Accuracy of ground heat flux simulation methods in the surface energy balance-based remote sensing evapotranspiration models

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Abstract. According to 230 flux site observations, intra-day and diurnal ground heat flux (G) accounted for 19.2% and 28.8% of the corresponding net radiation, respectively. This indicates that G plays an important role in remote sensing (RS) evapotranspiration (ET) models. The accuracy of the five G simulation methods in the surface energy balance-based RS ET
10 models was evaluated using half-hourly observations. The linear coefficient (LC) method and the methods embedded with the normalized difference vegetation index (NDVI) were able to accurately simulate a half-hourly G series at most sites. The mean and median Nash-Sutcliffe efficiency (NSE) values of all sites were generally higher than 0.50 in each half-hour period. However, the two methods embedded by fractional vegetation coverage showed poor performance in most half-hour periods, except the sunrise and sunset periods, with the mean and median NSE values of all sites below 0.20. The accuracy
15 of each method varied significantly at different sites and at half-hour intervals. The highest accuracy was exhibited during sunrise periods (6:00-7:00), followed by sunset periods (17:00-18:00). There were 92% (211/230) sites with an NSE of the LC method greater than 0.50 at 6:30. It showed a slightly higher accuracy during night periods than during daytime periods. The lowest accuracy was observed at noon periods (10:00-15:30). The sites with an NSE exceeding 0.50 only accounted for 51% (118/230) and 43% (100/230) at 10:30 and 13:30, respectively. The accuracy of Northern Hemisphere sites was
20 generally higher than that of Southern Hemisphere sites. In general, the highest and lowest accuracies were observed at the high- and low-latitude sites, respectively. The performance of the LC method and the methods embedded with NDVI were generally satisfactory at the Eurasian and North American sites, with the NSE values of most sites exceeding 0.70. Conversely, it exhibited relatively poor performance at the African, South American, and Oceanian sites, especially the African sites. Both the temporal and spatial distributions of the accuracy of the G simulation were positively correlated with
25 the correlation between G and the net radiation. Although the G simulation methods accurately simulated the G series at most sites and time periods, their performance was poor at some sites and time periods. The application of RS ET datasets covering these sites requires caution. The optimal parameter value for each method varied greatly at different sites. This indicates that the fixed parameter values in the G simulation methods are not appropriate. Further improvement of G simulations at these sites and time periods is recommended for the RS ET modelers.

1 Introduction

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Accurate simulations of evapotranspiration (ET) represent the core of hydrological processes, crop growth, and ecosystem water efficiency simulations (Ponce-Campos et al., 2013). Remote sensing (RS) is the only viable technique that can provide relatively frequent and spatially contiguous ET measurements on global and regional scales (Zhang et al., 2016; Ait Hssaine et al., 2020). Surface energy balance is the main method used in RS ET modeling (Zhang et al., 2016; Chen and Liu, 2020).

35 Ground heat flux (G) accounts for a significant fraction of the surface energy balance (Pauwels and Daly, 2016), but there is insufficient research on these models compared with sensible heat flux (H) (Mohan et al., 2020; Wu et al., 2020). Over bare soils or sparsely vegetated surfaces, G can reach half of the net radiation (Rn) (Heusinkveld et al., 2004). Even under full vegetation cover, G is significant, especially when turbulent processes are less active (Gentine et al., 2012).

G, which is the soil heat flux at the surface, is difficult to observe directly, due to technical limitations (Wang and Bou-Zeid, 40 2012; Gao et al., 2017), and direct estimation of G using RS data is not possible (Kalma et al., 2008; Allen et al., 2011; Saadi et al., 2018). Soil heat flux (referred to as G') is generally measured using heat flux plates near the surface (within a few millimeters of the surface). However, the difference between G' and G could be 50% because of the soil heat storage within the layer from the surface to the flux plate (Heusinkveld, 2004; Yue et al., 2011; Wu et al., 2020). A large error is produced if the soil heat storage is ignored in the G calculation (Meyers and Hollinger, 2004; Lu et al., 2018). In addition, the soil 45 above the heat flux plates can lose contact with the rest of the near-surface soil matrix, adversely affecting the water and heat flow (Leuninget al., 2012; Russell et al., 2015). The spatial scale of the G observation is also much smaller than that of the H and latent heat flux (LE) estimates (Shao et al., 2008; Verhoef et al., 2012).

There are numerous schemes for estimating G (Wang and Bou-Zeid, 2012; Gao et al., 2017; Wu et al., 2020), that can be classified into two categories. According to physical mechanisms, G can be calculated from the soil heat conductivity and 50 the vertical gradient of temperature using the so-called gradient approach (Yang and Wang, 2008). A more common approach is to combine G' at a specific reference depth with soil heat storage above (Kustas et al., 2000; Wu et al., 2020). G' can be simulated using the gradient approach or observed by heat flux plates. Soil heat storage in the soil layer above the measured depth can be calculated as the integral over the change in temperature with time multiplied by the volumetric heat capacity of the soil, which is called the calorimetry method (Liebethal and Foken, 2007; Agam et al., 2019). However, 55 applications of these physical mechanism-based approaches are restricted to only a few sites, due to the limitations of field observations of soil thermal properties (Mayocchi and Bristowa, 1995; Kustas et al., 2000). Soil thermal properties are affected by soil texture, mineralogical composition, bulk density, and the surrounding environment (e.g., soil moisture and temperature) (Peng et al., 2017; Ju and Hu, 2018). In other words, soil thermal properties vary with time and space. In addition to these physical mechanism-based approaches, G can also be estimated using empirical methods based on Rn, H, 60 or G' (Cellier et al., 1996; Leuning et al., 2012; Purdy et al., 2016).

To estimate ET in RS models, G is usually obtained from empirical relations with Rn. Choudhury et al. (1987) established an empirical function between G and Rn for bare and vegetated soils. They found that the ratio of G to Rn (G/Rn) was 0.4 for

bare soils. For vegetated land cover, the ratio could be described by an exponential relationship with the leaf area index.
Kustas and Daughtry (1990) also calibrated the ratio by ground-based measurements for bare soil, alfalfa, and cotton, and

65 found the corresponding value to be 0.29 ± 0.05, 0.16 ± 0.035, and 0.27 ± 0.02, respectively. The constant G/Rn has been used
in several RS-based ET models, including the Two-Source Energy Balance (TSEB) (Norman et al., 1995), the Atmosphere-
Land Exchange Inverse (ALEXI) (Anderson et al., 1997), and the Disaggregated ALEXI (DisALEXI) (Norman et al., 2003)
models. The ratio values in these models ranged from 0.15 to 0.35. The Global Land Evaporation Amsterdam Model
(GLEAM) used 0.05, 0.20, and 0.25, for tall canopy, short vegetation, and bare soil, respectively (Miralles et al., 2011). The

70 G/Rn is also usually parameterized as an empirical function with the vegetation index in other RS-based ET models,
including but not limited to the Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998), Surface
Energy Balance System (SEBS) (Su, 2002), Mapping Evapotranspiration at high Resolution with Internalized Calibration
(METRIC) (Allen et al., 2007) and Simplified TSEB (STSEB) (S ánchez et al., 2008) models. The solutions of G in the first
two models were also applied to the Simplified Surface Energy Balance Index (S-SEBI) and Four-source Surface Energy

75 Balance (SEB-4S) models, respectively (Roerink et al., 2000; Merlin et al., 2014). Some studies have modified the parameter
values in these empirical relationships, such as the modified SEBAL (Singh et al., 2008; Faridatul et al., 2020) and TSEB
models (Ait Hssaine et al., 2020). In addition, the empirical relations between G and Rn were applied to simulate G in
several RS-based global ET datasets. These ET datasets include, but are not limited to, the Breathing Earth System Simulator
(BESS) (Jiang and Ryu, 2016), Moderate Resolution Imaging Spectroradiometer (MODIS; MOD16A2) (Mu et al., 2011),

80 GLEAM (Miralles et al., 2011), and Numerical Terradynamic Simulation Group (NTSG) (Zhang et al., 2010) products.
Several studies have evaluated the empirical methods in the simulation of G. Liebethal and Foken (2007) evaluated six
parameterization approaches for G by using the reference data set, in which G' at a depth of -0.2 m and the heat storage in
the soil layer above -0.2 m was calculated by the gradient and calorimetry approaches, respectively. They found that the
physical mechanism-based calorimetric and simple measurement approaches showed better performance than empirical

85 methods. Similar results were also found in evaluations by Russell et al. (2015) and Gao et al. (2017) for eddy-covariance
tower measurements in Idaho and Washington, respectively. Saadi et al. (2018) evaluated three empirical methods using flux
station measurements and determined that the best results were obtained using the SEBAL method. However, these
evaluations were limited to a single site scale because field observations of soil thermal properties were available only at a
few sites.

90 The surface energy balance method provides an alternative solution for assessing the G simulation schemes (van der Tol et
al., 2012). This method could avoid the inconsistent spatial scale of G with that of LE and H in field measurements. The
FLUXNET dataset, which contains global flux tower observations, provides a good opportunity to evaluate G simulation
methods on a global scale (Knox et al., 2019; Pastorello et al., 2020; Liu, 2021). According to the surface energy balance
method, this study uses the FLUXNET dataset to comprehensively evaluate the ability of various schemes to accurately

95 simulate half-hourly G at global flux measurement sites.

This study addresses four key objectives: (1) investigating the temporal and spatial variations and common characteristics of the empirical relationship between G and Rn; (2) evaluating the accuracy of five methods in simulating half-hourly G from Rn; and (3) investigating the performance of five methods at different times during the intra-day and the spatial distribution of simulation accuracy at global flux observation sites.

2 Materials and methods

2.1 Data

This study used FLUXNET eddy covariance observations that cover all continents, including FLUXNET2015 (Pastorello et al., 2020) and FLUXNET-CH4 community products (Knox et al., 2019). FLUXNET2015 contains 212 observation sites from 1991 to 2014, while the FLUXNET-CH4 community product contains 81 sites from 2006 to 2018. The longest observational record was 25 years, whereas the shortest was less than one year. Half-hourly data series for LE, Rs, Rn, and G were used. All missing values were eliminated. For example, if there were missing values on a certain day, all data on that day were discarded. Therefore, only days with fully available half-hourly data were used in the analysis. Only sites with a data series longer than 360 days were used. These eliminations ultimately meant that a total of 189 FLUXNET2015 sites and 60 FLUXNET-CH4 sites were used in the analysis because of the lack of observations (**Table S1**). There were 19 sites belonging to both FLUXNET2015 and FLUXNET-CH4, and flux observation data from four sites in Australia were obtained from the TERN OzFlux dataset, which was a long and continuous series up to 2019 (Beringer et al., 2016). In addition, the normalized difference vegetation index (NDVI) data (Vermote et al., 2014), which were derived from surface reflectance data acquired by the Advanced Very High-Resolution Radiometer sensor, were used in this study. The dataset had a spatial resolution of $0.05 \times 0.05°$ and temporal coverage from June 1981 to the present.

2.2 Methods

2.2.1 The surface energy balance residual method for estimating G

The surface energy balance residual (SEBR) method (**Eq. (1)**) is an effective tool for estimating G, using the measurements of other components with a flux tower (van der Tol et al., 2012). Energy balance is an independent means of assessing G. In the surface energy balance, heat storage in the air between the ground and the height of the eddy covariance system is neglected, as is the horizontal advection of heat and other minor energy sources and sinks (Wilson et al., 2002; Leuning et al., 2012; Stoy et al., 2013). The SEBR method equation is expressed as follows:

$$G = Rn - LE - H \tag{1}$$

where G is ground heat flux; Rn is net radiation; and LE and H are latent and sensible heat flux, respectively. The estimated time series were used as referenced G for evaluating simulations of G in RS ET models. The mean and standard deviation approach was applied to detect outliers (Liu et al., 2019).

2.2.2 Simulations of G in RS ET models

Based on the half-hourly series of G simulated by the SEBR method at globally observed sites, the G simulation methods commonly used in five RS ET models were evaluated. The first is the linear coefficient (LC) method. It has been applied in the TSEB, ALEXI, DisALEXI, GLEAM, and other RS ET models to simulate G, but different models use different linear

130 coefficient values. Then, the linear models of embedding the NDVI in the form of the power (Bastiaanssen, 1995) and exponential (Choudhury et al., 1987) functions (referenced as LC_NDVI_P and LC_NDVI_E) were evaluated, which were typically applied in the SEBAL (Bastiaanssen et al., 1998) and modified SEBAL (Singh et al., 2008) ET models, respectively. Finally, the linear models embedded with fractional vegetation coverage, which were applied in the SEBS and STSEB models (referenced as LC_fc_SE and LC_fc_ST), were also evaluated. LC methods embedded with the vegetation

135 index have also been applied in many other RS ET models, such as the S-SEBI, NTSG, BESS, METRIC, MOD16A2, and SEB-4S models. However, different models may use different parameter values.

In this study, the parameters in these five methods were calibrated, rather than fixed parameter values in the original models. The half-hourly series of the observed Rn and simulated G by the SEBR method at each flux tower site were used for the optimal calibration of the parameters. These five methods are represented as LC, LC_NDVI_P, LC_NDVI_E, LC_fc_SE,

140 and LC_fc_ST. The expressions are as follows:

$$G = \alpha \; Rn \tag{2}$$

$$G = \alpha \; \{1 - 0.98 \; NDVI^4\] \; Rn \tag{3}$$

$$G = [\alpha \; exp(\text{-}b \; NDVI)] \; Rn \tag{4}$$

$$G = [\alpha_1 + (\alpha_2 - \alpha_1) \; (1\text{-}fc)] \; Rn \tag{5}$$

145 $$G = \alpha \; (1\text{-}fc) \; Rn \tag{6}$$

where α, α_1, α_2 and b are parameters to be calibrated, within the range of [0.01, 1.5], [0.01, 1.5], [0.01, 0.1], and [0.1, 1.5], respectively.

2.2.3 Evaluation criteria

The simulations of G were evaluated using the G series estimated using the SEBR method for each site in each half-hourly

150 period. The criteria used to evaluate these simulations included the relative error (RE), root-mean-square error (RMSE), Kling-Gupta efficiency (KGE), and Nash-Sutcliffe efficiency (NSE) (Gupta et al., 2009; Nash and Sutcliffe, 1970). The RE and RMSE represent the bias deviation from the observed values, whereas the KGE and NSE are indicative of the goodness-of-fit of the simulated and observed data series. The best-fit value was 1.0, and the goodness-of-fit deteriorated with increasing deviation from 1.0. The evaluation criteria were calculated as follows:

$$RE = \frac{1}{n} \sum\nolimits_{i=1}^{n} \frac{X_{si} - X_{ri}}{X_{ri}}, \tag{7}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}[(X_{si} - \overline{X_s}) - (X_{ri} - \overline{X_r})]^2} \; , \tag{8}$$

$$KGE = 1 - \sqrt{(1 - CC)^2 + RE^2 + \left(1 - \frac{SD_s}{SD_r}\right)^2} \tag{9}$$

$$SD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2}, \tag{10}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(X_{si} - X_{ri})^2}{\sum_{i=1}^{n}\left(X_{ri} - \overline{X_r}\right)^2}, \tag{11}$$

155   where X_{si} and X_{ri} are the ith values of the simulated and referenced G time series, respectively; n is the time series length; $\overline{X_s}$ and $\overline{X_r}$ are the means of the simulated and referenced G, respectively; and SD_s and SD_r are the standard deviations of the simulated and referenced G, respectively.

3 Results

3.1 Intra-day distribution of observed surface energy balance items and G/Rn

160   The intra-day distribution characteristics of each flux variable were analyzed based on field observation data. **Figure 1** shows the intra-day distribution of half-hourly Rn, H, LE, G, and G', derived from the mean of 230 FLUXNET sites. Overall, LE, H, and G accounted for 34.5%, 46.3%, and 19.2% of Rn, respectively. G accounted for 28.8% of Rn when only daytime periods were considered. This indicates that ignoring G in energy-based models greatly overestimates the ET values. The observed daytime G' value was only 24.1% of that of G. Considering the intra-day periods, G' was only 4.7% of G. All flux

165   variables were stable and showed little variance from 20:00-6:00. During this period, the LE was positive and accounted for only 7% of the total daily LE, whereas other flux variables were negative. It showed a unimodal distribution for all flux variables during the day. The intra-day distribution of H showed the best agreement with the measured Rn (**Fig. 1 a**). However, the intra-day distributions of LE, G, and G' showed an overall deviation from the measured Rn. The distribution of LE and G' was generally half an hour delayed compared to the measured Rn, while that of G was half an hour earlier. The

170   intra-day distribution of each flux variable during the daytime was compared with the Sine and Gaussian functions (**Fig. 1 b-f**). The results showed that daytime flux variables were more consistent with the latter than with the Sine function, which is commonly used to upscale instantaneous ET to daily values in RS applications. The Gaussian function perfectly matched each flux variable at any time during the day. The Sine function slightly underestimated flux variables at sunrise, noon, and sunset, while it tended to overestimate the flux variables during the morning and afternoon.

175

Figure 1.

The intra-day distribution characteristics of G/Rn and the ratio of G and H (G/H) were also analyzed based on field observation data. The intra-day distributions of G/Rn and G/H at each site are shown in **Fig. 2**. During data processing, data points with absolute values greater than 10 in the G/Rn or G/H daily series of each period were deleted. Outliers in the G/Rn or G/H series were then removed using the outlier detection method. The G/Rn varied significantly in different half-hour periods of the intra-day, and among the different sites (**Fig. 2-a**). The variation in G/Rn among the sites was lower during the daytime than that at night. The variation range of G/Rn among all sites was generally approximately 0.2 in the daytime. This indicates that the G/Rn of all sites showed high consistency during these periods. At night, the variation mostly ranged between 0.6 and 0.8. In other words, G/Rn was more consistent across sites during the daytime than that at night. The G/Rn of each site was concentrated between 0.2 and 0.5 in the daytime, and varied from 0.1 to 0.9 in the night. During 5:30-17:00, the median values were generally consistent with the mean values. The slope and R^2 of the linear fitting curve were -0.012 and 0.92, respectively. The R^2 of the polynomial fitting curve reached 0.98 (**Fig. 2-c**).

G/H also varied significantly in different half-hour periods of the intra-day and among the different sites (**Fig. 2-b**). The variation in G/H during each period was greater than that of G/Rn. In other words, G/H was less consistent across sites than G/Rn. Like G/Rn, the variation of G/H among sites during the daytime was significantly lower than that at night. The variation range of G/H among all sites in the daytime was approximately 1.0, while the corresponding range at night was approximately 2.0. The G/H of each site was mainly concentrated between 0.3 and 1.6 in the daytime, and between 0.6 and 2.8 in the night. In most half-hour periods, the mean and median values of G/H at all sites showed significant differences, with the former generally being approximately 0.5 higher than the latter. During 6:30-16:30, the median and mean values generally showed a unimodal distribution, and the R^2 of the polynomial fitting curve for the mean series was 0.95 (**Fig. 2-d**).

Figure 2.

3.2 Temporal and spatial analysis of the empirical relationship between G and Rn and between G/Rn and NDVI

The empirical relationship between G, Rn, and H was analyzed based on the measured data. Overall, G had a strong correlation with Rn but a relatively weak correlation with H. **Figure 3** shows the R^2 and slope of the linear fitting between G and Rn in each half-hour period of the intra-day. In each period, G and Rn showed a strong linear correlation at most sites, with a fitted R^2 generally above 0.4. The mean and median R^2 values of all sites were mainly between 0.5 and 0.8. The strong correlation between G and Rn indicates that it is reasonable to use Rn to calculate G in the RS inversion of ET. However, the correlation between G and Rn varied during the different periods. The correlation is relatively high in the periods of sunrise (around 6:00) and sunset (around 18:00). Especially during sunrise, the R^2 of the linear fitting between G and Rn was greater than 0.7 at most sites, and the median R^2 of all sites reached 0.8. The correlation between G and Rn in the night periods (20:00-4:30) was slightly stronger than that in the daytime periods (8:00-16:00). During the night periods, the R^2 of most sites was generally between 0.45 and 0.70, and the mean and median R^2 of all sites were mainly between 0.55

and 0.60. The R^2 of most sites generally ranged from 0.40 to 0.65 in the daytime periods, and the mean and median R^2 of all sites were concentrated around 0.50. The correlation between G and Rn was relatively low in the period from 10:00 to 15:00, and R^2 was lower than 0.65 at most sites, especially in the periods around 14:00, with the mean and median R^2 below 0.50.

The slope of the linear fitting of G and Rn in each half-hour intra-day period is shown in **Fig. 3-b**. The fitting slope showed significant differences among the different sites, ranging from 0.1 to 1.1. However, the slopes fitted at most sites also exhibited certain characteristics of a centralized distribution. In each period, the range of the slope at most sites was within 0.3, especially during the daytime periods (8:00-17:30), when the range of the slope was within 0.15. The slopes of most sites were relatively stable during all periods except for sunrise and sunset.

Figure 3.

The empirical relationship between G and Rn not only varied significantly at different intra-day periods, but also showed great spatial differences among the different sites. The linear fitted R^2 between the daily series of G and Rn at each site is shown in **Fig. 4**. As the median R^2 of 48 half-hour periods at each site (**Fig. 4-a**), 91% of the sites (210/230) showed an R^2>0.4. The linear fitting R^2 between G and Rn was >0.6 for 49% of the sites (114/230). The mean R^2 for all sites was 0.58. This indicated that the daily G in most half-hour periods had a strong correlation with Rn at most observed sites. However, there were also 20 sites where the R^2 ranged from 0.2 to 0.4. These sites were mainly located in the middle- and low-latitude regions, but were distributed across all observed continents. This means that daily G showed a relatively weak correlation with Rn at some sites located in these regions. The correlation was generally stronger in the Northern Hemisphere than that in the Southern Hemisphere, with the mean R^2 of the northern sites significantly higher than that of the southern sites. There was a strong correlation between G and Rn at most Eurasian, North American, and Oceanian sites, with a linear fitted R^2 generally exceeding 0.4. It showed a relatively weak correlation at many African and South American sites, with an R^2 value of less than 0.4. At different latitudes, the strongest correlation between G and Rn was found at the middle and high latitude (>45°) sites, with the highest R^2 values. The R^2 values of these sites exceeded 0.4, with a mean value of 0.65. It showed a relatively weak correlation at tropical (<23.4°) sites. The R^2 values of these sites were relatively low, with a mean value of 0.48.

The spatial distribution of the linear fitting R^2 of daily G and Rn at 10:30 and 13:30 (**Fig. 4-b** and **4-c**) was consistent with that in **Fig. 4-a**, while the R^2 value was generally lower than the median of each half-hour period. This indicates that the correlation between G and Rn in these two periods is weaker than that for the median values. At 10:30, the mean R^2 of all sites was 0.52. 26% of the sites (60/230) had R^2 values lower than 0.4, and 11 sites had R^2 values lower than 0.2. Although mainly distributed at low latitudes (<30°), these sites were found on all the observed continents. The highest R^2 values were at high-latitude (>60°) sites, with an average of 0.70. The R^2 values of low-latitude sites were significantly lower than those of other sites, with a value less than 0.4 for most sites, and an average of only 0.33. The correlation between G and Rn at 13:30 was weaker than that at 10:30, with R^2 values slightly lower than those at 10:30. There was a relatively weak

correlation between G and Rn at all African sites (R^2<0.4). Overall, the results showed a strong correlation between G and
245 Rn at most observed sites. It is reasonable to simulate a daily series of G values from Rn in most areas. However, it is
necessary to apply this relationship cautiously in some areas at mid-low latitudes, especially in tropical areas.

Figure 4.

250 The empirical correlation between G/Rn and NDVI was also analyzed. The results showed that the correlation between G/Rn
and NDVI was weak in the daily series but strong in the monthly series. **Figure 4-d** and **4-e** show the linear and exponential
fitted R^2 values between the monthly series of G/Rn and NDVI at each observed site, respectively. During data processing,
only monthly values of observation days greater than 15 days were used, and monthly values affected by frozen soil or snow
cover (mean air temperature below -5 ℃) were excluded. In general, there was a strong correlation between the monthly
255 G/Rn series and NDVI. The fitted R^2 values of the linear and exponential functions were consistent. The median and mean
R^2 of all sites were 0.71 and 0.65, respectively, and 72% of the sites (157/218) had an R^2 above 0.60. The exponential
correlation between G/Rn and NDVI was stronger than the linear correlation at several sites, including US-Gle and US-Twt.
The exponential fitted R^2 of the two sites could be increased from 0.55 and 0.31 of the linear R^2 to 0.77 and 0.50,
respectively. Conversely, the linear correlation was stronger than the exponential correlation at other sites, such as ES-AMO
260 and CN-QIA. The linear fitted R^2 of the two sites could be increased from 0.21 and 0.68 of the exponential R^2 to 0.43 and
0.83, respectively. Overall, the spatial distribution of the linear or exponential fitted R^2 of G/Rn and NDVI was similar to the
linear fitted results of G and Rn. The correlation between G/Rn and NDVI was stronger in the Northern Hemisphere than
that in the Southern Hemisphere. The mean R^2 value of the northern sites (0.69) was higher than that of the southern sites
(0.38). It showed the strongest correlation at the middle- and high-latitude (>50 °) sites. The R^2 values for these sites were
265 generally higher than 0.6, with an average of 0.76. A relatively weak correlation between G/Rn and NDVI was found at the
low-latitude sites, with a mean R^2 of 0.38. There were 13 and 15 sites showing weak linear and exponential correlations
between G/Rn and NDVI, respectively, with a fitted R^2 lower than 0.2. These sites were mainly located in Australia and
Southeast Asia.

3.3 Temporal and spatial accuracy of five G simulation methods

270 The evaluation of the model in this study included four criteria. The results showed that only NSE was suitable for the
evaluation of different sites and time periods, whereas RE and KGE were not suitable for the evaluation of different sites,
and the RMSE was unsuitable for the evaluation of different time periods. The RE, RMSE, and KGE simulated by the LC
method at each site and time period are shown in **Fig. 5**. The RE values tended to be affected by the mean value of the
referenced G in **Eq. (7)**. The RE values of all sites were within ±3% (**Fig. 5-a**) during the daytime periods from 7:00 to 16:00
275 because of the relatively large mean value of G during these periods (**Fig. 1-a**). However, when the mean value of the
referenced G was low during the period from 17:00 to 6:30, the RE value at each site was generally greater than that during

the daytime periods. In particular, if the mean value of the referenced G is much lower (e.g., close to 0) in a half-hour period for a site, even a small simulation bias could result in an extremely large RE value; for example, the RE of some sites exceeded 8,000% at 5:00 and 5:30 (**Fig. 5-a**). The mean RE value of all sites was also too high (e.g., 300%) during these

280 periods. Therefore, RE is unsuitable for evaluating different time periods or sites. However, the median RE values of all sites may be more robustly used for evaluation than the mean values. Because the RE is included in the formula of the KGE, the shortcomings of the RE are introduced into the KGE. Therefore, KGE is also unsuitable for the evaluation of different time periods or sites. According to **Fig. 5-b** and **Fig. 1-a**, there was a positive relationship between the RMSE and G values during half-hour periods in the intra-day period. The RMSE values were directly affected by the G values. Due to the

285 significant variations in G values in each period, the RMSE was not suitable for comparison evaluation of simulation accuracy between different periods.

Figure 5.

290 The NSE was used to evaluate the accuracy of the five G simulation methods at different sites and at half-hour intervals. **Figure 6** shows the NSE values simulated by the LC, LC_NDVI_P, LC_NDVI_E, LC_fc_SE, and LC_fc_ST methods. In general, the performance of each method varies significantly among different sites and time periods. The simulation accuracy of each method showed high consistency among the different half-hour intervals within the intra-day period. It was highest in sunrise periods (6:00-7:00), followed by sunset periods (17:00-18:00), whereas it was lowest in the noon periods

295 (10:00-15:30). Regarding the different methods, the accuracy of the first three methods (LC, LC_NDVI_P, and LC_NDVI_E) was significantly higher than that of the last two methods (LC_fc_SE and LC_fc_ST).

The LC method generally demonstrated its ability to accurately simulate the daily series of G at the site scale in each half-hour period, with the NSE of most sites exceeding 0.40. The mean and median NSE values of all sites were generally higher than 0.50 in each time period. It showed the highest accuracy at 6:00 and 6:30, with the NSE of most sites above 0.70. The

300 accuracy was the lowest from 11:30 to 15:00, with the mean and median NSE values of all stations being between 0.45 and 0.50. The mean and median NSE values of all the sites in the other periods were generally greater than 0.50. This indicates that the simple LC method was able to accurately simulate a half-hourly series of G from Rn at most sites, but also lost its ability with unsatisfactory accuracy at a few sites.

Although NVDI was embedded in the LC method, the performances of the LC_NDVI_P and LC_NDVI_E methods were

305 similar to those of the LC method. In other words, the consideration of NDVI resulted in limited improvement in the accuracy of the LC method. In addition, the accuracy of the LC_NDVI_E method was significantly lower than that of the first two methods at 14:30 and 15:00, with mean NSE values of only 0.28 and 0.33, respectively. This was because of the low accuracy (NSE<0.2) of the LC_NDVI_E method at more sites during these two periods.

The accuracy of the LC_fc_SE and LC_fc_ST methods based on fractional vegetation coverage was relatively low (**Fig. 6-d**

310 **and 6-e**). The two methods showed little difference across sites and periods. The two methods were able to accurately

simulate G only at 5:30-7:00 and 17:30-18:00, with the median NSE values of all sites exceeding 0.5. Conversely, the performance was poor in most night and daytime periods, such as 20:00-4:30 and 8:30-15:30. The NSE of most sites was below 0.4, and the mean and median NSE values of all sites were below 0.2. This indicates that the application of these two methods considering fractional vegetation coverage requires caution in the G simulation.

315

Figure 6.

The spatial distribution of the NSE simulated by the LC method at each site is shown in **Fig. 7**. Overall, there were significant differences in the performance of the LC method among sites, with the lowest and highest NSE values of each
320   site being -0.37 and 0.94, respectively. As for the median NSE of 48 half-hour periods at each site (**Fig. 7-a**), the performance of the LC method was satisfactory at most sites, with the mean NSE of all sites being 0.58. The NSE values of 70% of the sites (160/230) were higher than 0.5. However, 27 and 5 sites had NSE values lower than 0.4 and 0.2, respectively, indicating that the performance was poor at these sites. For different latitudes, the performance was generally satisfactory at the middle and high latitudes, with NSE values above 0.4. The best performance was observed at high
325   latitudes, with a mean NSE value of 0.69. The accuracy of the LC method was generally low at tropical sites, with a mean NSE of 0.47. The performance was generally satisfactory at most sites in Eurasia and North America, with NSE values higher than 0.5. The NSE values of many sites exceeded 0.7 in these regions. Conversely, relatively poor performance was found in the African, South American, and Oceanian sites, especially in African sites.

The LC method accurately simulated daily G of most sites at 6:30 (**Fig. 7-b**), with the mean and median NSE values of all
330   sites being 0.73 and 0.78, respectively. The sites with the NSE higher than 0.5 and 0.6 took up 92% (211/230) and 84% (193/230), respectively. The NSE was higher than 0.5 at all sites of Eurasia and North America, and the NSE of most sites exceeded 0.7. The method was also able to accurately simulate the daily G of most sites at 18:00 (**Fig. 7-e**), with a mean NSE of all sites being 0.62. 82% (188/230) and 59% (135/230) of sites had NSE values exceeding 0.5 and 0.6, respectively.

The LC method performed poorly at many sites at 10:30 (**Fig. 7-c**) and 13:30 (**Fig. 7-d**), where the mean NSE values of all
335   sites were 0.49 and 0.47, respectively. The sites with an NSE exceeding 0.5 only accounted for 51% (118/230) and 43% (100/230) during the two half-hour periods, respectively. The method still performed well at high-latitude sites, with a mean NSE of 0.69 and 0.65, respectively. Conversely, it lost the ability to accurately simulate G at tropical sites. The NSE values at most sites were lower than 0.5, with a mean NSE of only 0.29. The performance of the method was poor at the African and South American sites, with NSE values of each site below 0.5.

340

Figure 7.

According to the evaluation of the five methods mentioned above, LC, LC_NDVI_P, and LC_NDVI_E performed well. **Figure 8** shows the optimal values of the parameters of the three methods at each site and half-hour periods. As for the

results of the LC method (**Fig. 8-a**), on the one hand, the optimal parameter values varied significantly in different sites and half-hour periods. The median optimal parameter of all sites was generally around 0.4 in daytime periods and 0.7 at night. The optimal parameter of each site ranged from 0.4 to 1.1 in the night periods. In contrast, the optimal parameters of most sites showed a concentrated distribution. For example, the optimal parameter values of most sites were generally concentrated in the range of 0.25-0.45 during 8:30-16:30, while the corresponding optimal values were generally concentrated in the range of 0.6-0.85 during 19:30-5:30. The median optimal value of all sites was stable at about 0.35 and 0.75 during these two time periods, respectively. The optimal parameter values of the LC_NDVI_P method showed little difference from those of the LC method at each site and half-hour period (**Fig. 8-b**). The optimal parameter (b in **Eq. (4)**) values of the LC_NDVI_E method ranged from 0.01 to 1.4 among different sites and half-hour periods (**Fig. 8-c**). Similar to the LC and LC_NDVI_P methods, the optimal parameter values of the LC_NDVI_E method also showed a concentrated distribution in each period, especially during 7:30-15:00 and 19:30-5:00. Almost all sites with the optimal parameter values ranged from 0.01 to 0.4, and the optimal values of most sites were concentrated in the range 0.06 to 0.25 during these two periods.

Figure 8.

4 Discussion

4.1 Temporal and spatial variations in the simulation of G

The eddy covariance measurements of H and LE are generally considered to be the most accurate observations available. The **Eq. (1)** makes full use of the surface energy term that can be accurately measured at present. In other words, it assumes that the measurements of Rn, H and LE are accurate in this study. The uncertainties of measurements are not considered in this study. Intra-day and diurnal G accounted for 19.2% and 28.8% of Rn, respectively. This indicates that G plays an important role and cannot be ignored in RS ET models. Ignoring G would lead to a great deviation in ET estimates, including the term (Rn-G). The intra-day and diurnal G' values were only 4.7% and 24.1% of the corresponding G, respectively. This indicates that the measured G' must be carefully used in the application of the surface energy balance equation. If G' was used instead of G in the equation, the actual G would be largely underestimated. This is consistent with the results of Meyers and Hollinger (2004) and Lu et al. (2018).

Several methods for simulating G from Rn in energy balance-based RS ET applications have been evaluated in this study. G/Rn, which varied intra-day, was the key to these methods. Santanello and Friedl (2003) provided diurnal covariations in G and Rn. However, it requires intra-day land surface temperature (LST) data series, which cannot be obtained by RS. Because RS can only monitor instantaneous LST when a satellite overpasses, it cannot obtain intra-day LST data series. In this study, more concise linear and polynomial functions of the G/Rn diurnal distribution were fitted (**Fig. 2**) from 230 observation sites worldwide. The linear- and polynomial-fitted R^2 values were 0.92 and 0.98 respectively.

The evaluation results show that the accuracy of the G simulation varied significantly in different half-hour intra-day periods. The highest accuracy was exhibited during sunrise and sunset periods. It also showed a slightly higher accuracy during night periods than during daytime periods. The lowest accuracy is observed at noon. This is consistent with the correlation
380 between G and Rn, indicating that the accuracy of the G simulation is affected by the correlation between Rn and G. In other words, the stronger the correlation between Rn and G, the higher the accuracy of the simulation of G from Rn. However, RS ET models are generally applied during daytime periods. For example, MODIS is widely used at 10:30 and 13:30, but the simulation accuracy of these two periods is the lowest during intra-day periods. This is an urgent issue to be solved for G simulation in RS ET applications, which requires the attention of RS ET modelers.

385 The performance of G simulation methods also showed significant spatial variation. The accuracy of the G simulation varied significantly among the observation sites, with the corresponding NSE ranging from 0.2 to 0.9. The G simulation of most sites showed high accuracy in most half-hour periods. This verified the reliability of global RS ET products in these regions because the more accurate G simulation provided a guarantee for an accurate ET simulation, such as in Eurasia and North America. However, there were also some sites with low simulation accuracy, such as most sites in Africa, South America,
390 and Oceania. A large error in the G simulation would be induced in the ET simulation results and reduce the reliability of ET estimates. Therefore, the application of RS ET estimates and products in these areas needs more caution for its accuracy. The spatial distribution of the model accuracy was also consistent with the correlation between G and Rn.

4.2 Applicability of common G simulation methods in RS ET models

The LC method is most commonly used in the RS ET models. The coefficients applied to each model were different. The
395 coefficients of the LC method in the TSEB (Norman et al., 1995), ALEXI (Anderson et al., 1997), DisALEXI (Norman et al., 2003), MOD16A2 (Mu et al., 2011), and modified TSEB (Ait Hssaine et al., 2020) ET models were 0.35, 0.31, 0.30, 0.39, and 0.37, respectively. The coefficient of the method in the GLEAM model was 0.05, 0.2 and 0.25 for the tall canopy, short vegetation and bare soil, respectively (Miralles et al., 2011). Daytime RS images are generally applied in ET models. The evaluation results of 230 worldwide observation sites showed that the optimal parameter values of most sites were generally
400 concentrated in the range of 0.25-0.45 during daytime periods, with the median of all sites being stable at approximately 0.34. This indicates that the coefficient values applied in most ET models were reasonable, but the coefficient values applied in the GLEAM model were relatively low.

In the RS ET models, fixed parameters were applied to the global terrestrial G simulation. The fixed parameters might be suitable for some regions, but not on a global scale. This study confirmed that the optimal parameter values vary
405 significantly from site to site. Fixed parameter values induced large errors in the G simulations in other regions. Therefore, it is recommended that model developers consider the spatial variations of G simulation parameters in RS ET modeling on a global scale.

Some RS ET models embed vegetation indices (e.g., NDVI, LAI, or fractional vegetation coverage) or LST into the coefficient of the LC method, such as the SEBAL and SEBS models. Evaluation of the LC_NDVI_P and LC_NDVI_E

410 methods, which are the LC methods embedded by the NDVI, showed that the improvement in simulation accuracy was limited by considering the NDVI. The mismatch between flux observations at the site scale and vegetation index data at the grid scale may be one of the reasons for this result. In addition, the term containing the NDVI in these methods could be taken as a whole, which is similar to the coefficient in the LC method. Therefore, the performance of this method is expected to differ slightly from that of the LC method when the parameter is optimally calibrated. Other models embedded by the LAI

415 (Choudhury, et al., 1987; Allen et al., 2011) and LST (Bastiaanssen, 1995; Faridatul, 2020), which were not evaluated in this study due to data limitations, may have similar performances, such as the METRIC model embedded by the LAI and the modified SEBAL model (Faridatul et al., 2020) embedded by the LST and NDVI. Saadi et al. (2018) evaluated three such methods using data from a single observation site. Their results showed that the accuracy order was the Bastiaanssen (1995) method > Jackson et al. (1987) method > Choudhury et al. (1987) method, with RMSE values of 0.09, 0.15, and 0.2,

420 respectively. The results of this study indicate that the performance of the different methods varied at some site scales. However, the differences among the methods were not significant at global sites as a whole.

In general, the LC method and the methods embedded with the NDVI accurately simulated half-hourly G series at most global sites. There was little difference in simulation accuracy between the different models. However, the performance was poor at some sites. Moreover, the optimal values of the model parameters differed among the different sites. These issues

425 need to be considered in RS ET models to improve simulation accuracy. The optimal parameter values for each site showed relative stability between different half-hour periods in the daytime, indicating that it was feasible to apply the same coefficient value in different daytime periods. The accuracies of the LC_fc_SE and LC_fc_ST methods, which embed fractional vegetation coverage in the G simulation, were significantly lower than those of the previous three methods. The LC_fc_SE method was applied to some RS ET models, such as the NTSG (Zhang et al., 2010) and SEB-4S (Merlin et al.,

430 2014) models. A large error in the G simulation would be induced in the ET modelling process, thereby reducing the accuracy of the ET estimates.

5 Conclusions

Intra-day and diurnal G accounted for 19.2% and 28.8% of Rn, respectively. This indicates that G plays an important role and cannot be ignored in RS ET models. The accuracy of the five G simulation methods in energy balance-based RS ET

435 models was evaluated using half-hourly observations from 230 flux sites. The LC method and the methods embedded with the NDVI could accurately simulate a half-hourly G series at most sites. The mean and median NSE values of all sites were generally higher than 0.50 in each half-hour period. However, the two methods embedded by fractional vegetation coverage in the G simulation showed poor performance in most half-hour periods, except for the sunrise and sunset periods, with mean and median NSE values of all sites below 0.20. The performance of each method was generally consistent at different

440 sites and time periods.

The accuracy of each method varied significantly at different sites and at half-hour intervals. The highest accuracy was exhibited during sunrise periods (6:00-7:00), followed by sunset periods (17:00-18:00). There were 92% (211/230) sites with an NSE of the LC method greater than 0.50 at 6:30. It showed a slightly higher accuracy during night periods than during daytime periods. The lowest accuracy was observed at noon periods (10:00-15:30). For example, the sites with an NSE

445   exceeding 0.50 only accounted for 51% (118/230) and 43% (100/230) at 10:30 and 13:30, respectively. The NSE values of the different sites ranged from -0.37 to 0.94. The accuracy of the Northern Hemisphere sites was generally higher than that of the Southern Hemisphere sites. In general, it showed the highest accuracy at high-latitude sites, followed by middle-latitude sites, and exhibited the lowest accuracy at low-latitude sites, especially at tropical sites. As for the median NSE of 48 half-hour periods in the LC method, the mean NSE value of the high latitudes and tropical sites was 0.69 and 0.47

450   respectively. The performance of the LC method and the methods embedded with the NDVI were generally satisfactory at the Eurasian and North American sites, with the NSE values of most sites exceeding 0.70. Conversely, it exhibited relatively poor performance at the African, South American, and Oceanian sites, especially the African sites. Both the temporal and spatial distributions of the accuracy of the G simulation were positively correlated with the correlation between G and Rn.

Overall, the LC, LC_NDVI_P, and LC_NDVI_E methods accurately simulated the G series at most observation sites and

455   half-hour periods in the intra-day, with an NSE value exceeding 0.50. However, the performance of these methods was poor at some sites and time periods. This negatively affects the accuracy of energy balance-based RS ET simulations. The application of RS ET datasets covering these sites requires caution. In addition, the optimal parameter value of each method varied significantly at different sites. Therefore, the fixed parameter values in the G simulation methods do not match the actual situation. Further improvement of G simulations at these sites and time periods is recommended for the RS ET

460   modelers.

Data availability: The FLUXNET and TERN OzFlux datasets can be downloaded freely from https://fluxnet.org/data/download-data/ and http://www.ozflux.org.au/.

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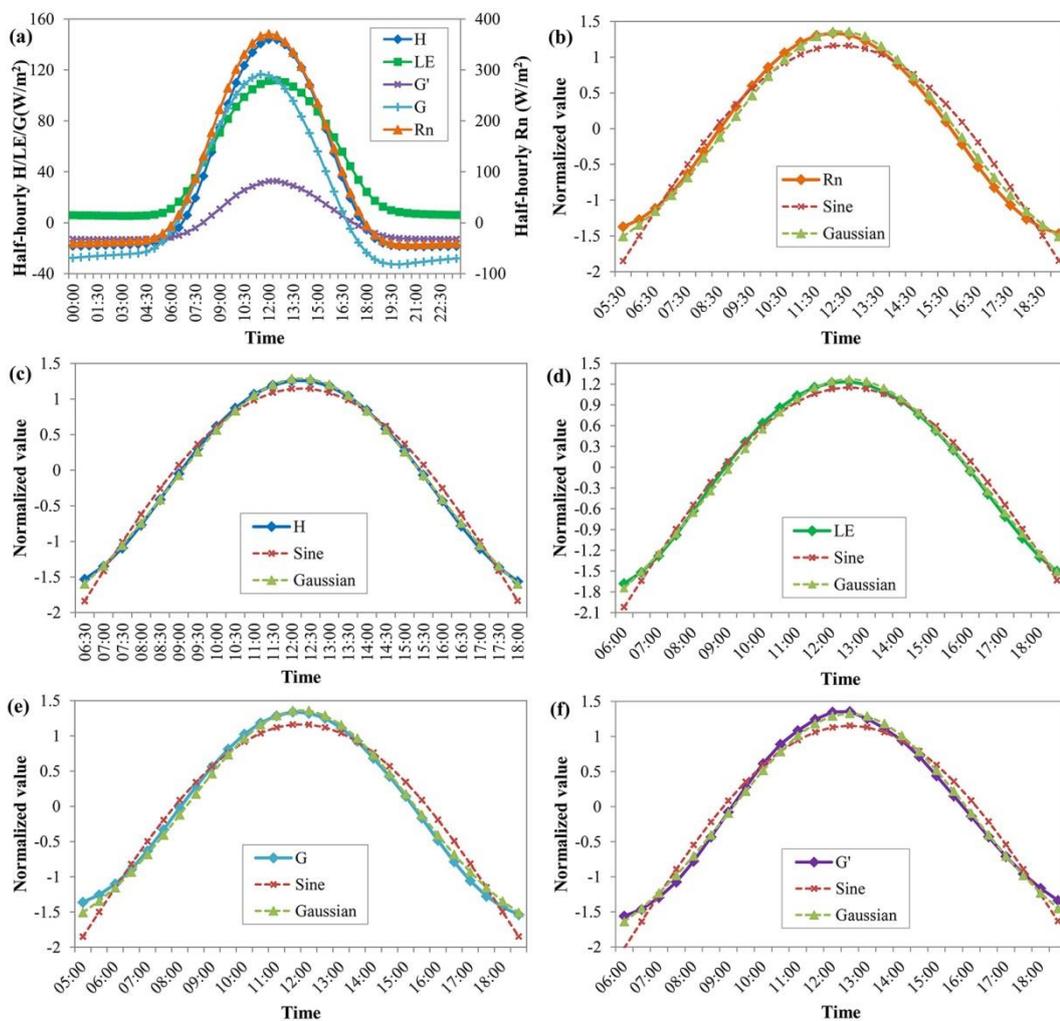


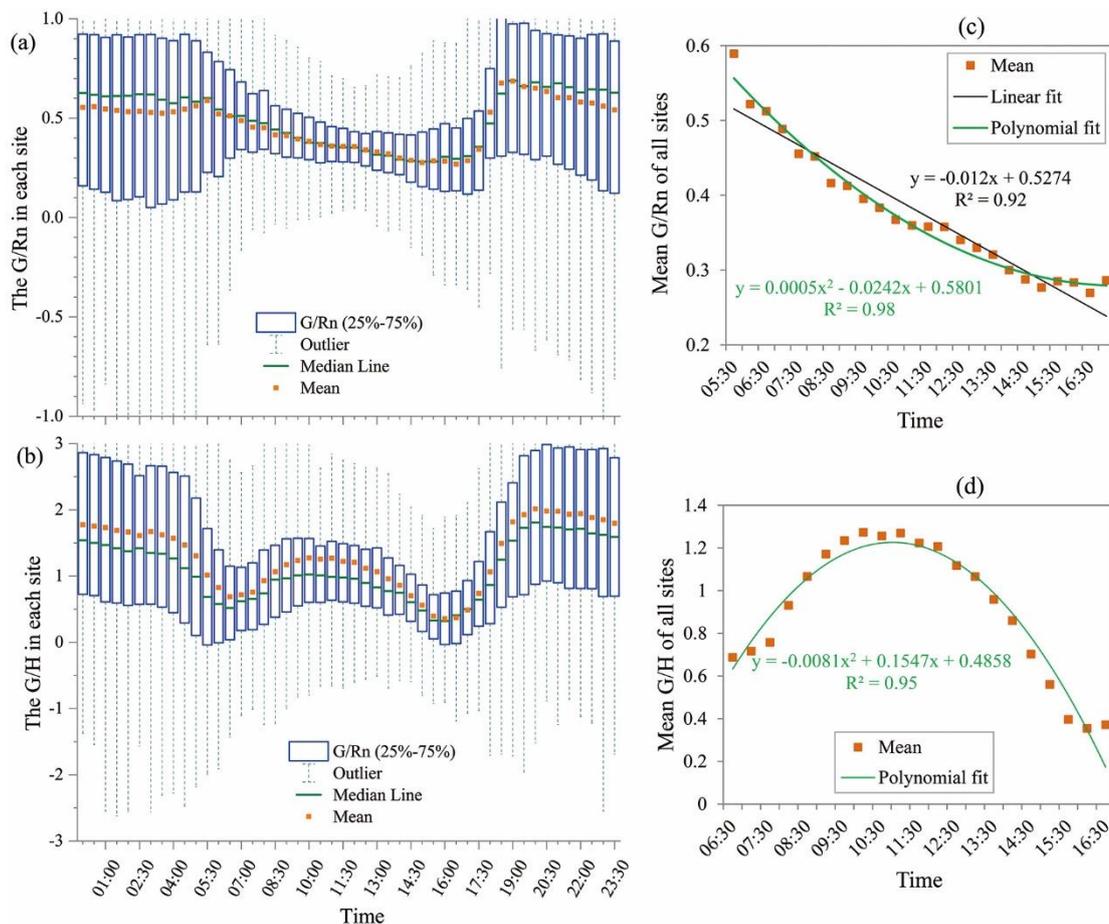
Figure 1: Intra-day distribution of raw and normalized Rn, H, LE, G, G', and the values from the Sine and Gaussian functions.

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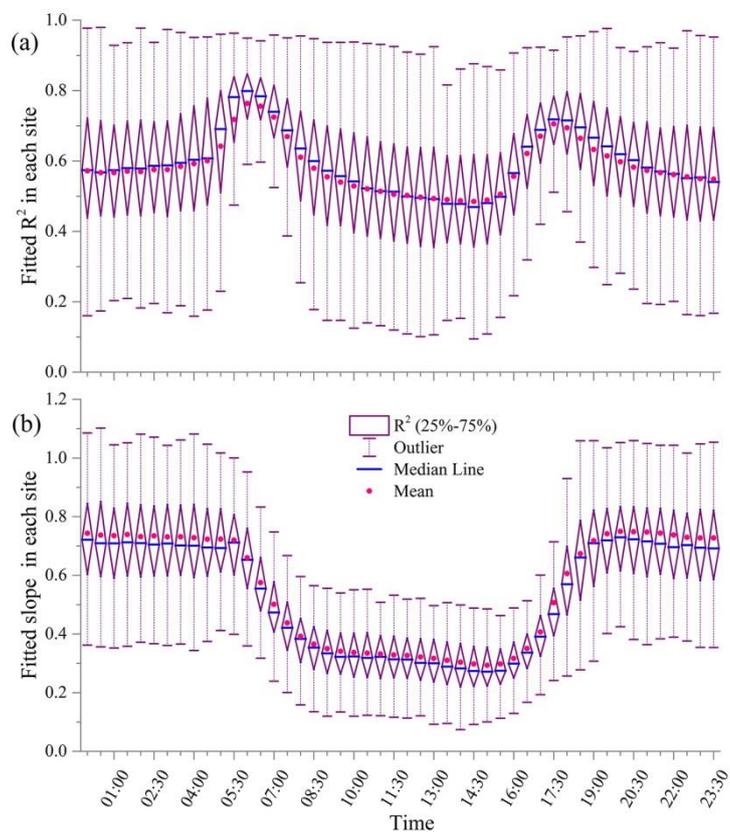
Figure 2: Intra-day distribution of the ratio of G and Rn (G/Rn) and the ratio of G and H (G/H) in each site (a and b are intra-day distributions of G/Rn and G/H ratios in each site, respectively; c and d are the fitted lines of the mean value of G/Rn and G/H in the daytime, respectively).

670   **Figure 3: Intra-day distribution of the linear fitted R^2 (a) and slope (b) between G and Rn.**

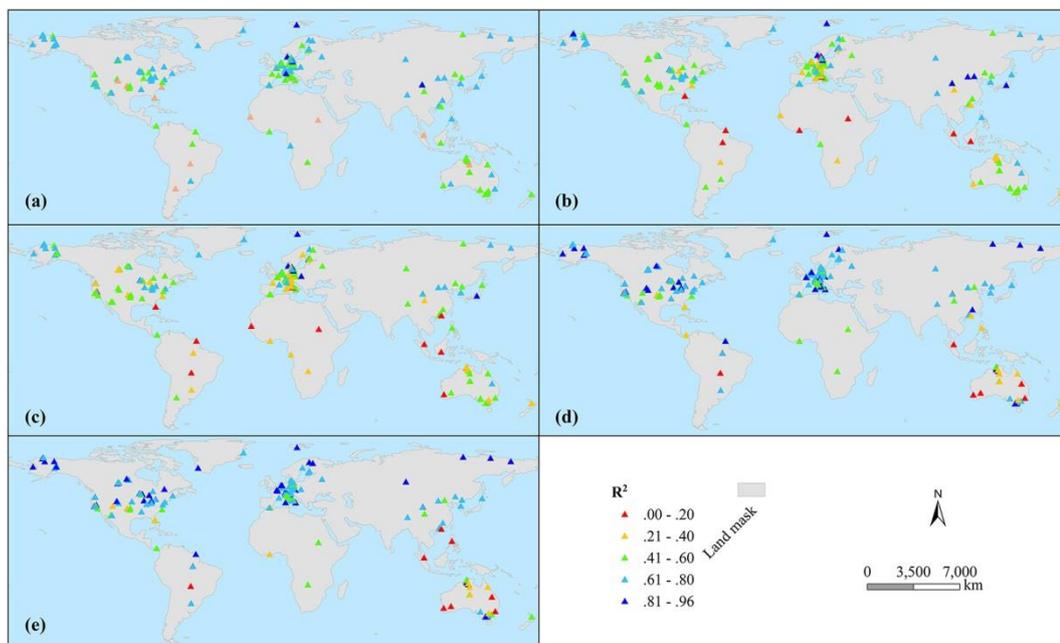



Figure 4: The linear or exponential fitting R² between daily series of G and Rn, and that between monthly series of G/Rn and NDVI at each observed site (a is the median R² of 48 half-hour periods at each site; b and c are the R² values between G and Rn at 10:30 and 13:30 respectively; d and e are linear and exponential functions fitting R² between G/Rn and NDVI, respectively).

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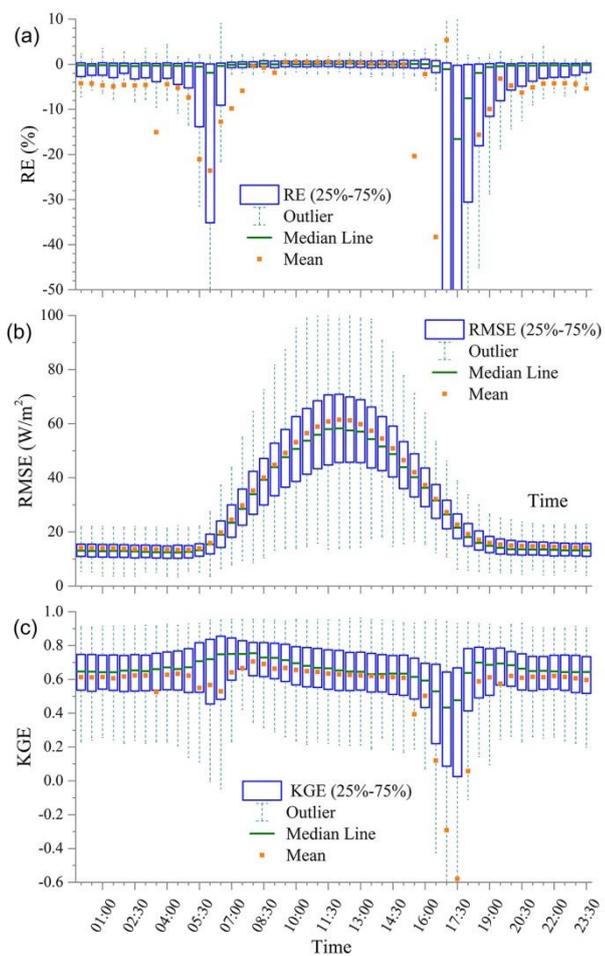


Figure 5: The RE, RMSE and KGE simulated by the LC method in each site and half-hour intervals.

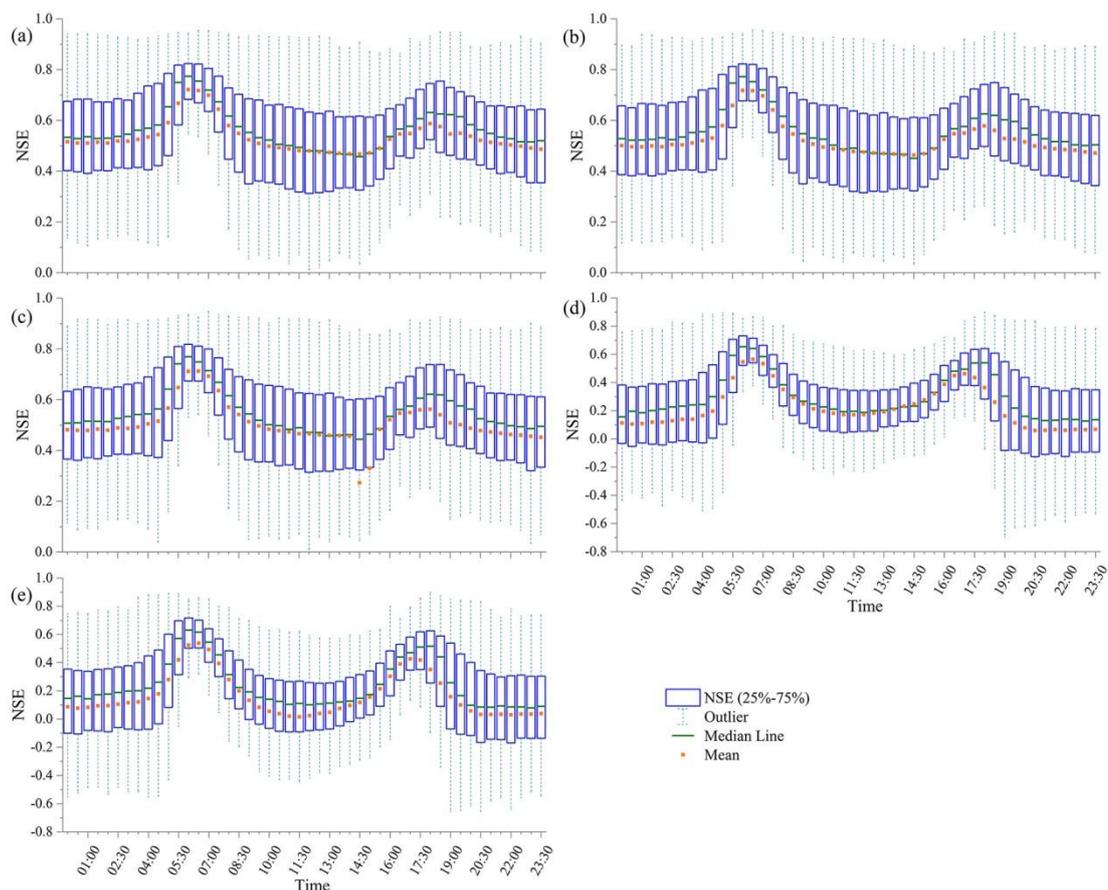
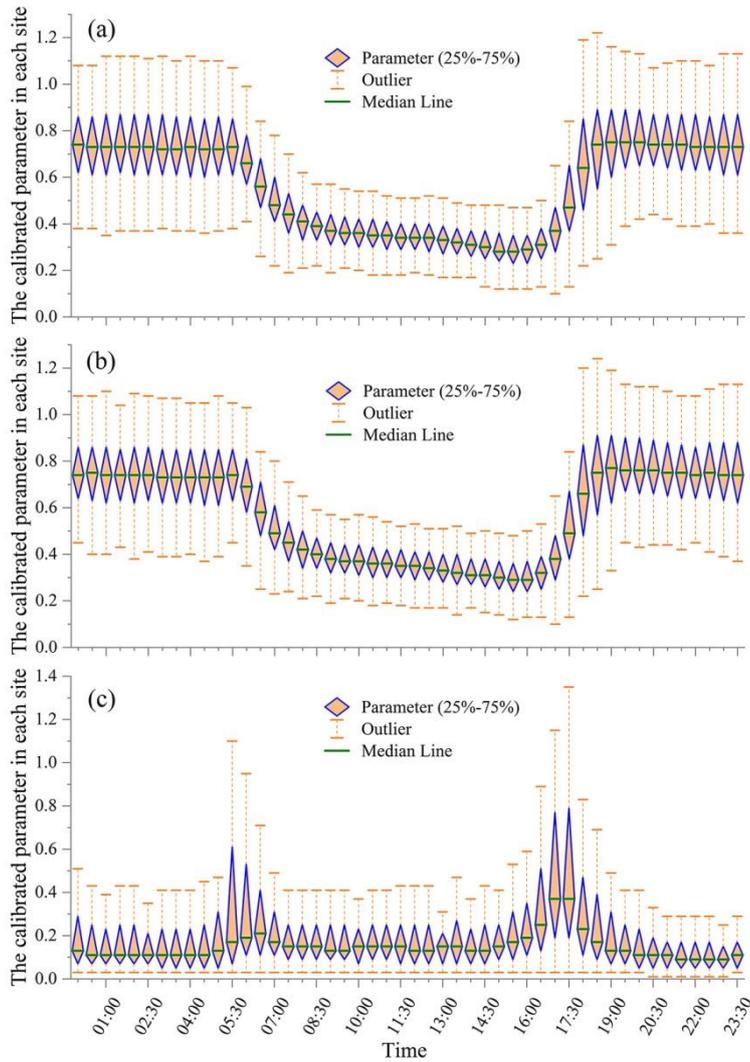



Figure 6: The NSE simulated by the (a) LC, (b) LC_NDVI_P, (c) LC_NDVI_E, (d) LC_fc_SE and (e) LC_fc_ST methods in each
680 **site and half-hour intervals.**

Figure 7: Spatial distribution of NSE values simulated by the LC method (a-e represent the median NSE of half-hour values at 6:30, 10:30, 13:30 and 18:00, respectively).

685   **Figure 8: The optimal parameters of the (a) LC, (b) LC_NDVI_P, and (c) LC_NDVI_E methods in each site and half-hour period.**