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

B. Bois, P. Pieri, C. Van Leeuwen, L. Wald, F. Huard, J.-P. Gaudillere, E. Saur

*UMR Ecophysiologie et Génomique Fonctionnelle de la Vigne, ISVV, Université Bordeaux 2 - INRA, BP 81, 33883 Villenave d’Ornon Cedex, France

Ecologie Nationale d’Ingénieurs des Travaux Agricoles de Bordeaux, 4 cours du Général de Gaulle, 33175 Gradignan Cedex, France

CEP, Ecole de Mines de Paris, BP 207, 84914 Avignon Cedex 9, France

*Corresponding author, Tel.: +33 5 57 35 07 55; Fax: +33 5 57 35 07 59. Email: k-van-leeuwen@enitab.fr

Abstract

Solar radiation is an important climatic variable for assessing reference evapotranspiration (E0), 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 E0 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 E0 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 E0 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 E0 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.

Introduction

Reference evapotranspiration (E0) 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 E0 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-
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 every 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 (Lefèvre 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:

\[
E_{PM} = \frac{0.408\Delta(R_s) + \gamma \frac{900}{(T + 273)} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34u_2)}
\]  

(1)

where \(\Delta\) is the slope of the saturation vapor pressure curve at air temperature [kPa °C⁻¹], \(\gamma\) 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:

\[
R_n = R_m - R_{nl}
\]  

(2)

where \(R_m\) is the net shortwave radiation [MJ m⁻²] given by:

\[
R_m = (1 - a)R_s
\]  

(3)

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

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

(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:

\[
R_{so} = (0.75 + 2\times10^{-5})R_s
\]  

(5)

where \(z\) is the station elevation above sea level [m] and \(R_{so}\) 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:

\[
e_a = e^o(T_{min}) \frac{RH_{max}}{100} + e^o(T_{max}) \frac{RH_{min}}{100}
\]  

(6)

where \(e^o(T_{min})\) and \(e^o(T_{max})\) 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:

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

(7)

where \(e^o(T)\) 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; García 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.
2.3.2 Empirical methods

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

Three radiation methods and one temperature method were compared to $PM$. Hargreaves radiation method (hereafter referred as to $HR$, Hargreaves and Samani, 1982) was 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 following prediction equation was then proposed:

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

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

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

where $T_{min}$ and $T_{max}$ are the minimum and the maximum air temperature, respectively [°C].

The Turc radiation method (hereafter referred to as $TU$; Turc, 1961), initially developed for 10-day periods, provides good results for a humid environment (Jensen et al., 1990). Reference evapotranspiration is calculated as follows:

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

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

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:

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

where $\alpha$ is an empirical and unitless coefficient, set to 1.26, and $R_n$, $\Delta$ and $\gamma$ 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:

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

where $e_a$ and $T_{min}$ have the same signification 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 $\alpha$ are necessary in numerous cases (Xu and Singh, 2002; Bois et al., 2005; Fisher et al., 2005), and a calculation method for $\alpha$ based on surface and aerodynamic resistance parameters was proposed by Pereira (2004). A recalibration of $\alpha$ 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 $\alpha$ set to 1.26, as recalibration of empirical formulae is not the main objective of the present study.

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:

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

(13)

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

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

(14)

$$S_{ij} = \frac{V_{ij} + \sum_{j<m} V_{ijm} + \cdots + V_{1,2,\ldots,k}}{V}$$

(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 $X_i$. $S_{ij}$ 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).

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

\[
T = \frac{T_{\text{min}} + T_{\text{max}}}{2} \quad \text{and} \quad RH = \frac{RH_{\text{min}} + RH_{\text{max}}}{2} \quad (16) ; (17)
\]

\[
\Delta T = T_{\text{max}} - T_{\text{min}} \quad \text{and} \quad \Delta RH = RH_{\text{max}} - RH_{\text{min}} \quad (18) ; (19)
\]

where \(T\) and \(RH\) are the daily average air temperature [°C] and the daily average relative humidity [%], \(\Delta T [°C]\) and \(\Delta RH [%]\) are their daily amplitude, and \(T_{\text{min}}, T_{\text{max}}, RH_{\text{min}}\) and \(RH_{\text{max}}\) having the signification and units as in equations (6) and (9). Once random samples are created, \(T, RH, \Delta T\) and \(\Delta RH\) 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:

\[
D_i = \text{Est}_i - \text{Ref}_i \quad (20)
\]

where \(D\) is the difference (or “error”) [mm], \(\text{Est}_i\) is the satellite-sensed solar radiation or the \(E_0\) estimated with an empirical method and \(\text{Ref}_i\) 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):

\[
bias = \frac{1}{n} \sum_{i=1}^{n} D_i \quad (21)
\]

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

Errors populations were also analyzed by means of coefficient of determination (R²).

### 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, \( U_2 \), \( \Delta RH \) and \( \Delta T \). 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
available, daily satellite sensed solar radiation should be preferred to temperature-based estimations: for both areas, daily irradiation RMSE are 3 to 4 times smaller than those obtained by Hunt et al. (2000) in Ontario (Canada), with empirical formulae based on air temperature. Moreover, HelioClim-1 irradiation may be as precise as pyranometer measurements where weather stations are not steadily maintained or not equipped with accurate devices: uncertainty reported varies from 5 to 25%, according to the class of material and the metrology experts (Llasat and Snyder, 1998; Droogers and Allen, 2002).

There are several sources of uncertainties when comparing satellite data to very local measurements, such as weather station records. This point has been widely discussed by Zelenka et al. (1999). First, it is difficult to compare pixel data, corresponding to a surface, with a discrete measurement, such as pyranometer weather station records. Another category of uncertainties comes from the spatial (1 pixel each 30 kilometer) and temporal (3 hours) resolutions of the initial data set used to create the HelioClim-1 database. In addition, the 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 irradiation data (e.g. the algorithm limits). The uncertainties inherent to the ISCCP-B2 data set could be avoided by applying the Heliosat-2 method to each original Meteosat pixel and for every hour. The HelioClim-2 database was created in that respect but begins only in 2004 and could not be used in this study.

3.3 Propagation of satellite sensed solar radiation errors in E₀ formulae

Replacing pyranometer measurement by Heliosat-2 estimations (i.e. HelioClim-1 data) induces little error for reference evapotranspiration calculation using the Penman-Monteith model (table 3). Estimation errors are higher for middle range E₀ values (figure 4B and 4E). This could be explained by the fact that most of the errors occur for partially cloudy days, due to uncertainties in retrieving daily solar radiation with Heliosat-2 method for this type of weather (Rigollier et al., 2004). In both areas, EPM is slightly underestimated. For SW, biases vary from -0.34 mm to 0.01 mm, according to the season (figure 5B). The annual RMSE value remains low (11% of E₀ mean value). In SE area, EPM bias is negligible (-0.20 mm to 0.01 mm, figure 5C). Relative RMSE in SE is 7% of E₀ mean value, which is lower than in SW. Heliosat-2 method is more successful for clear sky days, which could explain the difference between the two regions, as clear sky situations occur more frequently in SE than SW. Relative errors of EPM calculated with HelioClim-1 are lower during summer (9% for SW and 5% for SE, in July). Again, the better performance of Heliosat-2 method for clear sky days could explain this seasonal trend, as clear sky situations are more numerous during summer than during the other seasons. Yet, higher relative errors could have been expected: sensitivity analyses have shown that solar radiation has the greatest impact on PM model during summer (i.e. when evapotranspiration reaches its maximum) in Oceanic or Mediterranean climates (see section 3.1).

Errors are higher when pyranometer data is replaced by HelioClim-1 data in radiation methods, i.e. HR, TU and PT (figure 4C and 4F, table 3). Biases are mostly negative. Sensitivity to solar radiation errors is higher for radiation methods than for PM because radiation methods do not include advective effects on the evapotranspiration process and thus are mainly governed by radiative transfers. The largest error propagation can be observed for the Hargreaves radiation method (table 3, figures 5B and 5C).

3.4 Empirical formulae performance

Daily E₀ values of 4 empirical methods were compared to reference evapotranspiration 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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SoDa web site: http://www.soda-is.org
Monte Carlo generations of two independent random samples of $N$ repetitions

Input variable $(2^k-1)$ substitutions

$N(2^k-1)$ model runs

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

Sensitivity indexes $S_i, S_{Ti}$

Variance partitioning

Output empirical PDF

$\sqrt{\hat{V}(y)}$

$\bar{y}$
Fig 3. SA monthly indices
Fig 4. Scatterplots of satellite data vs Pyranometer

A. \( R_s \) pyranometer (MJ/m²)
\[
R^2 = 0.949
\]

B. \( E_{PM} \) pyranometer (mm)
\[
R^2 = 0.986
\]

C. \( E_{TU} \) pyranometer (mm)
\[
R^2 = 0.968
\]

D. \( R_s \) pyranometer (MJ/m²)
\[
R^2 = 0.993
\]

E. \( E_{PM} \) pyranometer (mm)
\[
R^2 = 0.976
\]

F. \( E_{TU} \) pyranometer (mm)
\[
R^2 = 0.966
\]
Fig 5. RMSE induced using Helioclim data by month.
Fig 6. RMSE of empirical formulae by month
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.
Table 1
List of weather stations used in the study

<table>
<thead>
<tr>
<th># code</th>
<th>Site</th>
<th>Latitude N (°)</th>
<th>Longitude W (°)</th>
<th>Elevation (m)</th>
<th>Mean $E_0$ (mm d$^{-1}$)</th>
<th>N$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>South West</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Bergerac</td>
<td>44.855</td>
<td>-0.521</td>
<td>33</td>
<td>2.34</td>
<td>1783</td>
</tr>
<tr>
<td>2</td>
<td>Bourran</td>
<td>44.334</td>
<td>-0.413</td>
<td>60</td>
<td>2.43</td>
<td>1606</td>
</tr>
<tr>
<td>3</td>
<td>Cadaujac</td>
<td>44.753</td>
<td>0.554</td>
<td>20</td>
<td>2.36</td>
<td>1827</td>
</tr>
<tr>
<td>4</td>
<td>Latresne</td>
<td>44.780</td>
<td>0.478</td>
<td>63</td>
<td>2.54</td>
<td>1826</td>
</tr>
<tr>
<td>5</td>
<td>Luxey</td>
<td>44.226</td>
<td>0.491</td>
<td>101</td>
<td>2.30</td>
<td>1818</td>
</tr>
<tr>
<td>6</td>
<td>Saint Laurent-de-la-Pree</td>
<td>45.990</td>
<td>1.033</td>
<td>3</td>
<td>2.46</td>
<td>1827</td>
</tr>
<tr>
<td>7</td>
<td>Saint Martin de Hinx</td>
<td>43.576</td>
<td>1.269</td>
<td>64</td>
<td>2.29</td>
<td>1826</td>
</tr>
<tr>
<td>8</td>
<td>Villeneave d’Ornon</td>
<td>44.789</td>
<td>0.578</td>
<td>25</td>
<td>2.55</td>
<td>1827</td>
</tr>
<tr>
<td>South East</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Avignon</td>
<td>43.916</td>
<td>-4.876</td>
<td>24</td>
<td>3.27</td>
<td>1827</td>
</tr>
<tr>
<td>2</td>
<td>Bellegarde</td>
<td>43.781</td>
<td>-4.477</td>
<td>61</td>
<td>3.15</td>
<td>1762</td>
</tr>
<tr>
<td>3</td>
<td>Fourques</td>
<td>43.692</td>
<td>-4.595</td>
<td>3</td>
<td>3.41</td>
<td>1826</td>
</tr>
<tr>
<td>4</td>
<td>Frejus</td>
<td>43.434</td>
<td>-6.717</td>
<td>3</td>
<td>3.13</td>
<td>1827</td>
</tr>
<tr>
<td>5</td>
<td>Gruissan</td>
<td>43.137</td>
<td>-3.121</td>
<td>40</td>
<td>3.04</td>
<td>1827</td>
</tr>
<tr>
<td>6</td>
<td>Les-Saintes-Maries-de-la-Mer</td>
<td>43.580</td>
<td>-4.499</td>
<td>1</td>
<td>3.23</td>
<td>1827</td>
</tr>
<tr>
<td>7</td>
<td>Montpellier</td>
<td>43.647</td>
<td>-3.874</td>
<td>50</td>
<td>2.60</td>
<td>1613</td>
</tr>
<tr>
<td>8</td>
<td>Roujan</td>
<td>43.491</td>
<td>-3.321</td>
<td>78</td>
<td>2.45</td>
<td>774</td>
</tr>
<tr>
<td>9</td>
<td>Saint-Marcel-les-Valence</td>
<td>44.977</td>
<td>-4.930</td>
<td>190</td>
<td>2.97</td>
<td>1827</td>
</tr>
<tr>
<td>10</td>
<td>Saint-Gilles</td>
<td>43.714</td>
<td>-4.412</td>
<td>72</td>
<td>3.15</td>
<td>1775</td>
</tr>
<tr>
<td>11</td>
<td>Salon de Provence</td>
<td>43.646</td>
<td>-5.014</td>
<td>68</td>
<td>3.27</td>
<td>1604</td>
</tr>
</tbody>
</table>

$E_0$ 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 part of total $E_0$ variance explained by each input variable. Figures in bold correspond to the highest sensitivity index of each month.

<table>
<thead>
<tr>
<th>Month</th>
<th>$T$</th>
<th>$\Delta T$</th>
<th>$R_s$</th>
<th>$RH$</th>
<th>$\Delta RH$</th>
<th>$U_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>South-West</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>January</td>
<td>0.14 (17%)</td>
<td>0.02 (3%)</td>
<td>0.05 (6%)</td>
<td>0.27 (32%)</td>
<td>0.03 (4%)</td>
<td><strong>0.32 (38%)</strong></td>
</tr>
<tr>
<td>April</td>
<td>0.19 (20%)</td>
<td>0.03 (3%)</td>
<td><strong>0.44 (48%)</strong></td>
<td>0.11 (12%)</td>
<td>0.03 (4%)</td>
<td>0.12 (13%)</td>
</tr>
<tr>
<td>July</td>
<td>0.13 (13%)</td>
<td>0.02 (2%)</td>
<td><strong>0.73 (70%)</strong></td>
<td>0.05 (5%)</td>
<td>0.01 (1%)</td>
<td>0.09 (9%)</td>
</tr>
<tr>
<td>South-East</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>January</td>
<td>0.14 (17%)</td>
<td>0.03 (3%)</td>
<td>0.04 (5%)</td>
<td>0.24 (28%)</td>
<td>0.02 (2%)</td>
<td><strong>0.36 (44%)</strong></td>
</tr>
<tr>
<td>April</td>
<td>0.18 (17%)</td>
<td>0.07 (7%)</td>
<td><strong>0.55 (54%)</strong></td>
<td>0.09 (9%)</td>
<td>0.01 (1%)</td>
<td>0.12 (12%)</td>
</tr>
<tr>
<td>July</td>
<td>0.15 (14%)</td>
<td>0.04 (4%)</td>
<td><strong>0.73 (71%)</strong></td>
<td>0.03 (3%)</td>
<td>0.01 (1%)</td>
<td>0.06 (6%)</td>
</tr>
</tbody>
</table>
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 | | Mean | Bias | RMSE | N | | | | | |
| $R_S$ (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 | | | | |
| $E_{RT}$ (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.

<table>
<thead>
<tr>
<th>Method</th>
<th>Acronym</th>
<th>Temperature</th>
<th>Solar radiation</th>
<th>Relative Humidity</th>
<th>Wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Method</td>
<td>HT</td>
<td>Grounda</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiation Methods</td>
<td>PT</td>
<td>Ground</td>
<td>Satb</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>HR</td>
<td>Ground</td>
<td>Sat</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TU</td>
<td>Ground</td>
<td>Sat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Penman-Monteith Method</td>
<td>PM</td>
<td>Ground</td>
<td>Ground</td>
<td>Ground</td>
<td>Ground</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th></th>
<th>Southwest (Oceanic climate)</th>
<th></th>
<th>Southeast (Mediterranean climate)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Method</td>
<td>$R^2$</td>
<td>Bias (mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>January</td>
<td>HT</td>
<td>0.150</td>
<td>0.08 (11%)</td>
</tr>
<tr>
<td></td>
<td>TU</td>
<td>0.205</td>
<td>-0.15 (-22%)</td>
</tr>
<tr>
<td></td>
<td>PT</td>
<td>0.112</td>
<td>-0.29 (-42%)</td>
</tr>
<tr>
<td></td>
<td>HR</td>
<td>0.053</td>
<td>-0.16 (-23%)</td>
</tr>
<tr>
<td>April</td>
<td>HT</td>
<td>0.668</td>
<td>0.17 (6%)</td>
</tr>
<tr>
<td></td>
<td>TU</td>
<td>0.830</td>
<td>-0.66 (-23%)</td>
</tr>
<tr>
<td></td>
<td>PT</td>
<td>0.816</td>
<td>-0.46 (-16%)</td>
</tr>
<tr>
<td></td>
<td>HR</td>
<td>0.825</td>
<td>-0.57 (-20%)</td>
</tr>
<tr>
<td>July</td>
<td>HT</td>
<td>0.624</td>
<td>0.56 (13%)</td>
</tr>
<tr>
<td></td>
<td>TU</td>
<td>0.866</td>
<td>-0.42 (-10%)</td>
</tr>
<tr>
<td></td>
<td>PT</td>
<td>0.868</td>
<td>-0.05 (-1%)</td>
</tr>
<tr>
<td></td>
<td>HR</td>
<td>0.869</td>
<td>-0.13 (-3%)</td>
</tr>
<tr>
<td>Year</td>
<td>HT</td>
<td>0.894</td>
<td>0.32 (-13%)</td>
</tr>
<tr>
<td></td>
<td>TU</td>
<td>0.914</td>
<td>-0.30 (-12%)</td>
</tr>
<tr>
<td></td>
<td>PT</td>
<td>0.938</td>
<td>-0.29 (-12%)</td>
</tr>
<tr>
<td></td>
<td>HR</td>
<td>0.906</td>
<td>-0.21 (-9%)</td>
</tr>
</tbody>
</table>