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Evaluation of Algorithms to estimate Daily Evapotranspiration from Instantaneous Measurements under All-sky Conditions

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Abstract. Instantaneous EvapoTranspiration (ET) can be estimated using a single set of instantaneous observations by polar orbiting satellites during the day. Daily, weekly or monthly total ET is required for hydrological studies and water resources assessment. This requires daily total ET regardless of cloud cover. The daily total ET is usually determined assuming that the evaporative fraction (EF) remains constant during at least the central hours of the day and that the product of EF times the daily total net radiation gives a satisfactory estimate of daily total ET. The impact of cloud cover is rarely discussed. In this paper, we used data collected at two experimental sites in the Heihe River basin in northwestern China: Arou with grassland in an alpine region and Yingke with agricultural crops in a semi-arid region. Two methods were evaluated to determine daily total ET with instantaneous observations: a) self-conservation of evaporative fraction (EF_const); b) assuming the diurnal course of ET is the same sinusoidal function of the time of the instantaneous observation as the solar irradiance (R_s) (ET-R_s). Daily ET calculated with the two methods were evaluated against observed daily values. The results showed that these assumptions did not hold and the accuracy of ET estimates obtained with either method was reduced by: a) diurnal variation of ET and b) the time lag between ET and net radiation under clear skies. Larger errors occurred when applying both methods under cloudy conditions during the growing season, while in the remaining part of the year the impact of cloud cover was lower.

1. Introduction

Evapotranspiration (ET) is an important component of the terrestrial water cycle, and accurate estimation of regional daily ET is essential in hydrology, agriculture and climatology. ET cannot be directly measured over large areas and methods have been developed [1, 2] to use remote sensing data, e.g. land surface temperature (LST), to estimate ET over large areas. A variety of ET models [3, 4] have been developed, from simple empirical relationships (e.g. [5]) to complex analytical approaches (e.g. [1]). Most of these models exploit polar orbiting satellite data with a higher spatial resolution, but lower observation frequency (one observation per day or less). As a result, instantaneous observations have to be extrapolated in time to estimate daily total ET. Literature documents the use of methods based on the hypothesis of constant evaporative fraction, EF (see e.g. [6]) or on assuming that ET and solar irradiance R_s have a similar diurnal evolution, which on clear days can described by a sine

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function of the acquisition time of the instantaneous observations [7]. Some studies, however, have documented a diurnal variation of the evaporative fraction [8, 9]. Intermittent cloud cover leads to a complex diurnal of both ET and R_s, but this aspect has not received sufficient attention in literature.

In this paper, we evaluated two widely used algorithms to estimate daily total ET with one-time-of-day instantaneous measurements of LST under different cloud cover conditions. We used ground measurements for both the instantaneous observations and the daily total ET. This experimental set up guarantees that any difference between estimated and observed daily total ET is only due to the extrapolation method. The data were collected at two sites, Arou and Yingke, in the framework of the WATER experiment [10].

2. Methodology

2.1 The EF constant method

The EF constant method (denoted as EF_const) is based on the assumption that the evaporative fraction (EF) is constant during daytime hours, where EF is defined as:

$$EF_i = LE_i \,/\, (R_n - G)_i \tag{1}$$

where *i* indicates the instantaneous measurement, LE is latent heat flux (W/m^2), R_n is net radiation (W/m^2), G is soil heat flux (W/m^2). Over land, the daily mean soil heat flux is close to zero, i.e. the downward flux in daytime and the upward flux at night balance each other approximately. This leads to the equation to calculate the total daily ET from one instantaneous observation:

$$ET_d = 8.64 \times 10^7 \cdot EF_i \cdot \frac{R_{ndaily} - G_{daily}}{\lambda \cdot \rho_w} = EF_i \cdot \frac{R_{n24}}{\lambda \cdot \rho_w} \tag{2}$$

where R_{ndaily} is the daily mean net radiation (W/m^2), G_{daily} is the daily mean soil heat flux (W/m^2), λ is latent heat of vaporization (MJ kg^{-1}or10^{6}Ws kg^{-1}), ρ_w is water density (1000kg m^{-3}). R_{n24} is the total net radiation of a day (MJm^{-2}day^{-1}).

2.2 The ET-R_s method

The second method, denoted as the ET-R_s method, is based on the assumption that ET and solar irradiance R_s have a similar diurnal evolution, which on clear days can described by a sine function of the acquisition time of the instantaneous observation [7]. The ratio of daily total solar irradiance (S_d) to instantaneous solar irradiance (S_i) at time *t* is given by

$$J = S_d \,/\, S_i = \int_0^N S_m sin(\pi t \,/\, N)dt \,/\, S_m \cdot sin(\pi t \,/\, N) = 2N \,/\, [\pi sin(\pi t \,/\, N)] \tag{3}$$

where S_m is the maximum solar irradiance at solar noon (W/m^2), *t* is elapsed time past sunrise (h), *N* is daylight duration (h). Then under the similarity assumption on ET and solar irradiance, daily total ET_d is estimated as:

$$ET_d = ET_i \cdot J = ET_i \cdot [2N \,/\, \pi sin(\pi t \,/\, N)] \tag{4}$$

The daytime period N can be calculated from Julian day and latitude.

In addition, the measured value of the 24h total ET was calculated by integrating 30-min instantaneous latent heat flux acquired by an EC system:

$$ET_{dm} = \sum_0^{47} ET_i \times \Delta t \tag{5}$$

3. Data

For this study we used meteorological data and ground measurements of radiative and turbulent heat fluxes by eddy covariance (EC) systems and automatic weather stations (AWS) at two sites (Arou & Yingke) in the Heihe river basin during the field experiment Watershed Allied Telemetry Experiment Research (WATER) [10]. The Arou site is located at 100°27′E, 38°03′N with an elevation of 3033 m, and the dominant land cover is alpine meadow which turns to drygrass after October. The Yingke site is located at 100°25′E, 38°51′N with an elevation of 1519 m, and the dominant land cover is cropland which turns to bare soil in winter. The data were collected from June 2008 to August 2009 at the Arou site and from January 2008 to August 2009 at the Yingke site. Days with rainfall or missing measurements were excluded. Level-2 EC data were generated after pre-processing and quality control. Net radiation was measured with a net radiometer at each site. Soil heat flux was calculated using a temperature prediction-correction method [11] from soil temperature and moisture data measured at AWS stations[12]. A surface energy balance adjustment method, i.e. the Bowen-ratio closure, was used to force the energy balance closure.

4. Results and Discussion

4.1. Examination of assumptions

The assumption of EF_const is that the EF is nearly constant during daytime. We found, however, that under clear sky the EF increases during the day in the growing season, while it has a bowl shape evolution with time in the other seasons. Under intermittent cloud cover, large spikes and fluctuations of EF are observed when solar radiation is attenuated by clouds, and the daily pattern of EF becomes erratic (see Fig.1). The above findings agree with other studies [13, 14].

The assumption of the ET-R_s method is that the diurnal solar radiation and ET can be adequately described by a sine function for clear days. At times on clear days during the growing season and at both sites (Fig. 2) we observed, however, a time lag between ET and solar irradiance. The mechanism behind this phenomenon is the complex interaction between vegetation and radiative forcing. Under light cloud cover or hazy conditions the latent heat flux dropped as the available energy decreased resulting in a non-sine evolution of ET and solar irradiance.

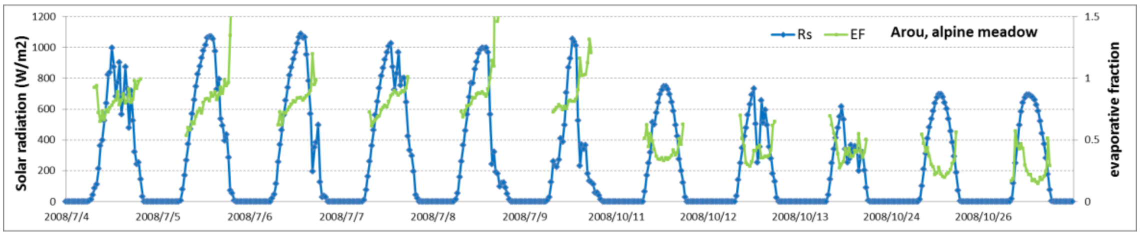

Figure 1. Observed EF and solar irradiance on selected days at Arou.

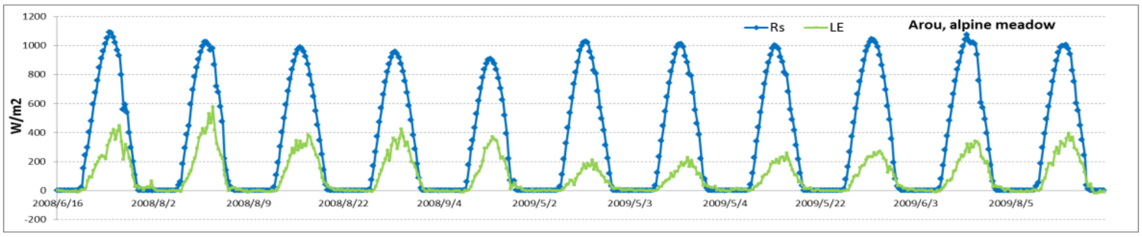

Figure 2. Time series of observed LE and R_s during clear days in the growing season at Arou site; a time lag between LE and R_s is observed.

4.2. Estimation of daily ET

4.2.1 Clear sky condition

The daytime evolution of EF and the time lag between ET and solar irradiance affect the accuracy of the extrapolation of the instantaneous measurements to daily values using the two methods described in Section 2. Three different instantaneous observations (10:15, 12:15, and 14:15) on each day were used to evaluate the two methods.

During the growing season and on clear days, the EF_const method gives relatively good results at Arou site with R^2 ranging from 0.86 to 0.91 (Fig. 3(a-c)). Results were poorer at Yingke site with R^2 ranging from 0.27 to 0.55 (Fig. 3(d-f)). This indicates that the accuracy of the EF_const method may depend on land cover. The RMSE rose from 0.45 to 0.84 mm/d at Arou and from 0.97 to 1.30 mm/d at Yingke when using morning and afternoon instantaneous measurements respectively due to the rising trend of EF over daytime. During senescence when the EF evolution was bowl-shaped, the results were better $R^2 > 0.85$ and RMSE ≅ 0.17mm/d at Arou site and $R^2 > 0.83$ and RMSE < 0.35mm/d at Yingke site when using two instantaneous measurements at noon and early afternoon (Fig. 4(b-c, e-f)). When using instantaneous measurement in the morning, larger errors occurred at both sites (Fig. 4(a, d)).

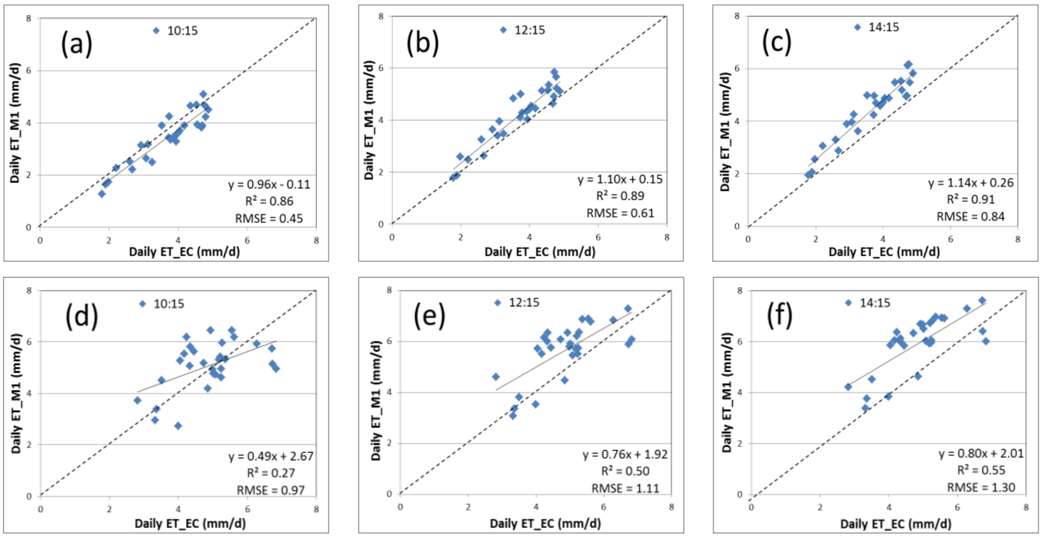

Figure 3. Comparisons of EC measurements with the estimated daily ET from EF_const method (M1) using instantaneous measurements at 10:15, 12:15 and 14:15 at Arou (a, b, c) and Yingke (d, e, f) during the growing season.

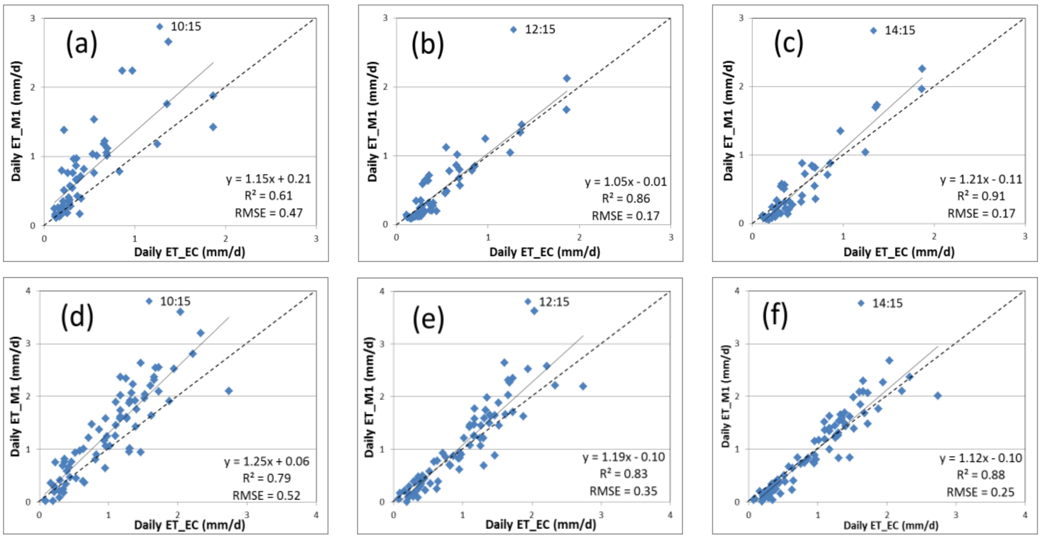

Figure 4. Comparisons of EC measurements with the estimated daily ET from EF_const method (M1) using instantaneous measurements at 10:15, 12:15 and 14:15 at Arou (a, b, c) and Yingke (d, e, f) during senescence period.

When applying the ET-R_s method on clear days in the growing season when the time lag between LE and R_s was observed (Fig. 2), the accuracy of the ET-R_s method decreases compared to days without the time lag (Fig. 5). The RMSE increases up to 0.88 mm/d for the former case (Fig. 5(d)), while it is only 0.59 mm/d for the latter case at Arou (Fig.5 (a)). Similar results were obtained at Yingke.

4.2.1 Cloudy sky condition

Under cloudy days, the data were classified into different groups according to cloud cover and both methods were applied. As mentioned earlier intermittent cloud cover gives fluctuations of EF. In the growing season and at both sites, the EF_const method gave significantly larger errors due to cloud cover: RMSE increased with cloud cover from 0.64 to 1.77 mm/d at Arou site (Fig. 6). However, no such increase was observed at the Yingke site.

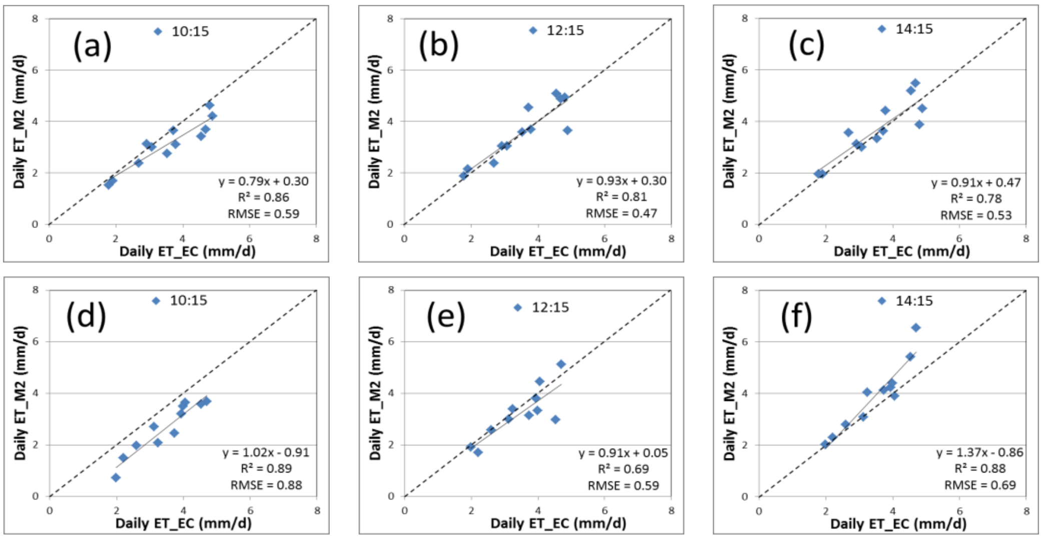

Figure 5. Comparisons of EC measurements with the estimated daily ET from ET-R_s method (M2) using instantaneous measurements at 10:15, 12:15 and 14:15 at Arou during the growing season (a, b, c) and when a time lag between LE and R_s was observed (d, e, f).

Under cloudy days in the growing season the ET-R_s method overestimated daily ET at Arou site, when the cloud amount was over 30% (Fig.7). On the contrary, ET was underestimated on clear days when using morning instantaneous measurements (Fig. 5(a)). The same results (not shown here) were obtained at the Yingke site. During the senescence period, cloud cover had a smaller impact and both methods generally performed as on clear days except on a few days when the cloud cover was about 30% and errors were larger at both sites.

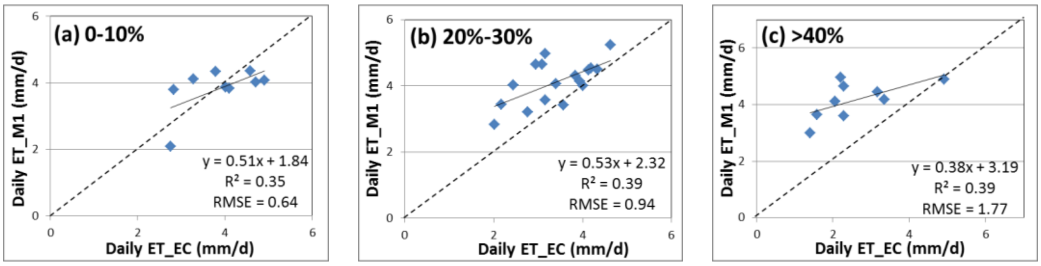

Figure 6. Comparisons of EC measurements with the estimated daily ET from EF_const method (M1) using instantaneous measurements at 10:15 under cloud coverage of (a) 0-10%, (b) 20%-30% , and (c) >40% at Arou during the growing season.

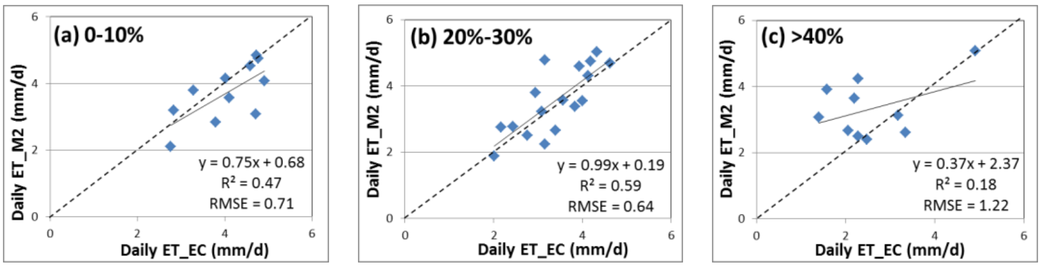

Figure 7. Same as in Figure 6, but ET-R_s method (M2) was used.

5. Conclusions

The study evaluated two commonly used methods to estimate daily ET from instantaneous measurements under different sky conditions and in different seasons. The EF_const method is based on the assumption that the EF is constant during daytime, while the ET-R_s method assumes that the diurnal evolution of both ET and solar irradiance is a sine function under clear days. The results showed that the evolution of EF during daytime degrades the performance of the EF_const method to an extent that depends on the season. The observed time lag between ET and R_s reduced the accuracy of the ET-R_s method. Clouds gave larger errors in the growing seasons than in the senescence period. To obtain more accurate daily ET more instantaneous measurements during the day may be required.

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