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How representative are instantaneous evaporative fraction measurements of daytime fluxes?

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Abstract. Sun-synchronous optical and thermal remote sensing is a promising technique to provide instantaneous ET (evapotranspiration) estimates during satellite overpass. The common approach to extrapolate the instantaneous estimates to values for daily or longer periods relies on the assumption that the EF (evaporative fraction, defined as the ratio of latent heat flux to surface available energy) remains nearly constant during daytime. However, there is still no consensus on the validity of the self-preservation of the EF. We use FLUXNET (a global network of eddy covariance stations) measurements to examine this self-preservation, and the conditions under which it can hold. It is found that the instantaneous EF could represent daytime EF under clear sky conditions, especially between 11:00 and 14:00 LT (local time) for all stations. However, the results show that the EF is more variable during cloudy sky conditions, so that an increase in cloud cover results in an increase in the variability of the EF during daytime.

1 Introduction

Estimates of land surface ET (evapotranspiration) are crucial for better understanding climate and hydrological interactions (Jung et al., 2010; Oki and Kanae, 2006). Over the last few decades, numerous physical and empirical remote sensing-based models that vary in complexity have been proposed to estimate ET. Most of them provide instantaneous ET estimates at the time of satellite overpass. For a review, see, e.g., Kalma et al. (2008) and Wang and Dickinson (2012). In order to acquire ET values over daily or longer time periods, there is a need to extrapolate instantaneous to daily values (Chávez et al., 2008). The most widely used method is the assumption of daytime self-preservation of EF (Evaporative Fraction) (Sugita and Brutsaert, 1991; Brutsaert and Sugita, 1992; Crago and Brutsaert, 1996). The EF is normally a diagnostic of surface energy balance and defined as the fraction of available energy partitioned toward latent heat flux. Theoretically, the EF is supposed to isolate vegetation and soil control from other factors in the determination of surface energy balance components. Furthermore, it can remove the daily sinusoidal-like variations of the latent heat flux and sensible heat flux at the land surface, and it remains almost constant during daytime under clear sky conditions (Gentine et al., 2007, 2011; Li et al., 2008) (Fig. 1). Shuttleworth et al. (1989), Nichols and Cuenca (1993) and Crago and Brutsaert (1996) used in situ measurements of surface energy balance components and showed that the EF is nearly constant during daytime under clear sky days. Model studies by Lhomme and Elguero (1999) and Gentine et al. (2007) found that daytime self-preservation of the EF is only satisfied under limited environmental conditions. Hoedjes et al. (2008) found that the EF remains fairly constant under dry conditions and presents a pronounced concave-up shape under wet conditions. However, most of the above studies are generally based on measurements from relatively short time periods and across a small range of environmental and climatological conditions. Since the daytime constant EF assumption is the basis for extrapolating instantaneous ET estimates to daily values, whether it holds or not is a fundamental issue

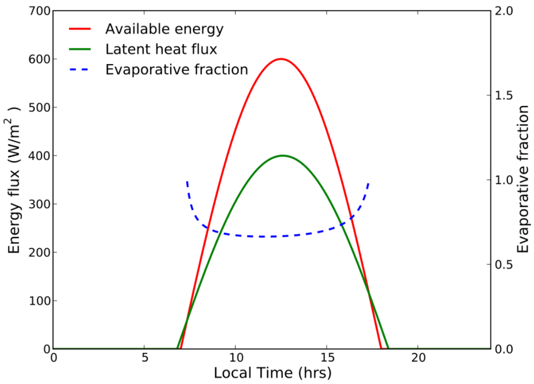

Fig. 1. Conceptual framework for the diurnal variations of surface energy components and EF. The solid red line represents surface available energy, the solid green line represents latent heat flux, and the dashed blue line represents EF.

for the satellite-based temporal extrapolation applications. The objective of this paper is to further examine how representative instantaneous EF measurements are of daytime values. To address this question, long-term time series of data from a global network of EC (eddy covariance) stations (FLUXNET) are analyzed across a wide range of ecosystems and climates. In order to systematically examine the self-preservation of the EF under different cloud cover conditions, we classify the cloud cover into clear sky, partly cloudy, and cloudy conditions. For practical hydrological applications, estimates of actual ET should represent both clear sky and cloudy conditions. However, fully clear sky conditions are rarely found in satellite applications, and depend greatly on the spatial scale of the observing system. The classification into clear sky and cloudy conditions therefore provides additional information on the uncertainty resulting from cloudy conditions for the EF daytime estimates. Taking advantage of the wide coverage of biomes of the FLUXNET sites, the influences of biome types on the self-preservation of the EF is also investigated to provide additional insight into the robustness of the EF representativeness.

2 Data and methods

The FLUXNET methodology and review papers can be found in the work of Aubinet et al. (1999), Baldocchi et al. (2001) and Baldocchi (2008). There are a total of seventy-two FLUXNET sites over a variety of vegetation types and geographic locations used in the present study (Table 1; Fig. 2). For each site, in situ measurements (non gap-filled) of net radiation, ground heat flux, latent heat flux and sensible heat flux are used to test the EF self-preservation hypothesis. These measurements are half-hourly measured and quality controlled. More information about the selected sites is given in Table 1. Energy balance closure is an important criterion for evaluating the quality of measured heat fluxes from EC

Table 1. Summary of the FLUXNET sites used in this study. More site information can be found at http://www.fluxdata.org/.

Site	Biome type	Elevation (m)	Years
CASF3	Closed shrublands	540	2003–2005
USLos	Closed shrublands	480	2001–2005
CAMer	Croplands	70	1998–2005
USGoo	Croplands	87	2002–2006
NLLut	Croplands	TBD	2006–2006
USBkg	Croplands	510	2004–2006
USBo1	Croplands	219	1996–2007
USNe1	Croplands	361	2001–2005
USNe2	Croplands	362	2001–2005
USNe3	Croplands	363	2001–2005
DEHai	Deciduous broadleaf forests	430	2000–2007
FRHes	Deciduous broadleaf forests	300	1997–2008
ITRo1	Deciduous broadleaf forests	235	2000–2006
ITRo2	Deciduous broadleaf forests	224	2002–2006
USBar	Deciduous broadleaf forests	272	2004–2005
USHa1	Deciduous broadleaf forests	340	1991–2006
USMMS	Deciduous broadleaf forests	275	1999–2005
USUMB	Deciduous broadleaf forests	234	1999–2003
USWCr	Deciduous broadleaf forests	520	1999–2006
AUTum	Evergreen broadleaf forests	1200	2001–2006
FRPue	Evergreen broadleaf forests	270	2000–2008
PTEsp	Evergreen broadleaf forests	95	2002–2008
ZMMon	Evergreen broadleaf forests	1053	2000–2009
CAMan	Evergreen needleleaf forests	259	1994–2003
CANS1	Evergreen needleleaf forests	260	2002–2005
CANS2	Evergreen needleleaf forests	257	2001–2005
CANS3	Evergreen needleleaf forests	258	2001–2005
CANS4	Evergreen needleleaf forests	260	2002–2003
CANS5	Evergreen needleleaf forests	254	2001–2005
CASF1	Evergreen needleleaf forests	536	2003–2005
CZBK1	Evergreen needleleaf forests	908	2000–2008
DETha	Evergreen needleleaf forests	380	1996–2003
DEWet	Evergreen needleleaf forests	785	2002–2008
FIHyy	Evergreen needleleaf forests	181	1996–2008
FISod	Evergreen needleleaf forests	180	2000–2008
FRLBr	Evergreen needleleaf forests	61	1996–2003
ILYat	Evergreen needleleaf forests	650	2001–2003
ITRen	Evergreen needleleaf forests	1730	1999–2008
ITSRo	Evergreen needleleaf forests	4	1999–2008
NLLoo	Evergreen needleleaf forests	25	1996–2008
RUFyo	Evergreen needleleaf forests	265	1998–2008
SESk2	Evergreen needleleaf forests	55	2004–2005
UKGri	Evergreen needleleaf forests	340	1997–2006
USBlo	Evergreen needleleaf forests	1315	1997–2006
ATNeu	Grasslands	970	2002–2007
CASF2	Grasslands	520	2003–2005
CHOe1	Grasslands	450	2002–2003
DEGri	Grasslands	385	2004–2009
HUBug	Grasslands	140	2002–2008
NLCa1	Grasslands	0.7	2003–2008
USARM	Grasslands	314	2003–2006
USAud	Grasslands	1469	2002–2006
USFPe	Grasslands	634	2000–2006
BEBra	Mixed forests	16	1997–2008
BEVie	Mixed forests	450	1996–2008
CHLae	Mixed forests	689	2004–2008
DEMeh	Mixed forests	286	2003–2006

Table 1. Continued.

Site	Biome type	Elevation (m)	Years
DKSor	Mixed forests	40	1996–2008
ITLav	Mixed forests	1353	2000–2002
ITNon	Mixed forests	25	2001–2003
UKESa	Mixed forests	97	2003–2005
USHo1	Mixed forests	60	1996–2004
USHo2	Mixed forests	91	1999–2004
USSyv	Mixed forests	540	2002–2006
CANS6	Open shrublands	260	2001–2005
CANS7	Open shrublands	297	2002–2005
ITPia	Open shrublands	18	2002–2003
BWMa1	Savannas	950	1999–2001
AUFog	Woody savannas	27	2006–2007
AUHow	Woody savannas	41	2001–2006
USTon	Woody savannas	177	2001–2006
USVar	Woody savannas	129	2001–2006

systems. However, flux towers typically do not exhibit energy closure because of systematic bias in instrumentation, mismatch in source areas, neglected energy sinks, and landscape heterogeneity (Foken et al., 2011; Twine et al., 2000; Wilson et al., 2002). In this study, the Bowen ratio correction method recommended by Twine et al. (2000) is used to adjust EC-measured heat fluxes to constrain energy balance closure.

The instantaneous EF (dimensionless) is then calculated from the corrected instantaneous latent heat and sensible heat flux values as follows:

$$\mathrm{EF}(t) = \frac{\mathrm{LE}(t)}{R_\mathrm{n}(t) - G(t)} = \frac{\mathrm{LE}(t)}{\mathrm{LE}(t) + H(t)}, \tag{1}$$

where R_n is the surface net radiation ($\mathrm{W\,m^{-2}}$), G is the ground heat flux ($\mathrm{W\,m^{-2}}$), LE is the latent heat flux ($\mathrm{W\,m^{-2}}$) and H is the sensible heat flux ($\mathrm{W\,m^{-2}}$). In addition, the daytime EF is determined by the following equation:

$$\mathrm{EF}_\mathrm{daytime} = \frac{\int_{t_1}^{t_2} \mathrm{LE}(t)\,\mathrm{d}t}{\int_{t_1}^{t_2} [R_\mathrm{n}(t) - G(t)]\,\mathrm{d}t} = \frac{\int_{t_1}^{t_2} \mathrm{LE}(t)\,\mathrm{d}t}{\int_{t_1}^{t_2} [H(t) + \mathrm{LE}(t)]\,\mathrm{d}t} \tag{2}$$

where the time difference t_2–t_1 refers to the time from 08:00 to 17:00 LT in the present study. In order to evaluate the relationship between instantaneous EF and daytime EF, the statistics metrics of R^2 (coefficient of determination), RMSD (root mean square difference) and RE (relative error) are chosen in this study.

Considering the effects of clouds on the stability of the EF, previous studies have not drawn consistent conclusions. For example, Hall et al. (1992) suggested that cloudiness-induced variations in net radiation should not affect the EF significantly, whereas Crago and Brutsaert (1996) attributed variations in the EF to cloudiness. In this study, the effects of different clouds cover on EF are analyzed. The clearness index K_T (the ratio of the global solar radiation measured at the surface to the total solar radiation at the top of the atmosphere) (Liu and Jordan, 1960; Okogbue et al., 2009) is used to perform the sky conditions classification. In order to examine the effects of cloudiness on the EF self-preservation, K_T values of $0 \leq K_\mathrm{T} \leq 0.15$, $0.15 < K_\mathrm{T} \leq 0.65$ and $0.65 < K_\mathrm{T} \leq 1$ are used to define cloudy, partly cloudy and clear sky conditions, respectively.

3 Results and discussion

3.1 Influence of sky conditions

In order to find the relationships between instantaneous EF and daytime EF under clear sky conditions, statistical results between the EF at different time periods and daytime EF are illustrated in Fig. 3a. These results are analyzed based on all seventy-two FLUXNET sites to reach more general conclusions. Figure 3a shows the box plots of R^2, RMSD and RE respectively for the relationships between instantaneous EF and daytime EF. In general, the EF at different time periods of the day agrees well with daytime EF except for the 08:00 to 09:00 LT and 16:00 to 17:00 LT periods. The relatively low R^2 and high RMSD and RE values for these time periods indicate the large variations in EF in the early morning and late afternoon. This agrees with Rowntree (1991) and Nichols and Cuenca (1993), who found that the EF at low levels of radiation loading was higher than through the midday period. From 11:00 to 14:00 LT, the minimum R^2 value is higher than 0.75, the maximum RMSD is less than 0.087, and RE is in the range from −10.15 to 3.79 %. These statistics indicate that EF during these time periods is close to the daytime EF. The midday (12:00 to 13:00 LT) EF is closest to daytime EF with $R^2 = 0.920 \pm 0.053$, RMSD = 0.050 ± 0.013, RE = $-4.47\,\% \pm 2.48\,\%$. A similar result was found by other authors (e.g., Farah et al., 2004). A possible reason for such a result is that energy fluxes change at a slower rate compared to early morning and late afternoon. Since the analysis is based on long-term FLUXNET measurements under a wide range of surfaces and environmental and climate conditions, we conclude that the instantaneous EF can generally represent daytime EF under clear sky conditions, especially from 11:00 to 14:00 LT. This EF self-preservation can also be explained from a physical perspective. The EF during daytime mainly depends on land surface properties such as vegetation amount, soil moisture and surface resistance to heat and momentum transfer. Most of them tend to vary slowly during daytime compared to other fast-changing variables (e.g., surface temperature, radiation). In summary, the above results confirm that the self-preservation of EF can be used to

Table 2. Statistical results for the comparisons between midday EF and daytime EF over different biome types.

Biome type	R^2	RMSD	Relative error (%)	Sample size
Croplands	0.954 ± 0.026	0.051 ± 0.008	-2.81 ± 1.50	8
Deciduous broadleaf forests	0.956 ± 0.034	0.043 ± 0.008	-4.48 ± 1.64	9
Evergreen needleleaf forests	0.904 ± 0.053	0.051 ± 0.014	-5.40 ± 1.35	21
Grasslands	0.901 ± 0.062	0.053 ± 0.015	-2.01 ± 3.62	9
Mixed forests	0.902 ± 0.052	0.054 ± 0.013	-4.70 ± 2.03	11
Woody savannas	0.946 ± 0.028	0.041 ± 0.010	-4.05 ± 0.93	4
Savannas	0.966 ± 0.000	0.042 ± 0.000	-11.15 ± 0.00	1
Open shrublands	0.915 ± 0.063	0.049 ± 0.019	-7.12 ± 1.60	3
Closed shrublands	0.968 ± 0.016	0.035 ± 0.002	-2.06 ± 0.67	2
Evergreen broadleaf forests	0.894 ± 0.031	0.053 ± 0.011	-5.63 ± 1.53	4
All types	0.920 ± 0.053	0.050 ± 0.013	-4.47 ± 2.48	72

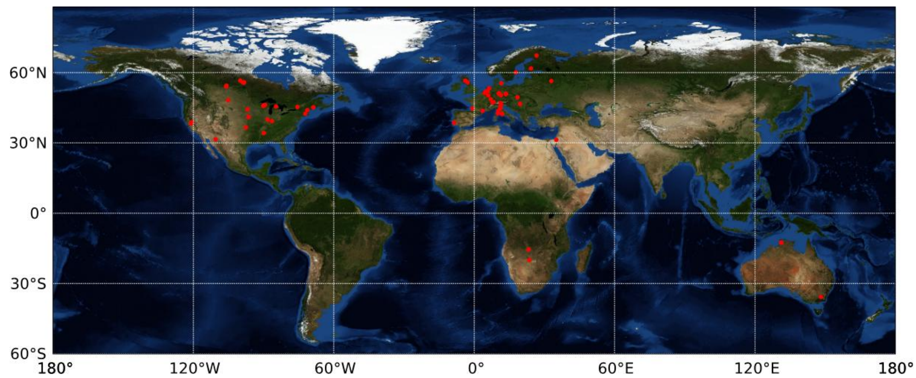

Fig. 2. The locations of the seventy-two FLUXNET sites used in this study (solid red circles).

calculate daytime ET from instantaneous estimates based on sun-synchronous satellite observations during clear sky conditions. Because the midday EF is closest to daytime EF, the midday overpass satellites (e.g., MODIS and AVHRR) are expected to provide better results than platforms which have an overpass time in the morning or late afternoon (e.g. Landsat). However, the self-preservation of the EF should be used with caution. The negative RE values ($-4.47\,\% \pm 2.48\,\%$) suggest that the midday EF tends to slightly underestimate daytime EF, due to the concave shape of the diurnal variation of the EF (Brutsaert and Sugita, 1992; Crago, 1996; Sugita and Brutsaert, 1991).

Figures 3b and c display the performance of the EF constant assumption under different cloud cover conditions. It can be seen that the stability of the EF is related to cloudiness. The EF is more variable under partly cloudy conditions compared to clear sky conditions. From 11:00 to 14:00 LT, the minimum R^2 value decreases to 0.56, the maximum RMSD increases to 0.139, and RE is in the range from -5.55 to 13.10 %. These statistics indicate that an increase in cloud cover results in an increase in the variability of the EF during daytime. For total cloud cover, the R^2 values between instantaneous EF in different time periods and daytime EF obviously decrease as compared to clear skies. Poorer RMSD and RE are also obtained at the same time. This is because cloudiness causes significant fluctuations in the available energy and the rate of surface heating, which further leads to variability in both instantaneous EF and daytime EF. Thus, the EF tends to be more variable during cloudy sky conditions. It is necessary to consider the effects of cloudiness when the EF self-preservation assumption is used to upscale instantaneous estimates to continuous longer time periods (Brutsaert and Sugita, 1992; Van Niel et al., 2012). The above results provide additional information on the uncertainty resulting from cloudy sky conditions for the EF daytime estimates.

3.2 Influence of biome types

As the FLUXNET sites cover a wide range of climates and biome types (croplands, deciduous broadleaf forests, evergreen needleleaf forests, grasslands, mixed forests, woody savannas, savannas, open shrublands, closed shrublands, and evergreen broadleaf forests), we investigate the influences of biome types on the self-preservation of the EF. Table 2 gives a comprehensive summary of the statistical metrics

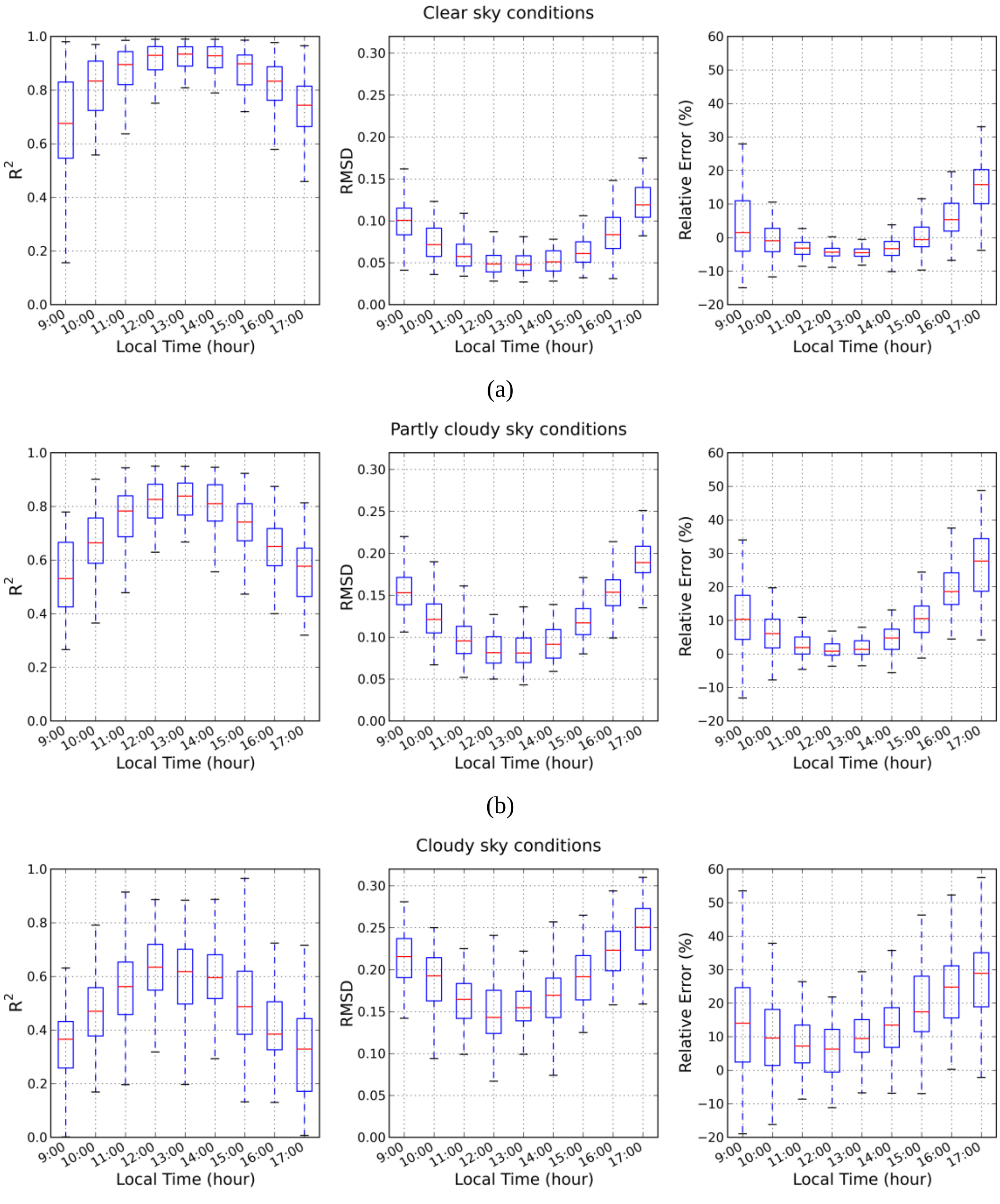

Fig. 3. Box plots of statistical results for the comparisons between instantaneous EF at different times of day and daytime EF for all the FLUXNET sites (number = 72) under different sky conditions: **(a)** clear sky; **(b)** partly cloudy sky; and **(c)** cloudy sky. Each box covers the range between the 0.25 and the 0.75 quartile, the median value is drawn as a horizontal red line, and the whiskers indicate the range of the data within the maximum and the minimum values.

for the comparisons between midday EF and daytime EF for different biome types. It can be observed that the self-preservation of the EF over different biome types has similar performances with R^2 higher than 0.894, RMSD lower than 0.054, and RE less than 11.15 %. The detailed comparison results between instantaneous EF at different time periods, and daytime EF over different biome types are provided in supplementary material Fig. 1. Therefore, little evidence was found from the above results based on FLUXNET data that the biome type affects the self-preservation of the EF.

4 Conclusions

The commonly used method to extrapolate remote sensing-based instantaneous EF to daily values is to assume constant EF during daytime (so-called daytime self-preservation). However, evidence for this constant EF approach is based on limited duration field measurements. Taking advantage of a global network of long-term ground-based measurements from FLUXNET, the daytime EF constant hypothesis is examined here. It is found that the EF during daytime from 11:00 to 14:00 LT agrees well with daytime EF under clear sky conditions ($R^2 > 0.75$, RMSD < 0.087, $-10.15\,\% <$ RE $< 3.79\,\%$), and the midday (12:00 to 13:00 LT) EF is closest to daytime EF with $R^2 = 0.920 \pm 0.053$, RMSD $= 0.050 \pm 0.013$, RE $= -4.47\,\% \pm 2.48\,\%$. However, the EF is more variable during cloudy conditions when compared to clear sky conditions, and an increase in cloud cover results in an increase in the variability of the EF during daytime. Thus the EF constant hypothesis is strictly true only for clear sky conditions. Nonetheless, the above results provide a basis for remote sensing-based estimation of the EF based on sun-synchronous satellite observations. The midday overpass satellites (e.g., MODIS and AVHRR) are expected to give better results than other overpass time platforms. The important conclusion from the present study is that the EF constant assumption is valid over a wide range of ecosystems and climates.

Supplementary material related to this article is available online at http://www.hydrol-earth-syst-sci.net/17/3913/2013/hess-17-3913-2013-supplement.pdf.

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