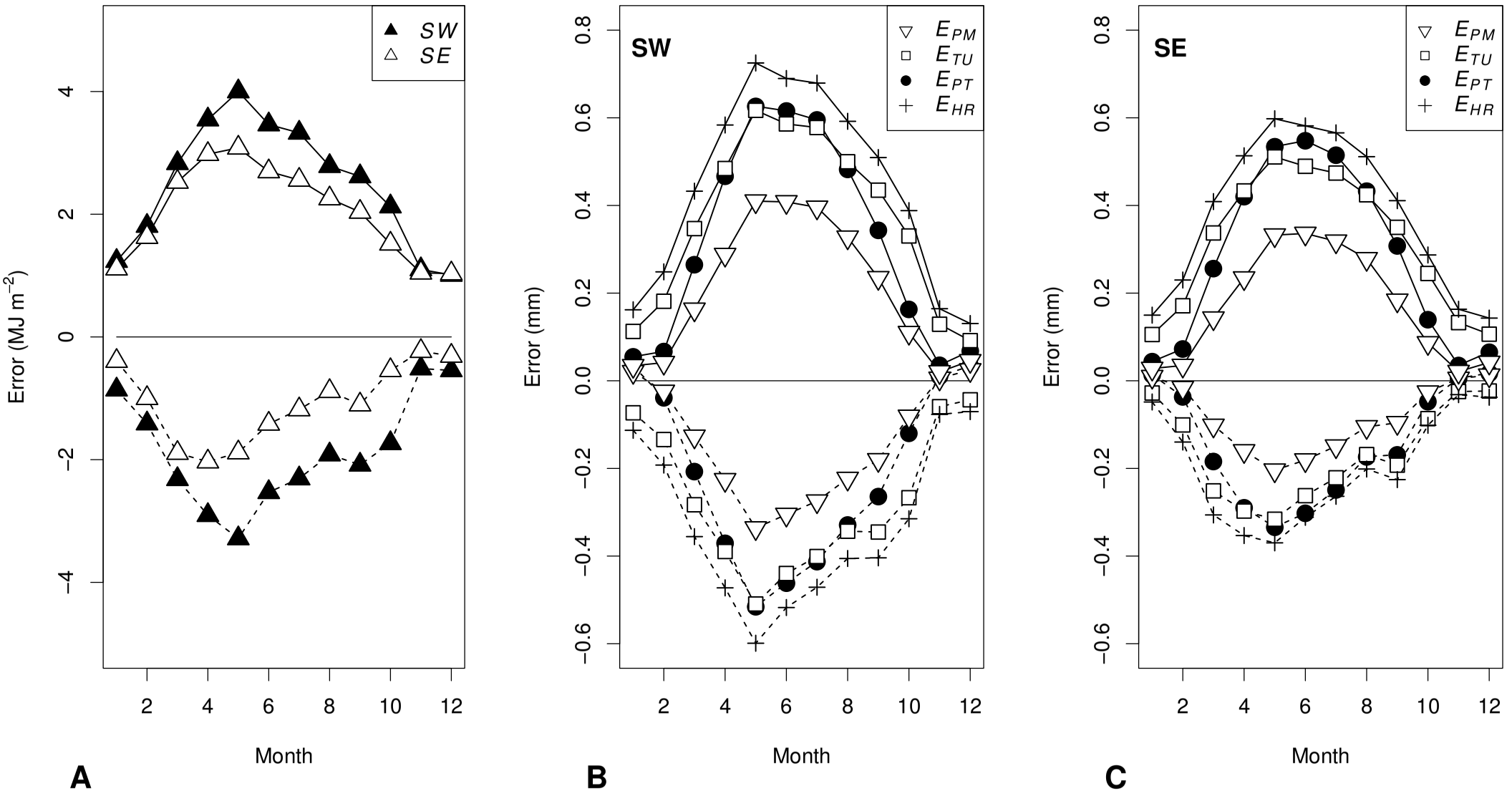
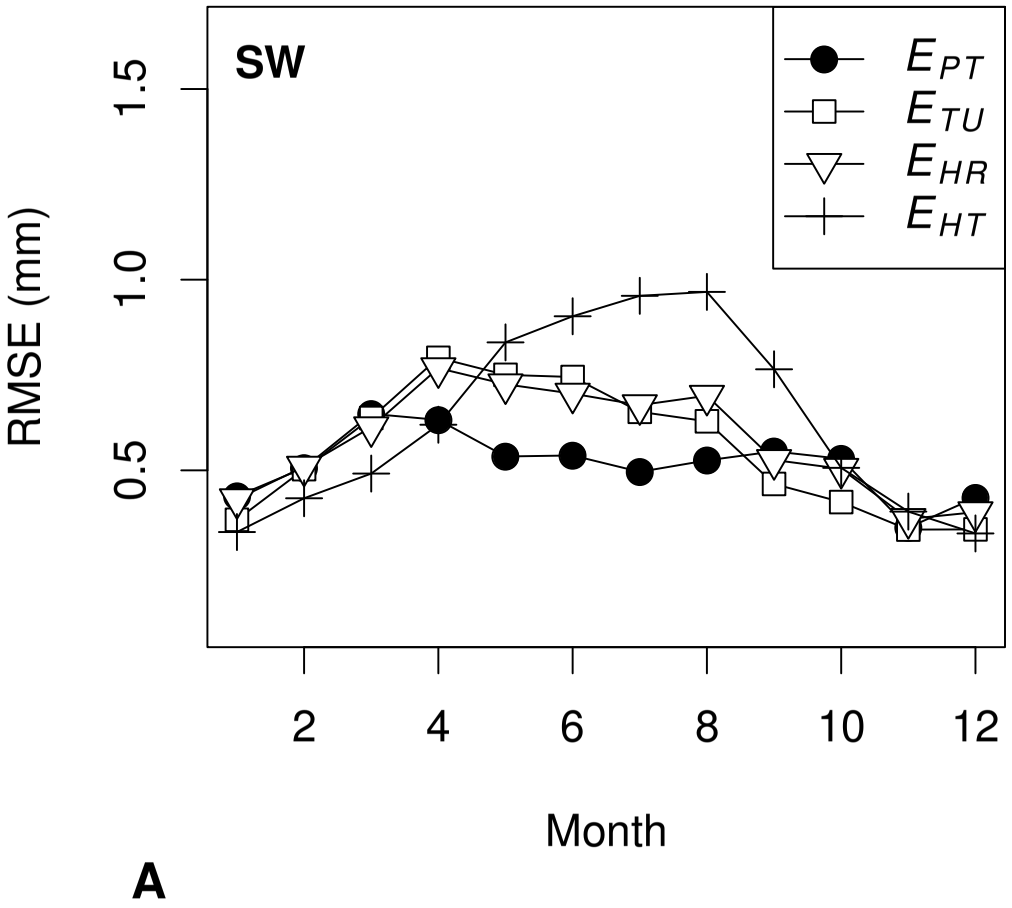
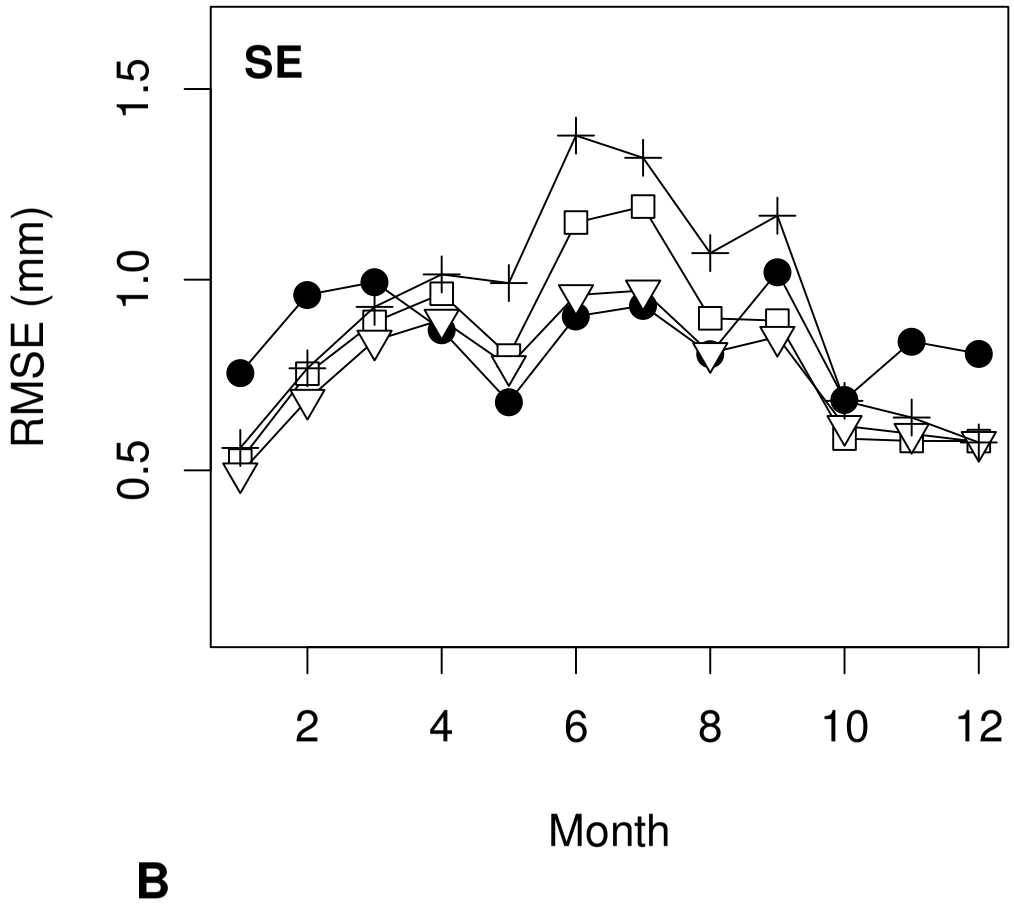


Fig 6. RMSE of empirical formulae by month



A



B

Figure captions

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.

Tables with Caption

Table 1
List of weather stations used in the study

# code	Site	Latitude N (°)	Longitude W (°)	Elevation (m)	Mean E_0 (mm d^{-1})[a]	N[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

[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	T	ΔT	R_s	RH	ΔRH	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**	**N[a]**	**Mean**	**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 reference evapotranspiration calculations in section *3.4*.

Method	Acronym	Temperature	Solar radiation	Relative Humidity	Wind speed
Temperature Method	*HT*	Ground[a]			
Radiation Methods	*PT*	Ground	Sat[b]		
	HR	Ground	Sat		
	TU	Ground	Sat		
Penman-Monteith Method	*PM*	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%)**