

Research Article

FAO-56 Penman-Monteith Daily ET_o from Linear Regression Calibrated Hargreaves Equation with Wind Terms in Tropics with Limited Data

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Hargreaves equation (HG), which lacks a wind speed (u_2) term, was modified, through a linear regression calibration method, into LHGu which has u_2 terms. LHGu is effectively a simplified method for approximating FAO-56 Penman-Monteith equation (FPM) daily reference evapotranspiration (ET_o) in tropics with only temperature data. In LHGu, the “0.0023” constant term in HG was calibrated as a shifted power function of u_2 , and the calibration constant was parametrized as a quadratic function of u_2 . LHGu was developed using simulated constant u_2 data and historical temperature data for four sites in West Africa: Abidjan, Accra, Daloa, and Lome. LHGu matched FPM ET_o better than HG over a wide range of u_2 : for Accra, for u_2 range 0.5–6.0 m/s, the modified coefficient of efficiency, E_1 , varied narrowly (0.83–0.98) for LHGu but widely (0.14–0.95) for HG optimized for $u_2 = 2.0$ m/s; the corresponding MBE ranges were -0.05 – 0.01 mm/d for LHGu and 0.02 – 0.63 mm/d for HG which cannot respond to varying daily u_2 . LHGu is useful for quickly computing practically accurate estimates of FPM ET_o for varying daily u_2 where only temperature data are available.

1. Introduction

The Hargreaves equation (HG) [1] for estimating reference grass evapotranspiration (ET_o) is widely used around the globe for estimating evapotranspiration for various applications because it is mathematically very simple and requires only temperature data—a very big advantage in regions with limited weather data. However, it is not suitable for applications that involve estimating the effects of varying wind speed (u_2) on ET_o estimates because it is normally calibrated for constant rather than variable u_2 .

The most reliable alternative to using HG for quantifying the effects of varying u_2 on ET_o in limited data situations is the FAO-56 Penman-Monteith equation (FPM) which has terms for variable u_2 . But FPM is complicated to use compared to HG since numerous intermediate computations need to be made to estimate the missing weather data; these computations create many potential error pitfalls for the nonexpert user and have thus inspired much research to simplify the estimation of ET_o by FPM [2–4].

The difficulties of applying FPM have also given rise to much research towards improving simpler empirical alternatives to FPM, especially HG, to match the accuracy of FPM (e.g., [5–8]). However, much of the literature on improving the simpler alternatives such as HG deals with fixed u_2 with little on variable u_2 conditions. This is a gap in the literature that needs to be filled with more research because wind speed greatly influences evapotranspiration [9, 10]. What is particularly needed is a simple equation like the popular HG for variable wind speed conditions as an alternative to the computationally more challenging FPM when only temperature data are available.

The main challenge in developing simple variable wind ET_o equations is that wind speed in the field is unsteady over the day and thus it is impossible to obtain ET_o data for constant daily wind speeds under natural settings [11]. In the literature, when both wind and ET_o data are available, empirical equations are developed by simply analyzing ET_o data for average daily wind speeds rather than for constant speeds. The approach used in this study is different in not

requiring actual wind data and it is therefore suitable for poor data situations where usually only temperature data are available; we circumvented the data problem using a methodology that is essentially the same as grafting the wind function of the widely accepted FPM into the Hargreaves equation. Thus, the resulting equation is really a computational shortcut for approximating FPM daily ET_o for variable u_2 conditions rather than another empirical alternative to FPM for data poor tropical sites.

The linear regression calibration method was chosen for this study because it is a popular method of calibrating empirical ET_o equations such as HG [9, 12] even though there are more efficient methods for calibrating HG against FPM [13, 14]. HG calibrated by the linear regression method is named LHG in this study. Because LHG lacks u_2 terms, its ET_o estimates are insensitive to even very large changes in u_2 . The aim of this work was therefore to develop LHGu, a modification of LHG that includes terms for u_2 , to be used as a simplified method of approximating FPM daily ET_o for varying u_2 where only temperature data are available. The objectives were to develop LHGu and evaluate its efficiency and accuracy for both constant daily u_2 and mixed-type daily u_2 . The hypothesis of this work was that LHG which has no u_2 term can be modified into LHGu which has u_2 parameters from the envelopes of optimal calibration parameters of LHG at various u_2 .

2. Methodology

This study focused on West Africa, using daily maximum and minimum temperature data from four weather stations: Accra (5.55°N), Abidjan (5.25°N), Daloa (6.86°N), and Lome (6.16°N). The calibration data used for Abidjan, Lome, and Daloa were 1999–2003 average daily data obtained from TuTiempo [15] and those for Accra were 1998–2006 average daily data from the Water Research Institute (WRI) in Accra. The test data for Abidjan, Lome, and Daloa were average 2004–2006 data and that for Accra were 2007 data.

The aim of the study was to place u_2 as a term in the linear regression calibrated HG equation, LHG; the modified LHG, LHGu, should produce ET_o estimates similar to those of FPM for u_2 in the range 0.5–6.0 m/s. Therefore, 56 different LHG (linear regression calibrated HG equations) were optimized against FPM at various possible values for u_2 in the range 0.5 m/s–6.0 m/s in steps of 0.1 m/s for each of the four locations in West Africa. The optimizations were done to maximize the modified coefficient of efficiency, E_1 , values while varying the k_{HG} and linear calibration constants (k_4) values using the solver add-in in Microsoft Excel (version 2010). Simple mathematical functions were then developed to efficiently describe the envelopes of the generated optimum k_{HG} and k_4 versus u_2 data.

The resulting LHGu was tested with both fixed u_2 data and mixed uniformly distributed wind data generated using the Data Analysis Pack in Excel [16]; although wind data is normally described by the Weibull distribution [17] this study evaluated LHGu for the fixed and mixed data situations because the aim of the work was to develop LHGu, to

match FPM equally well at every u_2 in the 0.5–6.0 m/s range regardless of wind distribution, rather than to be a new ET_o equation for estimating ET_o under one particular u_2 distribution only.

The FPM equation used was [12, 18]

$$ET_{o,FPM} = \frac{0.408\Delta(R_n - G) + \gamma(900/(T + 273))u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}, \quad (1)$$

where $ET_{o,FPM}$ is the reference grass evapotranspiration (mm d^{-1}); R_n is the net radiation at the crop surface ($\text{MJ m}^{-2} \text{d}^{-1}$); G is the soil heat flux density ($\text{MJ m}^{-2} \text{d}^{-1}$); T is the mean daily air temperature at 2 m above ground ($^{\circ}\text{C}$); u_2 is the wind speed at 2 m above ground surface (m s^{-1}); e_s is the saturation vapor pressure (kPa); e_a is the actual vapor pressure (kPa); Δ is the slope of vapor pressure-temperature curve ($\text{kPa } ^{\circ}\text{C}^{-1}$); γ is the psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$) [12]. In this work, the required data to use (1) were missing except air temperature; thus missing data were estimated from temperature data using equations described in Allen et al. [12] and other sources (Kra [3]; ASCE-EWRI [18]).

The Hargreaves equation (HG) Hargreaves and Samani [19] used was

$$ET_{o,HG} = 0.0023 \times (T + 17.8) (T_x - T_n)^{0.50} \frac{R_a}{\lambda}, \quad (2)$$

where $ET_{o,HG}$ is the reference grass evapotranspiration (mm d^{-1}); T_x is the maximum daily temperature ($^{\circ}\text{C}$), T_n is the minimum daily temperature ($^{\circ}\text{C}$), T is the average temperature, $T = (T_x + T_n)/2$, R_a is the extraterrestrial radiation ($\text{MJ m}^{-2} \text{d}^{-1}$), and λ is the latent heat of vaporization (MJ kg^{-1}), computed as $\lambda = 2.501 - 0.002361T$ in this study. For the purpose of this work, (2) was generalized as

$$ET_{o,LHG} = k_{HG} \times (T + 17.8) (T_x - T_n)^{0.5} \frac{R_a}{\lambda} + k_4, \quad (3)$$

where the original parameter values are $k_{HG} = 0.0023$ and $k_4 = 0 \text{ mm d}^{-1}$. Also, $k_{HG} = k_{RS} \times k_1$; for locations near large water bodies, $k_{RS} = 0.19$ [8], and thus $k_1 = 0.0121$. The calibration of k_{HG} and k_4 constants to make (3) match FPM with the highest efficiency for a whole year is referred to as linear regression calibration of Hargreaves (LHG) in this work.

2.1. Performance Parameters. The performance of the LHG and LHGu equations were measured using the following parameters applied to scatter plots of LHG and LHGu versus FPM ET_o : the modified coefficient of efficiency (E_1), mean absolute error (MAE), mean bias error (MBE), maximum absolute error (MxAE), coefficient of determination (r^2), and slope of the linear regression line.

The modified coefficient of efficiency, E_1 , [20, 21] was defined as

$$E_1 = 1 - \frac{\sum_{i=1}^N |ET_{o,FPM}^i - ET_{o,LHGGu}^i|}{\sum_{i=1}^N |ET_{o,FPM}^i - \overline{ET_{o,FPM}}|}, \quad (4)$$

where N is the total number of days of the year, i is the particular day of the year, and $\overline{ET_{o,FPM}}$ is the average $ET_{o,FPM}$ for the year.

The mean absolute error, MAE, was estimated using

$$MAE = \frac{1}{N} \sum_{i=1}^N |ET_{o,FPM}^i - ET_{o,LHG_u}^i|, \quad (5)$$

where the variables are as defined in (4).

The annual mean bias error (MBE) was estimated as

$$MBE = \frac{1}{N} \sum_{i=1}^N (ET_{o,LHG_u}^i - ET_{o,FPM}^i), \quad (6)$$

which was defined to be positive when LHGu, on the average, overestimates FPM ET_o and vice versa.

The annual maximum absolute error (MxAE) that was not considered an outlier was computed by

$$MxAE = \max(|ET_{o,FPM}^i - ET_{o,LHG_u}^i|). \quad (7)$$

3. Results

In these results, LHGu is the modified Hargreaves equation that incorporates u_2 terms; LHG (without “ u ”) is the Hargreaves equation which has been calibrated by the linear regression method for a specific u_2 value and therefore has no u_2 term.

3.1. Parametrization of k_{HG} and k_4 . The optimal k_{HG} versus u_2 data for LHG for the four sites were fitted, with $r^2 > 0.999$, by the general shifted power function:

$$k_{HG} = a \times (u_2 + b)^c \quad (8)$$

and the k_4 versus u_2 data were fitted, with $r^2 > 0.999$, by the general quadratic function:

$$k_4 = \alpha - \beta u_2 + \gamma u_2^2, \quad (9)$$

where a , b , c , α , β , and γ were local fitting constants determined from temperature data for each site (Table 1). The $r^2 > 0.999$ applies only to the agreement between the k_{HG} and k_4 values and u_2 and not to LHG versus FPM. The lower graphs of Figure 1 show the E_1 and r^2 values, respectively, of the plots of LHG versus FPM at each of the 56 u_2 values. It was not practical to plot all the 56 LHG and the 56 LHGu versus FPM plots for each site at calibration, but six examples from the application of LHG and LHGu to the Accra site are shown in Figure 2.

3.2. Accuracies of LHGu and LHG. Figure 3 shows the accuracies of previously calibrated LHGu and LHG measured by E_1 , r^2 , MAE, MBE, MxAE, and slope of the scatter plots of LHGu versus FPM ET_o when applied to the 2007 Accra site daily temperature data and homogeneous daily u_2 data in the interest range. Each point in each graph represents the relevant performance parameter for each of the 56 scatter

plots of LHGu versus FPM or one of the 56 scatter plots for LHG versus FPM ET_o . The LHG plots are for LHG that was calibrated for $u_2 = 2.0$ m/s—the global average wind speed.

Table 2 highlights the numerical values of interest in Figure 3, showing the peak values of the performance measures and the wind speeds at which they occurred when LHGu and LHG were applied to the 2007 Accra data for the various homogeneous u_2 data.

3.3. Tractability of LHGu. Table 3 outlines the intermediate parameters required to apply LHGu, LHG, and FPM. k_{HG} and k_4 for LHGu were computed from (11) but were constants for LHG. The formulas for computing the intermediate parameters for FPM can be found in references such as Kra [3] or Allen et al. [12] and are therefore not reproduced here.

3.4. LHG versus LHGu. The E_1^{\max} of LHG occurred at the u_2 for which it was calibrated against FPM, u_2^{calib} . E_1 reduced as u_2 increased or decreased from u_2^{calib} at a much faster rate than for LHGu when moving away from u_2^{opt} . At any u_2 , E_1 of LHG was always less than or equal to the E_1 of LHGu (Figure 3). Four other error parameters (MAE, MBE, MxAE, and slope) behaved like E_1 , but, interestingly, r^2 did not indicate any difference between LHGu and LHG at any u_2 value (Figure 3). However, scatter plots showed that although r^2 of LHGu and LHG were equal at each u_2 , the LHGu plots were significantly better aligned with the 1:1 line than the LHG plots (Figure 2).

Figure 2 shows snapshot comparisons of LHGu and LHG versus FPM when applied to three constant u_2 data for each day of 2007 Accra weather data; it compares the shapes of the scatter plots and the E_1 values for LHGu and LHG when r^2 values were constant at u_2 values of 0.5, 2.0, and 6.0 m/s.

Figure 4 compares the performance of LHGu and LHG applied to mixed u_2 data that were uniformly distributed across the range 0.5–6.0 m/s and randomly distributed over all the days of the 2007 weather data for the Accra site.

4. Discussion

The results generally confirm that the wind terms of FPM can be grafted into the Hargreaves equation through the linear regression calibration method and that the new equation, LHGu, can be used as a fast, simple, and practically adequate method for approximating FPM daily ET_o estimates over a wide range of u_2 when only temperature data are available for tropical locations.

The discussions below show that LHGu is accurate enough to be used in place of FPM to reduce computational effort in ET_o applications involving varying annual homogeneous daily wind speed and those that use mixed u_2 data for different days of the year.

4.1. The LHGu Equation. The smooth and gradual variation of k_{HG} and k_4 with u_2 made it easy to parametrize them almost perfectly with u_2 as reflected in the extremely high values of $r^2 > 0.999$. Therefore, (8) and (9) are as good as the data from which they were derived (Figure 1). The

TABLE 1: Local values for the k_{HG} and k_4 parameters of LHGu equation for u_2 range 0.5–6.0 m/s.

Location	Latitude ($^{\circ}\text{N}$)	$k_{\text{HG}} = a \times (u_2 + b)^c$			$k_4 = \alpha - \beta u_2 + \gamma u_2^2$		
		a	b	c	α	β	γ
Abidjan	5.25	0.00143	1.6508	0.4046	0.4875	0.3730	0.0174
Accra	5.55	0.00135	1.7953	0.4406	0.4892	0.3924	0.0165
Daloa	6.86	0.00137	1.7375	0.4348	0.7861	0.6029	0.0248
Lome	6.16	0.00142	1.4993	0.4310	0.5616	0.4429	0.0204

TABLE 2: Numerical highlights of Figure 3; Δ = Optimum – Nadir value of the test parameter.

Test parameter	LHGu					LHG (calibrated at $u_2 = 2$ m/s)				
	Optimum	u_2^{opt} (m/s)	Nadir	u_2^{nadir} (m/s)	Δ	Optimum	u_2^{opt} (m/s)	Nadir	u_2^{nadir} (m/s)	Δ
E_1	0.98	1.4	0.83	6.0	0.14	0.95	2.0	0.14	6.0	0.81
r^2	1.0	1.4	0.97	6.0	0.07	1.0	1.4	0.97	6.0	0.97
Slope	0.99	1.8	0.93	6.0	0.07	0.99	2.0	0.68	6.0	0.68
MAE (mm/d)	0.01	1.4	0.12	6.0	−0.11	0.02	2.0	0.63	6.0	−0.60
MBE (mm/d)	0.01	1.3	−0.03	6.0	0.04	0.01	1.9	−0.63	6.0	0.64
MxAE (mm/d)	0.08	1.3	0.86	6.0	−0.78	0.15	2.0	2.1	6.0	−1.93

successful parametrization of k_{HG} and k_4 implies that the complete LHGu equation was composed of (3), (8), and (9). For example, for Accra, the full LHGu equation was

$$\text{ET}_{\text{o,LHGu}} = k_{\text{HG}}(T_x - T_n)^{0.5} (T + 17.8) \frac{R_a}{\lambda} + k_4, \quad (10)$$

where after substitution of the appropriate constants (Table 1)

$$k_{\text{HG}} = 0.00135 \times (u_2 + 1.7953)^{0.4406}, \quad (11)$$

$$k_4 = 0.4892 - 0.3924u_2 + 0.0165u_2^2.$$

Although optimal k_{HG} increased while optimal k_4 decreased with u_2 , their resultant effect caused LHGu ET_o to increase with u_2 over the range 0.5–6.0 m/s; they must therefore be applied together, not selectively, to avoid errors in estimating ET_o .

4.2. Tractability of LHGu. LHGu is far less computationally intensive than FPM. The example of using LHGu to estimate FPM ET_o for one day given in Table 3 shows that LHGu is only slightly more difficult to use than the original Hargreaves equation. The only difference between LHGu and LHG was the evaluations of the simple expressions of (11). Using FPM however required computing at least nine extra intermediate parameters many of which are more complicated than LHGu's.

LHGu is more foolproof than FPM. In the example of Table 3 there were fewer mistake pitfalls with LHGu than with FPM. Equation (11) had only simple algebraic expressions with only one variable, u_2 , with familiar units (m/s) to note and is therefore not easy to slip with. Using FPM, however, required using many complicated and long equations with uncommon units and therefore presented many more opportunities for error; for example, some of the expressions required temperature in $^{\circ}\text{C}$ while others required it in K , thus presenting many more opportunities for mistakes than with LHGu.

TABLE 3: Example comparison of the number of intermediate calculations required to estimate ET_o for a day using LHG, LHGu, and FPM for latitude = 5.55°N , altitude = 69.0 m, $T_x = 32.6^{\circ}\text{C}$, and $T_n = 20.1^{\circ}\text{C}$; $u_2 = 3.2$ m/s.

Estimated parameter	Units	ET_o equation		
		LHG	LHGu	FPM
k_{HG}	—	—	0.0028	—
k_4	Mm d^{-1}	—	−0.5979	—
R_a	$\text{MJ m}^{-2} \text{d}^{-1}$	22.7655	22.7655	22.7655
Δ	$\text{kPa}^{\circ}\text{C}^{-1}$	—	—	0.2022
γ	$\text{kPa}^{\circ}\text{C}^{-1}$	—	—	6.7096
e_a	kPa	—	—	2.3528
e_s	kPa	—	—	3.6356
R_s	$\text{MJ m}^{-2} \text{d}^{-1}$	—	—	33.8897
R_{so}	$\text{MJ m}^{-2} \text{d}^{-1}$	—	—	25.4641
R_{nl}	$\text{MJ m}^{-2} \text{d}^{-1}$	—	—	4.2461
R_{ns}	$\text{MJ m}^{-2} \text{d}^{-1}$	—	—	17.5294
R_n	$\text{MJ m}^{-2} \text{d}^{-1}$	—	—	13.2834
ET_o	mm d^{-1}	5.0	5.4	5.6

4.3. Comparisons. The different values of the parameters of (8) and (9) for the four sites meant that they intersected one another and with the $k_{\text{HG}} = 0.0023$ and the $k_4 = 0$ lines at different u_2 values. Although the closeness of the points of intersection suggests that functions with certain common parameter values could be derived for the four sites, this was not attempted since the main aim of this study was rather to prove that LHGu was possible.

The main difference between LHGu and other simplifications of FPM in the literature such as Valiantzas [22] is that (10) has the form of a familiar popular simple equation—the Hargreaves equation. It is also different from the alternative approaches of fitting a u_2 function to the FPM/HG ratio

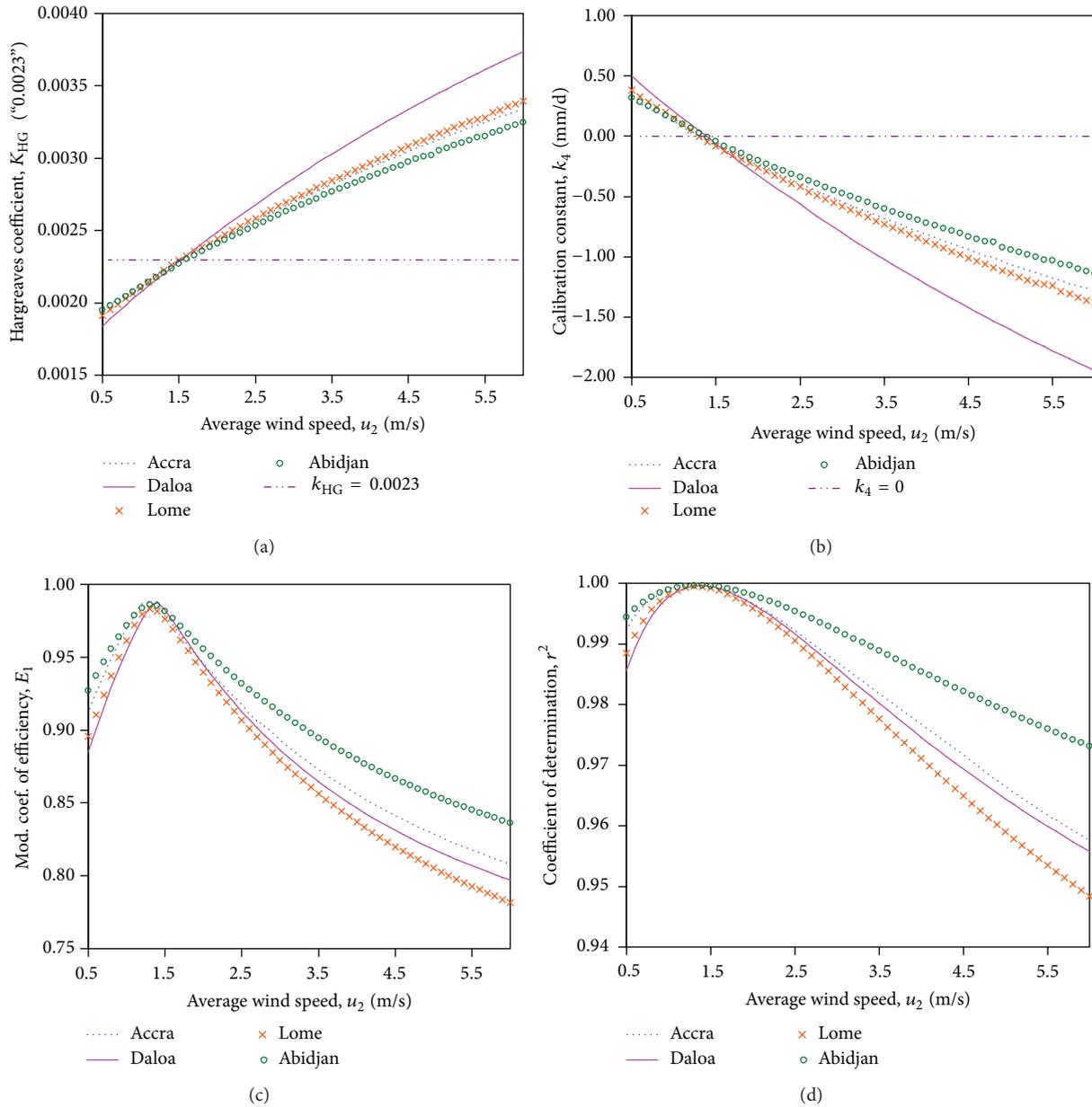


FIGURE 1: Calibrated optimal values of k_{HG} and k_4 for LHG and corresponding E_1 and r^2 for u_2 in the range 0.5–6.0 m/s for Abidjan, Accra, Daloa, and Lome.

used by some researchers in that (8) and (9) together appear more complicated than the simple power functions used by Martinez-Cob and Tejero-Juste [23]. However, LHGu achieved extremely much higher r^2 values in the range 0.98–0.99 (Table 4) under similar tests than those reported by Martinez-Cob and Tejero-Juste [23] and Jensen et al. [10]. The much higher r^2 values may be attributed to the presence of the u_2 parametrized k_4 which is absent in the other studies, but further studies directly comparing the two methods will need to confirm this.

Another significant difference between LHGu and similar works in the literature is the method of development of the wind functions. While the wind functions for the FPM/HG

ratio equations in the literature were developed for the entire considered wind speed range at once by minimizing the total error for the range, the wind functions for LHGu were developed independently for each of the 56 discrete wind speeds in the 0.5–6.0 m/s range before combining them into (8) and (9). Therefore the lower efficiencies of the wind function at higher wind speeds did not affect the higher efficiencies which centered around u_2^{opt} (Figure 1). Figure 3 shows the test statistics when LHGu and LHG were tested with homogeneous u_2 data and therefore indicates the maximum potential of LHGu and LHG as replacements for FPM at each u_2 . Thus, LHGu applied to mixed u_2 data situations found in nature will perform below E_1^{opt} of LHGu.

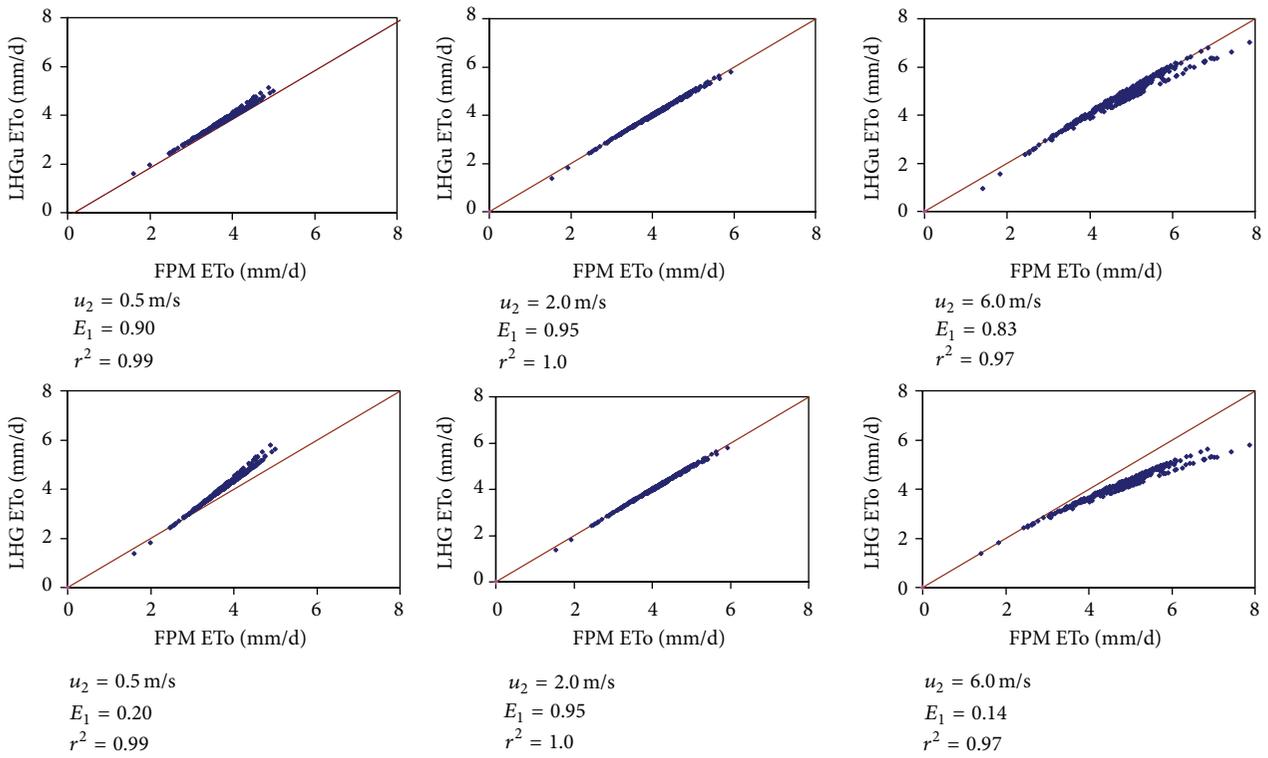


FIGURE 2: Scatter plots of LHGu and LHG versus FPM applied to 2007 Accra site data at three sample constant daily u_2 values, showing r^2 , E_1 , and scatter plot alignments with the 1:1 lines.

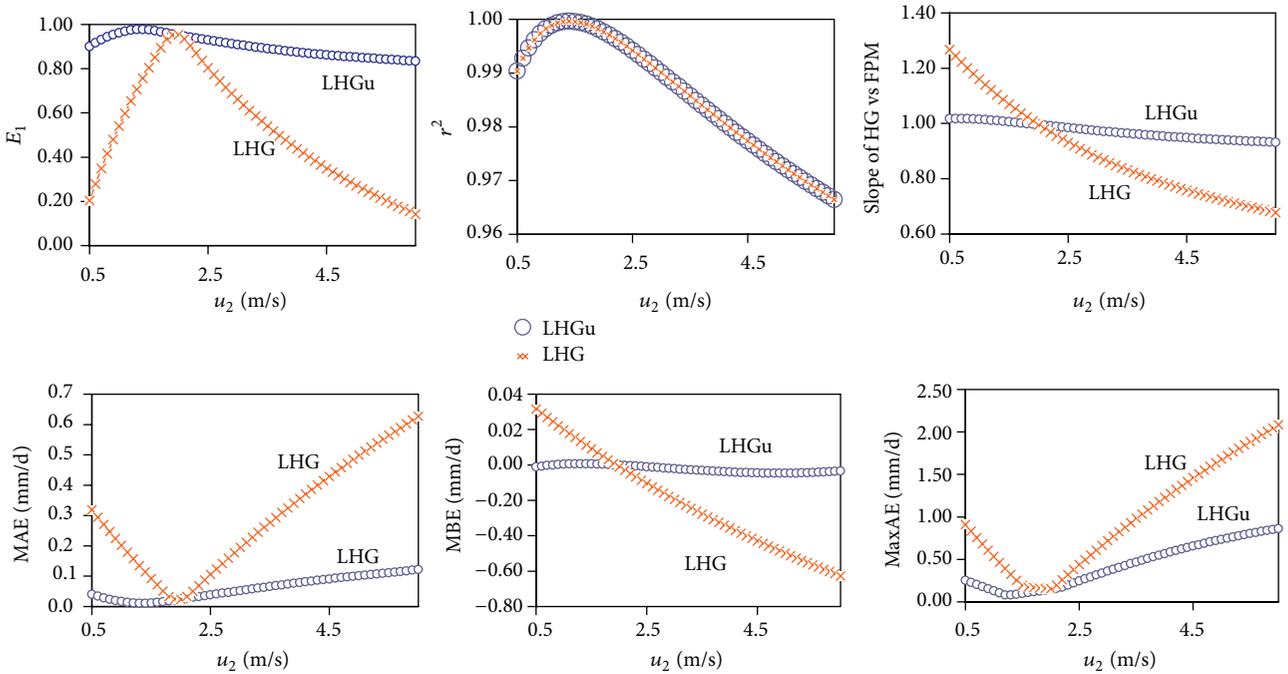


FIGURE 3: Performance statistics (E_1 , slope, MxAE, MBE, MAE, and r^2) of LHGu and LHG when applied to various constant daily u_2 data and 2007 Accra temperature data to estimate FPM ET_0 .

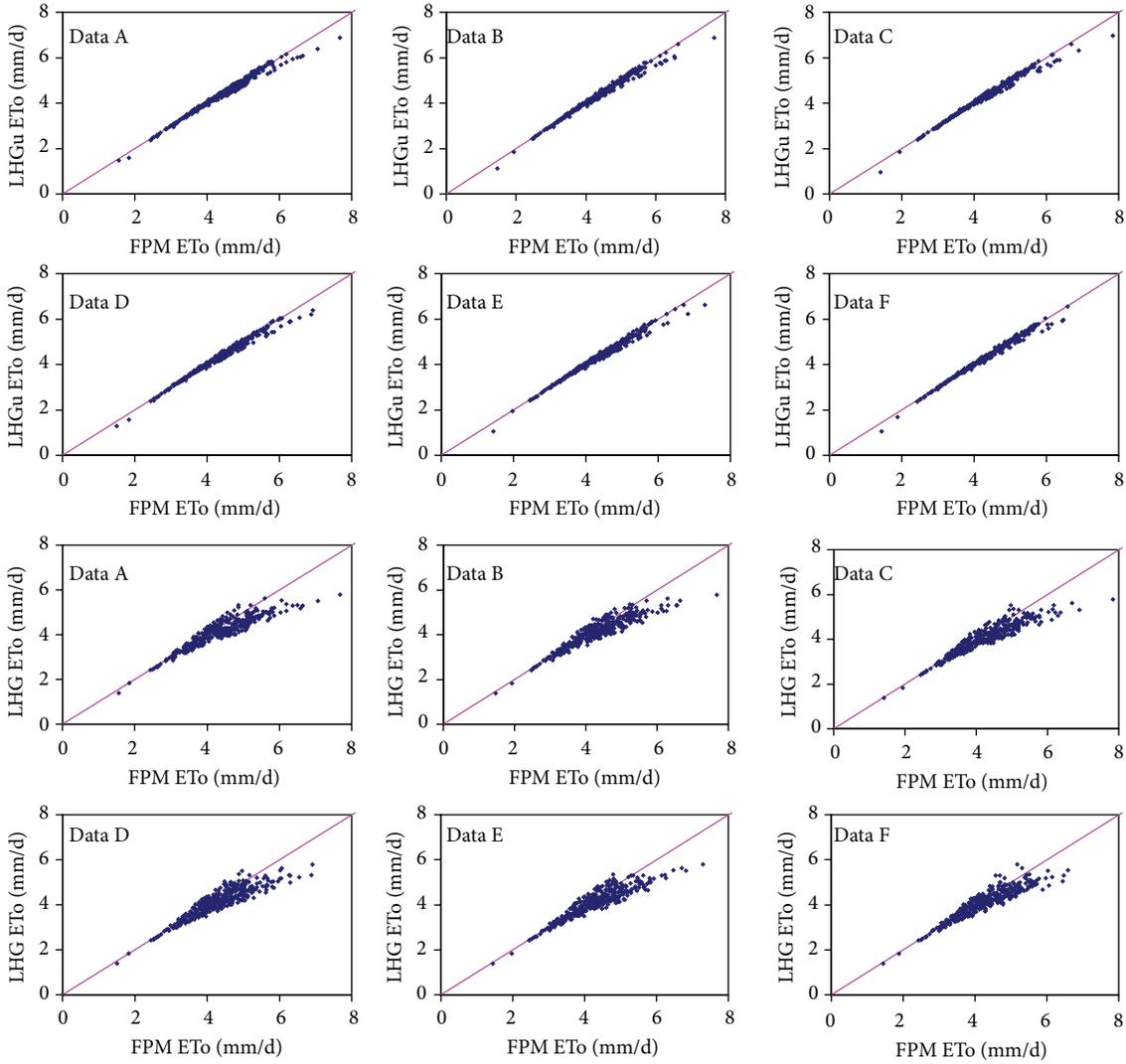


FIGURE 4: LHGu matched FPM far more precisely than LHG when applied to six different simulated mixed uniform daily u_2 data ranging 0.5–6.0 m/s and 2007 Accra site temperature data.

TABLE 4: Performance parameters of LHGu and LHG against FPM when applied to six different simulated mixed u_2 data in the range 0.5–6.0 m/s and 2007 weather data for the Accra site.

Parameter	Data A		Data B		Data C		Data D		Data E		Data F	
	LHG	LHGu										
E_1	0.52	0.90	0.55	0.90	0.54	0.90	0.53	0.90	0.53	0.90	0.56	0.91
r^2	0.85	0.98	0.86	0.98	0.86	0.98	0.83	0.98	0.84	0.98	0.85	0.99
Slope	0.71	0.95	0.74	0.95	0.73	0.96	0.74	0.95	0.75	0.96	0.76	0.98
MAE (mm/d)	0.32	0.07	0.28	0.06	0.30	0.06	0.29	0.06	0.28	0.06	0.27	0.05
MBE (mm/d)	-0.23	-0.03	-0.20	-0.02	-0.22	-0.02	-0.19	-0.02	-0.19	-0.02	-0.18	-0.02
MaxAE (mm/d)	1.89	0.80	1.89	0.80	2.05	0.85	1.57	0.67	1.51	0.67	1.39	0.52

Table 4 shows the performance of LHGu when applied to uniformly mixed u_2 data in the range 0.5–6.0 m/s.

For actual wind speed distributions the performance of LHGu with real data can be worse or better than the uniform distribution performance shown in Table 4 and Figure 4. If the wind speed distribution is skewed toward

u_2^{opt} the performance will be better and vice versa, but the performance cannot exceed E_1^{opt} neither can it fall below E_1^{min} , the best performance for homogeneous wind speed distribution at the maximum wind speed in the actual wind data. Thus although LHGu was not applied to actual wind data in this study we may conclude from the calibration

of LHGu for Accra and the results of its application to homogeneous u_2 distribution data that for real u_2 data for Accra, E_1 will be within 0.81–0.99 while r^2 will be within 0.96–1.00 for the 0.5–6.0 m/s u_2 range. Nevertheless, the objective of this work was not to make LHGu match FPM for only actual wind distribution data but any type of wind distribution in the range of interest so that it can be used to circumvent the more demanding intermediate computations of FPM when the available weather data is limited.

Although the above discussions used E_1 and r^2 they can be equally extended to the other test parameters: MAE, MBE, MxAE, and slope of the scatter plots of LHG and LHGu versus FPM. All the test parameters were consistent with E_1 at all u_2 . All the test parameters were consistent in showing that LHGu was more accurate than LHG for both the homogeneous and the mixed uniform u_2 data, except r^2 which was interestingly the equal for both at every u_2 for both calibration and testing with the homogeneous u_2 data suggesting, contrary to the others, that there was absolutely no difference between LHGu and LHG (Figure 3). The three samples of the 56 pairs of LHGu and LHG versus FPM in Figure 2 show that even though the r^2 were the same, the LHGu plots were much better aligned with the 1:1 lines, hence visually confirming the indications of the other test parameters that LHGu was much more accurate than LHG.

There was another curious finding about the behavior of r^2 when LHG was applied with homogeneous u_2 data to the 2007 Accra site temperature data. The r^2 versus u_2 for LHG was always the same (as in Figure 3) regardless of the u_2 of calibration, but the calibration u_2 influenced the shapes of the curves of all the other test parameters when LHG was subsequently applied to FPM data. For example, LHG calibrated at $u_2 = 2.0$ m/s attained a higher r^2 at $u_2 = 1.4$ m/s than at 2.0 m/s. Although the unexpected behavior of r^2 is explained by the fact that r^2 is a measure of correlation rather than of model performance (Legates and McCabe [21]), its behavior implies that using r^2 alone without other test parameters can lead to the erroneous conclusion that there was no significant gain in putting wind terms into the Hargreaves equation. Therefore r^2 must not be used alone to compare models although the practice is common in the literature. There was no r^2 puzzle for the mixed u_2 data plots where the indications of r^2 agreed with the others (Figure 4 and Table 4).

4.4. Point Comparisons of LHGu and FPM. The expected errors when using LHGu to approximate FPM ET_o for single computations depend on the u_2 data. The expected error increased with distance from u_2^{opt} . Thus when u_2 was about 1.3 m/s LHGu estimated FPM daily ET_o with efficiency of E_1 as high as 0.99 for Accra, which translated to MBE and MAE of merely 0.01 mm/d and maximum absolute error, MxAE of merely 0.08 mm/d (Figure 3). That implies that regardless of the temperature data, LHGu can estimate FPM ET_o virtually perfectly when u_2 is about 1.3 m/s. LHG can also estimate FPM ET_o to the same accuracy but only if it had previously been optimized for that particular u_2 . At the generally used global average wind speed of 2.0 m/s there was only a slight

decrease in the fidelity of LHGu to FPM. Even at 6.0 m/s the MAE and MBE were only 0.12 mm/d and -0.13 mm/d, respectively, significantly less than those for LHG. But MxAE of 0.9 mm/d may not be acceptable for some applications where accurate daily estimates are important. Therefore, LHGu is suitable for individual calculations around $u_2 = 1.3$ m/s, but for farther u_2 the original FPM is more appropriate for some applications. Other methods of calibrating Hargreaves may be explored for accuracies better than possible with LHGu.

4.5. Limitations of LHGu. Although LHGu matched FPM virtually perfectly at many wind speeds and for many days, the scatter plots and the nonperfect test scores of E_1 and r^2 also showed that LHGu is not a perfect approximator of FPM, especially at higher wind speeds and ET_o . This work was only part of a bigger research to simplify and reduce the number of intermediate steps required to apply FPM in limited data conditions in the tropics. Continuing research will explore other methods of calibrating HG and other simple ET_o equations to develop better procedures than LHGu.

5. Conclusions

Hargreaves equation can be modified to include wind speed terms without the use of actual wind data. The modified linear regression calibrated Hargreaves equation, LHGu, is significantly simpler to use and requires significantly fewer computations than FPM. LHGu approximates FPM well for the practical purposes of finding the effect of changing wind speeds on daily FPM ET_o estimates both for changing constant daily wind speeds and for a mixture of different daily wind speeds for a whole year, when only temperature data are available. Developing LHGu requires only daily historical temperature data and the range of possible daily wind speeds. Across the u_2 range 0.5–6.0 m/s, LHGu is significantly more accurate than the simple Hargreaves equation which lacks wind speed terms. The method used to develop LHGu is effectively a procedure for grafting FPM's aerodynamic terms into the calibration of Hargreaves. LHGu is not a perfect replacement for FPM, but more accurate approximations than LHGu may be developed by applying the methodology of this work to other methods of calibrating Hargreaves and to other simple ET_o equations.

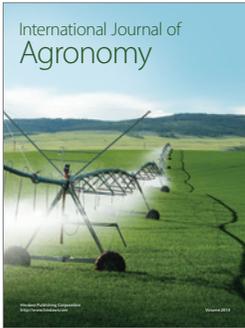
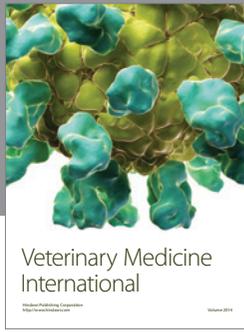
Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

References

- [1] G. H. Hargreaves and Z. A. Samani, "Reference crop evapotranspiration from ambient air temperature," in *Proceedings of the Winter Meeting of the American Society of Agricultural Engineers*, Paper no. 85-2517, Chicago, Ill, USA, December 1985.
- [2] J. D. Valiantzas, "Simplified versions for the Penman evaporation equation using routine weather data," *Journal of Hydrology*, vol. 331, no. 3-4, pp. 690–702, 2006.

- [3] E. Y. Kra, "An empirical simplification of the temperature Penman-Monteith model for the tropics," *The Journal of Agricultural Science*, vol. 2, no. 1, pp. 162–171, 2010.
- [4] M. N. ElNesr and A. A. Alazba, "Simple statistical equivalents of Penman-Monteith formula's parameters in the absence of non-basic climatic factors," *Arabian Journal of Geosciences*, vol. 5, no. 4, pp. 757–767, 2012.
- [5] P. Droogers and R. G. Allen, "Estimating reference evapotranspiration under inaccurate data conditions," *Irrigation and Drainage Systems*, vol. 16, no. 1, pp. 33–45, 2002.
- [6] H. R. Fooladmand, H. Zandilak, and M. H. Ravanan, "Comparison of different types of Hargreaves equation for estimating monthly evapotranspiration in the South of Iran," *Archives of Agronomy and Soil Science*, vol. 54, no. 3, pp. 321–330, 2008.
- [7] S. Subburayan, A. Murugappan, and S. Mohan, "Modified Hargreaves equation for estimation of ETo in a hot and humid location in Tamilnadu State, India," *International Journal of Engineering Science and Technology*, vol. 3, no. 1, pp. 592–600, 2011.
- [8] G. H. Hargreaves and R. G. Allen, "History and evaluation of Hargreaves evapotranspiration equation," *Journal of Irrigation and Drainage Engineering*, vol. 129, no. 1, pp. 53–63, 2003.
- [9] S. Shahidian, R. P. Serralheiro, J. Serrano, and J. L. Teixeira, "Parametric calibration of the Hargreaves-Samani equation for use at new locations," *Hydrological Processes*, vol. 27, pp. 605–616, 2013.
- [10] D. T. Jensen, G. H. Hargreaves, B. Temesgen, and R. G. Allen, "Computation of ETo under nonideal conditions," *Journal of Irrigation and Drainage Engineering*, vol. 123, no. 5, pp. 394–400, 1997.
- [11] C.-R. Chu, M.-H. Li, Y.-Y. Chen, and Y.-H. Kuo, "A wind tunnel experiment on the evaporation rate of class A evaporation pan," *Journal of Hydrology*, vol. 381, no. 3, pp. 221–224, 2010.
- [12] R. G. Allen, L. S. Pereira, D. Raes, and M. Smith, *Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements*, FAO Irrigation and Drainage. Paper no. 56, Food and Agricultural Organization of the United Nations, Rome, Italy, 1998.
- [13] E. Y. Kra, "Hargreaves equation as an all-season simulator of daily FAO-56 Penman-Monteith ETo," *Agricultural Science*, vol. 1, no. 2, pp. 43–52, 2013.
- [14] S. Trajkovic, "Hargreaves versus Penman-Monteith under humid conditions," *Journal of Irrigation and Drainage Engineering*, vol. 133, no. 1, pp. 38–42, 2007.
- [15] TuTiempo, "Tutiempo weather data website," 2009, <http://www.tutiempo.net>.
- [16] K. N. Berk and P. Carey, *Data Analysis with Microsoft Excel: Updated for Office 2007*, Cengage Brain, 2009.
- [17] M. Fidan, F. O. Hocaoglu, and Ö. N. Gerek, "Improved synthetic wind speed generation using modified mycielski approach," *International Journal of Energy Research*, vol. 36, no. 13, pp. 1226–1237, 2012.
- [18] ASCE-EWRI, *The ASCE Standardized Reference Evapotranspiration Equation: Standardization of Reference Evapotranspiration Task Committee Report*, ASCE-EWRI, Reston, Va, USA, 2005.
- [19] G. H. Hargreaves and Z. A. Samani, "Reference crop evapotranspiration from temperature," *Applied Engineering in Agriculture*, vol. 1, no. 2, pp. 96–99, 1985.
- [20] W. E. Bardsley and J. M. Purdie, "An invalidation test for predictive models," *Journal of Hydrology*, vol. 338, no. 1-2, pp. 57–62, 2007.
- [21] D. R. Legates and G. J. McCabe Jr., "Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation," *Water Resources Research*, vol. 35, no. 1, pp. 233–241, 1999.
- [22] J. D. Valiantzas, "Simple ETo forms of Penman's equation without wind and/or humidity data II comparisons with reduced-set FAO and other methodologies," *Journal of Irrigation and Drainage Engineering*, vol. 139, pp. 9–19, 2013.
- [23] A. Martinez-Cob and M. Tejero-Juste, "A wind-based qualitative calibration of the Hargreaves ETo estimation equation in semiarid regions," *Agricultural Water Management*, vol. 64, no. 3, pp. 251–264, 2004.



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