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2 Deriving daily evapotranspiration from remotely 3 sensed instantaneous evaporative fraction over olive 4 orchard in semi-arid Morocco

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KEYWORDS

Q4 Evapotranspiration;
Evaporative fraction;
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ASTER;
Semi-arid regions;
Olive orchard

Summary Hydrology and crop water management require daily values of evapotranspiration ET at different time-space scale. Sun synchronous optical remote sensing, which allows for the assessment of ET with high to moderate spatial resolution, provides instantaneous estimates during satellites overpass. Then, usual solutions consist of extrapolating instantaneous to daily values by assuming that evaporative fraction EF is constant throughout the day, providing that daily available energy AE is known. The current study aims at deriving daily ET values from ASTER derived instantaneous estimates, over an olive orchard in a semi-arid region of Moroccan. It has been shown that EF is almost constant under dry conditions, but it depicts a pronounced concave up shape under wet conditions. A new heuristic parameterization is then proposed, which is based on the combination of routine daily meteorological data for characterizing atmospheric dependence, and on optical remote sensing based estimates of instantaneous EF values to take into account the dependence on soil and vegetation conditions. Using the same type of approach, a similar parameterization is next developed for AE. The validation of both approaches shows good performances. The overall method is finally applied to ASTER data. Though performances are reasonably good, their moderate reduction is ascribed to errors on remotely sensed variables. Future works will focus on method portability since its empirical formulation does not account for the direct stomatal response to water availability, as well as on application over different surface and climate conditions.

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12 Introduction

13 Estimates of regional evapotranspiration (ET) are of crucial
14 need for climate studies, weather forecasts, hydrological
15 surveys, ecological monitoring, and water resource manage-
16Q1 ment (Van den Hurk et al., 1997; Su, 2000; Bastiaanssen
17 et al., 2000). Given that distributed hydrological models
18 can accurately estimate basin scale runoff while poorly
19 reproducing other hydrological cycle components, interme-
20 diate processes such as soil moisture and thus ET have to be
21 well simulated (Chaponnière et al., 2007). Within semiarid
22 agricultural regions, which hydrological cycle is strongly
23 influenced by ET through crop water consumption, a precise
24 ET estimation is of importance for water saving through effi-
25 cient irrigation practices (Allen, 2000; Ohmura and Wild,
26 2002; Porporato et al., 2004; Wild et al., 2004). Among
27 the several research programs designed to develop efficient
28 irrigation management tools in arid and semi-arid zones, the
29 SUDMED (Chehbouni et al., in press-a) and IRRIMED ([http://](http://www.irrimed.org)
30 www.irrimed.org) projects have taken place in southern
31 Mediterranean regions, to assess the spatio-temporal vari-
32 ability of water needs and consumption for irrigated crops
33 under water limited conditions.

34 Optical satellite remote sensing is a promising technique
35 for estimating instantaneous and daily ET at global and re-
36 gional scale, via surface energy budget closure. The meth-
37 ods proposed in the literature range from simple and
38 empirical approaches, to complex and data consuming ones
39 (Glenn et al., 2007). Among the complex methods are Soil
40 Vegetation Atmosphere Transfer (SVAT) models, which de-
41 scribe the diurnal course of heat and mass transfers, pro-
42 vided micrometeorological conditions and water/energy
43 balance parameters are documented (Braud et al., 1995;
44 Mahfouf et al., 1995; Olioso et al., 1996; Calvet et al.,
45 1998; Olioso et al., 2005; Coudert et al., 2006; Gentine
46 et al., 2007). Among the simple approaches are the simpli-
47 fied relationship, which links daily ET to midday near sur-
48 face temperature gradient (Jackson et al., 1977). In the
49 same vein, the FAO-56 method expresses daily ET using crop
50 coefficients derived from vegetation indexes, but needs to
51 be calibrated with ground measurements (Duchemin
52 et al., 2006; Er-Raki et al., 2007a, Yang et al., 2006). Be-
53 tween complex and empirical approaches, compromising
54 solutions are energy balance models. They compute at sat-
55 ellite overpass instantaneous ET as the residual term of en-
56 ergy budget, once net radiation, soil heat flux and sensible
57 heat flux are derived (Bastiaanssen et al., 1998; Norman
58 et al., 2003; Su, 2002; Caparrini et al., 2003, 2004; French
59 et al., 2005; Crow and Kustas, 2005; Allen et al., 2007; Cle-
60 ugh et al., 2007; Mu et al., 2007).

61 Instantaneous values of ET at satellite overpass can be
62 used as diagnostics for surface status (Chandrapala and
63 Wimalasuriya, 2003), or as controls for hydrological models
64 through assimilation schemes (Schuurmans et al., 2003).
65 However, their interest in terms of water management is
66 limited, since the latter requires daily values (Bastiaanssen
67 et al., 2000). Daily ET can be derived from FAO-56 or simpli-
68 fied relationship, but difficulties raise when extrapolating
69 outside the environmental conditions considered for cali-
70 bration. The ET diurnal course can be inferred assimilating
71 sun synchronous observations into SVAT models, but this is

72 limited by uncertainties when estimating SVAT parameters
73 and initial variables. The ET diurnal course can also be re-
74 trieved using geostationary observations, but the kilometric
75 resolutions severely limit water management at the field
76 scale. Probably, the most practical solution is estimating
77 instantaneous values from energy balance models combined
78 with sun synchronous observations, and next extrapolating
79 at the daily scale by presuming generic trends for the diur-
80 nal courses of ET and related variables.

81 Assuming generic trend for the ET diurnal course can
82 consist of approximating the latter by a sine function, given
83 it is similar to that of solar irradiance. However, this meth-
84 od is limited by its empirical character in terms of accuracy
85 (Zhang and Lemeur, 1995). Another possibility is assuming a
86 typical shape for Evaporative Fraction (EF) given Available
87 Energy (AE) is known. The EF is defined as the ratio of ET
88 to AE, and AE is the difference between net radiation and
89 soil heat flux. EF is in deed an important indicator of the
90 surface hydrological history, including wetting and drying
91 events (Shuttleworth et al., 1989; Nichols and Cuenca,
92 1993). Thus, it was suggested to assume a constant daytime
93 EF, to be used with daily AE for deriving daily ET (Sugita and
94 Brutsaert, 1991; Roerink et al., 2000; Gomez et al., 2005).

95 Assuming a daytime constant EF is not straightforward,
96 regarding what has been reported from both theoretical
97 and experimental based investigations (Crago, 1996; Crago
98 and Brutsaert, 1996). Zhang and Lemeur (1995) observed
99 EF changes with environmental variables, especially AE
100 and surface resistance. Suleiman and Crago (2004) reported
101 that EF increases with vegetation amount, soil moisture and
102 air dryness. Baldocchi et al. (2004) and Li et al. (2006) re-
103 ported that stomatal conductance drives EF according to
104 soil moisture since soil dryness tends to decrease both vari-
105 ables. During fair weather conditions over fully vegetated
106 surfaces, Lhomme and Elguero (1999) reported from model
107 simulation a typical concave-up shape for EF, quite constant
108 during midday, and mainly driven by changes in soil mois-
109 ture and solar energy. Thus, assuming a daytime constant
110 EF equal to the noon value induces underestimations since
111 this value is the lowest of the day. Finally, Gentine et al.
112 (2007) showed that EF diurnal course mainly depends on
113 both evaporative state and vegetation cover. Besides the
114 EF diurnal course, addressing the daytime AE is a delicate
115 issue. Empirical approaches have been proposed to derive
116 it from instantaneous values, mainly approximating AE by
117 a sine function (Jackson et al., 1983; Bastiaanssen et al.,
118 2000). Again, the most adequate solution is using geosta-
119 tionary satellite observations, but the corresponding spatial
120 resolutions make the use of such data complicated for water
121 management at field scale.

122 In the same context of the investigations discussed
123 above, the present study aims at inferring daily ET from
124 sun synchronous optical remote sensing, with the objective
125 of improving irrigation water management at the field scale.
126 The challenge is then considering an irrigated old olive orch-
127 ard in central Morocco, characterized by a semi-arid cli-
128 mate, tall trees, and strong soil moisture heterogeneity
129 due to irrigation practices. This challenge was addressed
130 in four steps. We first examine the EF diurnal behavior using
131 Eddy Correlation (EC) measurements, and then quantify
132 errors on daily ET when assuming EF self-preservation. 132

133 Second, we parameterize the EF diurnal course using a com-
134 bination of routinely available meteorological data and a
135 unique "one shot" instantaneous EF estimates. Third, we
136 parameterize the AE diurnal cycle from ground based mea-
137 surements of energy balance, also by considering routine
138 micrometeorological measurements and a single instanta-
139 neous estimates of AE. Finally, the proposed parameteriza-
140 tions after being calibrated using ground based data are
141 applied to ASTER data. These different steps are imple-
142 mented using data collected during the 2003–2004 period.
143 Given that ASTER data was only available in 2003, design
144 and calibration were performed using ground-based 2004
145 dataset, while validation was performed using the 2003 one.

146 Site description and experimental setup

147 The study took place in a semi-arid basin in central Morocco
148 (the Tensift basin, Fig. 1) within the framework of the SUD-
149 MED Program (<http://www.irrimed.org/sudmed>). In this
150 section, site description and experimental setup are briefly
151 summarized; the reader is referred to [Chehbouni et al. \(in](#)
152 [press-a\)](#) for a complete description of both project and site.
153 The regional climate was characterized by low and irregular
154 rainfalls with a 240 mm annual average, an evaporative de-
155 mand of about 1600 mm per year, and a dry atmosphere
156 with a 56% average humidity. The experiment was carried
157 out between Day Of Year (DOY) 288 in 2002 and DOY 271
158 in 2004, at the 275 ha Agdal olive orchard, southeastern of
159 Marrakech (31°36'N, 07°58'W). The average height of the ol-
160 ive trees is 6.5 m, the average crown diameter is 6.5 m. The
161 density of the olive trees at our site is about 225 ha⁻¹.
162 Understorey vegetation consists mainly of short weeds, with
163 ground cover ranging from almost no (10–20%) cover to al-
164 most complete (70–80%) cover ([Hoedjes et al., 2007](#)). The
165 olive trees are irrigated through level basin flood irrigation.
166 For this purpose, each tree is surrounded by a small earthen
167 levy, and water is directed to each tree through a network
168 of ditches ([Williams et al., 2004](#)). On average, the irrigation
169 takes approximately 12 days.

170 The experimental setup collected standard meteorologi-
171 cal measurements: wind speed and direction (Young Wp200
172 anemometer); air temperature and humidity (Vaisala
173 HMP45AC temperature and humidity probe). The instru-
174 ments were set 9 m above ground (3 m above canopy).

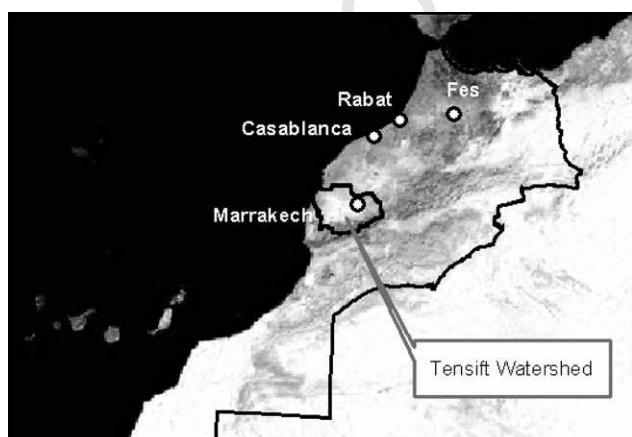


Figure 1 Location of the study area.

The four net radiation components were measured using a
Kipp and Zonen CNR1 radiometer, set at an 8.5 m height
to embrace vegetation and soil radiances by ensuring the
field of view was representative of their respective cover
fractions. Soil and vegetation brightness temperatures were
measured using two Apogee IRTS-P. The soil heat flux den-
sity was measured using heat flux plates (HFT3-L, Campbell
Scientific Ltd.) at three locations with contrasting amounts
of radiation reaching the soil. The measurement depth was
1 cm. The plates were placed: one below the tree, near the
trunk in order not to be exposed to direct solar radiation;
one was exposed directly to solar radiation, the last one
in an intermediate position. An average of these three mea-
surements was made to obtain a representative value. Soil
moisture and temperature were recorded at different
depths within the 0–50 cm horizon, using CS616 water con-
tent reflectometer and TP107 temperature probes (both
Campbell Scientific Ltd.), respectively. Measurements were
sampled at 1 Hz, and 30 min averages were stored on CR10X
dataloggers (Campbell Scientific Ltd.).

The EC system was installed at a 9.2 m height. During the
first three months it included a CSAT 3 3D sonic anemometer
(Campbell scientific Ltd.) and a LICOR-7500 open-path infra-
red gas analyzer (Campbell Scientific Ltd.). Raw data were
sampled at a 20 Hz rate, recorded using a CR23X datalogger
(Campbell scientific Ltd.). After three months, the LICOR-
7500 was replaced by a KH20 Krypton hygrometer (Campbell
Scientific Ltd.), and the CR23X was replaced with a CR5000
datalogger (Campbell Scientific Ltd.). The half-hourly fluxes
were later calculated off-line using Eddy Covariance pro-
cessing software 'ECpack', after performing all required
corrections for planar fit correction, humidity and oxygen
(KH20), frequency response for slow apparatus, and path
length integration ([Van Dijk et al., 2004](#)).

The analysis showed that the sum of latent and sensible
heat flux measured independently by the EC systems was of-
ten lower than available energy (AE). The absolute value of
average closure was about 8% and 9% of available energy
during the 2003 and 2004 seasons, respectively ([Er-Raki](#)
[et al., 2007b](#)). This problem could not be explained neither
by mismatching spatial extents for fluxes and AE measure-
ments, nor by uncertainties associated with measurements
of soil heat flux and net radiation ([Twine et al., 2000](#); [Hoed-](#)
[jes et al., 2002](#); [Chehbouni et al., in press-b, 2007c](#)). Cor-
rection was then performed using the approach suggested
by [Twine et al. \(2000\)](#), which assumes the energy balance
is due to underestimates from EC measurements while the
corresponding Bowen ratio is correctly estimated. Based
on this assumption, we re-computed sensible and latent
heat fluxes by forcing the energy balance using the
measured AE and Bowen ratio.

ASTER official products ([Abrams and Hook, 2002](#)) were
downloaded from the Earth Observing System Data Gateway
(EDG). Once instrumental effects are removed ([Fujisada,](#)
[1998](#); [Fujisada et al., 1998](#); [Abrams, 2000](#)), atmospheric
corrections are performed using radiative transfer codes
documented for atmospheric status ([Thome et al., 1998](#)),
providing surface reflectance's over the solar domain (bands
1–9) and surface brightness temperatures over the thermal
domain (bands 10–14). The latter are next used to derive
surface emissivity and radiometric temperature by applying
the Temperature Emissivity Separation algorithm ([Gillespie](#)

237 et al., 1998; Schmugge et al., 1998). Six ASTER images were
238 collected over the study area, one in 2002 (DOY 311), and 5
239 in 2003 (DOY 58, 138, 202, 282 and 289). Spatial resolution is
240 15 m (respectively 30 m) for visible and near infrared
241 (respectively shortwave) reflectance's, and 90 m for emis-
242 sivity and radiometric temperature. Higher resolution prod-
243 ucts were linearly degraded to 90 m, given aggregation
244 effects from spatial heterogeneities could be considered
245 as minor over flat semiarid regions (Jacob et al., 2004; Liu
246 et al., 2006).

247 **Method design, implementation and**
248 **assessment**

249 The parameterization is designed and assessed using ground
250 based EC data collected during the 2003–2004 experimental
251 period. ASTER data were only available in 2003. Therefore,
252 design and calibration were performed using the 2004 data-
253 set, whilst validation was performed using the 2003 ground
254 and ASTER dataset. Furthermore, only daytime observations
255 from 09:30 to 16:30 UTC are considered, since the most
256 important latent heat fluxes occur during this period.

257 **EF diurnal course and impact-assessment on ET**
258 **estimates**

259 In this section we assess the validity of EF self-preservation
260 using the EC data during dry and wet conditions. It is impor-
261 tant to mention that dry or wet conditions should normally
262 be characterized by soil moisture conditions. However,
263 since we are dealing with the EF which is influenced by both
264 surface and atmospheric conditions, we preferred instead
265 to use the Bowen Ratio ($BR = H/LE$) with a threshold value
266 higher (lower) than 1.5 as indicator of dry (wet) conditions.
267 Fig. 2a displays the observed diurnal variations of EF as well
268 as the EF constant value set up to that observed at 11:30
269 UTC (ASTER time overpass) for 10 cloud free days under
270 dry conditions, selected between DOY 80 and DOY 221 in
271 2004. The same curves are presented in Fig. 2b, for a 10-
272 day cloud free period in 2004 under wet conditions. It can
273 be seen that that assuming EF self-preservation is valid un-
274 der dry conditions, since EF is relatively constant despite

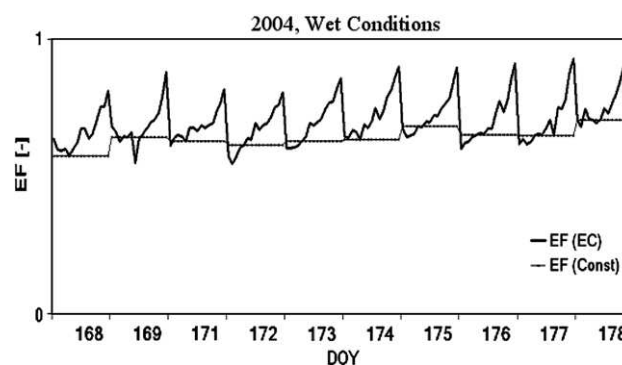


Figure 2b The same as Fig. 2a for 10 wet days following an irrigation event in 2004 (DOY 168–178).

275 observed some daily variation. But this assumption is not valid
276 under wet conditions, since EF depicts a concave-up
277 shape with a straight decrease in early morning and a sharp
278 increase in late afternoon. Thus, assuming EF is constant
279 and equal to EF @ 11:30 UTC underestimates actual daytime
280 EF and consequently latent heat flux. These results corrob-
281 orate those reported by Lhomme and Elguero (1999), Sulei-
282 man and Crago (2004) and Gentine et al. (2007).

283 Next, we quantify the errors on daytime ET when assum-
284 ing a constant EF. The ET diurnal course is estimated com-
285 bining a daily constant EF and in situ data of AE:

$$286 ET_{EF,const} = EF^{1130} AE = EF^{1130} (R_n - G) \quad (1) \quad 288$$

289 Fig. 3a and b displays comparisons of half hourly ET val-
290 ues simulated from Eq. (1) against observations for dry and
291 wet conditions in 2004, respectively. As it might be can be
292 expected, assuming EF self-preservation appears to be valid
293 under dry conditions, with an RMSE between observed and
294 simulated ET of 14 W m^{-2} (calibration residual error) and
295 a Nash–Sutcliffe coefficient of 0.94. Under wet conditions,
296 however, assuming a constant EF significantly underesti-
297 mates ET, with an RMSE between observations and simula-
298 tions of 46 W m^{-2} , and a Nash–Sutcliffe coefficient of

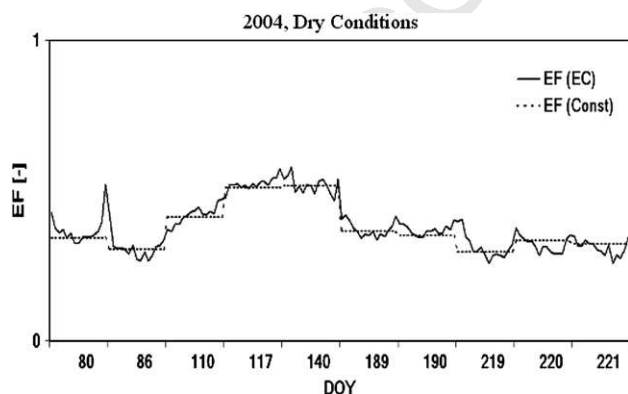


Figure 2a Eddy Covariance (EC) derived evaporative fraction EF (EC) and constant EF (at 11:30) for 10 selected dry and cloud free days within the 2004 selected between DOY 80 and DOY 221.

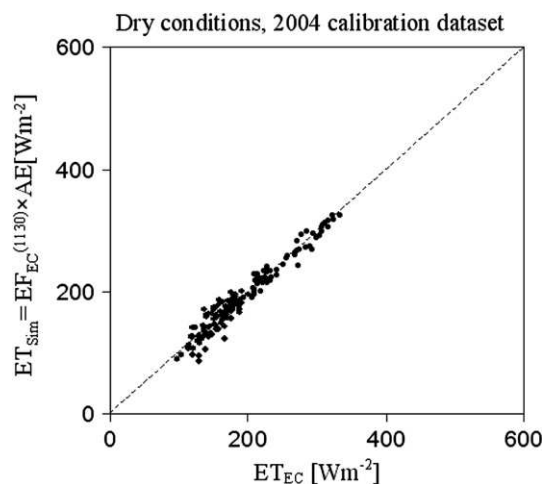


Figure 3a Comparison between eddy covariance latent heat flux (ET_{EC}) and latent heat flux calculated using EF_{EC} at 11:30 as constant during daytime (ET_{sim}) during the 10 dry days in 2004.

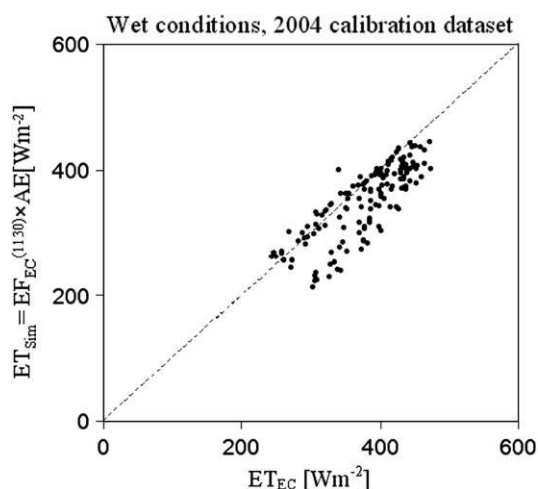


Figure 3b Comparison between eddy covariance latent heat flux (ET_{EC}) and latent heat flux calculated using EF_{EC} at 11:30 as constant during daytime (ET_{Sim}) during a 10-day period following an irrigation event in 2004.

299 0.34. Thus, the validity of assuming EF self-preservation de-
300 pends on soil moisture. It is therefore necessary under wet
301 condition to account for the diurnal cycle of EF to derive
302 accurate estimates of daytime ET.

303 Parameterizing the EF diurnal cycle

304 An alternative to assuming EF self preservation is proposed
305 here, through a heuristic approach that parameterizes the
306 EF diurnal cycle. The constraints are accounting for the EF
307 daytime relative stability under dry conditions, and ade-
308 quately reproducing the EF diurnal course during wet
309 conditions. For operational applications at the irrigation district
310 scale, the dependence must rely on routinely measured
311 parameters which remain reasonably constant at such scale,
312 or on parameters available from remote sensing. Given the
313 EF diurnal cycle depends on both atmospheric forcing and
314 surface conditions (Gentine et al., 2007), parameterizing
315 the diurnal behavior of EF is twofold. First, the diurnal cycles
316 of atmospheric forcing are considered, since atmospheric
317 demand is controlled by incoming radiation, relative humid-
318 ity and, to a lesser extent, wind speed. Second, we account
319 for land surface heterogeneities potentially available from
320 remotely sensed thermal data, since control on surface tem-
321 perature is exerted by vegetation characteristics and most
322 importantly by soil moisture status.

323 Since an increase in EF mainly results from an increase in
324 incoming solar radiation and a decrease in atmospheric
325 humidity (Lhomme and Elguero, 1999; Suleiman and Crago,
326 2004; Gentine et al., 2007), the first step consists of param-
327 eterizing the diurnal shape of EF as a function of the main
328 atmospheric forcing parameters, i.e. incoming solar radi-
329 ation S^{\downarrow} and relative humidity RH. The proposed parameter-
330 ization reads:

$$333 \quad EF_{Sim} = 1.2 - \left(0.4 \frac{S^{\downarrow}}{1000} + 0.5 \frac{RH}{100}\right) \quad (2)$$

Though Eq. (2) provides a good representation of the rela-
334 tive EF diurnal course, the magnitude and the day-to-day
335 variation of the EF absolute minimum depend on soil mois-
336 ture conditions. Therefore, the second step aims at incorpo-
337 rating, a daily scaling factor in order to produce the actual
338 day to day variation of EF (EF_{Sim}^{ACT}). In order to use effi-
339 ciently remote sensing data, this scaling factor r_{EF}^{1130} is ex-
340 pressed as the ratio of simulated to actual EF when ASTER
341 overpasses @ 11:30 UTC:

$$342 \quad EF_{Sim}^{ACT} = EF_{Sim} r_{EF}^{1130} \quad (3)$$

343 with

$$344 \quad r_{EF}^{1130} = \frac{EF_{Obs}^{1130}}{EF_{Sim}^{1130}} \quad (4)$$

345 For development purposes, EF_{Obs}^{1130} is obtained from EC latent
346 heat observations as well as locally measured AE @ 11:30
347 UTC, and is written as EF_{EC}^{1130} . Later on, EF_{Obs}^{1130} will be derived
348 from remote sensing data only, using ASTER data to derive
349 latent heat, and routinely available data to estimate AE;
350 it will be named EF_{ASTER}^{1130} .

351 To account for the validity of EF self preservation under
352 dry conditions which usually corresponds to Bower ratio
353 values higher than 1.5, the complete EF parameterization
354 becomes:

$$355 \quad EF_{Sim}^{ACT} = \begin{cases} EF_{Sim} r_{EF}^{1130} & \beta^{1130} \leq 1.5 \\ EF_{Obs}^{1130} & \beta^{1130} > 1.5 \end{cases} \quad \text{for} \quad (5)$$

356 To assess the performance of this proposed parametriza-
357 tion, we present in Fig. 4 chronicles of measured (EF_{EC})
358 and simulated (EF_{Sim}) EF, for the same 10-day period than
359 Fig. 2b (2004, wet conditions). Compared to the constant
360 daytime EF as provided in Fig. 2b, EF_{Sim} approximates in a
361 better way the observed EF diurnal variation (EF_{EC}). In or-
362 der to evaluate the resulting improvement in terms of evap-
363 oration estimates, latent heat flux is derived from
364 parameterized EF and in situ observations of AE during the
365 day:

$$366 \quad ET_{EF,Sim} = EF_{Sim}^{ACT} (R_n - G) \quad (6)$$

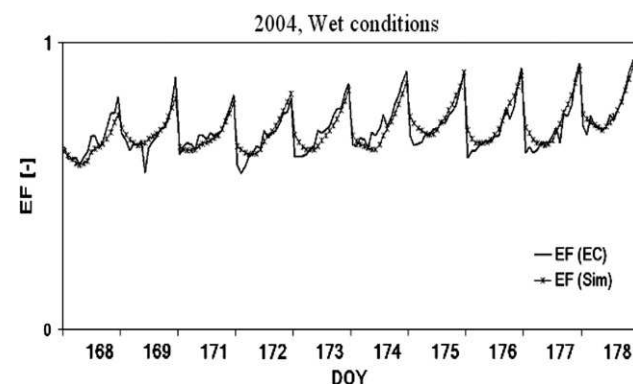


Figure 4 Comparison between time course of eddy correlation based EF values and those simulated using the parameterization given in Eqs. (2)–(4) for 10 days period under wet conditions in 2004 season.

376 Fig. 5 presents a comparison between measured ET values
377 and those simulated using Eq. (6) over the 10-day wet period
378 in 2004. It can be clearly seen that taking into account the
379 diurnal variation of EF significantly improves ET retrieval.
380 RMSE between measured and simulated ET values was of
381 18 W m^{-2} and a Nash–Sutcliffe coefficient of 0.9, as com-
382 pared to 46 W m^{-2} and 0.34, respectively when using a con-
383 stant EF.

384 In order to extend this evaluation with independent data-
385 set, a 10-day periods (wet conditions) during 2003 were se-
386 lected. Fig. 6 shows the comparison between $ET_{EF,Sim}$ and
387 ET_{EC} including ET estimates when assuming a constant
388 EF. It is shown that the proposed parameterization for EF
389 adequately retrieves the observed values of ET compared to
390 assuming a constant EF during the day. Indeed, RMSE
391 value is about 15 W m^{-2} and the Nash–Sutcliffe coefficient
392 is 0.90. Finally, the interest of the proposed EF param-
393 eterization for water balance studies is assessed in terms of

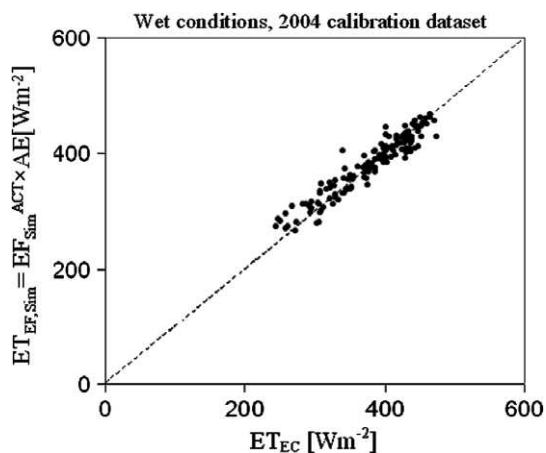


Figure 5 Comparison between measured ET values (ET_{EC}) and those simulated using Eq. (6) for the same 10-days period under wet conditions in 2004 season.

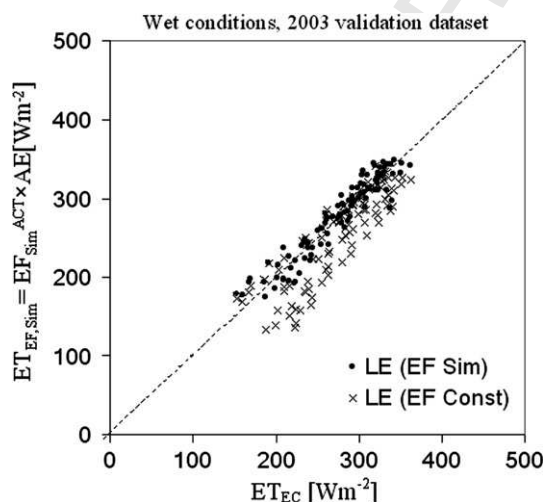


Figure 6 Comparison between ET_{EC} and ET_{Sim} during wet conditions in 2003. ET_{Sim} is calculated both using the proposed parameterization (dots) and, for illustration, using EF_{EC} at 11:30 as constant daytime value (crosses).

Table 1 Water lost through evapotranspiration during two 10-day wet periods (2004 and 2003, daytime values only); measured, simulated with constant EF and simulated with variable EF

Method	Measured (EC) [mm]	Simulated, Constant EF [mm]	Simulated, Variable EF [mm]
2004	41.3	38.1	41.3
2003	20.9	19.3	21.0

394 water losses through evapotranspiration during the two
395 wet periods in 2003 and 2004 (Table 1). In both cases, it is
396 shown using a daytime constant EF for the calculation of
397 ET underestimated the amount of water lost through evapo-
398 transpiration by 8%. Conversely, using the proposed EF
399 parameterization in the calculation of ET reduces the error
400 on water loss to less than 0.5%.

401 Parameterizing the AE diurnal course

402 Implementing Eq. (6) for ET calculation requires the diurnal
403 course of $AE = R_n - G$, which is not routinely available. Var-
404 ious formulations were proposed for estimating AE at a gi-
405 ven time of the day (Jackson et al., 1983; Seguin et al.,
406 1989; Bastiaanssen et al., 2000), usually based on sine func-
407 tions and thus not accounting for any atmospheric distur-
408 bance (e.g. Bisht et al., 2005). Another solution is using
409 instantaneous remote sensing observations when ASTER
410 overpasses (11:30 UTC), and then extrapolating the AE di-
411 urnal course from parameterizations based on meteorological
412 measurements that remain fairly constant at the scale of
413 the irrigation district. As for the EF parameterization, a heu-
414 ristic approach is used for the AE diurnal course, by consid-
415 ering surface net radiation without thermal emission com-
416 ponent:

$$417 \left(\frac{(R_n - G)^t}{(R_n - G)_{Obs}^{1130}} \right) = f \left(\frac{R^{*t}}{R^{*1130}} \right) \quad (7)$$

420 where R^{*t} is a function of solar irradiance (S^\downarrow) and atmo-
421 spheric thermal irradiance (L^\downarrow):

$$422 R^{*t} = (1 - \alpha)S^\downarrow t + \varepsilon L^\downarrow t \quad (8)$$

424 with α and ε surface albedo and emissivity, respectively.
425 They are available from remote sensing and are considered
426 relatively constant throughout the day. S^\downarrow is available from
427 meteorological networks or geostationary remote sensors,
428 and L^\downarrow can be derived from air temperature and humidity
429 (Brutsaert, 1982). Assuming albedo is constant throughout
430 the day can be far from reality (Jacob and Olioso, 2005),
431 but the validation exercise reported below shows this is
432 not critical for accurately retrieving the AE diurnal course.
433 The 2nd order function f is expressed as:

$$434 f \left(\frac{R^{*t}}{R^{*1130}} \right) = a_2 \left(\frac{R^{*t}}{R^{*1130}} \right)^2 + a_1 \left(\frac{R^{*t}}{R^{*1130}} \right) + a_0 \quad (9)$$

437
438 Calibrating Eq. (9) over the EC 2004 dataset provided for
439 the coefficients: $a_2 = 0.34285$; $a_1 = 1.15120$; $a_0 = -0.48495$.
440 By incorporating Eqs. (8) and (9) into Eq. (7); half hourly AE

441 values are obtained using only diurnal measurements of S^{\downarrow} ,
442 L^{\downarrow} , and the single observation $R_n - G_{Obs}^{130}$ when ASTER over-
443 passes. Fig. 7a and b displays the comparison between ob-
444 served and parameterized AE over the two years (2004 for
445 calibration and 2003 for validation), respectively. For both
446 cases, it is shown the proposed parameterization is ade-
447 quate, with RMSE values ranging from 22 W m^{-2} for the cal-
448 ibration dataset to 30 W m^{-2} for the validation dataset.

449 Application to ASTER data

450 The proposed parameterizations for the AE and EF diurnal
451 courses rely on standard meteorological data for character-
452 izing the daytime variations, and on remotely sensed obser-
453 vations to account for surface heterogeneities induced by
454 differences in soil moisture and vegetation. Given land sur-
455 face conditions hardly change throughout the day, and
456 cloud free meteorological conditions are almost homogene-
457 ous over the study area, the simulated AE, EF and ET
458 can be considered as representative. It is thus relevant

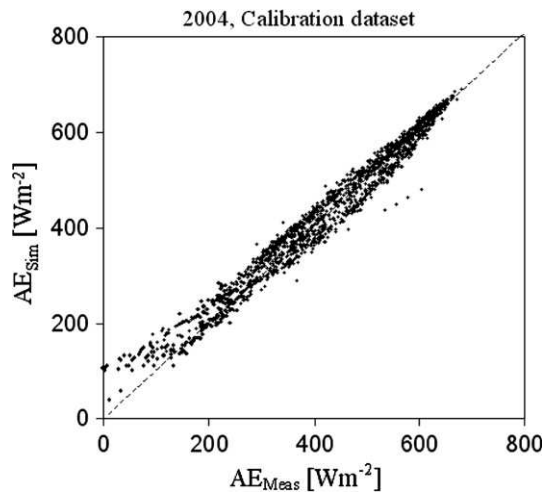


Figure 7a Measured vs. simulated available energy during the whole experimental period in 2004.

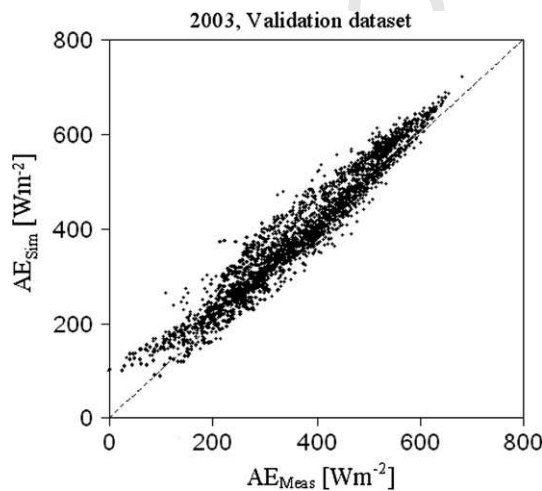


Figure 7b Validation of the AE parameterization for the 2003 experimental season.

459 applying this approach to ASTER observations, which 90 m
460 spatial resolution for thermal imagery is amongst the finest
461 possibilities and reduces problems due to mixed pixels
462 (French et al., 2005). Under unstable conditions, an ASTER
463 pixel footprint is larger than the source area for a typical
464 EC system. However, this source area is often located within
465 adjacent ASTER pixels. A footprint analysis is therefore nec-
466 essary before any comparison between remote sensing and
467 in situ observations. To compute the contribution of each
468 part of the source area (i.e. the footprint of the flux mea-
469 surement), several approaches have been developed over
470 the last decades. These range from simple analytical models
471 (e.g. Schuepp et al., 1990) to complex Lagrangian models
472 (e.g. Baldocchi, 1997; Rannik et al., 2000) or models based
473 on large eddy simulations (e.g. Leclerc et al., 1997). As
474 compared to analytical models, the complex models provide
475 more realistic footprint simulations over forest canopies,
476 and they can account for inhomogeneous turbulence. How-
477 ever, they require significantly larger computational power.
478 Despite the lack of complexity, Finn et al. (1996) reported
479 the analytical model proposed by Horst and Weil (1992,
480 1994) produces very similar results to a Lagrangian stochas-
481 tic model, and can therefore be considered as a reliable
482 method. We therefore select this model, which is fully de-
483 scribed over the same study site in Hoedjes et al., 2007.

Obtaining fluxes from ASTER observations

484 Calculating land surface net radiation and soil heat flux re-
485 quires apparent albedo (Jacob and Olioso, 2005), broadband
486 emissivity over the $[3-100] \mu\text{m}$ spectral range, and vegeta-
487 tion cover. Albedo (respectively emissivity) is calculated as
488 a linear combination of visible and near infrared reflectance
489 (respectively thermal infrared emissivities), following Jacob
490 et al. (2002) (respectively Ogawa et al. (2003)) for the
491 weighting coefficients. Vegetation cover is computed from
492 Normalized Difference Vegetation Index using the empirical
493 relationship proposed by Asrar et al. (1984), and following
494 Weiss et al., 2002 for implementation. Then, net radiation
495 (R_n^{ASTER}) is classically inferred using ASTER derived albedo,
496 broadband emissivity, and surface radiometric tempera-
497 ture, along with field observations for solar and thermal
498 irradiances. The ratio of soil heat flux (G^{ASTER}) to net radia-
499 tion is calculated according to Santanello and Friedl
500 (2003). Using radiative surface temperature inferred from
501 ASTER imagery, the semi-empirical model proposed by
502 Lhomme et al. (1994) is used to obtain sensible heat flux:
503

$$H^{ASTER} = \rho c_p \left[\frac{(T_r^{ASTER} - T_a) - c\delta T}{r_a - r_e} \right] \quad (10)$$

505 where c_p is specific heat of air at constant pressure, ρ is air
506 density, T_a is potential air temperature at reference height
507 (K) and r_a is aerodynamic resistance to heat transfer be-
508 tween the canopy source and the reference height (Brutsa-
509 ert, 1982). Equivalent resistance r_e is given by:
510

$$r_e = \frac{r_{af} r_{as}}{(r_{af} + r_{as})} \quad (11)$$

512 where r_{as} is aerodynamic resistance between the soil and
513 the canopy source height (Shuttleworth and Gurney,
514 1990), and r_{af} is canopy bulk boundary layer resistance
515

516 (Choudhury and Monteith, 1988). This one source model is
517 based on the bulk aerodynamic relationship, but benefits
518 from a direct use of radiometric surface temperature, in-
519 stead of aerodynamic surface temperature which is difficult
520 to estimate (Jacob et al., in press). Furthermore, the tem-
521 perature difference between the soil and the foliage is taken
522 into account through the term ($c\delta T$), which is given by:

$$524 \quad \delta T = a(T_r^{\text{ASTER}} - T_a)^m \quad (12)$$

525 and

$$527 \quad c = \left[\frac{1}{1 + (r_{af}/r_{as})} \right] - f \quad (13)$$

528 Here f is the fractional vegetation cover, a and m are empir-
529 ical coefficients ($a = 0.25$ and $m = 2$).

530 Using the footprint model, EC footprint weighted aver-
531 ages for R_n^{ASTER} , G^{ASTER} and H^{ASTER} are calculated for each AS-
532 TER image acquisition. From these average values, the
533 instantaneous EF, AE and Bowen ratio are estimated on AS-
534 TER overpass as

$$AE^{\text{ASTER}} = R_n^{\text{ASTER}} - G^{\text{ASTER}} \quad (14)$$

$$EF^{\text{ASTER}} = \frac{R_n^{\text{ASTER}} - G^{\text{ASTER}} - H^{\text{ASTER}}}{R_n^{\text{ASTER}} - G^{\text{ASTER}}} \quad (15)$$

$$536 \quad \beta^{\text{ASTER}} = \frac{H^{\text{ASTER}}}{R_n^{\text{ASTER}} - G^{\text{ASTER}} - H^{\text{ASTER}}} \quad (16)$$

537 Application of the methods

538 Fig. 8a and b displays the validation of H^{ASTER} against H_{EC}
539 and of AE^{ASTER} against measured AE, for the 6 ASTER imag-
540 ery acquisitions. The corresponding RMSE values between
541 ground based and ASTER based estimates were 27 W m^{-2}
542 for H and 51 W m^{-2} for AE. From these estimates, instan-
543 taneous EF and Bowen ratio are calculated using Eqs. (15) and
544 (16). A comparison between EF^{ASTER} and EF_{EC} is shown in
545 Fig. 9, the corresponding RMSE value being 0.06. Despite
546 some scatter, results are comparable to those reported in
547 earlier studies (Crow and Kustas, 2005; Batra et al., 2006;
548 Wang et al., 2006). From the calculated Bowen ratio values,
549 it is possible to examine occurrences of wet and dry condi-
550 tions over the six days of ASTER imagery acquisition. Dry
551 conditions were observed on one day, with $\beta^{\text{ASTER}} > 1.5$.
552 On two days, wet conditions were due to irrigation events
553 within one week before ASTER overpasses, with β^{ASTER} from
554 0.7 to 0.8. On three days, conditions were intermediate,
555 with β^{ASTER} from 1.1 to 1.3.

556 Once inferred, instantaneous EF^{ASTER} is used in place of
557 EF_{Obs}^{1130} in the parameterization scheme (Eqs. (3)–(5)), to ob-
558 tain r_{EF}^{1130} and consequently the EF diurnal course $EF_{\text{Sim}}^{\text{ASTER}}$.
559 Instantaneous AE^{ASTER} is used in Eq. (7) to calculate half-
560 hourly values of $AE_{\text{Sim}}^{\text{ASTER}}$. Finally, the ET diurnal course
561 $ET_{\text{EF,Sim}}^{\text{ASTER}}$ is obtained from Eq. (6) using $AE_{\text{Sim}}^{\text{ASTER}}$ and $EF_{\text{Sim}}^{\text{ASTER}}$.
562 Fig. 10 displays the validation of $ET_{\text{EF,Sim}}^{\text{ASTER}}$. Linear regression
563 yields $ET_{\text{EF,Sim}}^{\text{ASTER}} = 0.77 ET_{\text{EC}} + 53$, with $R^2 = 0.63$ and
564 $\text{RMSE} = 48 \text{ W m}^{-2}$. These moderate performances can result
565 from 1/amplifications through the ET calculation of errors
566 on remotely sensed variables, 2/assuming daytime albedo
567 is constant which can be far from the reality (Jacob and Oli-
568 oso, 2005), or 3/the error in H and AE simulations translates

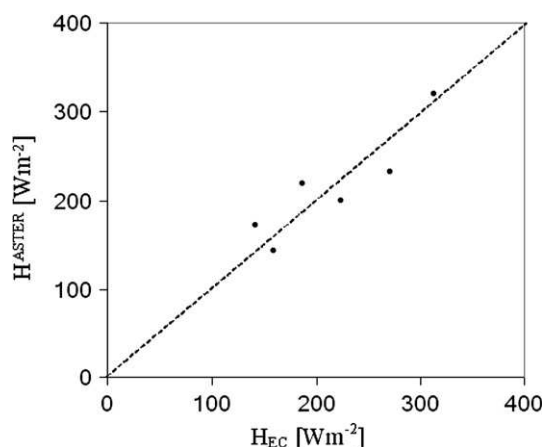


Figure 8a Comparison between sensible heat fluxes obtained from the eddy covariance system and sensible heat fluxes calculated using the model proposed by Lhomme et al. (1994) combined with ASTER thermal imagery.

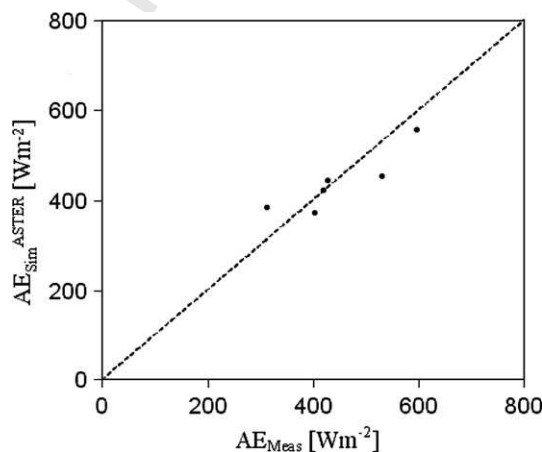


Figure 8b Comparison between measured available energy and that simulated using ASTER imagery.

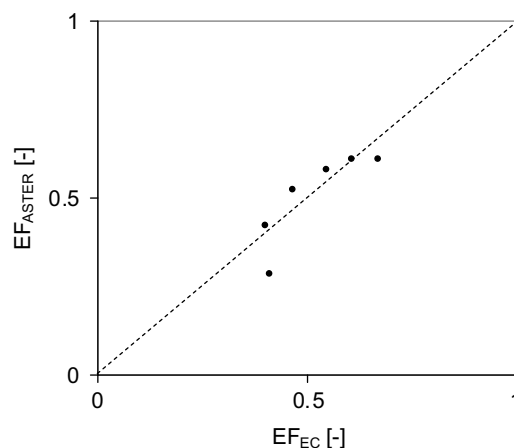


Figure 9 Eddy covariance derived evaporative fraction compared to ASTER derived evaporative fraction.

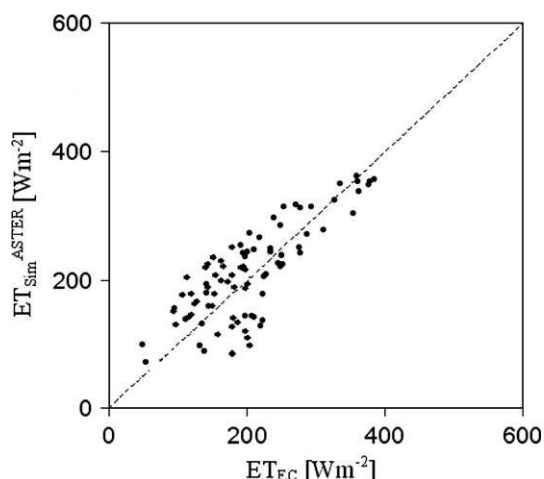


Figure 10 Latent heat fluxes measured by the EC-system compared to latent heat fluxes calculated using both proposed formulations (for the evaporative fraction and for the available energy) with ASTER data.

569 directly into error in ET since it is estimated as the residual
570 term of the energy balance equation, However, most ap-
571 proaches devoted to estimating ET from remote sensing
572 data are susceptible to comparable errors.

573 **Discussion and conclusion**

574 Sun synchronous optical remote sensing with high to moder-
575 ate spatial resolution is often used for mapping instantane-
576 ous sensible and latent heat fluxes and evaporative
577 fraction EF. The latter is often assumed to be constant
578 throughout the day, enabling the estimation of daily evapo-
579 transpiration ET provided available energy AE is known. The
580 daytime EF self preservation can be assumed under specific
581 conditions, albeit sensitive to the time when EF is mea-
582 sured. The current study shows although EF remains fairly
583 constant during daytime under dry conditions, but it depicts
584 a concave up shape under wet conditions. Since the latter
585 correspond to large evaporative fluxes, using a constant
586 EF value throughout the day induces large errors in the cal-
587 culation of daily ET.

588 Parameterizing the EF diurnal course from remotely
589 sensed instantaneous estimates is twofold, with the goal
590 of well reproducing a concave up shape under wet condi-
591 tions while EF is self preserved under dry conditions. The
592 first step integrates incoming solar radiation and relative
593 humidity, two main factors for atmospheric demand given
594 air temperature is indirectly considered through relative
595 humidity whereas the impact of wind speed is minor. By first
596 including these two atmospheric factors in the formulation,
597 the EF diurnal course is well reproduced. The second step of
598 the parameterization consists of incorporating land surface
599 condition, since soil moisture and vegetation control the EF
600 absolute value and day-to-day variations. Thus, the day to
601 day variation as well as the spatial heterogeneities is taken
602 into account by correcting EF from remotely sensed instan-
603 tantaneous ET.

604 This approach seems to include enough information on
605 both atmospheric demand and land surface conditions to ac-

count for the diurnal and day-to-day fluctuations of EF – at
at least – under the prevailing conditions over the study site.
However, this parameterization does not include the ET regu-
lation by stomatal conductance. Thus, the relationship
developed here is not universal, it needs to be assessed
for more diverse ecosystems since plants differently respond
to water stress whereas stomatal regulation depends on soil
moisture. One might indeed expect that for trees for in-
stance the physiological control on stem water storage or
release would significantly affect the diurnal course of EF.
Either the physiological control in our olive yard is mild in
potential conditions, or the empirical equation used to de-
rive the diurnal shape of EF takes into account the net ef-
fect of EF increase due to lower RH values and stomatal
closure in the afternoon. Therefore, despite this empirical
feature, the proposed approach is relevant for local applica-
tions. Indeed, its implementation over the considered
Moroccan olive orchard decreases errors on water consump-
tion estimates from 8% to 1% in relative, as compared to
assuming EF is self preserved.

The next step towards estimating daily ET is deriving the
AE diurnal course from a practical relationship. As for EF, a
heuristic approach is used, which relies on variables either
available from remote sensing data or fairly constant over
areas up to several kilometers. Thus, the AE diurnal course
is derived from remotely sensed AE when TERRA/ASTER
overpasses, to be used along with meteorological observa-
tions for incoming shortwave and long wave irradiances.
Though the proposed parameterization considers surface al-
bedo is constant, the validation emphasizes good perfor-
mances, with differences in AE lower than 30 W m^{-2} .

Once EF and AE are parameterized, the framework is ap-
plied to ASTER data, using a simple energy balance model
(Santanello and Friedl, 2003; Lhomme and Elguero, 1999).
The methodology is next applied to derive the ET diurnal
course. After analyzing the footprint configuration, valida-
tion shows performances are comparable to other methods
under similar conditions and data availabilities (Crow and
Kustas, 2005). As for remote sensing approaches devoted
to estimate daily ET, the proposed method is sensitive to er-
rors on remotely sensed parameters. However, optimal use
of in situ and remote sensing data allows a compromise be-
tween loosing (respectively gaining) local (respectively re-
gional) information. For operational applications, a
temporal sampling of few days is needed. This is currently
not possible with high spatial resolution TIR imagery, but
could be in the near future. In the meanwhile, disaggrega-
tion of low spatial resolution thermal remote sensing data
can be a possible solution; however this issue is still subject
of ongoing investigations. Finally, it is of interest to mention
that this proposed method has been recently applied to a
mosaic of agricultural fields in northern Mexico to very
encouraging results (Chehbouni et al., 2007c).

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