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Discussions

How representative are instantaneous evaporative fraction measurements for daytime fluxes?

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Abstract

Sun synchronous optical 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 EF. We used 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 here that the instantaneous EF could represent daytime EF under clear-sky conditions especially between 11:00 and 14:00 LT for all the stations. However, the EF is more unstable during cloudy skies. The increase in cloud cover would result in the increase in the variability of EF during daytime. Future works will focus on the evaluation of this EF constant assumption using real remote sensing data over different surface and climate conditions.

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 (Kalma et al., 2008; 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) (Delogu et al., 2012). 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 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 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 EF is only satisfied under limited environmental conditions. Hoedjes et al. (2008) found that 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 to the satellite-based temporal extrapolation applications. The objective of this paper is to further examine how representative instantaneous EF measurements are for daytime values. To address this question, long term time series of data from a global network of EC (Eddy Covariance) stations (FLUXNET) were analyzed across a wide range of ecosystems and climates.

2 Data and methods

The FLUXNET methodology and review papers could be found in the work of Aubinet et al. (2000), 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. 1). For each site, in situ measurements of net radiation, ground heat flux, latent heat flux and sensible heat flux were used to test the EF self preservation hypothesis. Table 1 shows the years of data analyzed in this study. Energy

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balance closure is an important criterion for evaluating the quality of measured heat fluxes from EC 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) was used to adjust Eddy covariance measured heat fluxes to constrain energy balance closure.

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

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

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

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

where the time difference $t_2 - t_1$ refers to the time from 08:00 to 17:00 LT (local time) in the present study. In order to evaluate the relationship between instantaneous EF and daytime EF, the statistics indices of R^2 (coefficient of determination) and RMSD (Root mean square difference) are chosen in this study.

Considering the effects of clouds on the stability of EF, previous studies have no consensus opinions. For example, Hall et al. (1992) suggested that cloudiness induced

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variations in net radiation should not affect EF significantly, whereas Crago and Brutsaert (1996) attributed variations of EF to cloudiness. In this study, the effects of different clouds cover on EF were analyzed. The widely used 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) was used to perform the sky conditions classification. In order to examine the effects of cloudiness on the EF self preservation, K_T values of $0 \leq K_T \leq 0.15$, $0.15 < K_T \leq 0.65$, $0.65 < K_T \leq 1$ were used to define cloudy, partly cloudy and clear-sky conditions.

3 Results and discussion

In order to find the relationship between instantaneous EF and daytime EF under clear sky conditions, statistical results between the EF in different time periods and daytime EF are illustrated in Fig. 3. These results were analyzed based on all the seventy-two FLUXNET sites to obtain more general conclusions. Figure 3a showed the box plots of R^2 and RMSD, respectively for the relationships between instantaneous EF and daytime EF. In general, EF in different time periods of daytime agree well with daytime EF except the period of 08:00–09:00 LT and 16:00–17:00 LT. In 11:00–14:00 LT, the minimum R^2 value is higher than 0.75, and the maximum RMSD is less than 0.087. These statistics indicate that EF during these time periods is closer to daytime EF. The best correlation between instantaneous EF and daytime EF appears at midday (12:00–13:00 LT). The possible reason for such result is that energy fluxes change at a slower rate compared to early morning and late afternoon. Since the analysis was based on long term FLUXNET measurements under a wide range of surface, environmental and climate condition, we conclude that the instantaneous EF could generally represent daytime EF under clear-sky conditions especially from 11:00 to 14:00 LT. This EF self preservation could 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

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them tend to vary slowly during daytime compared to other fast changing variables (e.g. surface temperature, radiation). In summary, the above results have strong implications for daily ET studies based on sun synchronous satellite observations. And the midday overpass satellites (e.g. MODIS and AVHRR) would provide better results than other overpass time platforms (e.g. Landsat).

Figure 3b, c displayed the performance of EF constant assumption under different cloud cover conditions. It can be seen that the stability of EF is related to cloudiness. The EF exhibited more unstable under partly cloudy situations compared with clear skies. The variability of EF increased with the increase in cloudiness. For total cloud cover the R^2 values between instantaneous EF in different time periods and daytime EF obviously went down as compared to clear skies. Poorer RMSD were also obtained at the same time. This is because cloudiness could induce a decrease in the available energy and the latent heat flux, which further causes the increase in both instantaneous EF and daytime EF. But these increases are probably in different degrees. Thus, the EF tends to be more unstable during cloudy skies. Nevertheless, the above results have no substantial influence on the remote sensing applications, since optical satellites only provide useful data under clear sky conditions.

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 is nearly constant under clear sky conditions ($R^2 > 0.75$, RMSD < 0.087), and the EF in 12:00–13:00 LT is almost equal to daytime EF. However, the EF is more unstable during cloudy conditions when compared to clear skies, and the variability of EF increased with the increase

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in cloudiness. Thus the EF constant hypothesis might only be true for clear skies. Nonetheless, the above results provide a basis for remote sensing-based estimation of EF based on sun synchronous satellite observations. The midday overpass satellites (e.g. MODIS and AVHRR) are supposed 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. Evaluation of this EF constant method will be carried out using real remote sensing data around global FLUXNET sites in the future.

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

Site	Biome type	Elevation (m)	Year
ATNe	Grassland	970	2002–2007
AUFo	Woody Savannas	27	2006–2007
AUHo	Woody Savannas	41	2001–2006
AUTu	Evergreen Broadleaf Forest	1200	2001–2006
BEBr	Mixed Forest	16	1997–2008
BEVi	Mixed Forest	450	1996–2008
BWMa	Savanna	950	1999–2001
CAMa	Evergreen needleleaf forest	259	1994–2003
CAMe	Cropland	70	1998–2005
CANS	Evergreen needleleaf forest	260	2002–2005
CANS	Evergreen needleleaf forest	257	2001–2005
CANS	Evergreen needleleaf forest	258	2001–2005
CANS	Evergreen needleleaf forest	260	2002–2003
CANS	Evergreen needleleaf forest	254	2001–2005
CANS	Open Shrubland	260	2001–2005
CANS	Open Shrubland	297	2002–2005
CASF	Evergreen needleleaf forest	536	2003–2005
CASF	Grassland	520	2003–2005
CASF	Closed Shrublands	540	2003–2005
CHLae	Mixed Forest	689	2004–2008
CHOe1	Grassland	450	2002–2003
CZBK1	Evergreen needleleaf forest	908	2000–2008
DEGri	Grassland	385	2004–2009
DEHai	Deciduous broadleaf forest	430	2000–2007
DEMeh	Mixed Forest	286	2003–2006
DETha	Evergreen needleleaf forest	380	1996–2003
DEWet	Evergreen needleleaf forest	785	2002–2008
DKSor	Mixed Forest	40	1996–2008
FIHyy	Evergreen needleleaf forest	181	1996–2008
FISoel	Evergreen needleleaf forest	180	2000–2008
FRHes	Deciduous broadleaf forest	300	1997–2008
FRLBs	Evergreen needleleaf forest	61	1996–2003
FRPur	Evergreen broadleaf forest	270	2000–2008
HUBue	Grassland	140	2002–2008
ILYat	Evergreen needleleaf forest	650	2001–2003
ITLav	Mixed Forest	1353	2000–2002
ITNon	Mixed Forest	25	2001–2003

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Table 1. Continued.

Site	Biome type	Elevation (m)	Year
ITPia	Mediterranean macchia	18	2002–2003
ITRen	Evergreen needleleaf forest	1730	1999–2008
ITRo1	Deciduous broadleaf forest	235	2000–2006
ITRo2	Deciduous broadleaf forest	224	2002–2006
ITSRo	Evergreen needleleaf forest	4	1999–2008
NLCa1	Grassland	0.7	2003–2008
NLLoo	Evergreen needleleaf forest	25	1996–2008
NLLut	Croplands	TBD	2006–2006
PTEsp	Evergreen broadleaf forest	95	2002–2008
RUFyo	Evergreen needleleaf forest	265	1998–2008
SESk2	Evergreen needleleaf forest	55	2004–2005
UKESa	Mixed Forest	97	2003–2005
UKGri	Evergeen coniferous forests	340	1997–2006
USARM	Grassland	314	2003–2006
USAud	desert grassland	1469	2002–2006
USBar	Temperate northern hardwood forest	272	2004–2005
USBkg	Croplands	510	2004–2006
USBlo	Evergreen needleleaf forest	1315	1997–2006
USBo1	Croplands	219	1996–2007
USFPe	Grassland	634	2000–2006
USGoo	Cropland	87	2002–2006
USHa1	Deciduous broadleaf forest	340	1991–2006
USHo1	Mixed Forest	60	1996–2004
USHo2	Mixed Forest	91	1999–2004
USLos	Alder-willow shrub wetland	480	2001–2005
USMMS	Mixed hardwood deciduous forest	275	1999–2005
USNe1	Croplands	361	2001–2005
USNe2	Croplands	362	2001–2005
USNe3	Croplands	363	2001–2005
USSyv	Old-growth hemlock-hardwood forest	540	2002–2006
USTon	Woody Savannas	177	2001–2006
USUMB	Deciduous Broadleaf Forest	234	1999–2003
USVar	Woody Savannas	129	2001–2006
USWCr	Deciduous broadleaf forest	520	1999–2006
ZMMon	Evergreen forest	1053	2000–2009

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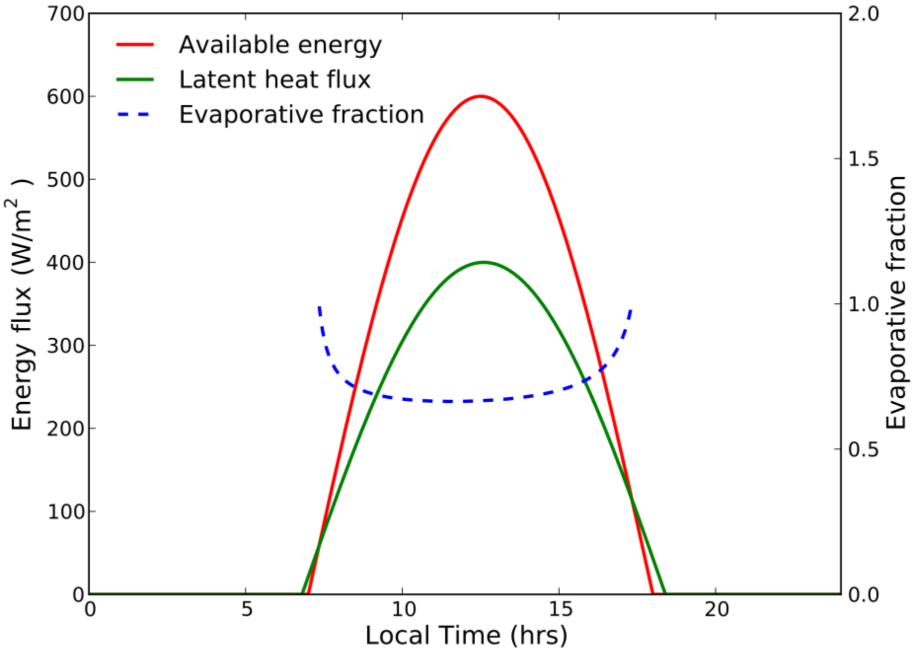

Fig. 1. Conceptual framework for the diurnal variations of surface energy components and EF. Solid red line represents surface available energy, solid green line represents latent heat flux, and dashed blue line represents EF.

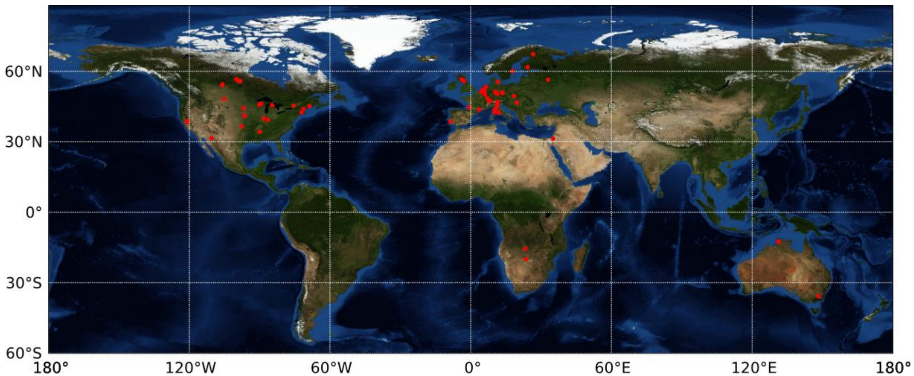

Fig. 2. The seventy-two FLUXNET sites locations (solid red circle).

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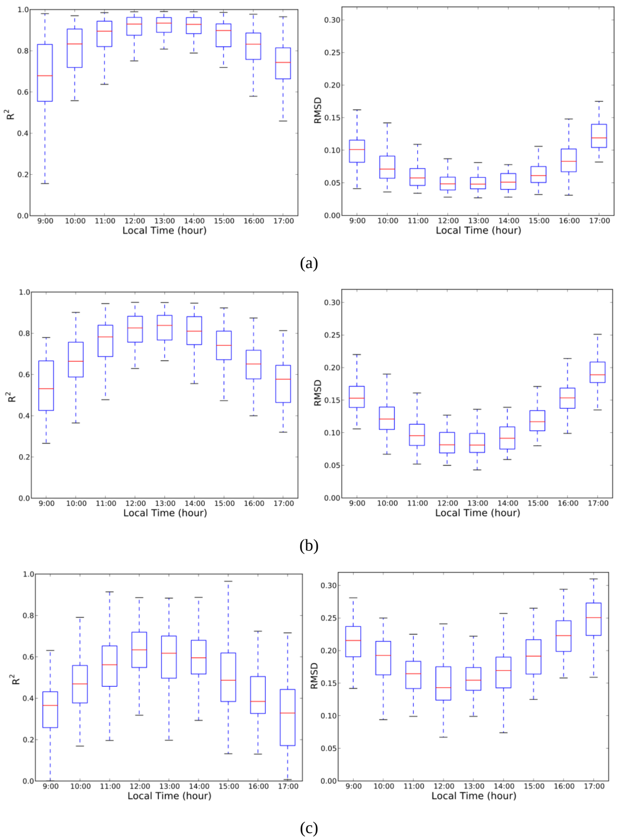

Fig. 3. Box plots of statistical results for the comparison between instantaneous EF in different time of daytime and daytime EF for all the FLUXNET sites (number = 72) under different sky conditions: **(a)** clear sky conditions; **(b)** partly cloudy sky conditions; and **(c)** cloudy sky conditions. Each box lies between the 0.25 and the 0.75 quartile, with the median value inside, and the whiskers indicate the range of the data within the maximum and the minimum values.

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