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Effect of the sampling frequency of meteorological variables on the estimation of the reference evapotranspiration

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Abstract

In this paper, we quantify the effect of the temporal sampling frequency of commonly measured climatic variables on the estimation of the reference evapotranspiration. Using a set of data sampled on an intensive basis (i.e. one measurement each minute) during a period of 6 months, we first analyse the effect of the temporal sampling frequency on the estimation of the daily means of the shortwave solar radiation, the wind speed, the dry and wet temperatures, and on the estimation of the daily maximum and minimum dry temperature. Subsequently, a sensitivity analysis of a reference evapotranspiration model is carried out to determine the most sensible meteorological variables. The sensitivity coefficients were then combined with the errors due to the temporal sampling to quantify for each variable the impact of the sampling frequency on the estimation of daily ETo. The results showed that the solar radiation and the wind speed are the most sensitive to bias induced by inadequate temporal sampling frequency. Daily errors of 5.1 MJ m^{-2} d^{-1} or 41.05% for the solar radiation, and 0.45 m s^{-1} or 18% for the wind speed may be obtained if these variables are inappropriately sampled. Moreover, the impact of inappropriate temporal sampling on the estimation of ETo can be significant with respective maximum bias of 0.62 mm d^{-1} due to inappropriate solar radiation sampling and 0.36 mm d^{-1} due to inappropriate maximum temperature sampling. A non-intensive hourly temporal sampling schedule of all meteorological variables may induce errors on the daily ETo so high as −0.76 mm d^{-1} or −27%. Fortunately, the errors generated on the estimation of the long-term integrated evapotranspiration are clearly lower (3.8%). Our study clearly demonstrates the importance of scheduling appropriately the sampling frequency of climatic variables to correctly estimate land surfaces fluxes as well in fundamental as in more practically oriented research studies.

Keywords: Evapotranspiration; Meteorological variable; Temporal sampling; Sensitivity analysis

1. Introduction

The transfer of water vapour through the process of evapotranspiration (ET) is a key process within the Earth's surface water and energy balance. An appropriate quantitative estimation of the ET flux across the soil–crop continuum is further a prerequisite for irrigation scheduling, crop yield forecasting, hydrological and global circulation modelling. Considerable progress has recently been made in our understanding of the physical and the biological processes that determine evaporation rate. However, the quantitative estimation of ET, especially at the larger regional scale remains a difficult task (Itier and Brunet, 1996). Empirical (e.g. Doorenbos and Pruitt, 1977) as well as more physically based approaches (e.g.

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Shuttleworth and Wallace, 1985) are currently adopted for the estimation of ET.

The two-step or the so-called "Kc.ETo" approach (Doorenbos and Pruitt, 1977) was presented by the FAO as a reference methodology for calculating crop water requirements and is now largely used, mainly for practical applications in irrigation scheduling. This approach calculates a reference ET for a standard surface, referred to as ETo, using reference parameters and agro-meteorological data. Then it applies appropriate empirical crop coefficients such as presented by Doorenbos and Pruitt (1977) and Wright (1981, 1982) for obtaining real crop ET. This versatile approach is widely adopted because it exploits the data available in agro-meteorological databases. However, given the recent advances in assessing crop water use, many shortcomings have been identified with the use of the original Doorenbos and Pruitt approach (Batchelor, 1984; Allen et al., 1989; Jensen et al., 1990). To mitigate to this problem, Allen et al. (1994a,b) presented an update to the original, which is now adopted by FAO as the new reference methodology (Allen et al., 1998). The updated reference methodology is still based on the "Kc.ETo" principle but uses an equation based on the Penman–Monteith model with adopted parameterization for the surface and aerodynamic resistances for obtaining reference ET from agro-meteorological data. Mainly used on a 24-h time scale, this methodology needs the estimation of maximum and minimum daily values for dry temperature, and the mean daily values for the other climatic variables.

Daily climatic variables available in agro-meteorological databases are subject to different sources of error. A first source of error is the error due to the properties of the sensor, to the instrument settings or to the instrument drift (Beven, 1979; Meyer et al., 1989; Ritchie et al., 1996). A second source of error is the one due to the estimation of climatic variables from other, less accurate, available meteorological data. This was illustrated for instance by Thompson (1976) and Lindsey and Farnsworth (1997) for the estimation of solar radiation from percent sunshine hours or percent sky cover. A third source of error which influences the estimation of daily mean, and which is surprisingly rarely cited in the literature, is related to the temporal sampling frequency of the climatic data. In fact, the temporal sampling frequency which is adopted depends very much on the aim of the study. Within the framework of fundamental research studies, the adopted temporal sampling frequency is often very high with, for instance, samples collected on a time step basis of one or a few seconds, and aggregated as a mean recorded of, for example, every 10 min or every hour (Lascano and Van Bavel, 1986). Within the framework of agronomical experiments for instance, the temporal sampling frequency is often less intensive, sometimes reduced to 30 min, hourly or even daily time steps (Al-Ghobari, 2000) based on the available data logging equipment. However, climatic variables are often prone to large fluctuations at the smaller time scale. If small scale temporal variability of climatic variables is likely to be high, then the adopted temporal sampling frequency can be suspected to play an important role in the estimation error of the daily mean of the different climatic data. In addition, the dependency of temporal sampling frequency on the estimation error will be different for each different climatic variable. In order to determine this impact for each climatic variables, two different approaches can be used. The first approach compares the ETo calculated with the climatic variables intensively sampled, except the variable of interest, with the "true" ETo determined with all the climatic variables intensively sampled. The second approach that is used in our study combines a sensitivity analysis of the ET model with the error of the studied variable due to the temporal sampling frequency. Various sensitivity analyses on ET models were previously carried out (McCuen, 1974; Saxton, 1975; Coleman and Decoursey, 1976; Beven, 1979; Rana and Katerji, 1998; Qui et al., 1998). Nevertheless, these sensitivity analyses are generally restricted to the study of rarely measured climatic variables, such as the net radiation, and most of them are carried on an hourly step time basis. Further, in order to quantify the impact of the error on the climatic variable on the estimation of the ET, the sensitivity analysis combines the relative sensitivity coefficients with an identical error for all of the climatic variables (Qui et al., 1998). Finally, none of the previous sensitivity analyses were carried out for the new reference methodology proposed by the FAO (Allen et al., 1998).

For mitigating some of the above-mentioned problems we present, in this paper, a propagation

Table 1
Measured and estimated climatic variables

Measured variables	Estimated variables
Shortwave radiation (R_s)	R_n
Maximum temperature ($T_{max.}$)	Δ, R_n, e_a
Minimum temperature (T_{min})	Δ, R_n, e_a
Dry temperature (T_d)	Δ, G, γ e_d
Wet temperature (T_w)	e_d
Wind speed (U)	U

analysis of the temporal sampling error on the estimate of the reference ET. The principle objectives of the study can be summarized as follows:

(1) To determine the effect of the temporal sampling on the estimation of the daily mean of the respective climatic variable. The investigated climatic variables are those available in reference agro-meteorological databases and those used in the FAO reference ET method;
(2) To analyse the sensitivity of the Penman–Monteith ET model to climatic factors and to calculate daily sensitivity coefficients for the climatic data of interest;
(3) To quantify, combining (1) and (2), the ETo error due to each climatic variable;
(4) To determine with the daily mean values calculated in (1) the effect of the temporal sampling frequency on the estimation of daily and cumulative reference ET.

2. Materials and methods

2.1. Experimental site and instrumentation

The study was conducted at the experimental site of Louvain-la-Neuve (50°N, 4°E, 120 m.s.l.) in Belgium, situated within a moderate humid climatic zone. Analysis was done for the data collected with an automatic weather station. The weather station is situated within an area consisting of a 1000 m^2 perennial ryegrass (*Lolium perenne* L.) regularly clipped to maintain a constant height of 10 cm. The meteorological station is equipped with four different sensors used in this study. The shortwave radiation was measured with a standard pyranometer (CM3, Kipp & zonen, TM, The Netherlands) and the wind speed at a 2 m height with a classical cup-anemometer (MDL33, TM, GME entreprise, Belgium). Dry and wet temperatures were also measured at a 2 m height with negative coefficient thermoresistances. All climatic variables were measured and recorded at 1 min interval in a data logger (EasyLog 3000, GME entreprise, TM, Belgium). All climatic variables are instantaneous values except for the wind speed where the recorded values are the means for the previous minute. The adopted experimental data were those collected from 6th of May through the 30th of October 1999.

2.2. Data analysis

According to the methodology recommended by FAO (Allen et al., 1994a,b), the estimation of reference ET, defined as ETo FAO Penman–Monteith, can be written for 24-h calculations as

$$\mathrm{ETo} = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T + 273}\right)U_2(e_a - e_d)}{\Delta + \gamma(1 + 0.34U_2)} \tag{1}$$

with ETo the reference crop ET (mm d^{-1}); Δ the slope of the vapour pressure curve (kPa °C^{-1}); R_n the net radiation (MJ m^{-2} d^{-1}); G the soil heat flux (MJ m^{-2} d^{-1}); γ the psychrometric constant (kPa °C^{-1}); U_2 the wind speed measured at 2 m height (m s^{-1}); e_a and e_d, respectively, the saturated and the actual vapour pressure (kPa). All these variables were calculated with the recommended procedures given by Allen et al. (1994b). In particular, for R_n and G, equations (1.53) and (1.56) in Allen et al. (1994b) were used. The estimation of the reference ETo is driven by the measured climatic variables. The selection of the different climatic variables used in our study (Table 1) was mainly dictated by the kind of measurements usually made in “non-research” meteorological stations. Indeed, net solar radiation and soil heat flux are not frequently measured in usual meteorological networks (Lindsey and Farnsworth, 1997).

The first step of our study focuses on the estimation of daily mean values for the different climatic variables, calculated for the different sampling intervals. As the minimum step time is one minute, a daily dataset of 1440 values is available for each climatic variable. Different temporal sampling intervals (12) were then selected: 1, 2, 3, 4, 5, 6, 10, 12, 15, 20, 30 and 60 min. Thus, for each day 12 different daily means are calculated, with a minimum of 24 values and with a maximum of 1440 values. The maximum step time (60 min) corresponds to the intervals usually adopted in autonomous meteorological stations. The minimum step time (1 min) is conditioned by the minimum time resolution of the data logger. The daily means, or the minimum and maximum values for dry temperature, calculated using the minimal step time are considered as reference values and are written $\langle \mathrm{var} \rangle_{\mathrm{true}}$ or $\langle \mathrm{var} \rangle_{1\ \mathrm{min}}$. The others daily means are noted $\langle \mathrm{var} \rangle_i$ with i referring to the different sampling intervals. The error due to the temporal sampling can now be characterized by its relative error, calculated as:

$$\epsilon_{\mathrm{rel}} = \frac{\langle \mathrm{var} \rangle_i - \langle \mathrm{var} \rangle_{\mathrm{true}}}{\langle \mathrm{var} \rangle_{\mathrm{true}}} 100(\%) \tag{2}$$

and its absolute error, formulated as:

$$\epsilon_{\mathrm{abs}} = \langle \mathrm{var} \rangle_i - \langle \mathrm{var} \rangle_{\mathrm{true}} \tag{3}$$

The second step of the study consists of a sensitivity analysis of the FAO Penman–Monteith model as described by Eq. (1), using a methodology presented by McCuen (1974), Beven (1979), Rana and Katerji (1998) and Qui et al. (1998) and summarized below.

The reference ET determined by Eq. (1) needs different climatic variables as input, any of which is subject to error. In a more general form, we can express Eq. (1) as:

$$\mathrm{ETo} = f(v_1, v_2, \ldots, v_n) \tag{4}$$

with $v_1, v_2, \ldots, v_n$, the n considered climatic variables. If Δv_i is a perturbation of the climatic variable i, then the perturbation of ETo as a result of the perturbation on the climatic variables can be quantified by:

$$\Delta\mathrm{ETo} = f(v_1 + \Delta v_1, v_2 + \Delta v_2, \ldots, v_n + \Delta v_n) \tag{5}$$

Expanding Eq. (5) in a Taylor series and ignoring second order terms, we can write:

$$\Delta\mathrm{ETo} = \frac{\partial \mathrm{ETo}}{\partial v_1}\Delta v_1 + \frac{\partial \mathrm{ETo}}{\partial v_2}\Delta v_2 + \cdots + \frac{\partial \mathrm{ETo}}{\partial v_n}\Delta v_n \tag{6}$$

This equation has an assumption built into it that the perturbations on the climatic variables are independent of each other. Although there is some correlation of the climatic variable, no correlation was found between the perturbations of the climatic variables. This can be explained by the fact that the perturbations in Eq. (6) have no physical meaning but are only determined by the temporal sampling frequency of the data logger. In Eq. (6), the derivatives $(\partial \mathrm{ETo})/(\partial v_i)$ define the sensitivity of the estimate to each climatic variables v_i. However, these sensitivity coefficients are themselves sensitive to the relative magnitudes of ETo and of v_i. Following McCuen (1974), a non-dimensional relative sensitivity coefficient may be defined as:

$$S_i = \frac{\partial \mathrm{ETo}}{\partial v_i}\frac{v_i}{\mathrm{ETo}} \tag{7}$$

The sensitivity coefficient described by Eq. (7) represents the fraction of change in v_i transmitted to the change of ETo, i.e. an S_i value of 0.1 would suggest that a 10% increase in v_i may be expected to increase ETo by 1%. Negative coefficients would indicate that a decrease in ETo would result from an increase of v_i. On the other hand, Eq. (7) remains sensitive to the absolute values of ETo and v_i. In some cases, when either ETo or v_i tend to zero independently, the relative sensitivity coefficients described by Eq. (7) may not be a good indication of the significance of v_i (Beven, 1979). In the present study, sensitivity coefficients were determined on a daily basis for the measured climatic variables summarized in Table 1. The partial derivatives, needed for the determination of the sensitivity coefficients, were calculated analytically by means of MATHCAD™ and programmed in a MATLAB™ procedure. Given the size of the analytical expressions, these are not described in this paper but can be obtained from the authors upon request.

The third step of the study combines the two previously described steps. The error caused by each variable on the estimation of ETo can be quantified by approximating the derivatives by finite differences and rewriting Eq. (7) as following:

$$\Delta\mathrm{ETo} = S_i \frac{\Delta v_i}{v_i}\mathrm{ETo} \tag{8}$$

Sensitivity analyses of the ET equation carried out in others studies were generally limited to the

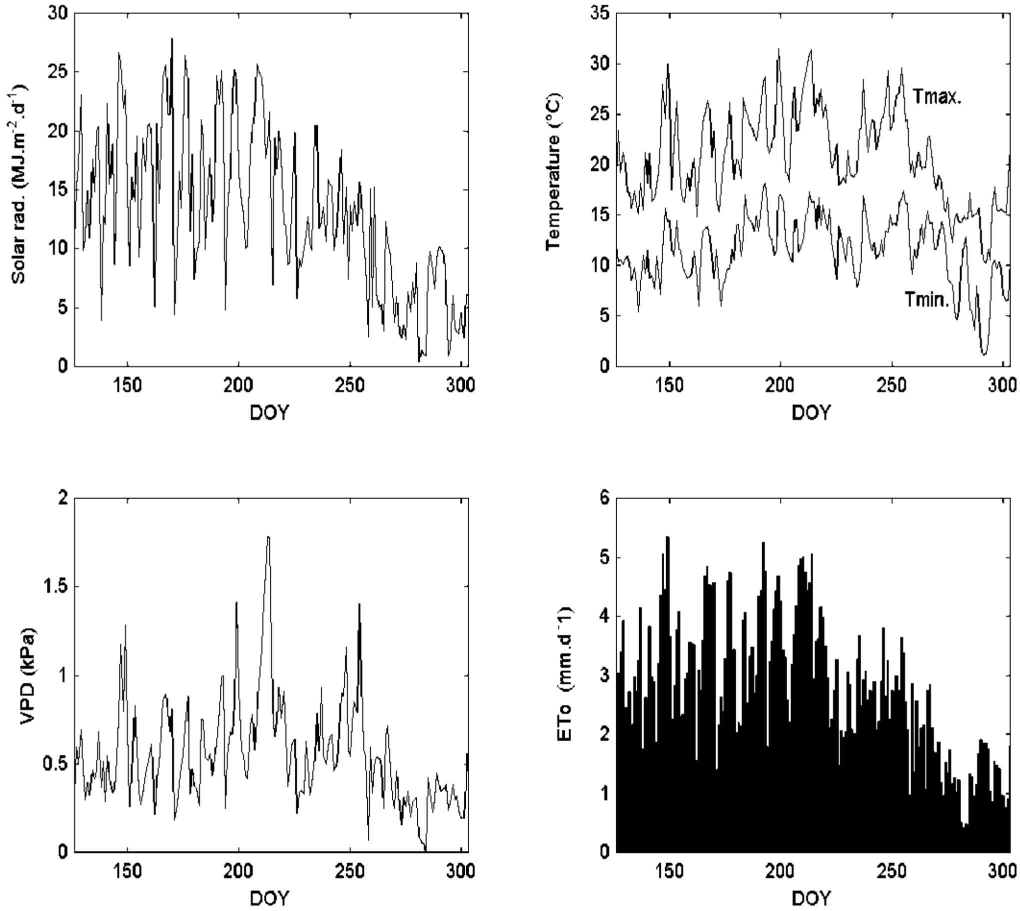

Fig. 1. Seasonal evolution of the daily climatic variables and the ETo as calculated with the most intensive temporal sampling frequency.

determination of the sensitivity coefficients. However, some of them, for instance Qui et al. (1998), estimated ΔETo using Eq. (8) and adopted an identical Δv_i for each of the climatic variables. In our study, we also use Eq. (8) considering, for each climatic variable and for each day of the study period, the sensitivity coefficient determined by Eq. (7), the daily mean error due to the temporal sampling (Δv_i) and the true value of ETo ($\langle \mathrm{ETo} \rangle_{1\ \mathrm{min}}$) calculated using all the weather data.

In a final step we quantify the effect of the temporal sampling on the ETo estimation. For this purpose, we simply use the different daily means determined with different temporal sampling. The calculated value $\langle \mathrm{ETo} \rangle_i$ is compared with the true value $\langle \mathrm{ETo} \rangle_{1\ \mathrm{min}}$. The comparisons are made for daily and for cumulated values.

3. Results and discussion

3.1. Weather data

The time course of the observed climatic data and calculated reference ET is given in Fig. 1. During the experimental study (DOY 126 to DOY 303), the daily mean shortwave solar radiation was 13.2 MJ m^{-2} d^{-1}. This value is in agreement with the commonly observed values for this period (Malcorps, 1999). The maximum observed value was 27.83 MJ m^{-2} d^{-1} (DOY 170) and the minimum

Table 2
The absolute value of the maximum daily relative error, the mean and the standard deviation of the relative daily error, for the investigated climatic variables and for 6 different sampling resolutions. The values presented in this table are expressed in percent

Climatic variables		Time step (min)					
		2	5	10	15	30	60
R_s	$\lvert\epsilon_{rel.\ max}\rvert$	2.83	6.15	13.21	17.71	24.84	41.05
	Mean	0.03	−0.06	−0.11	−0.14	−0.50	−2.2
	σ	0.72	1.66	3.36	3.93	7.8	12.15
U	$\lvert\epsilon_{rel.\ max}\rvert$	1.33	3.72	6.86	6.58	12.12	18.01
	Mean	0.0072	−0.096	−0.10	−0.1	0.19	0.103
	σ	0.51	1.09	1.82	2.29	3.43	5.36
$T_{max.}$	$\lvert\epsilon_{rel.\ max}\rvert$	2.67	4.08	5.91	8.26	10.79	12.71
	Mean	−0.34	−0.82	−1.36	−1.67	−2.29	−3.19
	σ	0.522	0.79	1.13	1.32	1.71	2.33
T_{min}	$\lvert\epsilon_{rel.\ max}\rvert$	1.24	3.84	4.25	6.55	6.64	11.47
	Mean	0.11	0.318	0.55	0.789	1.15	1.67
	σ	0.21	0.51	0.78	1.01	1.28	1.81
T_{dry}	$\lvert\epsilon_{rel.\ max}\rvert$	0.043	0.13	0.24	0.44	0.91	1.6
	Mean	−0.0016	-4.2×10^{-4}	-2.6×10^{-4}	9.5×10^{-4}	−0.005	−0.0052
	σ	0.012	0.04	0.081	0.124	0.23	0.46
T_{wet}	$\lvert\epsilon_{rel.\ max}\rvert$	0.048	0.13	0.258	0.54	1.01	1.77
	Mean	−0.0015	8.3×10^{-5}	0.0017	7.9.10−4	−0.01	−0.019
	σ	0.014	0.043	0.094	0.146	0.257	0.51

was 0.383 MJ m^{-2} d^{-1} (DOY 281). The daily variability is very pronounced during the summer period (June–August). The daily mean minimum temperature was 11.46°C and the daily mean maximum temperature was 20.09°C. The average wind speed value was moderate with a daily mean of 2.45 m s^{-1}. The daily mean vapour pressure deficit (0.55 kPa) was characteristic of the climate. The daily mean reference ET, calculated from Eq. (1) was 2.75 mm d^{-1} with a maximum of 5.33 mm d^{-1} (DOY 149) and a minimum of 0.41 mm d^{-1} (DOY 282).

3.2. *Effect of temporal sampling*

The effect of temporal sampling was quantified for each climatic variables by comparing the daily mean based on a given time step with the true mean calculated with all 1440 measured values. Table 2 gives for six different time steps (2, 5, 10, 15, 30 and 60 min) the mean and standard deviation of the observed relative error and the absolute value of the maximum relative error. For all the climatic variables, a consistent increased degradation of precision is observed with a decreasing temporal sampling intensity. Nevertheless, the observed errors are very different according to the different climatic variables. As an example, the absolute errors of the solar radiation and of the maximum temperature are illustrated in Fig. 2.

The error on the estimated daily shortwave solar radiation is the most sensitive to temporal sampling frequency. For a 60 min sampling interval, the daily relative error may reach a value as high as 41.05%, while the absolute error is 5.1 MJ m^{-2} d^{-1}. The mean daily relative error is, for each time interval, always negative, corresponding to a underestimation of the solar radiation. This has probably different interdependent causes for which different explanations could be put forward. One of them is described below. Under temperate climatic conditions where cloudless sky days are very rare, the cloud cover is intermittent, but most of part dominant with regard to the shining period, which creates very large instantaneous fluctuations of solar radiation. In some cases,

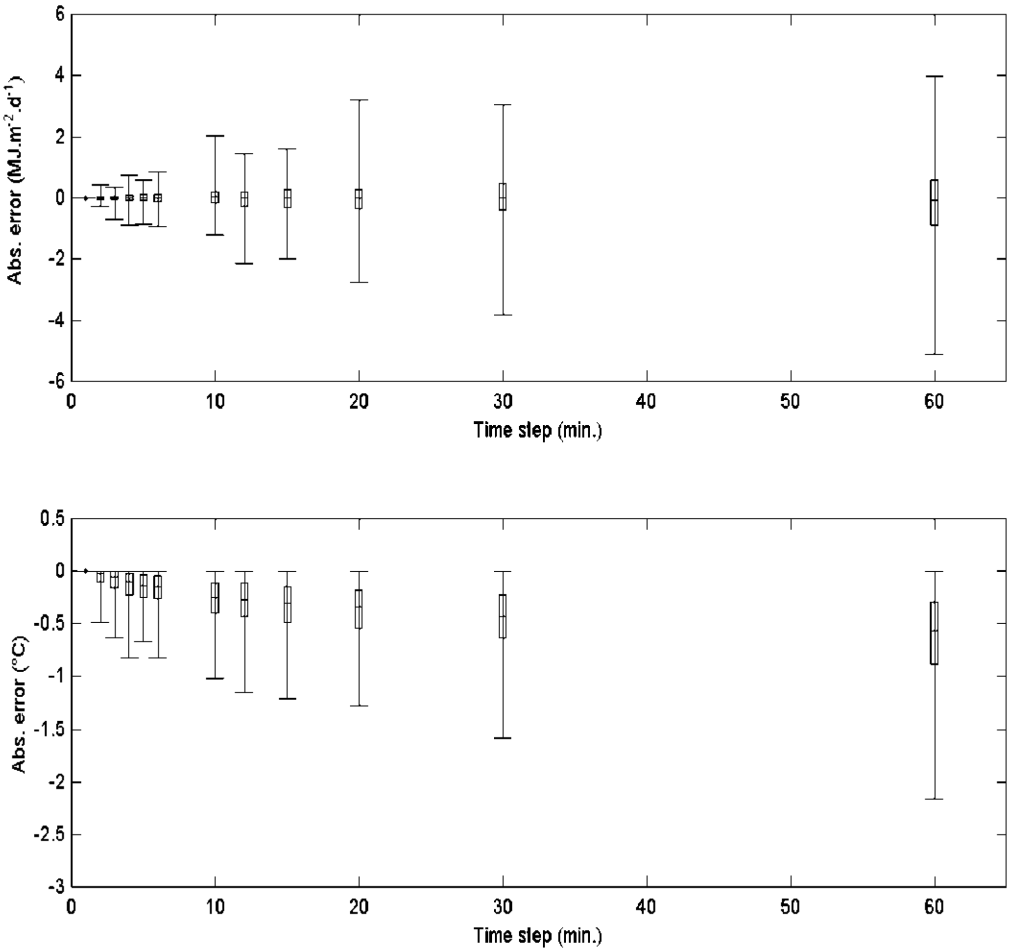

Fig. 2. Boxplot for the distribution of the absolute errors illustrated for: (a) the shortwave solar radiation; and (b) the maximum temperature. Each box lies between the 0.25 and the 0.75 quartile, and the central line is the median. The whiskers indicate the range of the data within the maximum and the minimum values.

the observed solar radiation can fluctuate between 850 and 300 W m^{-2} in only a few minutes. Nevertheless, when the cloud cover is incomplete, the sampling seems generally to occur disproportionately at times when the sky is cloudy, leading to an underestimation of the daily solar radiation Thus for this climatic variable, the temporal sampling frequency may have a significant impact on the estimated daily mean value. Furthermore, in order to estimate the net radiation with e.g. the empirical formulae proposed by Allen et al. (1994a,b), different empirical coefficients such as those given by Brunt (1952) and Doorenbos and Pruitt (1977) are generally adopted. However, these coefficients can be considered as dependent on the temporal sampling frequency of the underlying experimental database. This clearly demonstrates that the interest related to the temporal sampling intensity is not only of concern for the estimation of daily mean values but is also of interest for developing more efficient parameterization schemes in evaporation models.

The wind speed, is the second most important variable in terms of the error due to the temporal sampling frequency. For a time step of 60 min, the maximum value of the relative error is 18%, while the maximum absolute error is 0.45 m s^{-1}. These errors are clearly

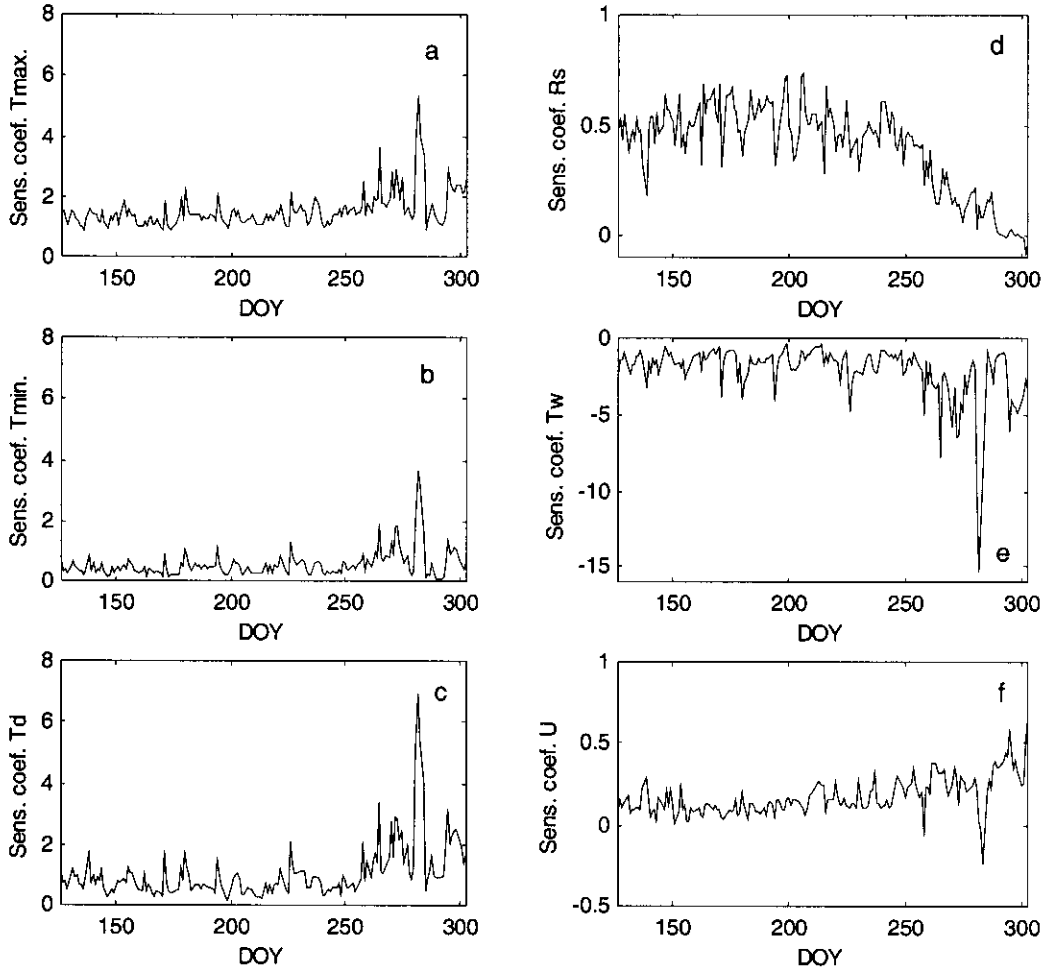

Fig. 3. Seasonal evolution of the different relative sensitivity coefficients presented for: (a) the maximum temperature; (b) the minimum temperature; (c) the dry temperature; (d) the shortwave solar radiation; (e) the wet temperature; and (f) the wind speed.

smaller than those for the solar radiation errors, but are nevertheless still high especially as the wind speed measurements are not instantaneous but averaged on a per-minute basis.

For the maximum and minimum temperature, the absolute value of the relative errors are, for a time step of 60 min, respectively 12.71% (absolute error of −2.16°C) and 11.47% (absolute error of 0.76°C). The differences between the maximum absolute errors of those two variables can be explained as follows. Given the fact that the daily maximum temperature varies more rapidly than the minimum temperature, a less intensive temporal sampling generates a higher error for the maximum temperature than for the minimum. For these two variables, the mean error is therefore different. In fact, decreasing the sampling intensity (fewer samples per day) will increase the underestimation for the maximum temperature. Similarly for minimum temperature, the decreasing sampling rate increases the overestimate of the minimum temperature.

The observed errors are the lowest for the dry and the wet temperature. For a time interval of 60 min, the absolute value of the relative error is 1.6% for the dry temperature and 1.8% for the wet temperature. The maximum absolute errors are 0.20 and −0.17°C,

Table 3
Impact of the temporal sampling intensity of the different climatic variables on the estimation of ETo. The values presented in this table are expressed in mm d^{-1} and determined by combining the sensitivity coefficient and the error due to inappropriate temporal sampling of the respective variable

Climatic variables		Time step (min)					
		2	5	10	15	30	60
R_s	$\lvert\epsilon_{max}\rvert$	0.052	0.074	0.24	0.24	0.46	**0.62**
	Mean	2.29×10^{-4}	9.3×10^{-4}	4.9×10^{-3}	-1.57×10^{-3}	-5×10^{-3}	−0.021
	σ	0.009	0.0219	0.045	0.05	0.1	0.147
U	$\lvert\epsilon_{max}\rvert$	0.018	0.031	0.054	0.042	0.135	**0.162**
	Mean	7.3×10^{-5}	-5.4×10^{-4}	-8.8×10^{-4}	-6.2×10^{-4}	6.3×10^{-4}	5.9×10^{-4}
	σ	0.0026	0.0063	0.0102	0.012	0.021	0.033
$T_{max.}$	$\lvert\epsilon_{max}\rvert$	0.095	0.147	0.18	0.19	0.255	**0.36**
	Mean	−0.013	−0.03	−0.048	−0.06	−0.08	−0.114
	σ	0.019	0.029	0.039	0.049	0.055	0.077
T_{min}	$\lvert\epsilon_{max}\rvert$	0.012	0.038	0.038	0.043	0.06	**0.065**
	Mean	0.0011	0.003	0.005	0.0075	0.011	0.016
	σ	2.2×10^{-3}	4.2×10^{-3}	5.8×10^{-3}	7.7×10^{-3}	0.011	0.014
T_{dry}	$\lvert\epsilon_{max}\rvert$	6.1×10^{-4}	2.2×10^{-3}	6.3×10^{-3}	0.012	0.016	**0.027**
	Mean	-3.8×10^{-5}	-4.1×10^{-5}	-5.5×10^{-5}	-1.9×10^{-4}	-3.9×10^{-4}	-9.1×10^{-4}
	σ	2.6×10^{-4}	8.5×10^{-4}	1.8×10^{-3}	2.5×10^{-3}	4.9×10^{-3}	9.7×10^{-3}
T_{wet}	$\lvert\epsilon_{max}\rvert$	2.52×10^{-3}	5.8×10^{-3}	0.013	0.016	0.04	**0.07**
	Mean	8.03×10^{-5}	1.17×10^{-4}	3.61×10^{-5}	4.03×10^{-4}	1.12×10^{-3}	2.58×10^{-3}
	σ	5.91×10^{-4}	1.79×10^{-3}	4.09×10^{-3}	6.02×10^{-3}	1.07×10^{-2}	2.18×10^{-2}

respectively. For these two variables, increasing the temporal sampling frequency is clearly of little interest.

3.3. Sensitivity analysis

The sensitivity analysis was carried out on a daily basis using climatic daily means calculated from the most intensive temporal sampling frequency (1440 measurements per day). The investigated meteorological variables are those needed for the estimation of ETo calculated by Eq. (1). The sensitivity coefficients relative to each climatic variable are illustrated in Fig. 3.

The daily sensitivity coefficients all exhibit large fluctuations during the study period. The mean sensitivity coefficient for the wind speed is 0.177, with a maximum value of 0.657. Nearly all the calculated values are positive.

The sensitivity coefficient for the solar radiation shows a pronounced seasonal trend, similar to the trend within the measured solar radiation. The decrease of the sensitivity coefficients for the solar radiation corresponding to an increase in the sensitivity for the wind speed at the end of the season is due to a decrease of the energetic term in favour of the increase of significance of the aerodynamic term. Similar findings were reported when analysing the sensitivity of the ET models at the temporal scale of the day and the season (Saxton, 1975; Beven, 1979; Rana and Katerji, 1998).

The mean sensitivity coefficient for the solar radiation is 0.404 and the maximum value is 0.734. These sensitivity coefficients are positive except during the last decade where some very small negative values were found (min. −0.07 for DOY 302). These negative coefficients, can probably be explained by the formulation of the net longwave radiation based on the use of the shortwave solar radiation. Thus, with the use of this formulation and in some rare situations, an increase of the shortwave solar radiation induces a short decrease of the net radiation.

The sensitivity coefficients for the maximum and the minimum temperature show a similar trend. Nonetheless, the sensitivity coefficients for the minimum temperature are systematically below those of the maximum temperature. The mean sensitivity coefficients are 1.52 for the maximum temperature and 0.55 for the minimum temperature. These high sensitivity coefficients can be explained by the fact that they are used to estimate several relatively sensible terms within the ETo model such as the net radiation, the saturated vapour pressure and the slope of the vapour pressure curve. Furthermore, during the DOY 282-284, abnormally high sensitivity coefficients are observed with a maximum value of 5.52 for the maximum temperature and 3.65 for the minimum temperature. In this short period, high sensitivities were also observed for the other climatic variables except for the solar radiation. These high values are due to the formulation of the relative sensitivity coefficients, that may not be a good indication of the significance of the parameter sensitivity if ETo or v_i tend to zero independently (Beven, 1979). As shown by Fig. 1, this was typically the case for the DOY 282-284 with very small values of daily ETo (<0.5 mm).

The sensitivity coefficients for the dry temperature show a similar trend to those for the maximum temperature but with a larger amplitude and with a more pronounced variation. The mean value is 1.04 and the maximum value is 6.93. The sensitivity coefficient for the wet temperature is consistently always negative. The mean coefficient is -2.15, the maximum value -0.36 and the minimum value -15.32.

It is difficult to compare our results with those presented in the literature (e.g. McCuen, 1974; Saxton, 1975; Coleman and Decoursey, 1976; Beven, 1979; Rana and Katerji 1998; Qui et al., 1998), given the different approaches in parameterizing the ET models, the different definitions of the sensitivity coefficients and the different spatio-temporal scales for which previous studies were carried out.

3.4. Error propagation analysis for each climatic variable

For each climatic variables, the effect of the errors due to the temporal sampling frequency on the estimation of the ETo can be quantified by means of Eq. (8). The absolute value of the maximum error, the mean and the standard deviation of the errors are presented in Table 3. The solar radiation causes the most significant error. For a sampling interval of 60 min, the absolute value of the absolute error reaches 0.62 mm d^{-1}. For more intensive sampling frequencies, the error remains high and only decreases significantly when the sampling interval is smaller than 10 min. The maximum temperature causes a maximum error of 0.36 mm d^{-1} for a time step of 60 min. Nevertheless, as for the solar radiation, the mean error is rather low with a maximum of -0.114 mm d^{-1}. The wind speed involves errors of the same order of magnitude with a maximum of 0.162 mm d^{-1} for the lowest temporal sampling frequency, but with mean errors and standard deviations which are very low. For the dry, wet and minimum temperature, a low temporal sampling frequency causes only small errors as compared to the meteorological variables described previously. For a time step of 60 min, the absolute values of the maximum error are 0.065, 0.027 and 0.07 mm d^{-1}, respectively, for the minimum, dry and wet temperature. These three meteorological variables have mean errors and standard deviations that are very small and very similar. The same results were obtained by calculating the impact of each climatic variable on the ETo calculated with the climatic variables intensively sampled, except the variable of interest, and compared with the "true" ETo determined with the climatic variables intensively sampled. The previous results illustrate clearly the relative weight of the sensitivity coefficients and the error due to the temporal sampling frequency on the calculated ETo error. Indeed, as seen for the dry temperature and for the solar radiation, the sensitivity coefficients have a very limited impact on the error of the ETo estimation. On the other hand, for the maximum temperature, the importance of the sensitivity coefficient and the error due to the temporal sampling frequency seems to be similar. In a more general way, these results emphasize the importance of connecting the sensitivity analysis with different and coherent errors relative to each variables.

3.5. Error analysis for daily and cumulative ETo

The error of ETo is determined on a daily basis by

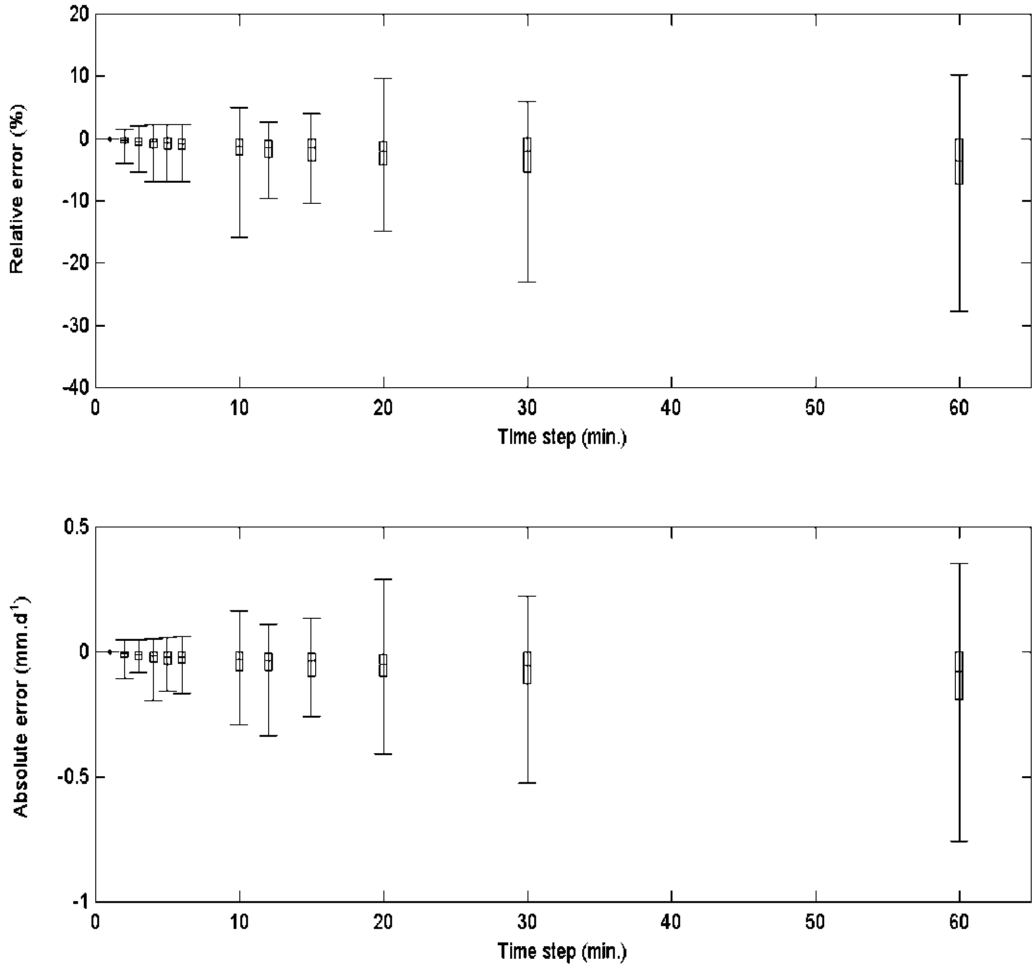

Fig. 4. Boxplot for the distribution of the relative and absolute errors made on the daily ETo estimation. Each box lies between the 0.25 and the 0.75 quartile, and the central line is the median. The whiskers indicate the range of the data within the maximum and the minimum values.

Table 4
Reference ET cumulated for the study period and calculated with different temporal sampling frequencies

Step time (min)	Nb of measurements/day	Cumulative ETo (mm)	Rel. error (%)
1	1440	491.1	0
2	720	489.3	0.36
3	480	488.38	0.553
4	360	487.24	0.785
5	288	486.92	0.851
6	240	486.71	0.894
10	144	484.95	1.252
12	120	482.79	1.692
15	96	482.48	1.755
20	72	481.19	2.018
30	48	479.94	2.272
60	24	472.39	3.809

comparing the $\langle ETo \rangle_{i\ min}$ (calculated with the climatic variables sampled to the time step i) with the $\langle ETo \rangle_{1\ min}$. Fig. 4 illustrates for each different sampling interval the relative and absolute errors of ETo. For a temporal sampling frequency of 60 min, the maximum relative error is −27% and the maximum absolute error is $-0.76\ mm\ d^{-1}$. For more intensive temporal samplings (every 30 or 20 min), the maximum value of the absolute error is still high, −0.52 and $-0.4\ mm\ d^{-1}$, respectively. A relatively clear decrease of the error is observed for a time step of 6 min. For this time step, the maximum absolute value is $-0.15\ mm\ d^{-1}$ and the relative error is −6.96%.

For the cumulative ET, the errors are clearly lower (Table 4). Indeed, for a less intensive temporal sampling frequency, the relative error is only 3.8%, corresponding to an absolute error of 18.71 mm for a "reference" cumulative value of 491.1 mm. These low errors generated on the estimation of the cumulative ET as compared to the large errors on the daily values can be explained by the random character of the error due to the temporal sampling. The values presented in Table 4 illustrate a systematical underestimation of ETo, corresponding to a "loss" of information when the sampling frequency decreases.

4. Conclusions

The reference method to estimate the reference ETo, proposed by the FAO and based on the Penman–Monteith ET model, uses as input readily available climatic variables such as solar radiation, wind speed, and dry and wet temperature. For daily estimations of the ETo, daily mean or extreme values for these climatic variables are required. In addition to the random and systematic errors which are intrinsic to meteorological measurements, the daily means and the extreme values may also be prone to errors due to inappropriate temporal sampling frequency of the measured climatic variables. In this context, one needs to define optimal sampling strategies for reduction of bias in ET calculations.

Our study showed that the climatic variables which are mostly subjected to bias due to inappropriate temporal sampling of the climatic variables are the solar radiation and the wind speed, with maximum daily relative errors of 41.05 and 18%, respectively. The sensitivity analysis illustrated further that the maximum and the dry temperature are sensitive in calculating reference ET with sensitivity coefficients of 1.52 and 1.04, respectively. By combining the sensitivity analysis with the errors due to inappropriate temporal sampling, solar radiation and maximum temperature were identified as the two meteorological variables that will have the most pronounced impact on the estimation of the daily ETo. Our study also showed that the ETo estimation error due to inappropriate temporal sampling may be as high as $-0.76\ mm\ d^{-1}$ corresponding to a relative error of −27%. These high values demonstrated that, beside the standard random and systematic errors, inappropriate temporal sampling causes non-negligible errors on daily estimates of ETo, which may be easily reduced or even deleted by intensifying the temporal sampling frequency. However, we also showed that the estimation error due to inappropriate sampling for the cumulated ETo is relatively low, reaching 3.8% for the less intensive temporal sampling (one measurement per hour). Nevertheless, this low value would be considered as non-negligible for "reference" methods. We finally recommend more detailed analysis of the impact of inappropriate sampling on land surface fluxes also in other climatic areas.

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