Estimating daily evapotranspiration from remotely sensed instantaneous observations with simplified derivations of a theoretical model

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Key Points:

- Five methods are developed for converting remotely sensed instantaneous ET to daily values
- The applicability and robustness of the five methods are evaluated using ground-based eddy covariance measurements and MODIS-based estimates
- The constant Ω method, the constant R_c method, and the constant R_c/R_a method could produce daily ET estimates with a reasonable accuracy

Abstract

Surface evapotranspiration (ET) is one of the key components in global hydrological cycle and energy budget on the earth. This paper designs a theoretical relationship between daily and instantaneous ETs with a multiplication of multiple fractions through a mathematical derivation of the physics-based Penman-Monteith equation and further develops five methods for converting remotely sensed instantaneous ET to daily values, one of which is equivalent to the conventional constant evaporative fraction (EF) method. The five methods are then evaluated and intercompared using long-term ground-based eddy covariance system-measured half-hourly latent heat flux (LE) and three groups of MODIS-based instantaneous LE datasets collected from April 2009 to late October 2011 at the Yucheng station. Overall, the constant decoupling factor (Ω) method, the constant surface resistance (R_c) method, and the constant ratio of surface resistance to aerodynamic resistance (R_c/R_a) method could produce daily LE estimates that are in reasonably good agreement with the ground-based EC measurements whereas the constant EF method and the constant Priestley-Taylor parameter (α) method underestimate the daily LE with larger biases and root mean square errors. The former three methods are of more solid physical foundation and can effectively capture the effect of temporally variable meteorological factors on the diurnal pattern of surface ET. They provide good alternatives to the nowadays commonly applied methods for the conversion of remotely sensed instantaneous ET to daily values.

Key words: Evapotranspiration, Remote sensing data, Constant evaporative fraction method

1. Introduction

Evapotranspiration (ET, water in mm/d, equivalent to latent heat flux) is one of the key components in global hydrological cycle and energy budget on the earth. Continuous efforts have been made over the past decades to develop models with varying degree of structure complexities and uncertainties for estimating land surface ET with remote sensed data [Li *et al.*, 2009; Kalma *et al.*, 2008]. Nonetheless, most models only provide instantaneous snapshots of surface ET at the satellite overpass times. To improve the practical applicability of the remotely sensed ET, researchers have always been seeking for a temporally stable ratio of ET to a physical variable that can be applied to effectively convert the instantaneous ET to daily values and a number of methods with different level of accuracies are developed under such context [Brutsaert & Sugita, 1992; Trezza, 2002; Ryu *et al.*, 2012; Tang & Li, 2017].

One of the most representative schemes is the well-known constant evaporative fraction (EF, defined

as the ratio of ET to surface available energy) method. This method, which simply assumes that the instantaneous EF equals the daily average, is perhaps the most widely used scheme for the conversion of instantaneous ET to daily values. However, due to the concave-up shape of the daytime EF on clear-sky or constant-cloud days, many authors have reported that the constant EF method tends to significantly underestimate the daily ET [Tang *et al.*, 2012, 2013a; Tang & Li, 2017; Van Niel *et al.*, 2011; Cammalleri *et al.*, 2012; Delogu *et al.*, 2012; Xu *et al.*, 2015; Chávez *et al.*, 2008] and the underestimation can even reach as large as 34% [Van Niel *et al.*, 2012]. Similar to the constant EF method that makes use of surface available energy as the conversion variable, some other schemes [Trezza, 2002; Chávez *et al.*, 2008; Ryu *et al.*, 2012; Van Niel *et al.*, 2012; Tang *et al.*, 2015a, 2017] have also attempted to assume a temporally stable ratio of ET to surface downward solar radiation, surface net radiation, extraterrestrial solar radiation, or reference grass/alfalfa ET in a diurnal cycle. Except the constant reference EF (the ratio of actual ET to reference grass/alfalfa ET) method, which assumes the constancy of reference EF, the conversion schemes are incapable of accounting for the temporally variable environmental factors (e.g., wind speed, air humidity, air temperature, air pressure) and the horizontal advection on the ET in a diurnal cycle. Note that all these schemes have been extensively evaluated and applied for the conversion of instantaneous ET to daily values, but consistent conclusions have seldom been drawn, perhaps because each scheme has its own advantages and drawbacks and scope of application. For example, Tang *et al.* [2013a] comprehensively reviewed several ET conversion methods and discussed in-depth their advantages and weaknesses and found that the constant reference EF method had the best performance for the ET conversion; Van Niel *et al.* [2012] concluded from results on selected days over a ~10-year period that using surface downward solar radiation as the conversion variable performed better than using extraterrestrial solar radiation and surface available energy; Chávez *et al.* [2008] reported that the constant EF method complemented the constant reference EF method and the former performed better under heterogeneous vegetation cover conditions with moderate to considerable soil water stress and under non-advective climate conditions while the latter worked better under more homogeneous surface conditions with little to no plant soil water stress and under advective conditions.

The objectives of this paper are twofold: 1) to develop alternative methods for the conversion of instantaneous ET to daily values, and 2) to test the applicability and robustness of the methods using ground-based eddy covariance measurements and MODIS-based estimates. To this end, a theoretical relationship between instantaneous and daily ETs is first deduced from the classical Penman-Monteith

equation. Five conversion methods are then derived from the derivatives of the theoretical relationship with a certain degree of assumptions. Section 2 presents the methodology of how the five ET conversion methods are derived. Section 3 describes the study site, the ground-based meteorology and energy flux measurements, and the MODIS-based instantaneous ET datasets. Section 4 provides the results and discussion of the ET conversion. Conclusions are finally made in Section 5.

2. Methodology

This study is motivated by the oversimplification of the widely applied constant EF method and several other similar methods that cannot capture the diurnal variation of environment variables and as a result may produce significant biases in converting instantaneous ET to daily values. Beginning with the physics-based Penman–Monteith equation, *McNaughton & Jarvis* [1983] rearranged it in the following form to study the relative contribution of the radiative (LE_{rad}) and aerodynamic (LE_{aero}) terms to the overall evapotranspiration,

$$LE = LE_{rad} + LE_{aero} = \Omega LE_{eq} + (1 - \Omega) LE_{im} \quad (1)$$

where LE is the latent heat flux, W/m^2 ; LE_{eq} is the equilibrium evapotranspiration, W/m^2 ; LE_{im} is the evapotranspiration imposed by the surrounding air, W/m^2 ; and Ω (-) is the decoupling factor representing the degree of atmosphere–vegetation interaction. With a series of computations and substitutions, Eq. (1) can be rewritten as follows [*Pereira*, 2004]:

$$LE = \alpha LE_{eq} = \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G) \quad (2)$$

$$\alpha = \Omega / \Omega^* \quad (3)$$

$$\Omega = \frac{1}{1 + \frac{\gamma}{\Delta + \gamma} \frac{R_c}{R_a}} \quad (4)$$

$$\Omega^* = \frac{1}{1 + \frac{\gamma}{\Delta + \gamma} \frac{R^*}{R_a}} \quad (5)$$

$$R^* = \frac{(\Delta + \gamma) \rho C_p VPD}{\Delta \gamma (R_n - G)} \quad (6)$$

where α is the Priestley-Taylor parameter, Δ is the slope of the saturated vapor pressure versus air temperature curve, $kPa/^\circ C$; γ is the psychrometric constant, $kPa/^\circ C$; R_c is the surface resistance, s/m ; R_a is

the aerodynamic resistance, s/m; R^* is the critical surface resistance when LE equals equilibrium evapotranspiration, s/m; ρ is the air density, kg/m³; C_p is the specific heat of the air, J/(kg·°C); VPD is the vapor pressure deficit of the air, kPa; R_n is the surface net radiation, W/m²; and G is the soil heat flux, W/m².

Studies have shown that Eqs. (2-6) are valid at both instantaneous and daily time scales [Allen *et al.*, 1998; ASCE-EWRI, 2005]. Applying Eq. (2) to estimate both instantaneous LE (LE_i) and daily LE (LE_d) given meteorological inputs at corresponding time scales, and assuming LE_d estimated using appropriately averaged meteorological quantities equals that derived by averaging multiple LE_i estimates, one can theoretically link the daily LE to the instantaneous EF, daily surface available energy ($R_n - G$), and other environmental factors with the following equation:

$$LE_d = \frac{LE_i}{(R_n - G)_i} (R_n - G)_d \frac{\Delta_d}{\Delta_d + \gamma_d} \frac{\Delta_i + \gamma_i}{\Delta_i} \frac{\alpha_d}{\alpha_i} \quad (7)$$

$$= \frac{LE_i}{(R_n - G)_i} (R_n - G)_d \frac{\Delta_d}{\Delta_d + \gamma_d} \frac{\Delta_i + \gamma_i}{\Delta_i} \frac{\Omega_i^*}{\Omega_d^*} \frac{\Omega_d}{\Omega_i}$$

Eq. (7) clearly depicts the physical relationship between daily LE (or EF) and instantaneous LE (or EF) with a multiplication of multiple fractions ($EF_d = EF_i \frac{\Delta_d}{\Delta_d + \gamma_d} \frac{\Delta_i + \gamma_i}{\Delta_i} \frac{\Omega_i^*}{\Omega_d^*} \frac{\Omega_d}{\Omega_i}$). There is essentially only one unknown parameter (daily R_c) in this equation if instantaneous LE is already estimated and other instantaneous and daily meteorological parameters are known.

To obtain the daily LE from instantaneous values, five conversion methods can be derived with different assumptions/simplifications made to Eq. (7) as follows,

- (i) Assuming $\frac{\Delta_d}{\Delta_d + \gamma_d} \frac{\Delta_i + \gamma_i}{\Delta_i} \frac{\Omega_i^*}{\Omega_d^*} \frac{\Omega_d}{\Omega_i} = 1$, which is equivalent to $EF_i = EF_d$, called the constant EF method.
- (ii) Assuming $\frac{\Omega_i^*}{\Omega_d^*} \frac{\Omega_d}{\Omega_i} = 1$, equivalent to $\alpha_i = \alpha_d$ in Eq. (2), called the constant α method.
- (iii) Assuming $\frac{\Omega_d}{\Omega_i} = 1$, called the constant Ω method.
- (iv) Assuming $(R_c)_i = (R_c)_d$, called the constant R_c method.

(v) Assuming $(\frac{R_c}{R_a})_i = (\frac{R_c}{R_a})_d$, called the constant R_c/R_a method.

Methods (ii-v) can also be interpreted as a correction of method (i). Daily values of air temperature, wind speed, air vapor pressure, air pressure, and surface available energy, if demanded, are computed as the average of multiple (48 half-hourly in this study) measurements from 0:00 h to 24:00 h local time. Daily psychrometric constant and daily slope of the vapor pressure curve are estimated using daily air pressure and daily air temperature, respectively, following Eqs. (8) and (13) in *Allen et al.* [1998]. Daily VPD is computed as daily saturated vapor pressure (estimated using daily air temperature) minus daily air vapor pressure. Aerodynamic resistance (R_a) is calculated for simplicity by assuming that the atmosphere is under neutral conditions (i.e., no stability correction function is applied).

3. Test site and data

3.1 Test site

Yucheng station, located in the southwest of Yucheng County, Shandong province in North China and with a latitude of 36.8291° N and a longitude of 116.5703° E, has been measuring continuously the long-term exchange of carbon dioxide, water vapor and heat between the land and atmosphere (<http://www.chinaflux.org/>). It is characterized by a subhumid and monsoon climate with mean annual temperature and precipitation of 13.1 °C and 528 mm, respectively. Winter wheat is rotated with summer corn at this station and the soil type belongs to the sandy loam. Crop height is measured approximately every 15 days during the winter wheat and summer corn growth period. Sensors have also been equipped to regularly measure surface meteorological and energy flux variables at an half-hourly time interval, including air temperature, air relative humidity, wind speed, air pressure, surface 4-component radiation (downward and upward shortwave and longwave radiation), and soil heat flux. See the work of *Tang et al.* [2011a, 2013a, 2015b] for the specifics of the sensors and the sensor deployment. In addition, an eddy covariance (EC) system, consisting of an open-path CO₂/H₂O gas analyzer (model LI-7500, Licor Inc., Lincoln, Nebraska) and a 3-D sonic anemometer/thermometer (model CSAT3, Campbell Scientific Inc., Logan, Utah), is setup to measure the turbulent sensible heat flux and latent heat flux. Measurements from the EC are collected by a data logger at a 10-Hz frequency for archiving and 30-min averaged fluxes are computed. Online flux computation and post-field data programs are applied to correct for the effect of the sonic virtual temperature, the time-lag, the performance of the planar fit coordinate rotation, the density

fluctuation, and the frequency response [Webb *et al.*, 1980; Burba & Anderson, 2010]. The eddy fluxes are quality-controlled following the work of Aubinet *et al.* [2000] and Foken *et al.* [2004]. The height of the EC sensors switches from ~4.3 m above surface ground (ASG) in late July or early August to ~2.9 m ASG in mid- to late October each year.

Half-hourly measurements of surface meteorological and energy flux variables from late April 2009 to late October 2011 were collected for analysis in this study. These data were first carefully checked following the procedures proposed by Tang *et al.* [2013a] to ensure quality and completeness. Specifically, these procedures are 1) the removal of data spikes and abnormalities in sensible heat flux and latent heat flux measurements ($< -100 \text{ W/m}^2$ or $> 700 \text{ W/m}^2$, beyond the limits of surface net radiation), 2) the exclusion of days that have data gaps (e.g., caused by rainfall, instrument malfunction or maintenance) in any of the 48 half-hourly measurements or have $\text{abs}(\text{EF}) > 3$ at assumed satellite overpass time and at daily scale. Moreover, because the constant r_c method and the constant r_c/r_a method are significantly impaired under conditions of wind speed $< 0.5 \text{ m/s}$ or relative humidity = 100%, the days with such extreme weather at assumed satellite overpass times are further excluded in the analysis. The daily LE for the validation is derived by averaging the 48 half-hourly EC measurements with or without an energy imbalance correction in a diurnal cycle.

3.2 MODIS-based datasets

Three groups of reliable MODIS-based instantaneous LE and R_n -G datasets, which were estimated using a typical dual-source surface energy balance model at the Yucheng station, are extracted from our previous studies for the evaluation of the five ET conversion methods. These datasets are characterized by different magnitudes of model-estimation bias and error and would be especially helpful for testing the robustness of the five ET conversion methods. Specifically, these datasets are derived using (A) the N95 [Norman *et al.*, 1995] two-source model at 33 clear-sky TERRA overpass times from late April to late September in 2009 in the work of Tang *et al.* [2011a], (B) the N95 two-source model at 55 clear-sky TERRA overpass times and (C) the N95 two-source model at 46 clear-sky AQUA overpass times from late April 2009 to late October 2011 in the work of Tang *et al.* [2013a]. These three datasets have been proven to reasonably agree with the ground-based measurements. A positive bias of 1 W/m^2 and a root mean square error (RMSE) of 42 W/m^2 are found in the work of Tang *et al.* [2011a] when the N95-derived LEs are validation against ground-based large-aperture scintillometer-derived LEs; In the validation of the

N95-derived LEs at TERRA and AQUA overpass times in the work of *Tang et al.* [2013a], biases of 16 W/m² and -1 W/m² and RMSEs of 46 W/m² and 34 W/m² are obtained, respectively. These statistics are within the generally acceptable ranges of bias and RMSE. For details about how the three groups of MODIS-based instantaneous LE and R_n-G datasets are estimated, please refer to the work of *Tang et al.* [2011a] and *Tang et al.* [2013a].

The five methods for converting instantaneous ET to daily values will be evaluated and intercompared using two groups of inputs (see Figure 1), namely (1) the completely ground-based measurements of surface meteorology, EC-observed half-hourly LE, and R_n-G observations without any bias, which can separate the errors induced by the methods from those by the inputs, and (2) the ground-based measurements of surface meteorology and MODIS-based instantaneous LE and R_n-G datasets with a certain degree of bias, which can quantify the accuracy of the derived daily LE by introducing the error caused by the instantaneous LE and R_n-G estimates. Moreover, to see if there is any dependence of each of the five methods on the time of ET conversion, the evaluation with the first group of inputs will be conducted at both 10:30 h and 13:30 h local time which approximately correspond to the MODIS/TERRA and MODIS/AQUA daytime overpass times, respectively. Studies [*Twine et al.*, 2000; *Prueger et al.*, 2005; *Foken*, 2008; *Tang et al.*, 2011b, 2013b] have reported that an energy imbalance is often found between the EC-measured turbulent heat fluxes and surface available energy whereas an energy balance among the energy flux components is by definition enforced in remotely sensed surface energy balance models. This contradiction compels an energy balance correction made to the EC measurements. Since maintaining a constant Bowen ratio is physically more reasonable based on the underlying theory of eddy covariance [*Twine et al.*, 2000] and forcing closure by applying the residual to the LE is valid only for arid and semi-arid regions where the Bowen ratio tend to be quite high [*Prueger et al.*, 2005], evaluation of the five ET conversion methods will be conducted using EC measurements corrected by the Bowen ratio (BR) method. In addition, to determine whether the energy imbalance correction influences the consistency of the model performance, evaluation of the five ET conversion methods with the first group of inputs is also discussed using uncorrected EC measurements and using EC measurements corrected by the residual energy (RE) method [*Twine et al.*, 2000]. The BR correction method conserves the EC-measured Bowen ratio to repartition surface available energy into sensible heat flux and LE. The RE correction method brings all of the imbalanced energy (surface available energy minus the sum of sensible heat flux and LE) to the EC-measured LE. The ratio of the EC-measured daytime to daily LEs before and after the correction

is assumed constant to derive the corrected daily LE measurement, as done in our previous studies [Tang et al., 2013a, 2017] to overcome the weakness of the BR or RE method.

Figure 1 Flowchart of the evaluation of the five ET conversion methods under two scenarios, i.e., using completely ground-based measurements (left) and a combination of remote sensing datasets and ground-based measurements (right).

4. Results and discussion

4.1 Validity of the constancy assumption of the ET conversion methods

Before evaluating the five ET conversion methods (namely the constant EF method, the constant α method, the constant Ω method, the constant Rc method, and the constant Rc/Ra method), we first examined how the EF, α , Ω , Rc, and Rc/Ra at half-hourly scale were different from those at daily scale (i.e., the validity of the assumption of constant EF, α , Ω , Rc, and Rc/Ra). Figure 2 shows the daytime

variation of the multi-day averaged EF, α , Ω , Rc, and Rc/Ra that were estimated using ground-based EC and meteorology measurements at the Yucheng station. The estimated daily values of the five variables were averaged over 374 days while the available days were different for averaging each half-hourly values. From mid-morning (9:00 h local time) to mid-afternoon (15:00 h local time), covering the daytime overpass times of most polar-orbiting satellites, the multi-day averaged half-hourly EF, α , Ω , and Rc underestimated their daily mean whereas the half-hourly Rc/Ra overestimated its daily mean. The α at half-hourly scale relative to its daily mean had a larger underestimation than the EF and the Ω , and the Ω had the smallest underestimation among these three variables. The underestimation of EF, α , and Rc became weaker whereas the overestimation of Rc/Ra became stronger when the conversion time varied from morning to afternoon. The half-hourly Ω remained relatively more stable from mid-morning to mid-afternoon than the other four variables. The half-hourly EF had a very similar non-linear variation shape to the half-hourly α while the half-hourly Ω varied almost inversely with the half-hourly Rc/Ra during the daytime. The Rc had a more significant change in its diurnal pattern than the other four variables. Figure 3 compares the half-hourly EF, α , Ω , Rc, and Rc/Ra estimated at 10:30 h (N=357) and 13:30 h (N=360) local time and those at daily scale. The EF and α at half-hourly scale relative to their daily mean were underestimated with large biases of -0.22 and -0.39 (relative biases of -32% and -36%) and RMSEs of 0.50 and 1.09 (relative RMSE of 73% and 99%) at 10:30 h local time and biases of -0.16 and -0.35 (relative biases of -24% and -32%) and RMSEs of 0.48 and 1.06 (relative RMSE of 69% and 95%) at 13:30 h local time, respectively. The Ω and Rc were underestimated with lower biases of -0.06 and -145 s/m (relative biases of -12% and -25%) and RMSEs of 0.14 and 881 s/m (relative RMSE of 29% and 151%) at 10:30 h local time and biases of -0.06 and -34 (relative biases of -13% and -6%) and RMSE of 0.16 and 973 s/m (relative RMSE of 33% and 166%) at 13:30 h local time, respectively. Overestimations of Rc/Ra were found with biases of 1.3 and 3.1 (relative biases of 23% and 53%) and RMSEs of 9.6 and 14.6 (relative RMSE of 171% and 261%) at 10:30 h and 13:30 h local time, respectively. In addition, the bias tended to be larger at high values of the five variables, especially for the EF, α , Rc, and Rc/Ra. For the Ω variable, there were almost no differences between the bias and RMSE at 10:30 h and those at 13:30 h; for the Rc variable, the bias at 10:30 h local time was much higher than that at 13:30 h local time while for the Rc/Ra variable opposite results were obtained; for the EF and α variables, slight differences of the bias and RMSE were found between the two conversion time.

Figure 2. Daytime variation of multi-day averaged half-hourly (a) evaporative fraction, (b) Priestley-Taylor parameter, (c) decoupling factor, (d) surface resistance, (e) ratio of surface resistance to aerodynamic resistance, and their daily mean, estimated using ground-based measurements at the Yucheng station.

Figure 3. Comparison of (a) evaporative fraction, (b) Priestley-Taylor parameter, (c) decoupling factor, (d) surface resistance, (e) ratio of surface resistance to aerodynamic resistance at 10:30 h (N=357) and 13:30 h (N=360) local time and those at daily scale estimated with ground-based measurements at the Yucheng station.

4.2 Evaluation of the ET conversion methods using completely ground-based measurements

Figure 4 compares the daily LE estimated using the five derived conversion methods at 10:30 h and 13:30 h local time with ground-based EC measurements corrected using the BR method. Figure 5 compares the relative bias and relative RMSE in the validation of the daily LE. Several findings are summarized as follows. i) Overall, the constant R_c method and the constant Ω method could produce good daily LE with the lowest bias (relative bias falling in between -10% and 7%) and RMSE (relative RMSE falling in between 20% and 15%), respectively, and the two statistics were of limited variation when the conversion time was switched from 10:30 h to 13:30 h local time, whereas large underestimations in the validation of the estimated daily LE were found in the constant EF method and the constant α method, with relative biases of -22% and -25% (-17% and -23%) and relative RMSEs of 30% and 34% (25% and 31%) at 10:30 h (13:30 h) conversion time, respectively. ii) The constant EF method, the constant α method, the constant Ω method, and the constant R_c/R_a method were all shown to underestimate the daily LE whereas the constant R_c method showed a change from an overestimation at 10:30 h to a very small underestimation at 13:30 h of the daily LE. The underestimation bias (the difference between the estimated and observed daily LE) and RMSE for the former four methods varied between -18.2 W/m^2 and -3.3 W/m^2 and between 24.4 W/m^2 and 14.5 W/m^2 at 10:30 h conversion time, respectively, and they varied between -16.5 W/m^2 and -7.1 W/m^2 and between 22.2 W/m^2 and 13.7 W/m^2 at 13:30 h conversion time, respectively. The bias and RMSE for the constant R_c method were 5.5 W/m^2 and 14.0 W/m^2 at 10:30 h conversion time, respectively, and they were -0.4 W/m^2 and 10.3 W/m^2 at 13:30 h conversion time. iii) The constant α method and the constant EF method overall produced the highest and the second highest underestimation bias and RMSE, respectively, but the underestimation of the daily LE was reduced when the conversion time was switched from 10:30 h to 13:30 h local time.

The evaluation using uncorrected EC measurements or EC measurements corrected by the RE method did not change much the better or worse performance of a given ET conversion method relative to other methods that is obtained using EC measurements corrected by the BR method, as could be seen from Figure 5. Overall, the constant Ω method and the constant R_c method were still among the top two schemes for producing reasonably good daily LE whereas the constant α method and the constant EF method overall were still the two worst schemes. The constant R_c/R_a method had a similar performance to the constant Ω method at 13:30 h local time when the RE correction method was applied.

Figure 4 Comparison of daily LE estimated using the five conversion methods with ground-based EC measurements corrected using the Bowen ratio (BR) method. (a) Converting 357 half-hourly measurements at 10:30 h local time to the daily scale. (b) Converting 360 half-hourly measurements at 13:30 h local time to the daily scale.

Figure 5 Relative bias (the ratio of the BIAS to the mean of the EC measurements) and relative RMSE (the ratio of the RMSE to the mean of the EC measurements) in the comparison of daily LE estimated using the five conversion methods with ground-based EC measurements without an energy imbalance correction or with an energy imbalance correction based on the Bowen ratio (BR) and residual energy (RE) methods.

4.3 Evaluation of the ET conversion methods using MODIS-based datasets

Figures 6-7 compare the daily LE estimated from the three groups of instantaneous MODIS-based datasets using the five conversion methods with ground-based EC measurements corrected using the BR method. Figure 8 illustrates the relative bias and relative RMSE in the validation of the daily LE converted from the MODIS-based datasets. The constant EF method and the constant α method both showed an underestimation of the daily LE. They produced the relative biases of -9% ~ -12% and of -15% ~ -17% and the relative RMSEs of 20% ~ 27% and of 25% ~ 31%, respectively. The constant Rc method overestimated the daily LE by 6% ~ 18% with the relative RMSE varying between 16% and 30% for the three groups of the MODIS-based datasets. The constant Ω method and the constant Rc/Ra method overestimated the daily LE by 4% ~ 9% and 2% ~ 7% for two (N95-derived LE datasets from *Tang et al.* [2011a] and MODIS/TERRA-based LE datasets from *Tang et al.* [2013a]) of the three groups of the MODIS-based datasets, respectively, and underestimated the daily LE by -2% and -6% for the left group of the MODIS-based datasets (MODIS/AQUA-based LE datasets from *Tang et al.* [2013a]). The relative RMSE varied between 13% and 28% for the constant Ω method and between 15% ~ 29% for the constant Rc/Ra method. For each of the three groups of the MODIS-based datasets, the constant Ω method and the constant Rc/Ra method produced smaller (at least similar) biases and RMSEs than the constant EF method and the constant α method.

Overall, the constant Ω method and the constant Rc/Ra method performed the best and could produce reasonably good daily LE when remote sensing instantaneous LE and other inputs were provided without significant biases. The constant Rc method, which produced a similar magnitude of RMSE to the constant Ω method and the constant Rc/Ra method but had a relatively larger bias, performed slightly worse. The constant α method performed the worst with a largest underestimation of the daily LE. The constant EF method with the second largest bias and RMSE performed slightly better than the constant α method.

Figure 6 Comparison of daily LE estimated from 33 N95-derived instantaneous LE at MODIS/TERRA overpass times from *Tang et al.* [2011a] using the five conversion methods with ground-based EC measurements corrected using the Bowen ratio (BR) method.

Figure 7 Comparison of daily LE estimated using the five conversion methods with ground-based EC measurements corrected using the Bowen ratio (BR) method. (a) Converting 55 N95-derived instantaneous LE at MODIS/TERRA overpass times from *Tang et al.* [2013a] to the daily scale. (b) Converting 46 N95-derived instantaneous LE at MODIS/AQUA overpass times from *Tang et al.* [2013a] to the daily scale.

Figure 8 Relative bias (the ratio of the BIAS to the mean of the EC measurements) and relative RMSE (the ratio of the RMSE to the mean of the EC measurements) in the comparison of daily LE estimated using the five conversion methods and remotely sensed instantaneous LE datasets with ground-based EC measurements corrected using the Bowen ratio (BR) method. A. N95-derived LE from *Tang et al.* [2011a]. B. MODIS/TERRA-based LE from *Tang et al.* [2013a]. C. MODIS/AQUA-based LE from *Tang et al.* [2013a].

4.4 Discussion and sensitivity analysis

All of the five methods proposed in this study for converting remotely sensed instantons ET to daily values are essentially reduced forms of the rearranged Penman-Monteith equation and their performance depends on how the instantaneous EF, α , Ω , Rc, and Rc/Ra differ from those at daily scale. If the assumption on each of the five ET conversion methods, as presented in Section 2, is tenable, these methods

will produce daily LE estimates without any bias. If daily EF, α , and Ω are higher than (daily Rc and Rc/Ra are lower than) their instantaneous values, the corresponding method will underestimate the daily LE, and vice versa. Results as presented in Section 4.1 clearly indicate that daily EF, α , Ω , and Rc is overall higher than instantaneous values while Rc/Ra at daily scale is lower than that at instantaneous scale in most cases. Varying degree of assumptions or simplifications make the five methods differ in model inputs, structure, and accuracy. Given the roughest assumption as presented in Section 2, the constant EF method estimates daily LE with only instantaneous EF and daily surface available energy as inputs. The constant α method, the constant Ω method, the constant Rc/Ra method, and the constant Rc method gradually relax the assumption of the constant EF method and thus allow themselves to adjust for the relative difference between the instantaneous EF (or α , Ω , Rc/Ra) at the time of the satellite overpass and the EF (or α , Ω , Rc/Ra) during other timeframes in a more physics-based manner. The concave-up shape of the daytime EF from morning to afternoon that is reported by many studies and also shown in this study partly contributes to the underestimation of daily LE in the constant EF method. Moreover, due to the unstable EF resulting from the negative surface available energy and the very low ET in the nighttime, the constant EF method cannot effectively consider the effect of the nocturnal ET on the total daily ET. The direct relationship between the EF and the α as shown in Eq. (2) results in the very similar non-linear shape of daytime EF to that of daytime α . Because $\Delta/(\Delta+\gamma)$ increases when air temperature rises, the underestimation will further be strengthened using the constant α method compared to the constant EF method, leading to a larger underestimation of daily LE. The relationship between the Ω and the Rc/Ra as presented in Eq. (4) explains the inverse shape of daytime Ω and Rc/Ra. Because of the limited variability of $\gamma/(\Delta+\gamma)$, the constant Ω method could have a similar performance to the constant Rc/Ra method under some circumstances. The significant change of daytime Rc is attributed to the wide variation of environmental variables and causes a more complex relationship between daily Rc and instantaneous Rc. However, the constant Rc method seems to be less dependent on this complex relationship. The smaller underestimation of half-hourly EF, α , and Rc (the larger overestimation of half-hourly Rc/Ra) relative to the daily mean in the afternoon than in the morning indicates that using remotely sensed data acquired at afternoon overpass rather than morning overpass can produce better (worse) daily LE estimates with these three methods. Due to the more stable daytime Ω , the constant Ω method could produce daily LE estimates that are more independent on the satellite overpass time. Different from the constant EF method, the other four methods are capable of considering the non-linear effect of meteorological factors on the ET. In

particular, since the constant Ω method, the constant Rc method, and the constant Rc/Ra method require air temperature, wind speed, air vapor pressure, air pressure at both instantaneous and daily (estimated as the average of multiple half-hourly measurements) scales as inputs, these three methods can capture the effect of temporally variable meteorological factors on the diurnal pattern of surface ET. With a more rigid assumption, these three methods can evidently improve the daily ET estimates, which are expected, compared to the constant EF method and the constant α method that may be oversimplified.

Three of the five proposed methods, namely the constant EF method, the constant α method, and the constant Rc method, have already been separately attempted by some authors for converting instantaneous ET to daily values. The designed relationship between daily and instantaneous ETs as shown in Eq. (7) in this study physically connects these ET conversion methods with each other. The underestimation of the daily ET in the constant EF method as shown in this study has also been widely reported by a number of authors [Delogu *et al.*, 2012; Van Niel *et al.*, 2011; Cammalleri *et al.*, 2012; Chávez *et al.*, 2008]. Some authors [Brutsaert & Sugita, 1992; Van Niel *et al.*, 2011] have suggested multiplying additional calibration factors in the formulation of the constant EF method to correct the underestimation of the daily ET. However, these corrections are generally more empirical and less physically based, which is different from the correction from this study that is of more physical foundation (e.g., the constant Ω method). The constant α method is rarely investigated for the instantaneous ET conversion. One example is from Crago [1996] who once made an attempt to estimate daytime ET from the Priestley-Taylor equation using midday α instead of daytime average values. The author also found an underestimation when compared to the daytime ET measurements and the results produced using the constant EF method, which is consistent with the results obtained from the constant α method in this study. The seldom applied constant Rc method is also reported by Liu *et al.* [2011] to outperform the constant EF method. The better performance of the constant Rc method is partly attributed to the fact that the sensitivity of this method to surface resistance is lower than that of the constant EF method to evaporative fraction, which can be seen from Section 4.1 and 4.2. Note that Tang *et al.* [2013a] found that the constant reference EF method had a better performance than the constant EF method. Whether the other four alternative methods are better than the constant reference EF method is beyond the scope of our paper. We will make comparisons between our new methods and the constant reference EF method in future work.

Each of the five methods developed in this study has its own strengths and weaknesses. The constant EF method and the constant α method have fewer number of input variables but relatively a lower accuracy of

the daily ET estimates than the constant Ω method, the constant Rc method, and the constant Rc/Ra method. Other strength of the latter three methods is their more solid physical foundation and the weakness primarily lies in the requirement of additional instantaneous and daily ground-based meteorological data (air temperature, VPD, and wind speed) and vegetation height (or surface roughness length), besides the instantaneous EF and daily surface available energy, as inputs, which may be unavailable from remote sensing data. The five methods can be applied to different ecosystems for the conversion of remotely sensed instantaneous ETs to daily values. The findings at the cropland site in this study may be extended to other ecosystems as long as the inputs (instantaneous and daily meteorological variables, remotely sensed instantaneous LE and R_n-G) for each method are provided with reasonable accuracies. Note that the application of the constant Rc method or the constant Rc/Ra method firstly requires the instantaneous Rc to be inversely estimated from the Penman-Monteith equation.

To better understand the error propagation of the five methods, a sensitivity analysis adapted from the work of Zhan *et al.* [1996] was made. In this sensitivity analysis, the model-estimated daily LE by converting half-hourly measurements at 13:30 h local time was used as the reference daily LE. We made a certain perturbation to each of the inputs of the five ET conversion methods and the daily LE estimates were then updated with the inputs of the perturbed variable and other unchanged variables. Results (see Table 1) showed that instantaneous LE, among other inputs, had the largest effect on all of the five methods. A perturbation of 10% in instantaneous LE on average resulted in a variation of -10% to 10% in the daily LE estimates in the constant EF method, the constant α method, and the constant Ω method, a slightly lower variation of -8.4% to 8.2% of the daily LE estimates in the constant Rc method, a slightly higher variation of -11.0% to 11.2% of the daily LE estimates in the constant Rc/Ra method. Because daily values of the input meteorological variables are primarily obtained using the average of the half-hourly measurements, the sensitivity of these variables may be counteracted or further enhanced. For example, A perturbation of 10% in instantaneous and daily surface available energies had no effect on the constant EF method and the constant α method and led to a very small variation (<1%) of the daily LE estimates in the other three methods. A perturbation of 1 °C in instantaneous and daily air temperatures had a very limited effect (0.3% variation of daily LE estimates) on the constant α method and produced a similar magnitude of variation (-4.2% to 3.7%) of the daily LE estimates in the constant Ω method, the constant Rc method, or the constant Rc/Ra method. A perturbation of 10% in all other inputs resulted in a variation < 1.5% of the daily LE estimates.

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463 Table 1 Sensitivity of the five conversion methods (first column) in estimating daily LE to their inputs (first row). LE_i is the instantaneous LE, $(R_n-G)_i$ is the
464 instantaneous surface available energy, $T_{a,i}$ is the instantaneous air temperature, u_i is the instantaneous wind speed, VPD_i is the instantaneous vapor pressure deficit, P_i
465 is the instantaneous air pressure, $hveg$ is the vegetation height. MD_R is the relative difference, defined as MD (the mean difference of updated daily LE and
466 reference daily LE) divided by the mean of reference daily LE. SD_R is the relative standard deviation, defined as SD (the standard deviation of the difference of
467 updated daily LE and reference daily LE) divided by the mean of reference daily LE. Note that because daily meteorological variables are obtained using the average
468 of multiple half-hourly measurements, the perturbations on instantaneous meteorological variables are also made simultaneously on daily variables.

		LE_i (W/m ²)		$(R_n-G)_i$ (W/m ²)		$T_{a,i}$ (°C)		P_i (hPa)		VPD_i (hpa)		u_i (m/s)		$hveg$ (m)	
		10%	-10%	5%	-5%	1	-1	10%	-10%	10%	-10%	10%	-10%	10%	-10%
EF	MD_R (%)	10.0	-10.0	0.0	0.0										
	SD_R (%)	8.8	8.8	0.0	0.0										
α	MD_R (%)	10.0	-10.0	0.0	0.0	0.3	-0.3	-0.5	0.5						
	SD_R (%)	8.8	8.8	0.0	0.0	0.3	0.3	0.5	0.5						
Ω	MD_R (%)	10.0	-10.0	-0.4	0.4	3.1	-3.5	0.3	-0.3	0.8	-0.9	0.8	-0.9	0.4	-0.5
	SD_R (%)	8.6	8.6	0.8	0.8	3.0	3.5	1.4	1.5	1.6	1.7	1.6	1.7	1.0	1.0
Rc	MD_R (%)	8.2	-8.4	0.1	-0.1	3.8	-4.2	0.6	-0.7	1.4	-1.5	1.4	-1.5	0.9	-0.9
	SD_R (%)	8.8	7.8	1.7	2.1	3.3	3.7	1.6	1.6	1.5	1.6	1.5	1.6	1.1	1.1
Rc/Ra	MD_R (%)	11.2	-11.0	-0.8	0.8	2.7	-3.0	0.4	-0.5	0.4	-0.5	0.4	-0.5	0.2	-0.2
	SD_R (%)	10.3	9.9	1.1	1.2	2.7	3.2	1.4	1.6	1.4	1.6	1.4	1.6	1.0	1.0

5. Conclusions

This paper designs the theoretical relationship between daily and instantaneous ETs with a multiplication of multiple fractions through a mathematical derivation of the physics-based Penman-Monteith equation. With rough to rigid assumptions on the designed relationship, this paper further develops five methods for converting remotely sensed instantaneous ET to daily values, one of which is equivalent to the conventional constant EF method that has already been widely applied. The five methods are then evaluated and intercompared using long-term ground-based EC-measured half-hourly LE and three groups of MODIS-based instantaneous LE datasets collected from April 2009 to late October 2011 at the Yucheng station.

Overall, the constant Ω method, the constant R_c method, and the constant R_c/R_a method could produce daily LE estimates that are in reasonably good agreement with the ground-based EC measurements whereas the constant EF method and the constant α method have been shown to underestimate the daily LE with large biases and RMSE. The former three methods can all reduce the underestimation of the daily LE that is found in the latter two methods. The lower bias and RMSE in the validation of the daily LEs estimated using either ground-based half-hourly LE without any bias or MODIS-based instantaneous LE with certain degrees of biases demonstrate the robustness of the former three methods and their superiority over the latter two methods. The former three methods are of more solid physical foundation and can capture the effect of temporally variable meteorological factors on the diurnal pattern of surface ET. These three methods (especially the former two) provide good alternatives to the constant EF method and other commonly applied methods for the conversion of remote sensing instantaneous ET to daily values. In view of the strengths and weaknesses of the five developed ET conversion methods, although the evaluation in this study is only focused on a single cropland ecosystem, the findings are instructive. To make general conclusions, more validation work will be conducted under other climate/land cover conditions in the future.

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