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# Estimating Daily Evapotranspiration From Remotely Sensed Instantaneous Observations With Simplified Derivations of a Theoretical Model

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

3

4

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5

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14 **Key Points:**

15 • Five methods are developed for converting remotely sensed instantaneous ET to daily values

16 • The applicability and robustness of the five methods are evaluated using ground-based eddy  
17 covariance measurements and MODIS-based estimates

18 • The constant  $\Omega$  method, the constant  $R_c$  method, and the constant  $R_c/R_a$  method could produce daily  
19 ET estimates with a reasonable accuracy

20

## 21 **Abstract**

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

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

## 39 **1. Introduction**

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

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

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

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

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

## 85 2. Methodology

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

$$92 \quad LE = LE_{rad} + LE_{aero} = \Omega LE_{eq} + (1 - \Omega) LE_{im} \quad (1)$$

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

$$97 \quad LE = \alpha LE_{eq} = \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G) \quad (2)$$

$$98 \quad \alpha = \Omega / \Omega^* \quad (3)$$

$$99 \quad \Omega = \frac{1}{1 + \frac{\gamma}{\Delta + \gamma} \frac{R_c}{R_a}} \quad (4)$$

$$100 \quad \Omega^* = \frac{1}{1 + \frac{\gamma}{\Delta + \gamma} \frac{R^*}{R_a}} \quad (5)$$

$$101 \quad R^* = \frac{(\Delta + \gamma) \rho C_p VPD}{\Delta \gamma (R_n - G)} \quad (6)$$

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

104 the aerodynamic resistance, s/m;  $R^*$  is the critical surface resistance when LE equals equilibrium  
 105 evapotranspiration, s/m;  $\rho$  is the air density, kg/m<sup>3</sup>;  $C_p$  is the specific heat of the air, J/(kg·°C);  $VPD$  is the  
 106 vapor pressure deficit of the air, kPa;  $R_n$  is the surface net radiation, W/m<sup>2</sup>; and  $G$  is the soil heat flux,  
 107 W/m<sup>2</sup>.

108 Studies have shown that Eqs. (2-6) are valid at both instantaneous and daily time scales [Allen *et al.*,  
 109 1998; ASCE-EWRI, 2005]. Applying Eq. (2) to estimate both instantaneous LE ( $LE_i$ ) and daily LE ( $LE_d$ )  
 110 given meteorological inputs at corresponding time scales, and assuming  $LE_d$  estimated using appropriately  
 111 averaged meteorological quantities equals that derived by averaging multiple  $LE_i$  estimates, one can  
 112 theoretically link the daily LE to the instantaneous EF, daily surface available energy ( $R_n - G$ ), and other  
 113 environmental factors with the following equation:

$$\begin{aligned}
 114 \quad LE_d &= \frac{LE_i}{(R_n - G)_i} (R_n - G)_d \frac{\Delta_d}{\Delta_d + \gamma_d} \frac{\Delta_i + \gamma_i}{\Delta_i} \frac{\alpha_d}{\alpha_i} \\
 &= \frac{LE_i}{(R_n - G)_i} (R_n - G)_d \frac{\Delta_d}{\Delta_d + \gamma_d} \frac{\Delta_i + \gamma_i}{\Delta_i} \frac{\Omega_i^*}{\Omega_d^*} \frac{\Omega_d}{\Omega_i}
 \end{aligned} \tag{7}$$

115 Eq. (7) clearly depicts the physical relationship between daily LE (or EF) and instantaneous LE (or EF)  
 116 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  
 117 only one unknown parameter (daily  $R_c$ ) in this equation if instantaneous LE is already estimated and other  
 118 instantaneous and daily meteorological parameters are known.

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

- 121 (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  
 122 constant EF method.
- 123 (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  $\alpha$  method.
- 124 (iii) Assuming  $\frac{\Omega_d}{\Omega_i} = 1$ , called the constant  $\Omega$  method.
- 125 (iv) Assuming  $(R_c)_i = (R_c)_d$ , called the constant  $R_c$  method.

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

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

### 135 3. Test site and data

#### 136 3.1 Test site

137 Yucheng station, located in the southwest of Yucheng County, Shandong province in North China and  
138 with a latitude of 36.8291° N and a longitude of 116.5703° E, has been measuring continuously the  
139 long-term exchange of carbon dioxide, water vapor and heat between the land and atmosphere  
140 (<http://www.chinaflux.org/>). It is characterized by a subhumid and monsoon climate with mean annual  
141 temperature and precipitation of 13.1 °C and 528 mm, respectively. Winter wheat is rotated with summer  
142 corn at this station and the soil type belongs to the sandy loam. Crop height is measured approximately  
143 every 15 days during the winter wheat and summer corn growth period. Sensors have also been equipped  
144 to regularly measure surface meteorological and energy flux variables at an half-hourly time interval,  
145 including air temperature, air relative humidity, wind speed, air pressure, surface 4-component radiation  
146 (downward and upward shortwave and longwave radiation), and soil heat flux. See the work of *Tang et al.*  
147 [2011a, 2013a, 2015b] for the specifics of the sensors and the sensor deployment. In addition, an eddy  
148 covariance (EC) system, consisting of an open-path CO<sub>2</sub>/H<sub>2</sub>O gas analyzer (model LI-7500, Licor Inc.,  
149 Lincoln, Nebraska) and a 3-D sonic anemometer/thermometer (model CSAT3, Campbell Scientific Inc.,  
150 Logan, Utah), is setup to measure the turbulent sensible heat flux and latent heat flux. Measurements from  
151 the EC are collected by a data logger at a 10-Hz frequency for archiving and 30-min averaged fluxes are  
152 computed. Online flux computation and post-field data programs are applied to correct for the effect of the  
153 sonic virtual temperature, the time-lag, the performance of the planar fit coordinate rotation, the density

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

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

### 170 **3.2 MODIS-based datasets**

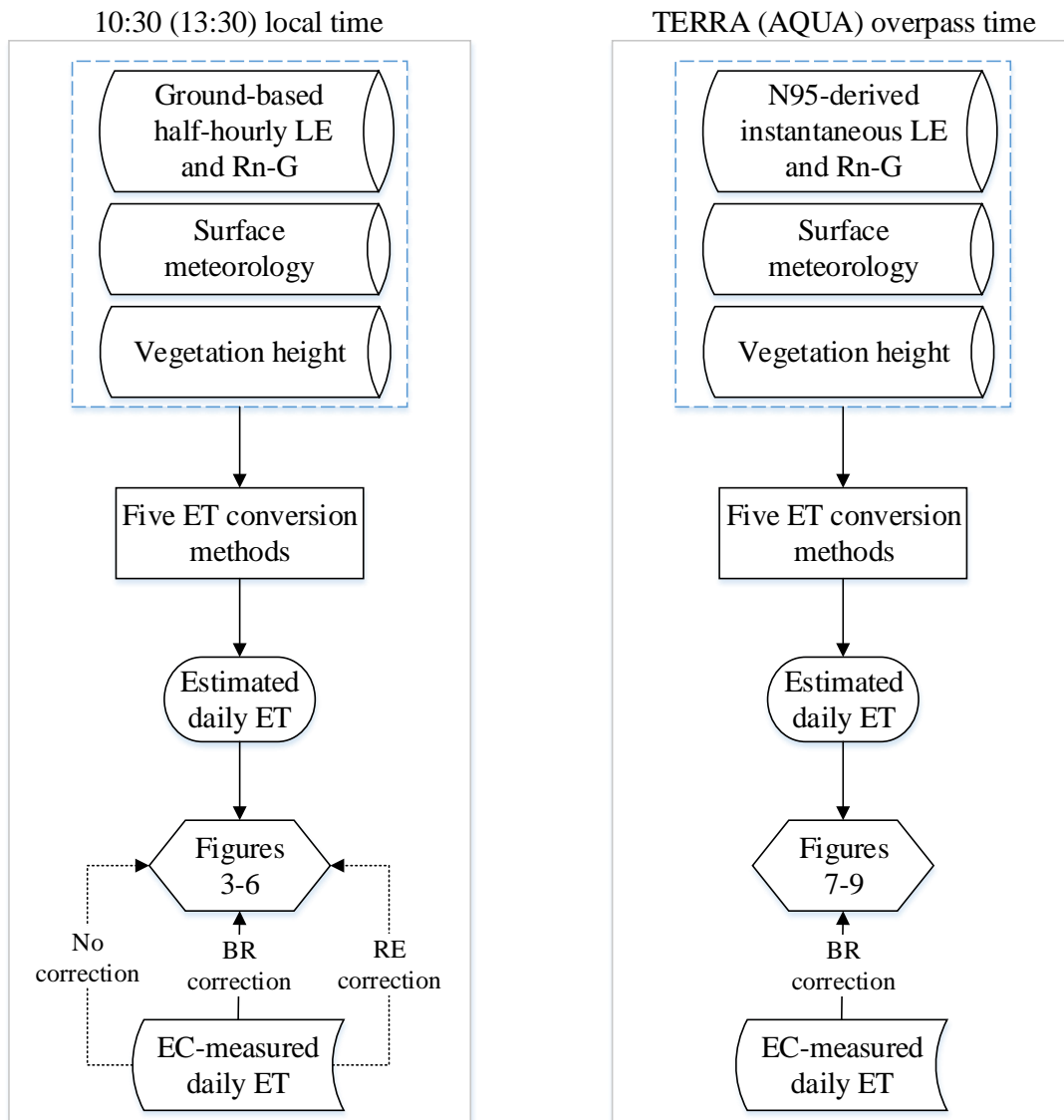
171 Three groups of reliable MODIS-based instantaneous LE and  $R_n$ -G datasets, which were estimated  
172 using a typical dual-source surface energy balance model at the Yucheng station, are extracted from our  
173 previous studies for the evaluation of the five ET conversion methods. These datasets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



183 N95-derived LEs at TERRA and AQUA overpass times in the work of *Tang et al.* [2013a], biases of 16  
184  $\text{W/m}^2$  and  $-1 \text{ W/m}^2$  and RMSEs of  $46 \text{ W/m}^2$  and  $34 \text{ W/m}^2$  are obtained, respectively. These statistics are  
185 within the generally acceptable ranges of bias and RMSE. For details about how the three groups of  
186 MODIS-based instantaneous LE and  $R_n$ -G datasets are estimated, please refer to the work of *Tang et al.*  
187 [2011a] and *Tang et al.* [2013a].

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

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



215  
 216 Figure 1 Flowchart of the evaluation of the five ET conversion methods under two scenarios, i.e.,  
 217 using completely ground-based measurements (left) and a combination of remote sensing datasets and  
 218 ground-based measurements (right).  
 219

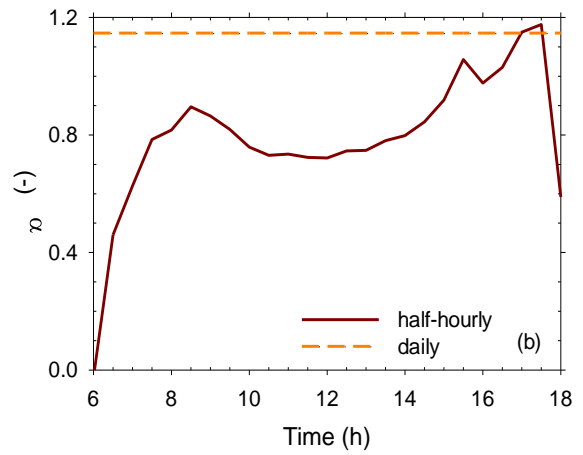
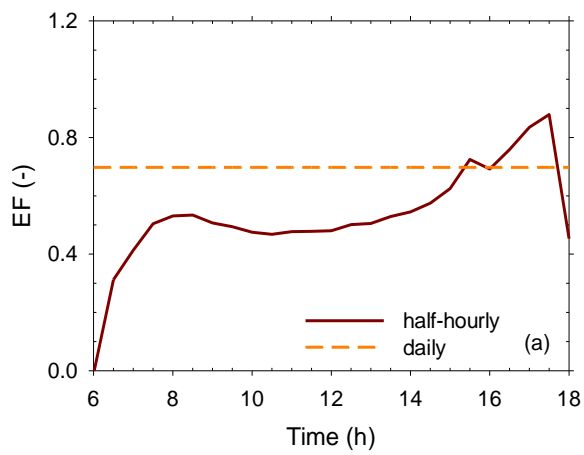
## 220 4. Results and discussion

### 221 4.1 Validity of the constancy assumption of the ET conversion methods

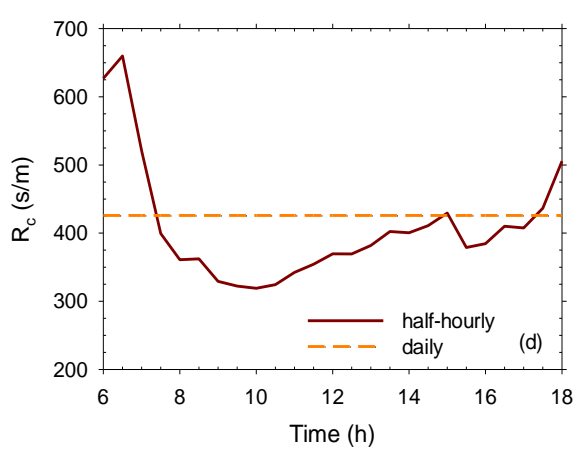
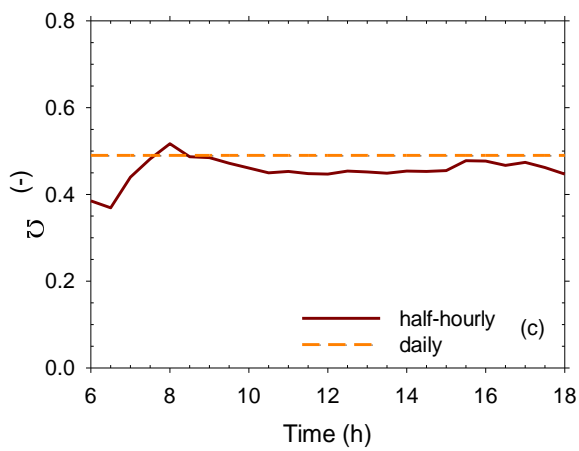
222 Before evaluating the five ET conversion methods (namely the constant EF method, the constant  
 223  $\alpha$  method, the constant  $\Omega$  method, the constant Rc method, and the constant Rc/Ra method), we first  
 224 examined how the EF,  $\alpha$ ,  $\Omega$ , Rc, and Rc/Ra at half-hourly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

226 variation of the multi-day averaged EF,  $\alpha$ ,  $\Omega$ , Rc, and Rc/Ra that were estimated using ground-based EC  
227 and meteorology measurements at the Yucheng station. The estimated daily values of the five variables  
228 were averaged over 374 days while the available days were different for averaging each half-hourly values.  
229 From mid-morning (9:00 h local time) to mid-afternoon (15:00 h local time), covering the daytime  
230 overpass times of most polar-orbiting satellites, the multi-day averaged half-hourly EF,  $\alpha$ ,  $\Omega$ , and Rc  
231 underestimated their daily mean whereas the half-hourly Rc/Ra overestimated its daily mean. The  $\alpha$  at  
232 half-hourly scale relative to its daily mean had a larger underestimation than the EF and the  $\Omega$ , and the  $\Omega$   
233 had the smallest underestimation among these three variables. The underestimation of EF,  $\alpha$ , and Rc  
234 became weaker whereas the overestimation of Rc/Ra became stronger when the conversion time varied  
235 from morning to afternoon. The half-hourly  $\Omega$  remained relatively more stable from mid-morning to  
236 mid-afternoon than the other four variables. The half-hourly EF had a very similar non-linear variation  
237 shape to the half-hourly  $\alpha$  while the half-hourly  $\Omega$  varied almost inversely with the half-hourly Rc/Ra  
238 during the daytime. The Rc had a more significant change in its diurnal pattern than the other four  
239 variables. Figure 3 compares the half-hourly EF,  $\alpha$ ,  $\Omega$ , Rc, and Rc/Ra estimated at 10:30 h (N=357) and  
240 13:30 h (N=360) local time and those at daily scale. The EF and  $\alpha$  at half-hourly scale relative to their  
241 daily mean were underestimated with large biases of -0.22 and -0.39 (relative biases of -32% and -36%)  
242 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  
243 and -0.35 (relative biases of -24% and -32%) and RMSEs of 0.48 and 1.06 (relative RMSE of 69% and  
244 95%) at 13:30 h local time, respectively. The  $\Omega$  and Rc were underestimated with lower biases of -0.06 and  
245 -145 s/m (relative biases of -12% and -25%) and RMSEs of 0.14 and 881 s/m (relative RMSE of 29% and  
246 151%) at 10:30 h local time and biases of -0.06 and -34 (relative biases of -13% and -6%) and RMSE of  
247 0.16 and 973 s/m (relative RMSE of 33% and 166%) at 13:30 h local time, respectively. Overestimations  
248 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  
249 14.6 (relative RMSE of 171% and 261%) at 10:30 h and 13:30 h local time, respectively. In addition, the  
250 bias tended to be larger at high values of the five variables, especially for the EF,  $\alpha$ , Rc, and Rc/Ra. For the  
251  $\Omega$  variable, there were almost no differences between the bias and RMSE at 10:30 h and those at 13:30 h;  
252 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  
253 the Rc/Ra variable opposite results were obtained; for the EF and  $\alpha$  variables, slight differences of the bias  
254 and RMSE were found between the two conversion time.

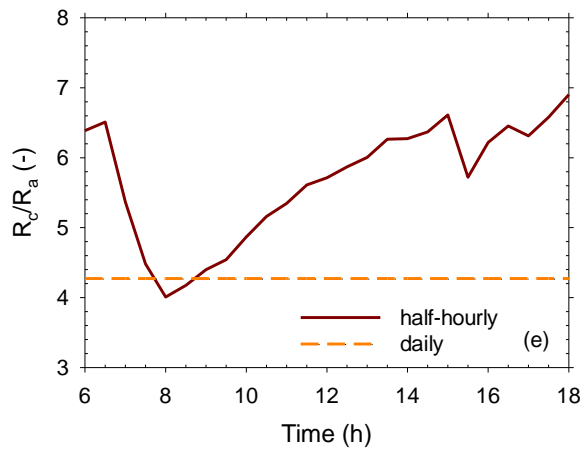
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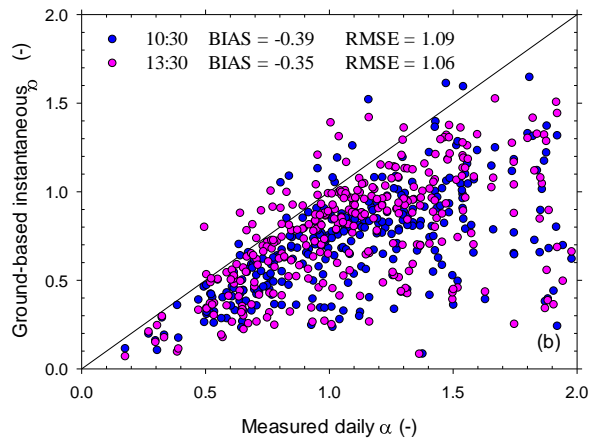
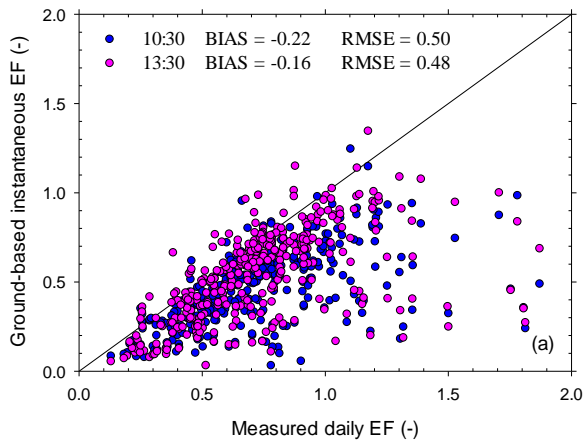
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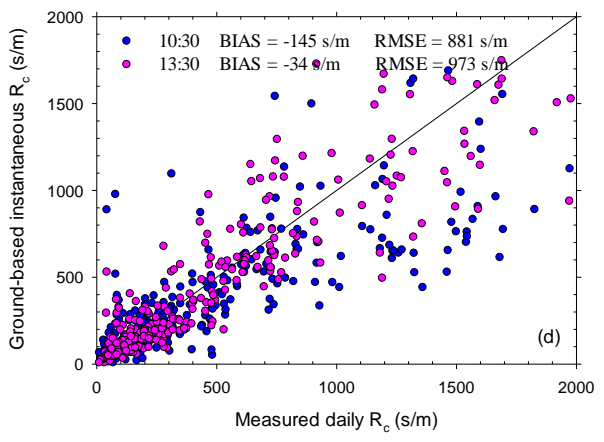
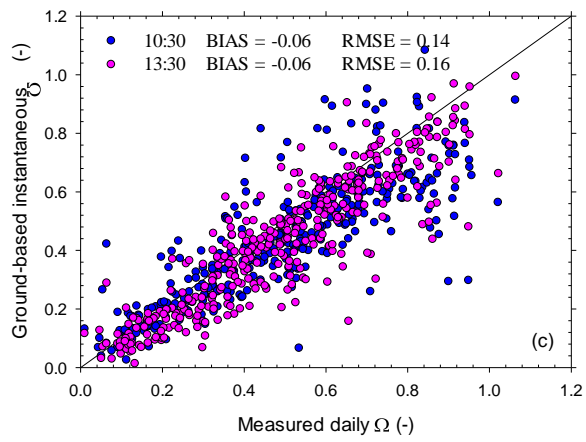
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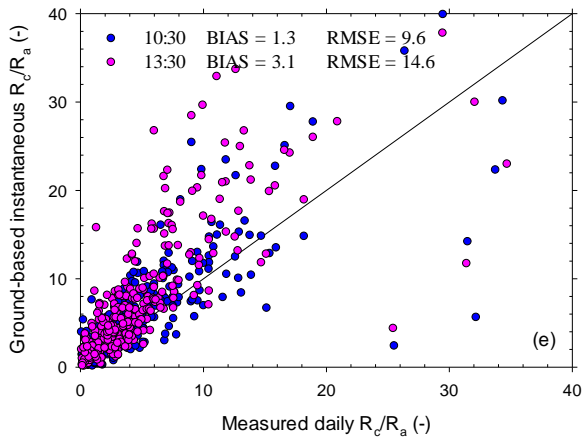
Figure 2. Daytime variation of multi-day averaged half-hourly (a) evaporative fraction, (b) Priestley-Taylor parameter, (c) decoupling factor, (d) surface resistance, (e) ratio of surface resistance to aerodynamic resistance, and their daily mean, estimated using ground-based measurements at the Yucheng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



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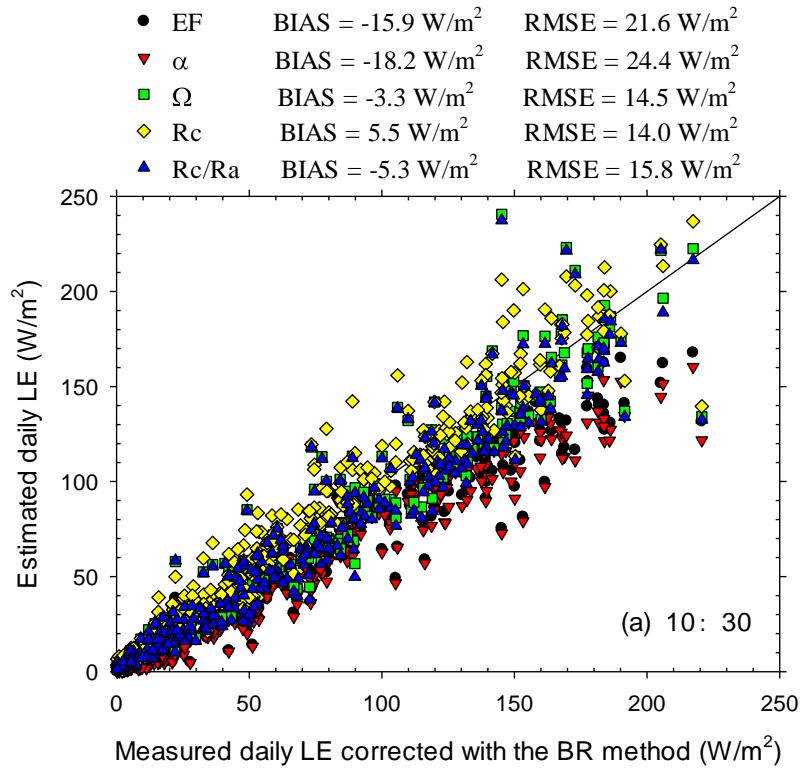
Figure 3. Comparison of (a) evaporative fraction, (b) Priestley-Taylor parameter, (c) decoupling factor, (d) surface resistance, (e) ratio of surface resistance to aerodynamic resistance at 10:30 h (N=357) and 13:30 h (N=360) local time and those at daily scale estimated with ground-based measurements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

## 272 4.2 Evaluation of the ET conversion methods using completely ground-based measurements

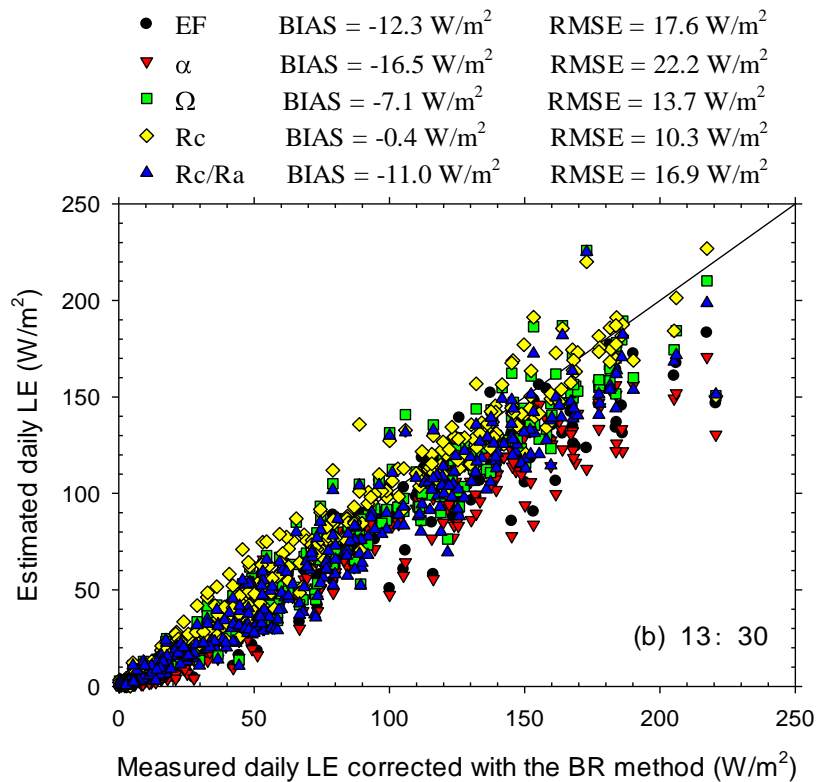
273 Figure 4 compares the daily LE estimated using the five derived conversion methods at 10:30 h and  
274 13:30 h local time with ground-based EC measurements corrected using the BR method. Figure 5  
275 compares the relative bias and relative RMSE in the validation of the daily LE. Several findings are  
276 summarized as follows. i) Overall, the constant  $R_c$  method and the constant  $\Omega$  method could produce good  
277 daily LE with the lowest bias (relative bias falling in between -10% and 7%) and RMSE (relative RMSE  
278 falling in between 20% and 15%), respectively, and the two statistics were of limited variation when the  
279 conversion time was switched from 10:30 h to 13:30 h local time, whereas large underestimations in the  
280 validation of the estimated daily LE were found in the constant EF method and the constant  $\alpha$  method,  
281 with relative biases of -22% and -25% (-17% and -23%) and relative RMSEs of 30% and 34% (25% and  
282 31%) at 10:30 h (13:30 h) conversion time, respectively. ii) The constant EF method, the constant  
283  $\alpha$  method, the constant  $\Omega$  method, and the constant  $R_c/R_a$  method were all shown to underestimate the  
284 daily LE whereas the constant  $R_c$  method showed a change from an overestimation at 10:30 h to a very  
285 small underestimation at 13:30 h of the daily LE. The underestimation bias (the difference between the  
286 estimated and observed daily LE) and RMSE for the former four methods varied between -18.2  $W/m^2$  and  
287 -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  
288 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  
289 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  
290 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)  
291 The constant  $\alpha$  method and the constant EF method overall produced the highest and the second highest  
292 underestimation bias and RMSE, respectively, but the underestimation of the daily LE was reduced when  
293 the conversion time was switched from 10:30 h to 13:30 h local time.

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

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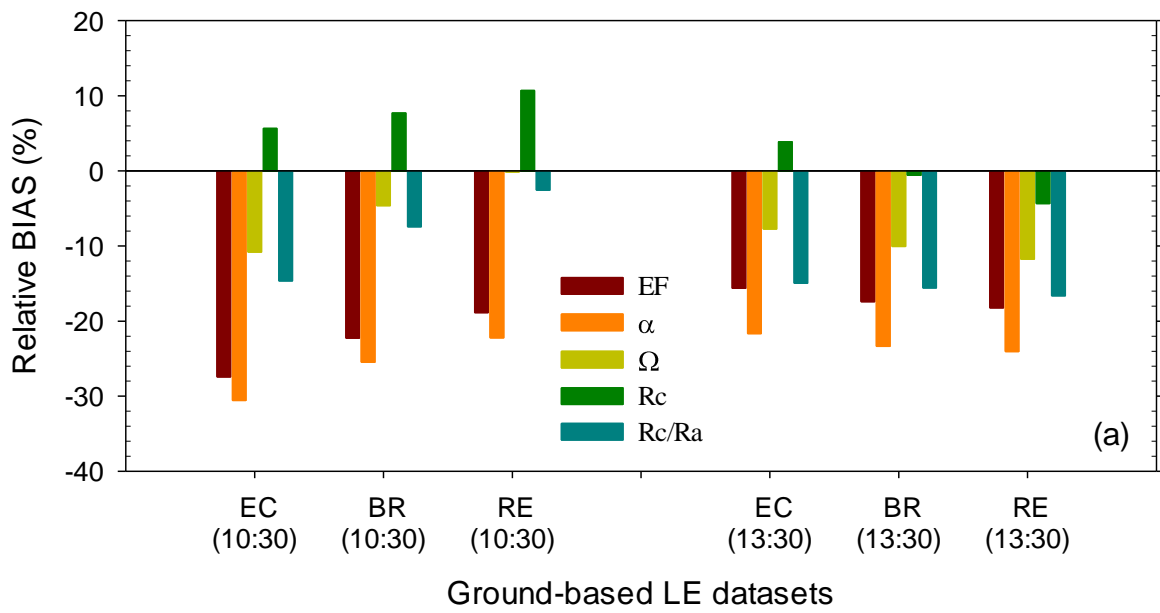
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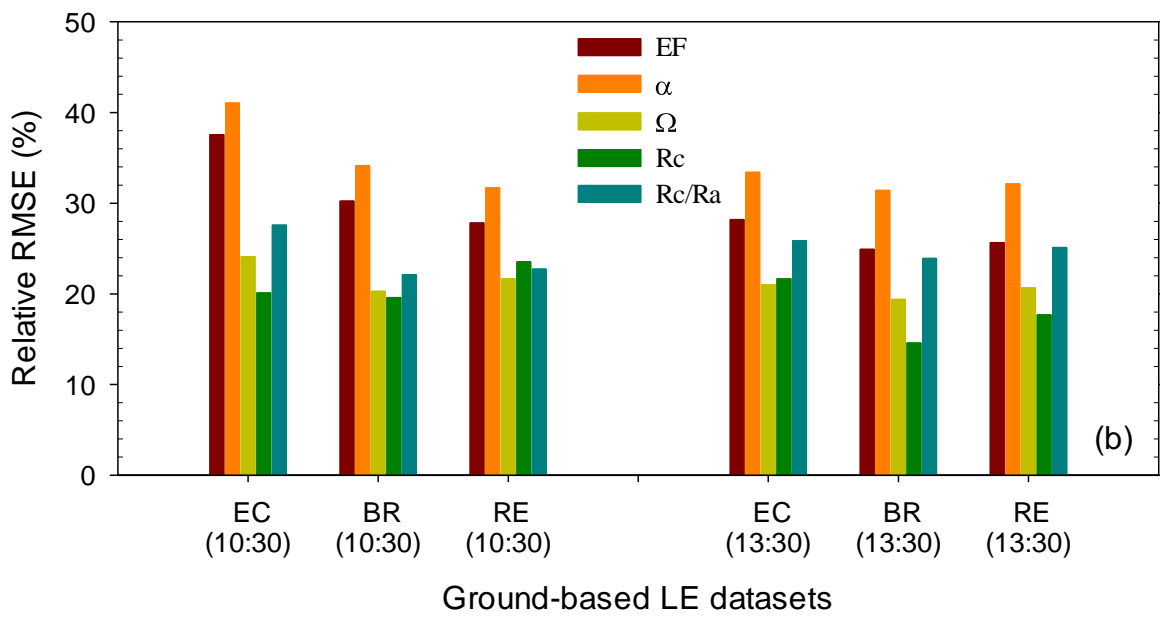
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304 Figure 4 Comparison of daily LE estimated using the five conversion methods with ground-based EC  
 305 measurements corrected using the Bowen ratio (BR) method. (a) Converting 357 half-hourly  
 306 measurements at 10:30 h local time to the daily scale. (b) Converting 360 half-hourly measurements at  
 307 13:30 h local time to the daily scale.

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

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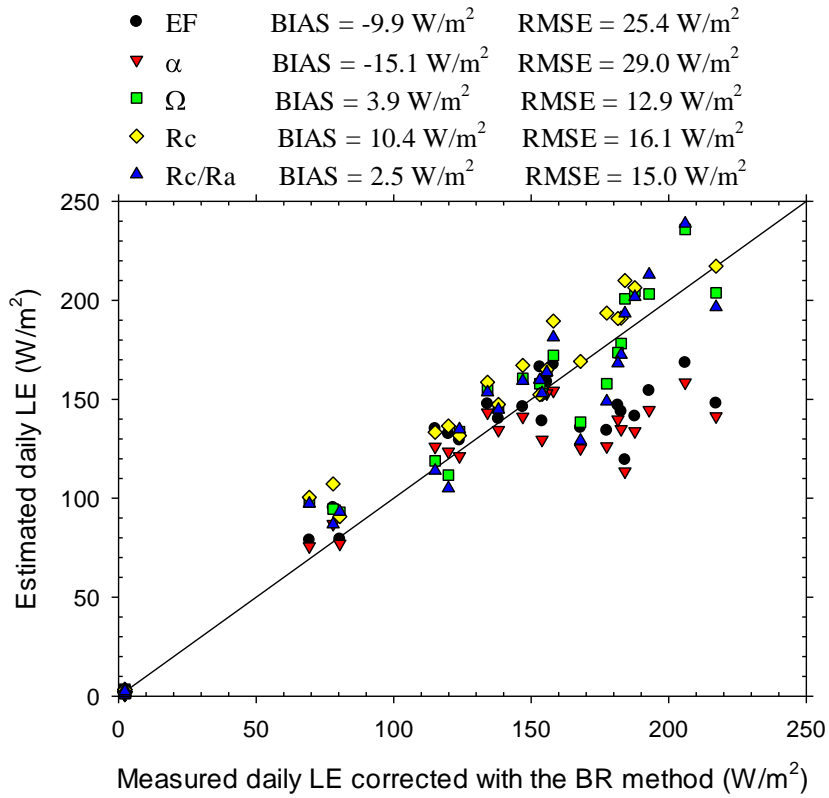


### 321 4.3 Evaluation of the ET conversion methods using MODIS-based datasets

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

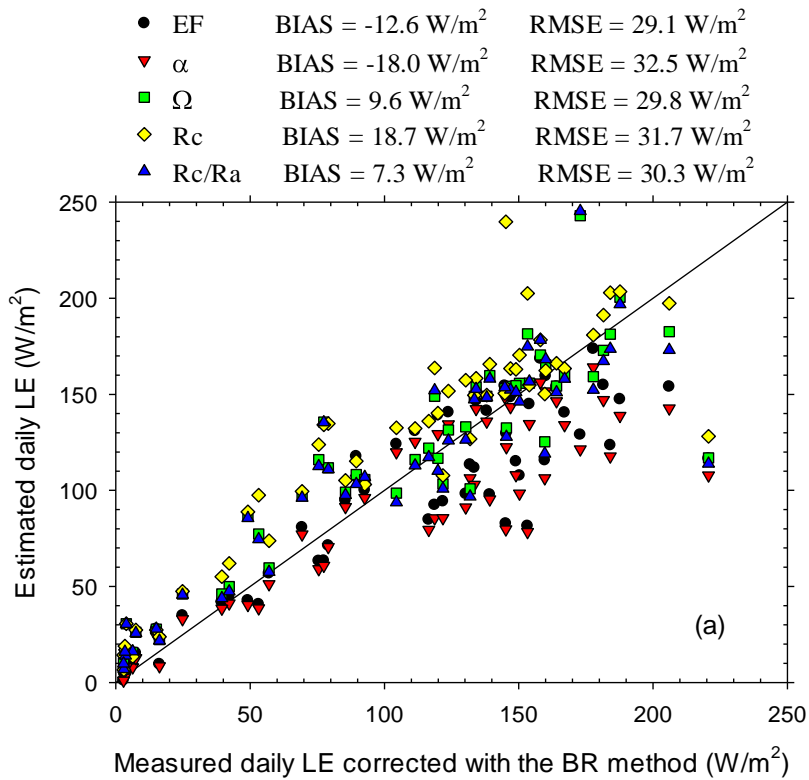
338 Overall, the constant  $\Omega$  method and the constant Rc/Ra method performed the best and could produce  
339 reasonably good daily LE when remote sensing instantaneous LE and other inputs were provided without  
340 significant biases. The constant Rc method, which produced a similar magnitude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

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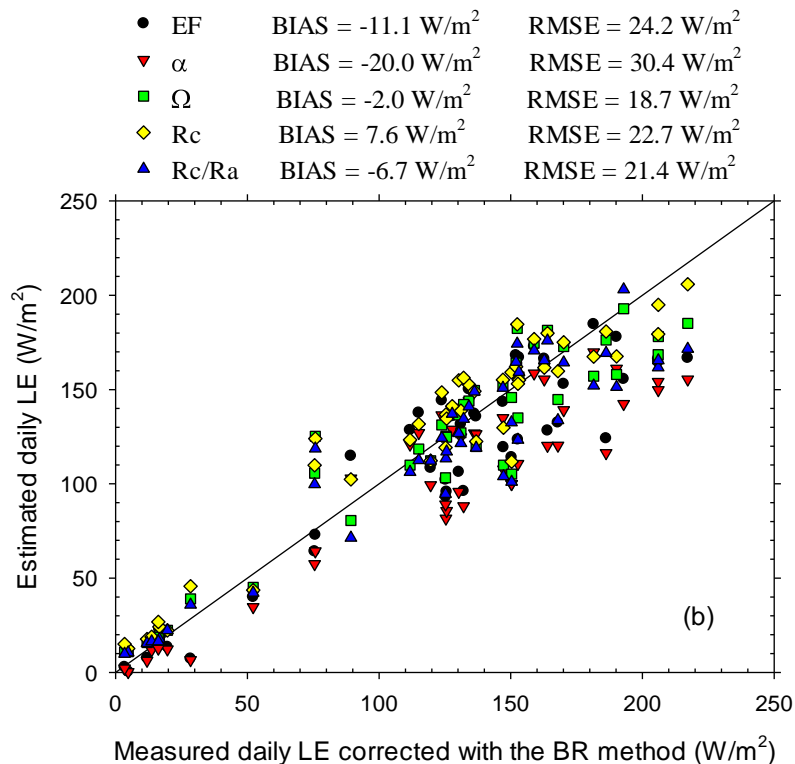


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Figure 6 Comparison of daily LE estimated from 33 N95-derived instantaneous LE at MODIS/TERRA overpass times from *Tang et al.* [2011a] using the five conversion methods with ground-based EC measurements corrected using the Bowen ratio (BR) method.



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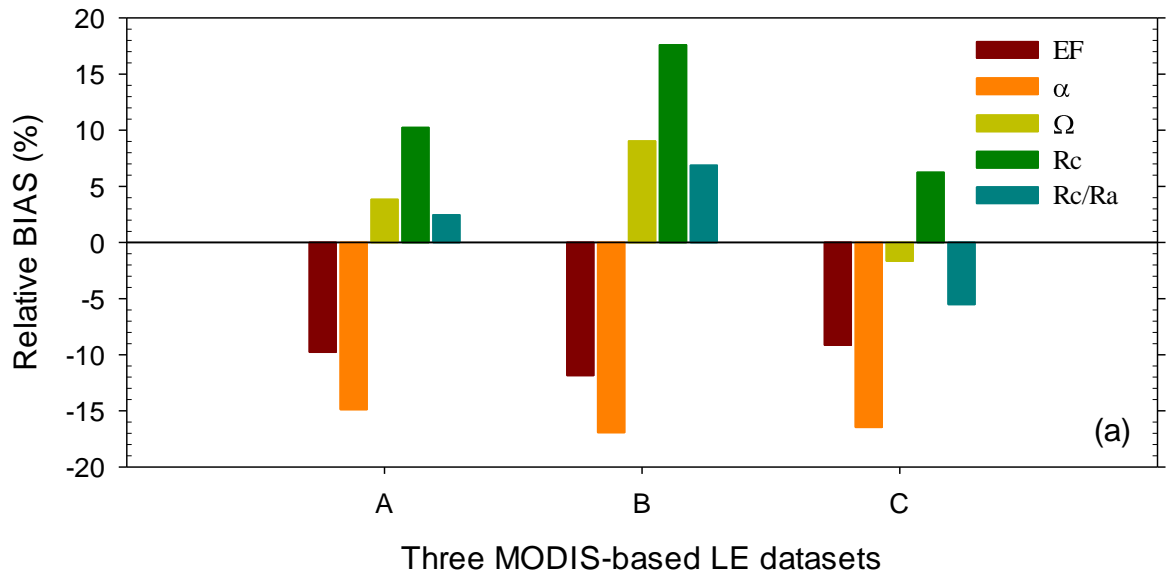
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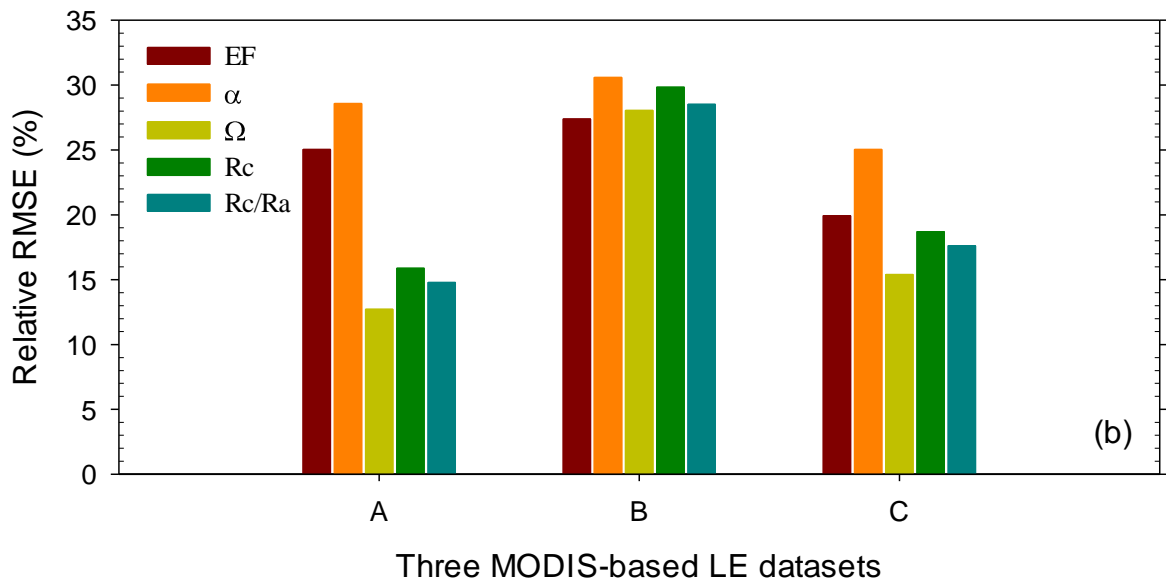
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Figure 7 Comparison of daily LE estimated using the five conversion methods with ground-based EC measurements corrected using the Bowen ratio (BR) method. (a) Converting 55 N95-derived instantaneous LE at MODIS/TERRA overpass times from *Tang et al.*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



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361 Figure 8 Relative bias (the ratio of the BIAS to the mean of the EC measurements) and relative RMSE  
 362 (the ratio of the RMSE to the mean of the EC measurements) in the comparison of daily LE estimated  
 363 using the five conversion methods and remotely sensed instantaneous LE datasets with ground-based  
 364 EC measurements corrected using the Bowen ratio (BR) method. A. N95-derived LE from *Tang et al.*  
 365 [2011a]. B. MODIS/TERRA-based LE from *Tang et al.* [2013a]. C. MODIS/AQUA-based LE from  
 366 *Tang et al.* [2013a].

#### 367 4.4 Discussion and sensitivity analysis

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

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

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

408 Three of the five proposed methods, namely the constant EF method, the constant  $\alpha$  method, and the  
409 constant Rc method, have already been separately attempted by some authors for converting instantaneous  
410 ET to daily values. The designed relationship between daily and instantaneous ETs as shown in Eq. (7) in  
411 this study physically connects these ET conversion methods with each other. The underestimation of the  
412 daily ET in the constant EF method as shown in this study has also been widely reported by a number of  
413 authors [Delogu *et al.*, 2012; Van Niel *et al.*, 2011; Cammalleri *et al.*, 2012; Chávez *et al.*, 2008]. Some  
414 authors [Brutsaert & Sugita, 1992; Van Niel *et al.*, 2011] have suggested multiplying additional calibration  
415 factors in the formulation of the constant EF method to correct the underestimation of the daily ET.  
416 However, these corrections are generally more empirical and less physically based, which is different from  
417 the correction from this study that is of more physical foundation (e.g., the constant  $\Omega$  method). The  
418 constant  $\alpha$  method is rarely investigated for the instantaneous ET conversion. One example is from Crago  
419 [1996] who once made an attempt to estimate daytime ET from the Priestley-Taylor equation using midday  
420  $\alpha$  instead of daytime average values. The author also found an underestimation when compared to the  
421 daytime ET measurements and the results produced using the constant EF method, which is consistent with  
422 the results obtained from the constant  $\alpha$  method in this study. The seldom applied constant Rc method is  
423 also reported by Liu *et al.* [2011] to outperform the constant EF method. The better performance of the  
424 constant Rc method is partly attributed to the fact that the sensitivity of this method to surface resistance is  
425 lower than that of the constant EF method to evaporative fraction, which can be seen from Section 4.1 and  
426 4.2. Note that Tang *et al.* [2013a] found that the constant reference EF method had a better performance  
427 than the constant EF method. Whether the other four alternative methods are better than the constant  
428 reference EF method is beyond the scope of our paper. We will make comparisons between our new  
429 methods and the constant reference EF method in future work.

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

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

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

462

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.

		$LE_i$ ( $W/m^2$ )		$(R_n-G)_i$ ( $W/m^2$ )		$T_{a,i}$ ( $^{\circ}C$ )		$P_i$ (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										
$\alpha$	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						
$\Omega$	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



469 **5. Conclusions**

470 This paper designs the theoretical relationship between daily and instantaneous ETs with a  
471 multiplication of multiple fractions through a mathematical derivation of the physics-based  
472 Penman-Monteith equation. With rough to rigid assumptions on the designed relationship, this paper  
473 further develops five methods for converting remotely sensed instantaneous ET to daily values, one of  
474 which is equivalent to the conventional constant EF method that has already been widely applied. The five  
475 methods are then evaluated and intercompared using long-term ground-based EC-measured half-hourly LE  
476 and three groups of MODIS-based instantaneous LE datasets collected from April 2009 to late October  
477 2011 at the Yucheng station.

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

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498 acquired at Yucheng National Agriculture Ecosystem Observation and Research Station  
499 (<http://yca.cern.ac.cn/>) after registration and application. This work was partly supported by the National  
500 Natural Science Foundation of China under Grant 41571351 and 41571367 and by the International  
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