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

3

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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 Ω 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 (Ω) 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 (α) 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 Ω (-) 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 α is the Priestley-Taylor parameter, Δ is the slope of the saturated vapor pressure versus air
 103 temperature curve, $kPa/^\circ C$; γ 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; ρ is the air density, kg/m³; 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/m²; and G is the soil heat flux,
 107 W/m².

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 α method.
- 124 (iii) Assuming $\frac{\Omega_d}{\Omega_i} = 1$, called the constant Ω 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 CO₂/H₂O 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.

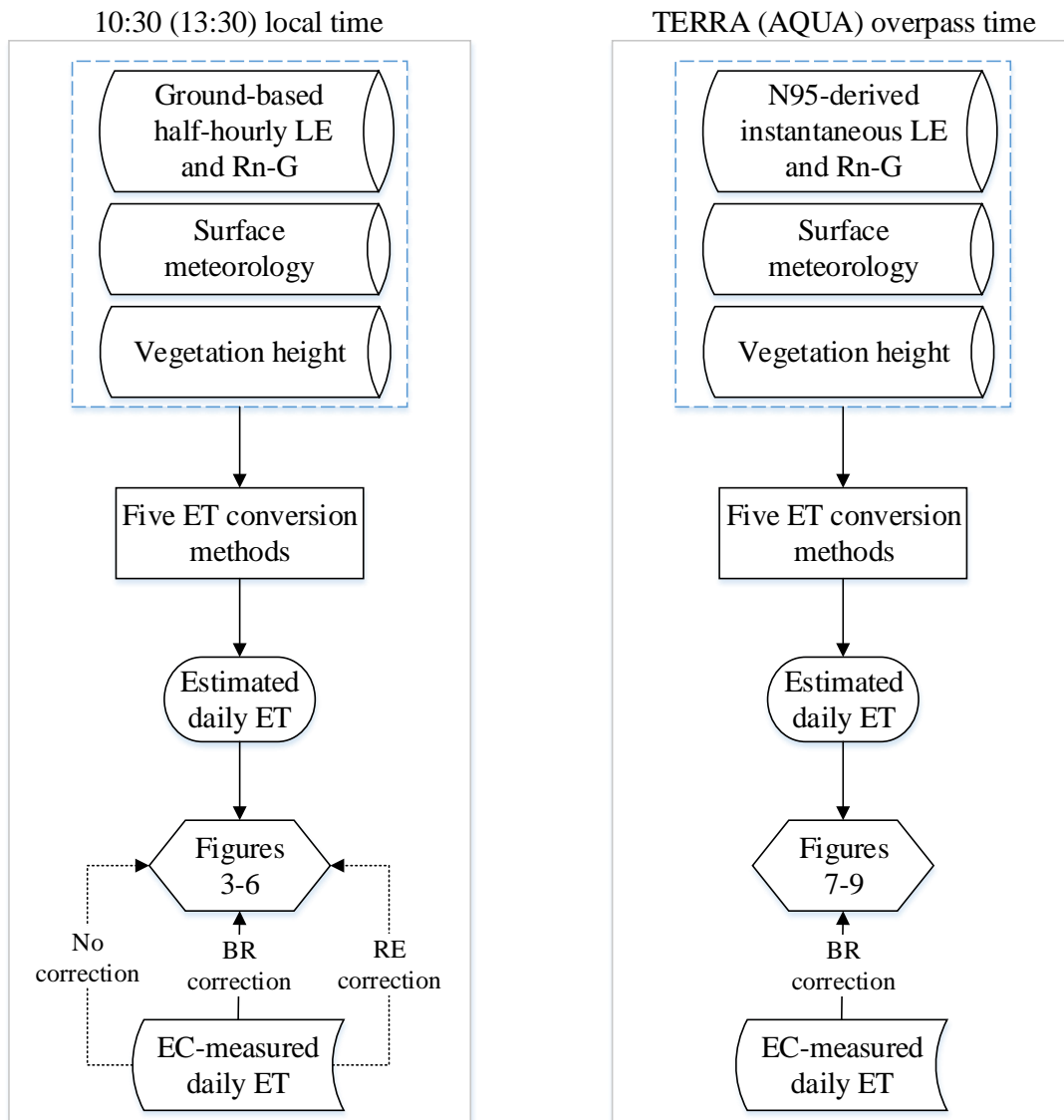
170 **3.2 MODIS-based datasets**

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 W/m^2 and a root mean
181 square error (RMSE) of 42 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 W/m^2 and -1 W/m^2 and RMSEs of 46 W/m^2 and 34 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).
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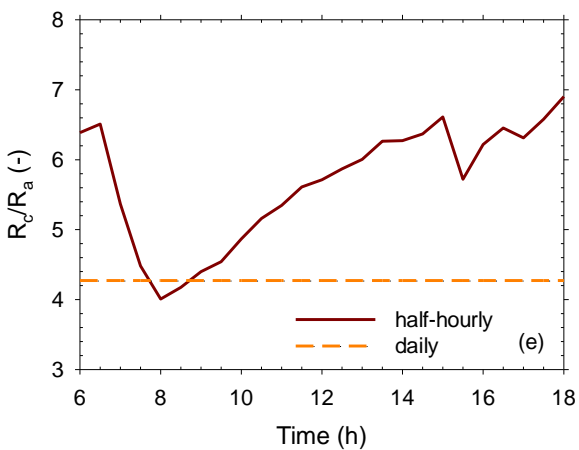
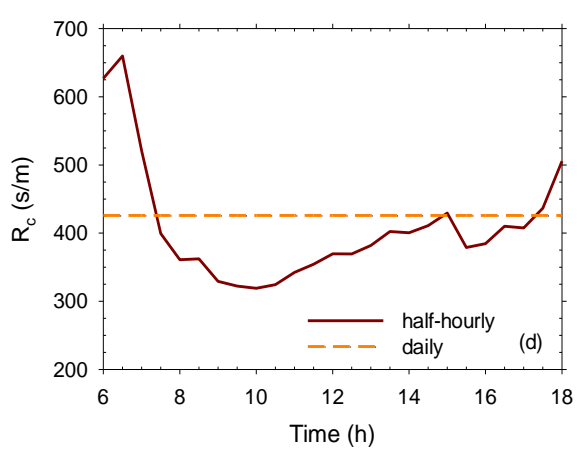
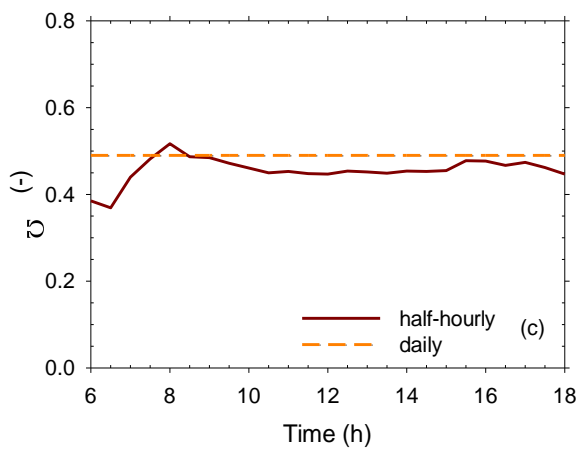
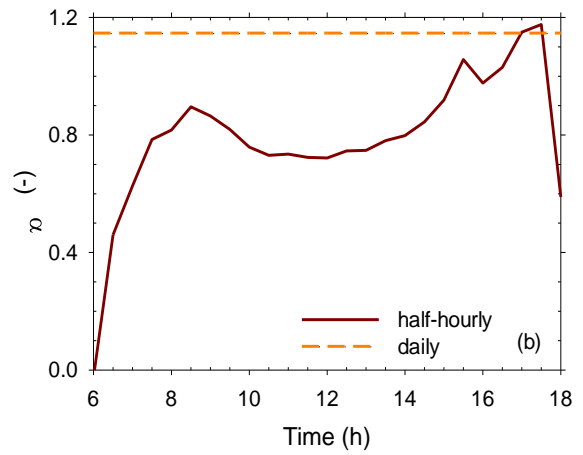
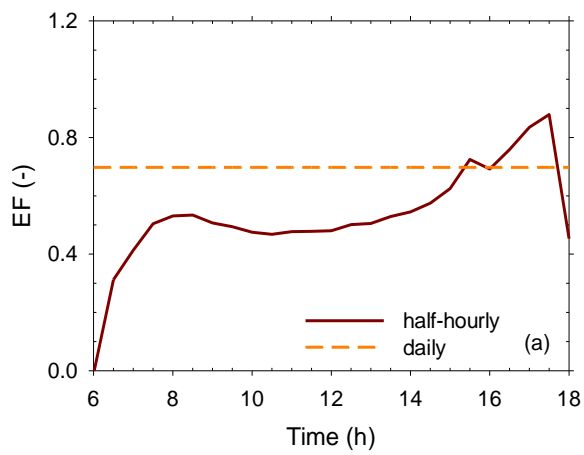
220 4. Results and discussion

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 α method, the constant Ω method, the constant Rc method, and the constant Rc/Ra method), we first
 224 examined how the EF, α , Ω , 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, α , Ω , Rc, and Rc/Ra). Figure 2 shows the daytime

226 variation of the multi-day averaged EF, α , Ω , 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, α , Ω , and Rc
231 underestimated their daily mean whereas the half-hourly Rc/Ra overestimated its daily mean. The α at
232 half-hourly scale relative to its daily mean had a larger underestimation than the EF and the Ω , and the Ω
233 had the smallest underestimation among these three variables. The underestimation of EF, α , 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 Ω 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 α while the half-hourly Ω 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, α , Ω , 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 α 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 Ω 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, α , Rc, and Rc/Ra. For the
251 Ω 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 α variables, slight differences of the bias
254 and RMSE were found between the two conversion time.

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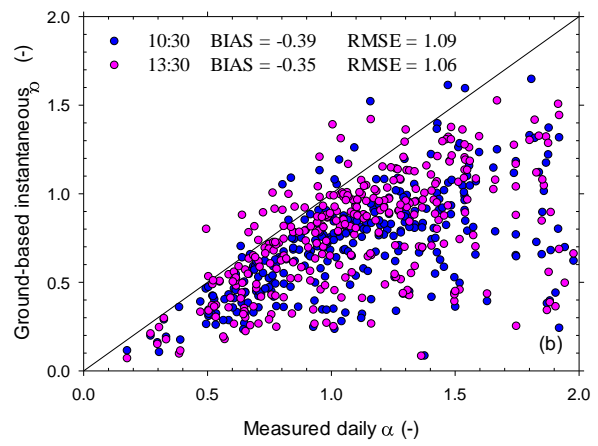
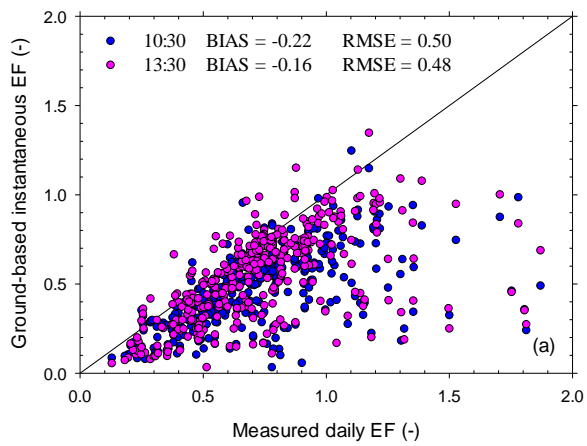
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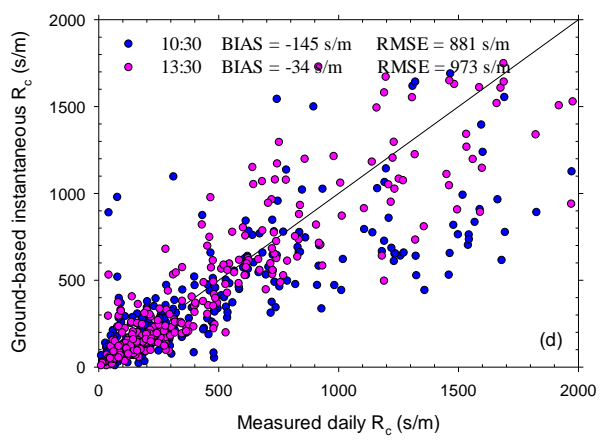
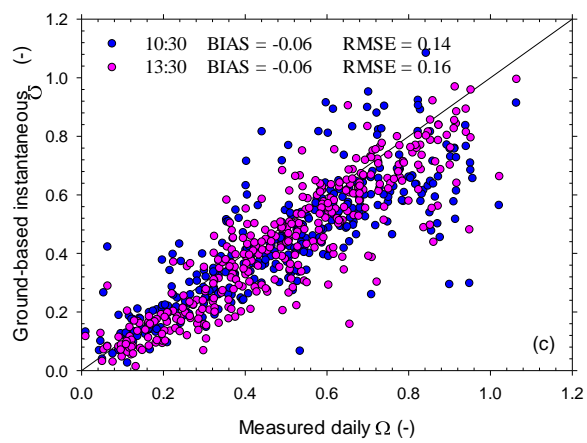
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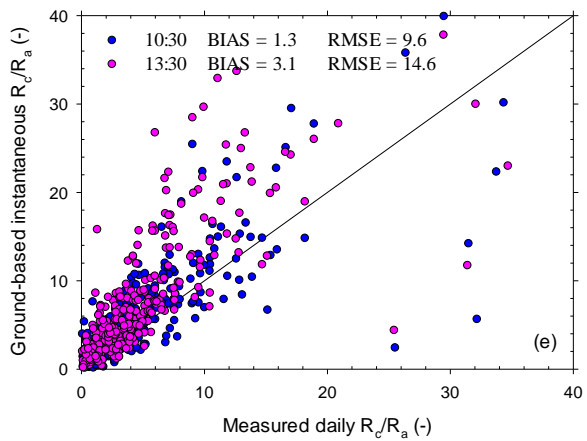
Figure 2. Daytime variation of multi-day averaged half-hourly (a) evaporative fraction, (b) Priestley-Taylor parameter, (c) decoupling factor, (d) surface resistance, (e) ratio of surface resistance to aerodynamic resistance, and their daily mean, estimated using ground-based measurements at the Yucheng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



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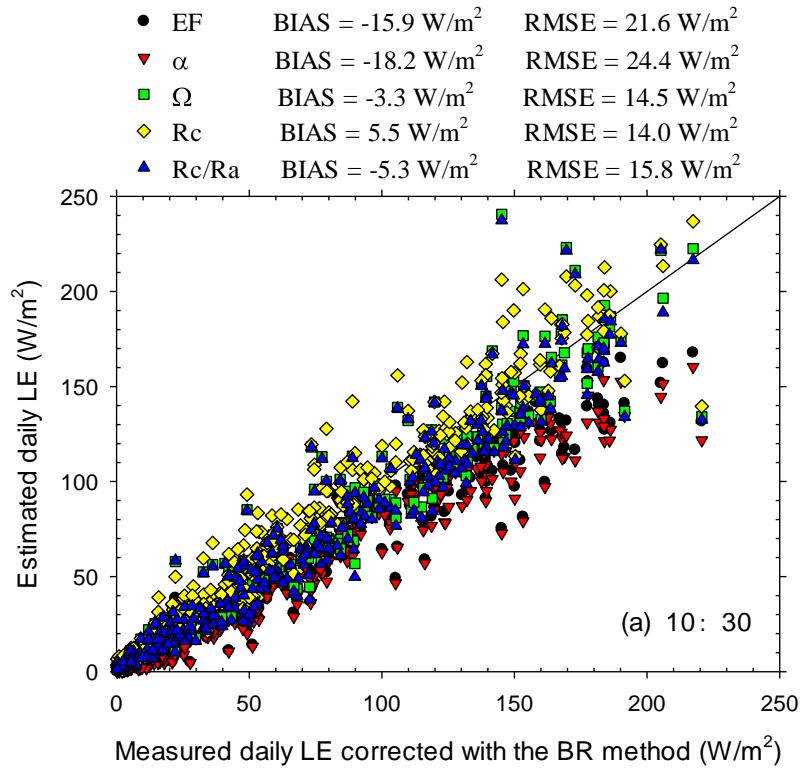
Figure 3. Comparison of (a) evaporative fraction, (b) Priestley-Taylor parameter, (c) decoupling factor, (d) surface resistance, (e) ratio of surface resistance to aerodynamic resistance at 10:30 h (N=357) and 13:30 h (N=360) local time and those at daily scale estimated with ground-based measurements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

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

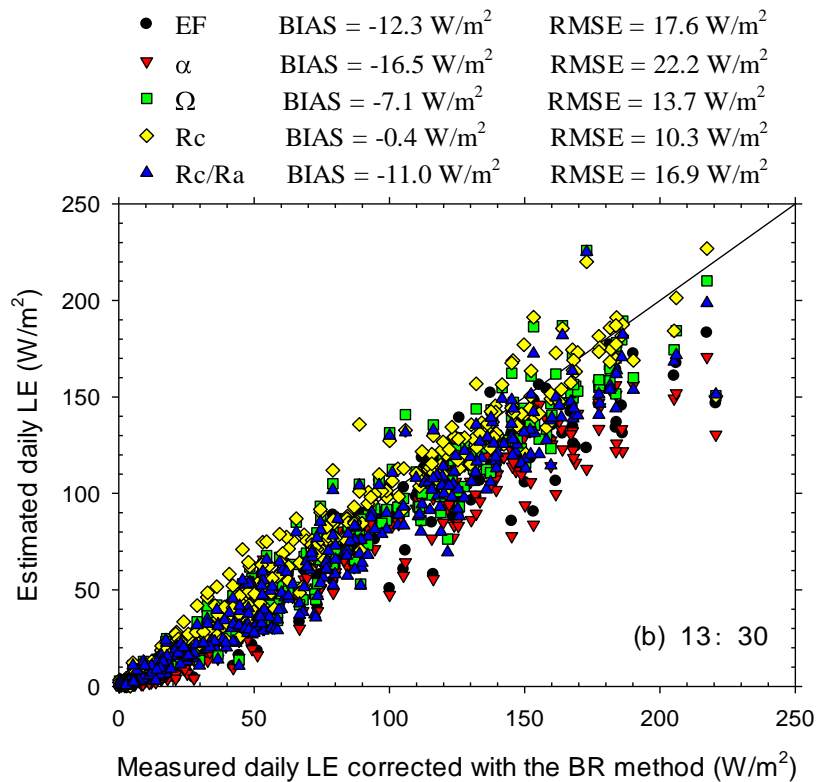
273 Figure 4 compares the daily LE estimated using the five derived conversion methods at 10:30 h and
274 13:30 h local time with ground-based EC measurements corrected using the BR method. Figure 5
275 compares the relative bias and relative RMSE in the validation of the daily LE. Several findings are
276 summarized as follows. i) Overall, the constant R_c method and the constant Ω 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 α 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 α method, the constant Ω 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 α 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 Ω method and the constant R_c method were still among the top two
298 schemes for producing reasonably good daily LE whereas the constant α 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 Ω method at 13:30 h local time when the RE correction method was applied.

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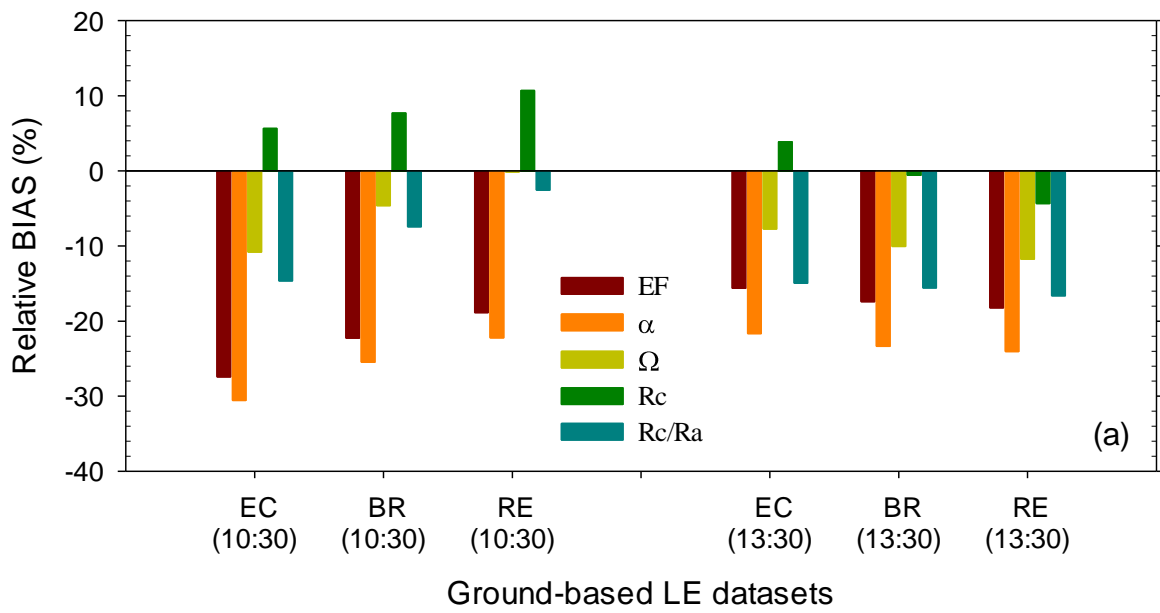
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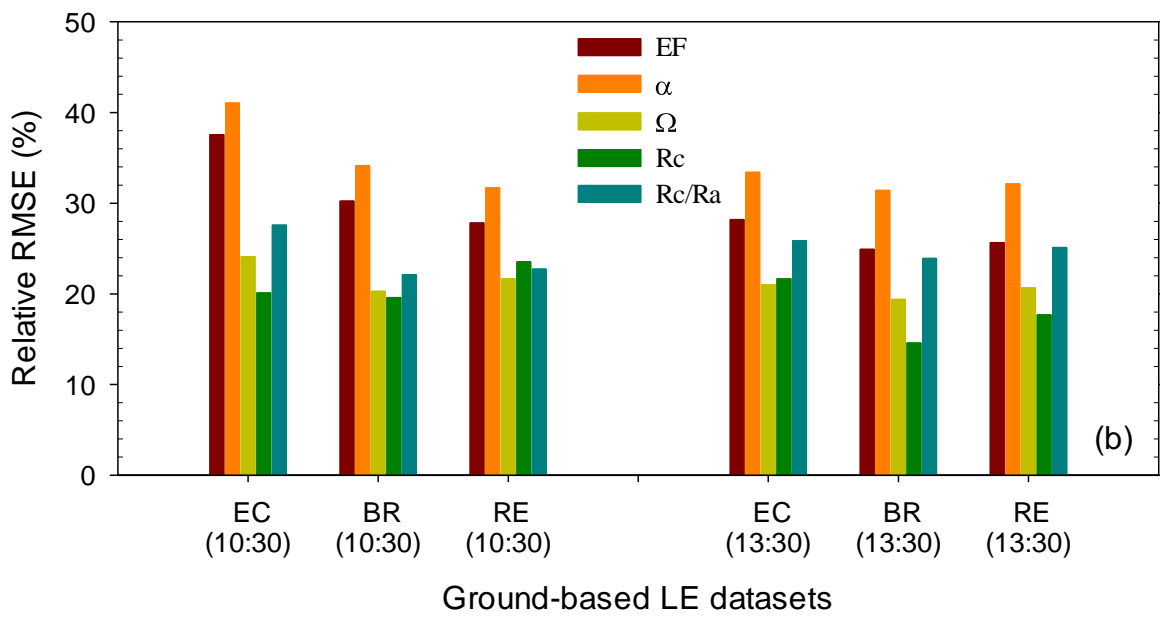
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304 Figure 4 Comparison of daily LE estimated using the five conversion methods with ground-based EC
 305 measurements corrected using the Bowen ratio (BR) method. (a) Converting 357 half-hourly
 306 measurements at 10:30 h local time to the daily 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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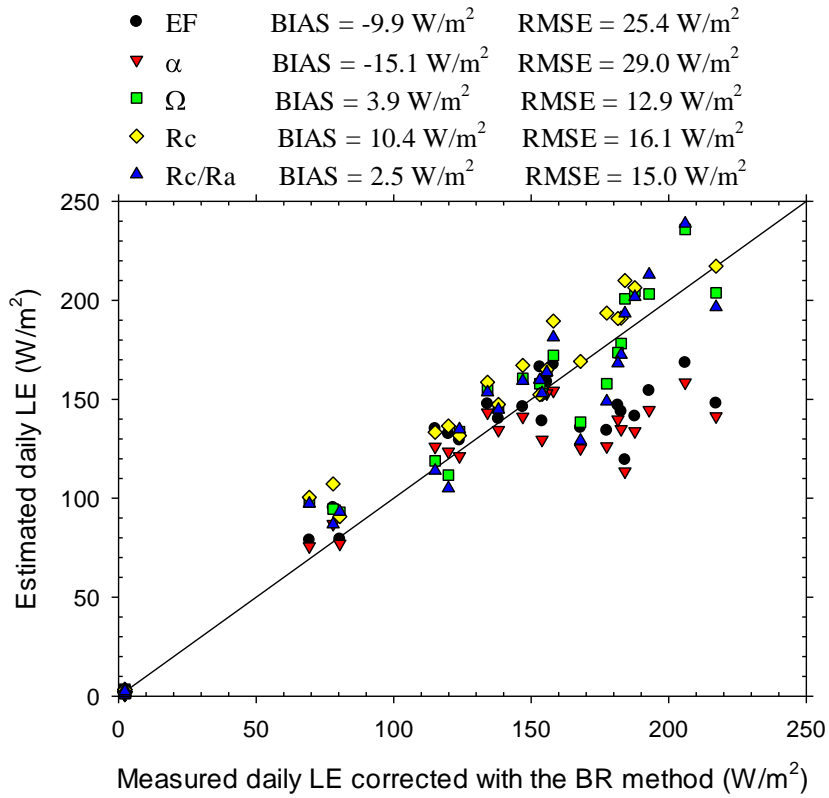
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321 4.3 Evaluation of the ET conversion methods using MODIS-based datasets

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 α 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 Ω 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 Ω 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 Ω 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 α method.

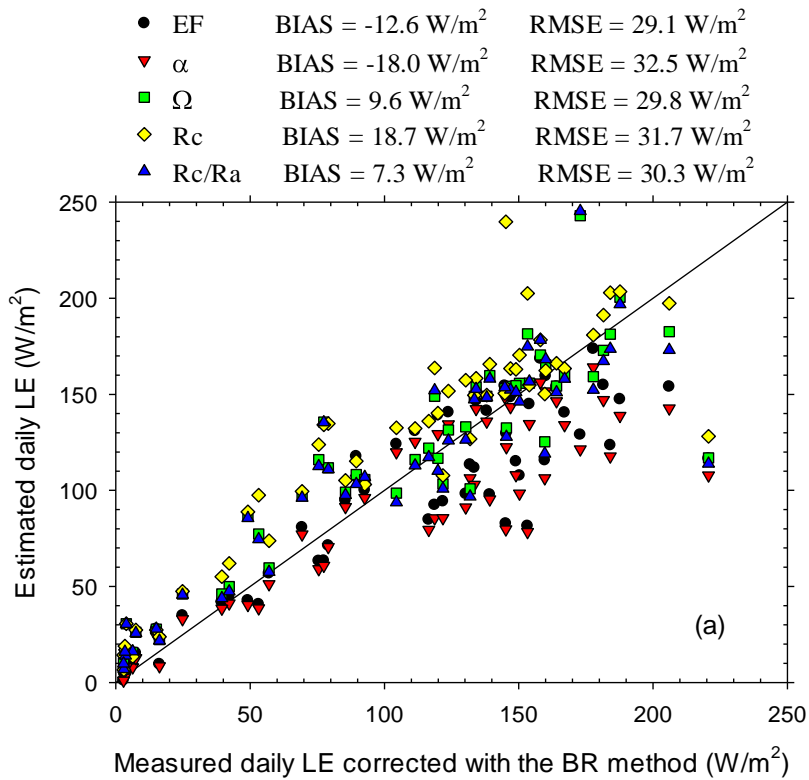
338 Overall, the constant Ω method and the constant Rc/Ra method performed the best and could produce
339 reasonably good daily LE when remote sensing instantaneous LE and other inputs were provided without
340 significant biases. The constant Rc method, which produced a similar magnitude of RMSE to the constant
341 Ω method and the constant Rc/Ra method but had a relatively larger bias, performed slightly worse. The
342 constant α 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 α method.

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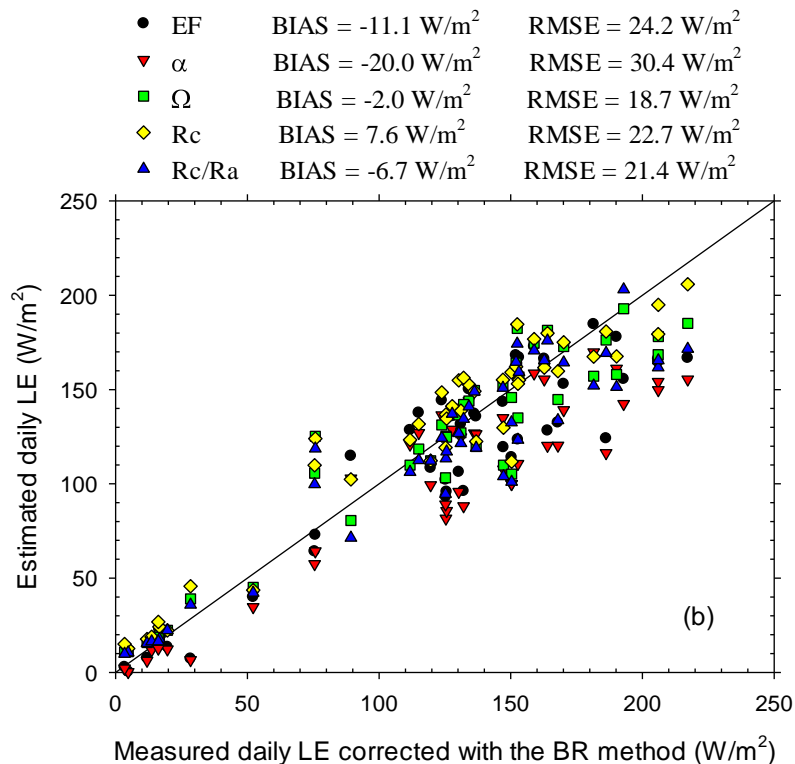


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Figure 6 Comparison of daily LE estimated from 33 N95-derived instantaneous LE at MODIS/TERRA overpass times from *Tang et al.* [2011a] using the five conversion methods with ground-based EC measurements corrected using the Bowen ratio (BR) method.



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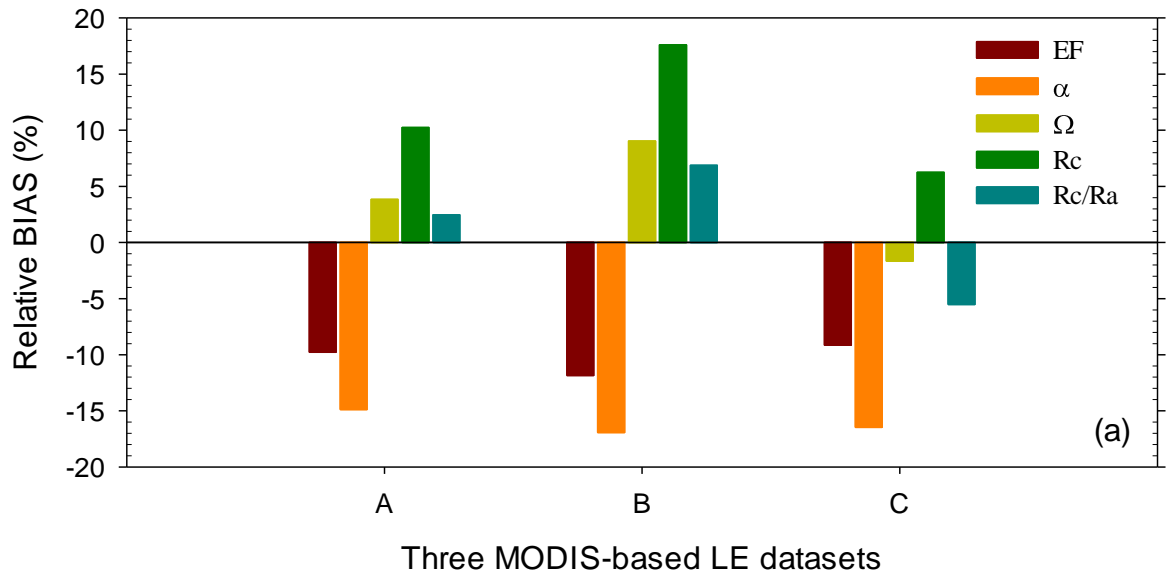
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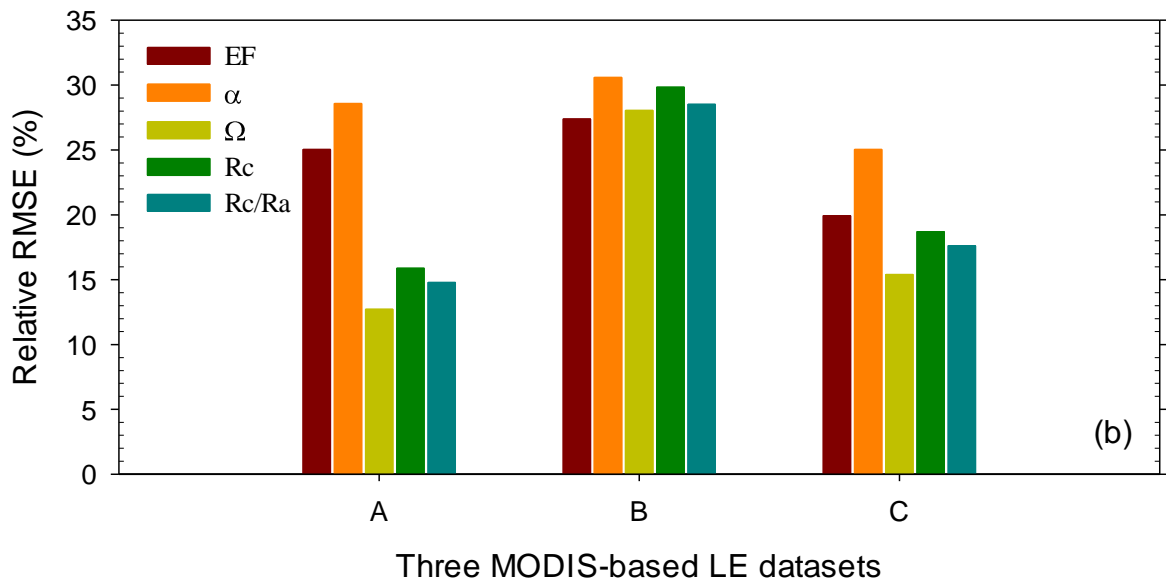
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Figure 7 Comparison of daily LE estimated using the five conversion methods with ground-based EC measurements corrected using the Bowen ratio (BR) method. (a) Converting 55 N95-derived instantaneous LE at MODIS/TERRA overpass times from *Tang et al.* [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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360

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, α , Ω , 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, α , and Ω 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, α , Ω , 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 α method, the constant Ω 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 α , Ω , Rc/Ra) at the time of the satellite overpass and
382 the EF (or α , Ω , 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 α as shown in Eq. (2) results in the very similar non-linear
388 shape of daytime EF to that of daytime α . Because $\Delta/(\Delta+\gamma)$ increases when air temperature rises, the
389 underestimation will further be strengthened using the constant α method compared to the constant EF
390 method, leading to a larger underestimation of daily LE. The relationship between the Ω and the Rc/Ra as
391 presented in Eq. (4) explains the inverse shape of daytime Ω and Rc/Ra. Because of the limited variability
392 of $\gamma/(\Delta+\gamma)$, the constant Ω 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, α , 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 Ω , the constant Ω 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 Ω 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 α method that may be oversimplified.

408 Three of the five proposed methods, namely the constant EF method, the constant α 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 Ω method). The
418 constant α 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 α 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 α 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 α method have fewer number of input variables but relatively a lower accuracy of

432 the daily ET estimates than the constant Ω 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 α method, and the constant Ω 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 α 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 α method and produced a similar magnitude
459 of variation (-4.2% to 3.7%) of the daily LE estimates in the constant Ω 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)		$T_{a,i}$ (°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

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 Ω 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 α 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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