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A re-examination of two methods for estimating daily evapotranspiration from remotely sensed instantaneous observations

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ABSTRACT

The significance of estimating land surface evapotranspiration (ET) has been widely recognized in the fields of hydrology, meteorology, agriculture, and global change. This article compares two ET conversion methods, the constant decoupling factor (Ω) method and the constant reference evaporative fraction (EF_r) method, that estimate daily ETs from instantaneous values. The daily ET was estimated either by (1) summing multiple half-hourly or hourly ET estimates that were derived through an application of the two ET conversion methods to half-hourly or hourly meteorological variables (i.e. aggregating the ET outputs) or by (2) directly applying the two ET conversion methods to daily meteorological variables (i.e. aggregating the meteorological inputs). The comparison was made using ground-based eddy covariance (EC) system measurements and the moderate resolution imaging spectroradiometer (MODIS)-based latent heat flux (LE) datasets collected from April 2009 to late October 2011 at the Yucheng station over the North China Plain. The results show that both the constant Ω method and the constant EF_r method produced daily latent evaporation (LE) estimates that were in agreement with the ground-based EC measurements. When the two methods were applied to the MODIS-based LE datasets that have a small bias of -8 W m^{-2} and an root mean square error (RMSE) $<60 \text{ W m}^{-2}$, the validation results of the estimated daily LE against the ground-based EC measurements showed a relative bias of $<7\%$ and a relative RMSE of $<20\%$. For both ET conversion methods, aggregating the ET outputs produced better agreement with the ground-based EC measurements than directly obtaining the daily ET by aggregating the meteorological inputs did. No significant difference was observed in the model performance between the constant Ω method and the constant EF_r method.

ARTICLE HISTORY

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1. Introduction

The significance of estimating land surface evapotranspiration (ET, water in mm, equivalent to latent heat flux and often used interchangeably with latent heat flux) has been widely recognized in the fields of hydrology, meteorology, agriculture, and global change. Remote-sensing technology is regarded as the only viable means to map regional or global ET in a globally consistent and economically feasible manner. However, direct ET estimates from models using remote-sensing data are instantaneous values provided at satellite overpass times (Kalma, McVicar, and McCabe 2008; Li et al. 2009), which do not help researchers and practitioners who require ET datasets at daily and longer timescales. Several techniques with varying degrees of complexity and accuracy have been developed to convert remotely sensed instantaneous ET values to daily values over the past three decades (Brutsaert and Sugita 1992; Delogu et al. 2012; Ryu et al. 2012; Van Niel et al. 2012; Tang, Li, and Sun 2013; Cammalleri, Anderson, and Kustas 2014), primarily including the constant evaporative fraction (EF) method, the constant reference evaporative fraction method, the constant decoupling factor (Ω) method, and the constant flux ratio method (e.g. the ratio of latent heat flux to global solar radiation/extraterrestrial solar radiation/surface net radiation).

The constant Ω method, recently proposed by Tang and Li (2017a, 2017b) through a simplified deviation of the Penman–Monteith equation, is a new, physically based technique that has proven to provide good estimates of daily ET from instantaneous values. This method assumes that the relative constancy of Ω in a diurnal cycle or, in a more straightforward way, that the instantaneous Ω derived at satellite overpass times equal the Ω at a daily scale. Because this new method requires instantaneous and daily meteorological measurements of air temperature, wind speed, air vapour pressure, and air pressure as inputs, it can capture the effect of temporally variable meteorological factors in the diurnal pattern of surface ET. This method is more physically based than the commonly applied constant EF method and can be applied operationally with little model complexity and less computation time. This method can also adjust the relative difference between the instantaneous EF at the time of the satellite overpass and the EF during other timeframes in a theoretically reasonable manner, and thus, it significantly reduces the underestimation of the daily ET, estimated using the constant EF method. Tang and Li (2017a, 2017b) have demonstrated the robustness of the new ET conversion method and its superiority over the conventional constant EF method for converting instantaneous ET to daily values. The constant reference evaporative fraction (EF_r , the ratio of actual to reference grass/alfalfa ET) method, proposed by Trezza (2002), is another technique that can also incorporate the effect of horizontal advection and variable environmental factors on the ET in a diurnal cycle. Similar to the constant Ω method, the constant EF_r method assumes that the instantaneous EF_r equals daily EF_r . The daily ET is estimated by multiplying the daily EF_r by the daily reference ET. The constant EF_r method has been widely applied for converting remotely sensed instantaneous ET to daily values, and its effectiveness has been demonstrated by a number of studies (Colaizzi et al. 2006; Chávez et al. 2008; Allen, Tasumi, and Trezza 2007; Tang, Li, and Sun 2013; Tang et al. 2015a; Tang et al. 2017c). Previous studies have also reported that this method provides better daily ET estimates than the constant EF method (Tang, Li, and Sun 2013; Chávez et al. 2008; Colaizzi et al. 2006). The daily ET can be estimated either by (1) summing multiple half-hourly or hourly ET estimates that are derived through an application of the two ET conversion methods to half-hourly or hourly meteorological variables (hereinafter referred to as aggregating the ET outputs) or by (2)

directly applying the two ET conversion methods to daily meteorological variables (hereinafter referred to as aggregating the meteorological inputs). Because the constant Ω method and the constant EF_r method have similar meteorological inputs and both produce reliable daily ET estimates, it is interesting to explore which method performs better.

The objectives of this article are twofold: (1) to investigate which aggregation technique (aggregating the meteorological inputs or the ET outputs) performs better for each of the two ET conversion methods and (2) to examine which ET conversion method performs better for the daily ET estimates. Data used for this analysis are from ground-based meteorological and flux measurements and moderate resolution imaging spectroradiometer (MODIS)-based datasets collected between April 2009 and October 2011 at the Yucheng station.

2. Methodology

Daily ET values can be obtained from instantaneous ET, using the constant Ω method and the constant EF_r method, in two ways (see Figure 1): (1) by first applying the ET conversion method to half-hourly or hourly meteorological variables and then summing the derived multiple half-hourly or hourly ET estimates and (2) by applying the ET conversion method to daily meteorological variables to directly obtain the daily ET values. Inputs for the two ET conversion methods primarily include the instantaneous ET at the satellite overpass time, instantaneous and daily air temperature, vapour pressure deficit, wind speed, and air pressure.

2.1. Constant reference evaporative fraction method

In the constant EF_r method, the latent heat flux at the non-satellite overpass time can be estimated by using the reference ET at both the non-satellite overpass time and at the satellite overpass time (or a given time), and the latent heat flux at the satellite overpass time (or a given time) with the following equation:

$$LE_i = (LE)_s \times \frac{(ET)_{r,i}}{(ET)_{r,s}} \quad (1)$$

where LE is the latent heat flux, $W\ m^{-2}$; ET_r is the reference ET, $mm\ hour^{-1}$ (or $mm\ day^{-1}$); i represents the instantaneous (half-hourly or hourly) or daily timescale; and s indicates the satellite overpass time.

The ET_r at an instantaneous or daily scale is estimated using the Penman–Monteith equation for a hypothetical grass that is characterized by a height of 0.12 m, a surface resistance of $50\ s\ m^{-1}$ during daytime and $200\ s\ m^{-1}$ during night-time, and an albedo of 0.23, as suggested by ASCE-EWRI (2005),

$$ET_r = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T_a + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \quad (2)$$

where Δ is the slope of the saturated vapour pressure versus air temperature curve, $kPa\ ^\circ C^{-1}$; γ is the psychrometric constant, $kPa\ ^\circ C^{-1}$; R_n is the surface net radiation, $W\ m^{-2}$; G is the soil heat flux, $W\ m^{-2}$; T_a is the air temperature, $^\circ C$; u_2 is the wind speed at a 2 m height, $m\ s^{-1}$; $e_s - e_a$ is

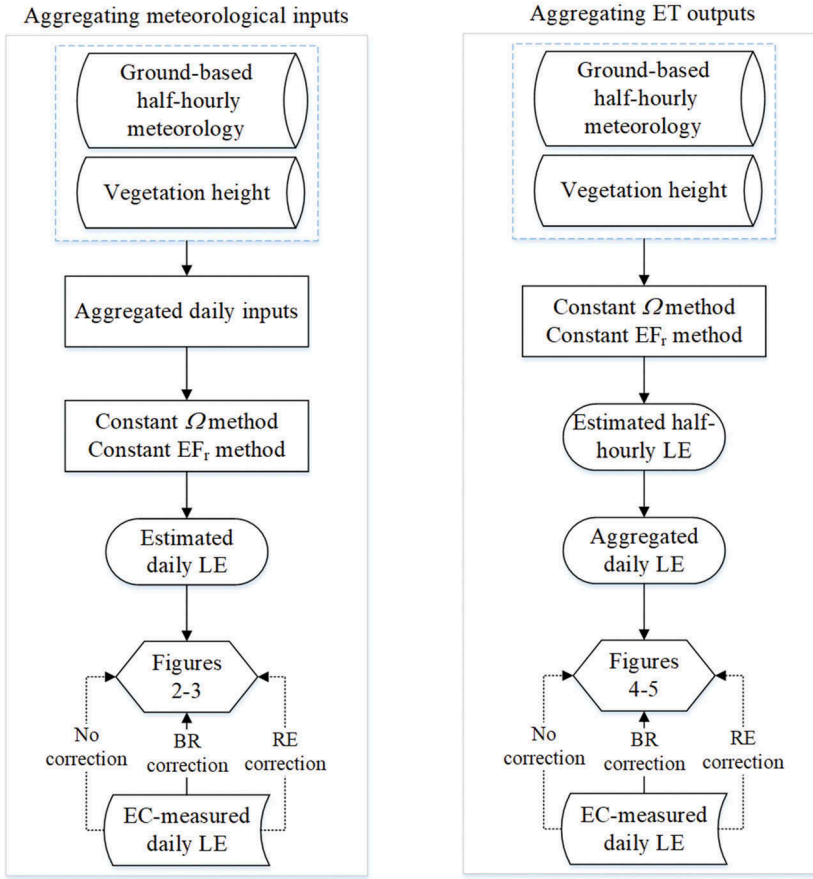


Figure 1. Flow chart of the evaluation of the constant Ω method and the constant EF_r method under two aggregation schemes.

the vapour pressure deficit of the air, kPa; C_n equals 900 at the daily timescale and 37 at the hourly scale; and C_d equals 0.34 at the daily scale and 0.24 at the hourly scale during daytime (0.96 during night-time). The procedure specified by ASCE-EWRI (2005) is used to calculate each of the variables.

2.2. Constant decoupling factor method

In the constant Ω method, the instantaneous or daily latent evaporation (LE) at the non-satellite overpass time is estimated from the LE at the satellite overpass time (or a given time) using the following relationship (Tang and Li 2017a, 2017b):

$$LE_i = \frac{(LE)_s}{(R_n - G)_s} (R_n - G)_i \frac{\Delta_i}{\Delta_i + \gamma_i} \frac{\Delta_s + \gamma_s \Omega_s^*}{\Delta_s \Omega_i^*} \quad (3)$$

where Ω^* is the critical decoupling factor when ET equals the equilibrium ET and can be estimated using the following equations:

$$\Omega^* = \frac{1}{1 + \frac{\gamma}{\Delta + \gamma} r_a^*} \quad (4)$$

$$r_a^* = \frac{(\Delta + \gamma) \rho C_p (\text{VPD})}{\Delta \gamma (R_n - G)} \quad (5)$$

where r_a is the aerodynamic resistance, $s \text{ m}^{-1}$, and is calculated for simplicity by assuming that the atmosphere is under neutral conditions (i.e. no stability correction function is applied). When the constant Ω method is applied at half-hourly or hourly scale, the daily LE is obtained by averaging the multiple half-hourly or hourly LE estimates. When the constant Ω method is applied at a daily scale, the corresponding daily meteorological and flux inputs (air temperature, vapour pressure, wind speed, and surface available energy) are estimated to be the average of multiple half-hourly or hourly measurements, and the daily LE is directly obtained. The daily slope of the vapour pressure curve is computed using the daily air temperature, and the daily VPD equals the daily saturated vapour pressure (estimated using the daily air temperature) minus the daily air vapour pressure. Please see Tang and Li (2017a, 2017b) for more details about the constant Ω method.

3. Test site and data

3.1. Site and ground data

The Yucheng station has a latitude/longitude of 36° 49' 45" N/116° 34' 13" E and is located on the North China Plain. Data collected between late April 2009 and late October 2011 at the Yucheng station are used for analysis in this study. This station has a soil type of sandy loam and is characterized by a sub-humid and monsoon climate, with a mean annual temperature and precipitation of 13.1°C and 528 mm, respectively. Winter wheat and summer corn are rotated with each other. Surface meteorological variables and energy flux, including wind speed, relative humidity, air temperature, atmospheric pressure, surface 4-component radiation (downwelling and upwelling shortwave and longwave radiation), soil heat flux, sensible heat flux, and latent heat flux are regularly measured and recorded at half-hour intervals at this station. Tang et al. (2011a, 2013) and others describe the details of the sensor type and deployment and how the turbulent flux measurements are post-processed. Following the procedures proposed by Tang, Li, and Sun (2013) for ensuring the quality and completeness of the half-hourly measurements of surface meteorological variables and energy flux, we remove the data spikes and abnormalities in the sensible heat flux and latent heat flux measurements ($< -100 \text{ W m}^{-2}$ or $> 700 \text{ W m}^{-2}$) and exclude the days that have data gaps in any of the 48 half-hourly measurements or have an absolute evaporative fraction > 3 at a half-hourly scale. Moreover, days under extreme conditions of half-hour wind speeds $< 0.5 \text{ m s}^{-1}$ or half-hour relative humidity = 100% are also excluded in the analysis. Forty-eight half-hour, eddy covariance (EC)-measured latent heat fluxes from 0:00 h to 24:00 h local time each day are averaged to get the daily value for the validation.

The EC system measured turbulent heat fluxes and available surface energy are generally reported to have an energy imbalance (Twine et al. 2000; Wilson et al. 2002; Foken 2008; Stoy et al. 2013; Tang, Li, and Chen 2011b; Tang et al. 2015b). Because the remotely sensed surface energy balance-based ET models, by definition, force an energy balance among the

flux components, it is imperative to close the energy imbalance in the EC measurements to obtain a more conclusive validation. The Bowen ratio (BR) method proposed by Twine et al. (2000) assumes the conservation of the EC-measured BR and it is applied to correct the energy imbalance of the EC measurements, since maintaining a constant BR is physically more reasonable. In addition, to examine whether the consistency of the model performance is influenced by the energy imbalance correction technique, the ET conversion methods are also evaluated using the EC measurements without a correction and corrected using the residual energy (RE) method (summing the imbalance energy to the EC-measured LE). To overcome the weakness of the BR or RE method, the corrected daily LE measurements are obtained by assuming that the ratio of daytime LE to daily LE before the correction equals the ratio after correction (Tang, Li, and Sun 2013).

3.2. MODIS-based datasets

The remotely sensed instantaneous LE and R_n-G datasets are from the MODIS-based estimates at the Yucheng station that were derived in our recent study (Tang and Li 2017d) using a newly developed dual-source energy balance model. These MODIS-based datasets were proven to reasonably agree with the ground-based large aperture scintillometer measurements. A small bias of -8 W m^{-2} and an root mean square error (RMSE) $<60 \text{ W m}^{-2}$ that fall in between the generally acceptable upper and lower ranges of bias and RMSE were found in the validation of sensible heat flux and latent heat flux. Tang and Li (2017d) provide details on how these instantaneous LE and R_n-G values are estimated. These MODIS-based datasets are used to evaluate the performances of the constant Ω method and the constant EF_r method in their practical applications in this study.

To separate the errors caused by the methods from those caused by the inputs, the two ET conversion methods are first evaluated using ground-based measurements of surface meteorology, EC-observed half-hour LE, and R_n-G observations without any bias. To quantify the accuracy of the estimated daily LE by introducing the error that originates from the instantaneous LE and R_n-G estimates, the two methods are then evaluated using a combination of ground-based measurements of surface meteorology and MODIS-based instantaneous LE and R_n-G datasets with a certain degree of bias. To see whether the performances of the two ET conversion methods are dependent on the conversion time, an evaluation of the two methods is made at both 10:30 h and 13:30 h local time that corresponded to the MODIS-Terra and MODIS-Aqua daytime overpasses, respectively.

4. Results and discussion

4.1. Evaluation using ground-based measurements

The constant Ω method and the constant EF_r method were first evaluated by estimating the daily ET from meteorological variables at a daily scale (aggregating meteorological inputs). Figure 2 compares the daily LE estimated using the two ET conversion methods at 10:30 h and 13:30 h local time with the daily LE estimated using ground-based EC measurements corrected using the BR method. The relative bias and the relative RMSE in the evaluation are shown in Figure 3. Several findings can be summarized as follows: (1) overall, the constant Ω method and the constant EF_r method were found to produce a similar magnitude of bias

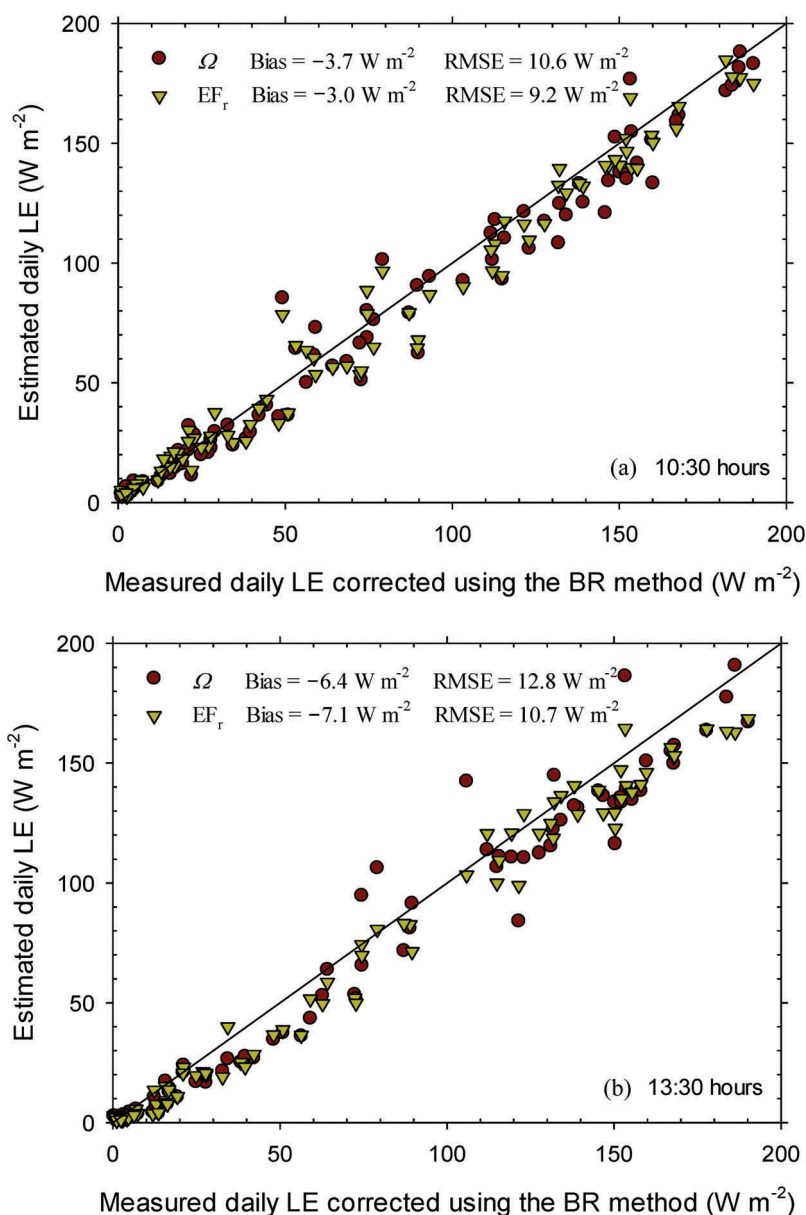


Figure 2. Comparison of the daily LE estimated by applying the *in situ* decoupling factor/reference evaporative fraction at (a) 10:30 h and (b) 13:30 h to daily meteorological variables with that measured by the eddy covariance system and corrected by the Bowen ratio method.

and RMSE and thus performed similarly in estimating the daily LE from instantaneous values; (2) both methods underestimated the observed daily LE, but the underestimation was slightly lower at 10:30 h than that at 13:30 h conversion time; (3) the relative bias and the relative RMSE were -5.2% and 14.8% for the constant Ω method and -4.2% and 12.9% for the constant EF_r method at 10:30 h conversion time, and they were -9.3% and 18.6% for the constant Ω method and -10.4% and 15.5% for the constant EF_r method at 13:30 h

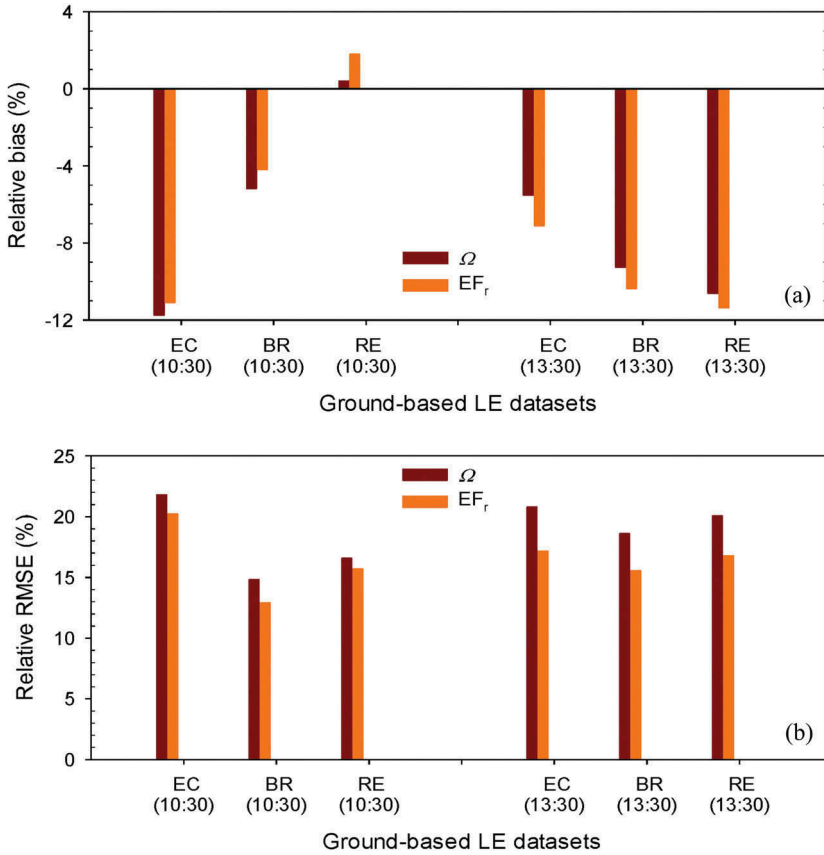


Figure 3. (a) Relative bias and (b) relative RMSE of the validation of the daily LE estimated by applying the *in situ* decoupling factor/reference evaporative fraction at 10:30 h and 13:30 h to the daily meteorological variables using the EC measurements without or with correction by the Bowen ratio method or residual energy method.

conversion time. Using the uncorrected EC measurements or the EC measurements corrected by the RE method as the validation data, the evaluation of the two methods also showed that there were no significant differences in the statistical results for estimating the daily LE, as presented in Figure 3, and a similar performance between the constant Ω method and the constant EF_r method was obtained. The relative RMSE was slightly higher for the constant Ω method than the constant EF_r method at 13:30 h conversion time, but the corresponding relative bias was lower for the former method. Compared to the results with the EC measurements corrected by the BR method, the evaluation with the uncorrected EC measurements and the EC measurements corrected by the RE method showed a higher and lower bias at the 10:30 h conversion time but a lower and higher bias at the 13:30 h conversion time, respectively.

The constant Ω method and the constant EF_r method were then applied to each of the 48 half-hour meteorological variables to obtain 48 half-hour ETs. Summing these 48 estimated half-hour ETs to obtain the daily ET, we evaluated the two methods in a different way (aggregating the ET outputs). Figure 4 compares the daily LE estimated using the two

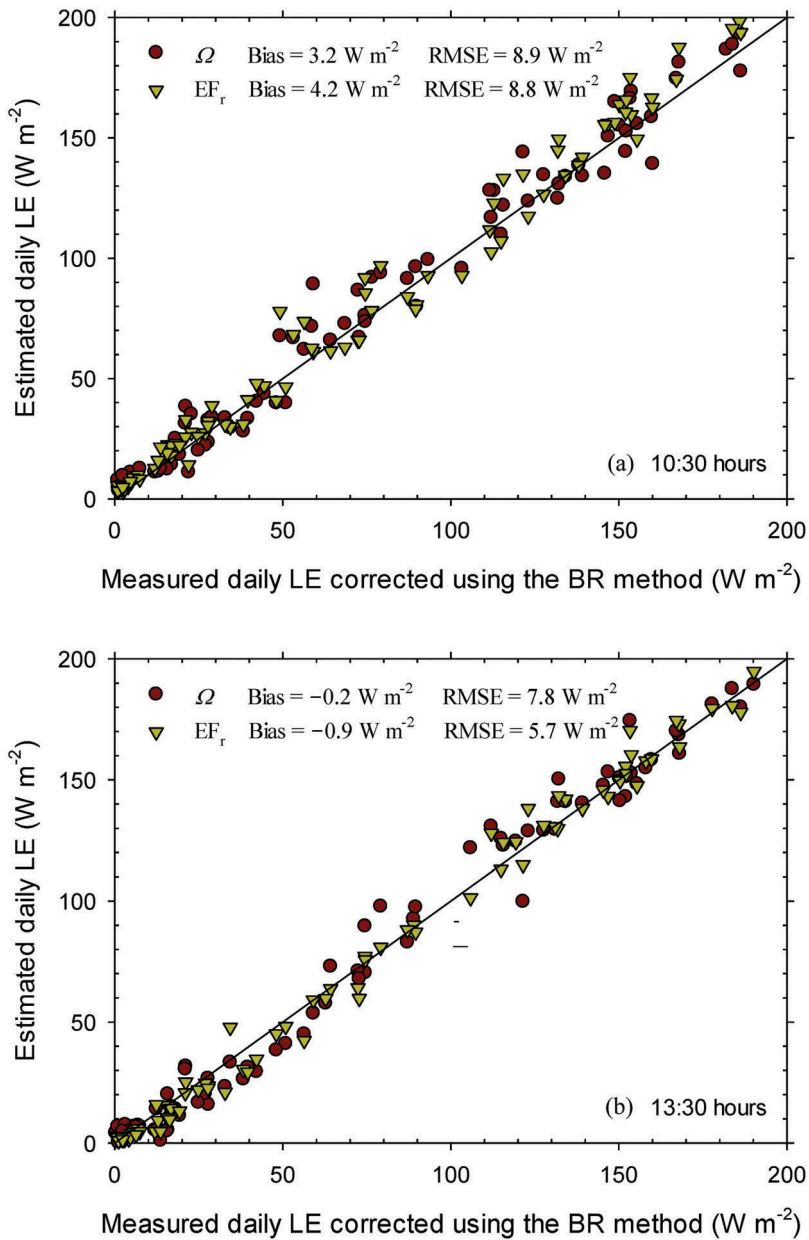


Figure 4. Comparison of the daily LE obtained by averaging the 48 half-hour LE estimates that were derived through an application of the *in situ* decoupling factor/reference evaporative fraction at (a) 10:30 h and (b) 13:30 h to other half-hour meteorological variables with that measured by the eddy covariance system and corrected by the Bowen ratio method.

methods at 10:30 h and 13:30 h local time with that from the ground-based EC measurements corrected using the BR method. The corresponding relative bias and relative RMSE in the evaluation are shown in Figure 5. The findings are as follows: (1) similar performances were observed for the two methods in estimating the daily LE from instantaneous values; (2)

slight overestimations and underestimations were found for the two methods at the 10:30 h and 13:30 h conversion times, respectively; (3) the relative bias and the relative RMSE were 4.4% and 12.5% for the constant Ω method and 5.8% and 12.4% for the constant EF_r method at 10:30 h conversion time, and they were -0.2% and 11.4% for the constant Ω method and -1.3% and 8.5% for the constant EF_r method at the 13:30 h conversion time. When the energy imbalances of EC measurements were not corrected or were corrected using the RE method, no significant differences in the model performance between the constant Ω method and the constant EF_r method were observed for converting instantaneous ETs to daily values (see Figure 5), which were similar to the results obtained by aggregating the meteorological inputs. At 10:30 h conversion time, using the RE-corrected EC measurements produced the worst daily LE estimates for the two methods compared to that produced using the uncorrected or BR-corrected EC measurements, whereas at the 13:30 h conversion time, using the uncorrected EC measurements gave the worst performance. Using uncorrected or corrected EC measurements, the constant Ω method produced lower daily LE estimates than the constant EF_r method at 10:30 h conversion time but higher daily LE estimates at 13:30 h conversion time. Compared to the results obtained by aggregating meteorological inputs, the evaluation by aggregating ET outputs overall showed a degree of improvement in the model performance with a lower bias and a lower RMSE for both methods. This improvement was evident, especially at 13:30 h conversion time.

4.2. Evaluation using MODIS-based datasets

Because (1) aggregating the ET outputs was shown to produce better daily LE estimates than aggregating the meteorological inputs and (2) correcting or not correcting the EC measurements did not change the results that there was no significant difference in the model performance, the evaluation of the two methods using the instantaneous MODIS-based datasets was only conducted by averaging the 48 half-hour LE estimates to obtain the daily LE. Moreover, because similar performances for the two methods were observed at both 10:30 h conversion time and 13:30 h conversion time, the evaluation using the MODIS-Terra-based datasets was not separated from that using the MODIS-Aqua-based datasets. Figure 6 compares the daily LE estimated from the constant Ω method and the constant EF_r method with ground-based EC measurements corrected using the BR method. Overall, a reasonable agreement was observed for the validation of the model-estimated daily LE for both methods. The constant Ω method showed an overestimation of the observed daily LE, while the constant EF_r method produced almost unbiased daily LE estimates, which means that the former method produced higher daily LE estimates than the latter method. The bias and the RMSE were 9.3 W m^{-2} and 27.7 W m^{-2} (relative bias of 6.5% and relative RMSE of 19.3%), respectively, for the constant Ω method and 0.7 W m^{-2} and 27.2 W m^{-2} (relative bias of 0.5% and relative RMSE of 18.9%), respectively, for the constant EF_r method. When large deviations occurred, the constant Ω method produced slightly better daily LE estimates than the constant EF_r method.

4.3. Discussion

The constant EF_r method has been widely applied in different regions of the world, whereas the constant Ω method is a new, effective technique recently developed by Tang and Li

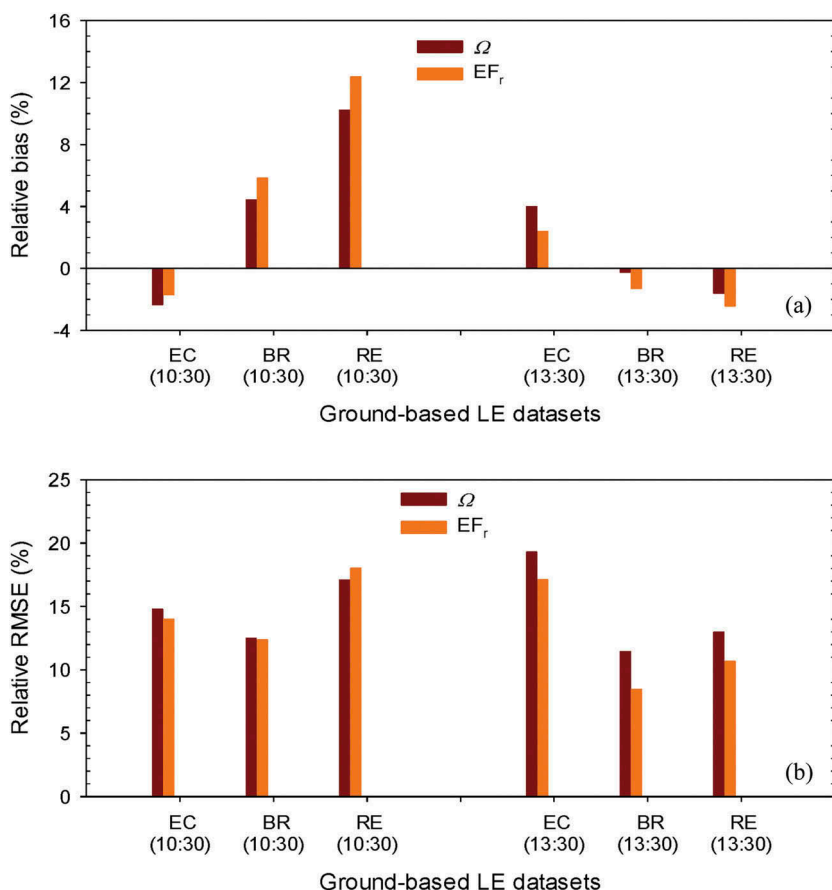


Figure 5. (a) Relative bias and (b) relative RMSE of the validation of the daily LE estimated by averaging the 48 half-hour LE estimates that were derived through an application of the *in situ* decoupling factor/reference evaporative fraction at 10:30 h and 13:30 h to other half-hour meteorological variables with EC measurements without or with correction by the Bowen ratio method or residual energy method.

(2017a, 2017b) for converting instantaneous ETs to daily values. Tang and Li (2017a, 2017b) have discussed in detail the advantages, weaknesses, and sensitivity/uncertainty of this new ET conversion method. The constant Ω method had a similar number of meteorological inputs as the constant EF_r method. The former and the latter methods assume the constancy of Ω and EF_r over time in a diurnal cycle. Whether the constant Ω method produced a better estimate of daily LE than the constant EF_r method depended on which assumption of the two methods was more valid. The similar performance of the two methods can be partly attributed to the fact that both methods can effectively capture the effect of temporally variable meteorological factors on the diurnal pattern of surface ET. The better performance of each of the two methods by aggregating the ET outputs rather than by aggregating the meteorological inputs indicates that the daily reference ET, or actual ET, can be more accurately estimated by summing the 48 half-hour reference ETs, or actual ETs, than by directly using daily meteorological inputs. Compared to the constant EF_r method that requires the reference ET estimate, the constant Ω method has a relatively simple model structure and can be

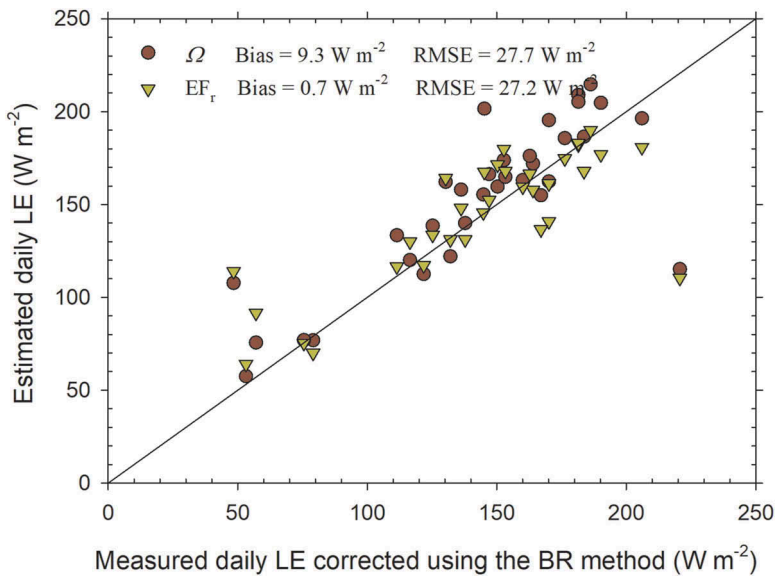


Figure 6. Comparison of the daily LE obtained by averaging the 48 half-hour LE estimates that were derived through an application of MODIS-based estimates of the decoupling factor/reference evaporative fraction to other half-hour meteorological variables with that measured by the eddy covariance system and corrected by the Bowen ratio method.

applied in a more straightforward manner. In practical applications, the accuracy of the conversion method and the accuracy of remotely sensed instantaneous ET codetermine the accuracy of the model-estimated daily LE. The large deviation between the estimated daily LE and the measurement in Figure 6 is attributed to the large difference between the MODIS-based estimates of instantaneous LE and surface available energy ($R_n - G$) and the corresponding ground-based EC measurements. The constant Ω method is more physically based, and Tang and Li (2017a, 2017b) found that this method was superior to the most frequently applied constant EF method. Tang, Li, and Sun (2013) demonstrated that the constant EF_r method was one of the best techniques to produce high-quality daily ET estimates from instantaneous ETs. Since the constant Ω method has a similar performance to the constant EF_r method but is less difficult to apply, it may be a good alternative to the widely applied constant EF_r method. The requirement of relatively more meteorological inputs, which may be unavailable, limits the application of these two methods over some regions of the world.

5. Summary and conclusion

This article compares two ET conversion methods, the constant Ω method and the constant EF_r method, to estimate the daily ET from instantaneous values. This comparison was made using two types of datasets, collected from April 2009 to late October 2011, at the Yucheng station, including completely ground-based measurements of surface meteorology, EC-observed half-hour LE, and $R_n - G$ observations without bias and the combination of

ground-based measurements of surface meteorology and MODIS-based instantaneous LE and R_n-G datasets with a degree of bias.

Overall, both the constant Ω method and the constant EF_r method produced daily LE estimates that agreed with the ground-based EC measurements. The evaluation conducted by aggregating the meteorological inputs showed that these two methods tended to underestimate the observed daily ET, while slight overestimations and underestimations can be found if these two methods are evaluated by aggregating the ET outputs. For both the constant Ω method and the constant EF_r method, summing 48 half-hour ET estimates (derived by applying the ET conversion method to half-hour meteorological variables) was shown to be in better agreement with the ground-based EC measurements than directly obtaining the daily ET values (by applying the ET conversion method to daily meteorological variables). When the two methods were applied to MODIS-based datasets that had a small bias of -8 W m^{-2} and a RMSE $<60 \text{ W m}^{-2}$, the estimated daily ET was in agreement with the ground-based EC measurements, with a relative bias of $<7\%$ and a relative RMSE of $<20\%$. No significant difference was observed when the performance of the constant Ω method was compared to that of the constant EF_r method. The constant Ω method has only been evaluated at the Yucheng cropland site since its development. In future work, more extensive assessments and validations are recommended to evaluate this promising ET conversion method in different regions of the world that have a broader range of climate, soil moisture, and plant functional types.

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Disclosure statement

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