Simple and Reliable methods of Estimating Ground Heat Flux at a Tropical location in Nigeria

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Abstract. Ground heat flux ($G_0$) plays an important role in the partitioning of energy budget at earth’s surface. The estimates of $G_0$ are required as part of boundary conditions by all general circulation models. In this work, reliability of four simple and computationally cheap models was tested against a more complex and reliable model as the reference. The simple models selected for investigation are: Simple measurement (SM), Percentage of net radiation (PR), Universal function of net radiation (UR), and Linear function of net radiation (LR) models. Force restore model (FR) was used as the reference model.

The data of soil temperature measured at the surface and 0.05 m depth, soil heat flux, measured at 0.05m, and net radiation were obtained from Nigerian Micrometeorological Experiment, Ile Ife. Force restore model was first calibrated with direct measurements for soil heat flux at 0.05 m depth with satisfactory result before it was employed to generate reference $G_0$ estimates. Estimates of SM, PR, UR and LR were compared with FR using simple statistics of coefficient of determination ($R^2$), slope, intercept, root mean square error (RMSE) and mean bias error (MBE).

The SM model reproduced the day-time and night-time variations of $G_0$ better than all the models that parameterized $G_0$ as a function of net radiation ($R^2$, slope, intercept, RMSE and MBE values of 0.85, 0.87, 3.43W/m², 32.69, W/m², -3.70 W/m² respectively). This model however requires measurement of both soil heat flux and temperature. The LR model generated the best estimates of $G_0$ out of all the models that utilized net radiation measurements ($R^2$, slope, intercept, RMSE and MBE values are 0.60, 0.58,4.55 W/m², 53.81 W/m² and 3.60 W/m² respectively) while UR model is the worst. The LR model, though depend only on one measurement, requires site-specific calibrations and can therefore be deployed for gap filling where SM model cannot be used.

Keywords: Ground heat flux, soil heat flux, soil temperature, estimation, tropics
1. INTRODUCTION

Ground heat flux is the process where heat energy is transferred from the Earth’s surface to the subsurface of the Earth via conduction. It is one of the components of the energy budget equation at the earth’s surface. It hence plays a very important role in the earth’s surface–atmosphere interactions and meteorological modelling of complex processes of its ecosystem. However, out of all the components of surface energy budget, that is, net radiation and turbulent fluxes and ground heat flux, it is only ground heat flux that is not measured directly in the atmosphere. Sensors that are employed to determine $G_0$, conventionally, are installed by digging an aperture in the soil to avoid fluctuations due to surface atmospheric processes [1]. There is therefore, considerable attenuations of the flux with depth in addition to the inconveniences of installation when compared with other components. This may be the reason why so much research has been published about the best way to simulate $G_0$ from atmospheric data [2].

Early global circulation models either neglect $G_0$ or parameterized it as a fraction, $p$, of other energy budget components, such as net radiation($Q^*$) [3-6]. However, many empirical studies had shown that $G_0$ is neither constant nor negligible on a diurnal time scale. Field observations showed that $p$ ranges between 0.05 and 0.50 depending on the time of the day, soil moisture, thermal properties, biomass amount and health [7]. Furthermore, different combinations of measurements of surface temperature, soil temperature, soil moisture, or air temperature, together with estimation of soil thermal properties, have been used to indirectly compute ground heat flux from the heat equation solution [8 - 12].

The choice of the model used in the estimations of ground heat flux is a function of many factors. For instance, many global circulation models may prefer simple models to reduce computation cost whereas hydrological models often require more computation intensive complex models that deliver more accurate results. For the later class of modes, accuracy is of great importance because errors in estimating ground heat flux usually translate into biases in latent, sensible heat fluxes and surface
temperature. Therefore, this work focuses on identifying simple but reliable methods for estimating the ground heat flux at a tropical location in Nigeria.

2. Experimental data and Methods

The data of soil temperature measured at the surface and 0.05 m, soil heat flux measured at 0.05m and net radiation were obtained from Nigerian Micrometeorological Experiment carried out at the experimental farm of Obafemi Awolowo University (O.A.U) Ile-Ife. The data obtained covered a period of 5 days (February 24 to February 28, 2004) with time interval of 30 minutes between each measurement. There was no surface temperature data between 20:00 UTC Feb. 26 and 07:30 UTC Feb 27, hence, no estimate of $G_0$ could be obtained during those periods.

Since ground heat flux cannot be measured directly by the soil heat flux plate at the soil surface, Force Restore Method (FR) which has been adjudged as one of the best models for simulating soil thermal fields (i.e. soil temperature and soil heat flux) in the literature [2] was used in this work as the reference method.

2.1 Force Restore Method (FR)

The FR method is based on a simple two-layer assumption, dividing the soil into an upper, thermally active layer of thickness $z$ and a lower, thermally inactive layer. Bhumralkar[13] and Blackadar [14] gave the formula for force restore method as:

$$G_{0,FR}(t) = \Delta z \cdot c_v + \frac{\partial \tau_g}{\partial t} + \left( \frac{\omega \cdot c_v \cdot k}{2} \right)^{0.5} \cdot \left( \frac{1}{\omega} \frac{\partial \tau_g}{\partial t} + T_g(t) - T_g^* \right)$$

(1)

where $\Delta z$ is the damping depth, $c_v$ is the volumetric heat capacity, $k$ is thermal conductivity, $\omega$ is the angular frequency, $T_g$ is the temperature of the thin upper layer, approximately, it is the same as surface temperature, and $T_g^*$ is the average temperature of the lower soil layer that restores the atmospheric forcing. It can be replaced by the average temperature of the upper soil layer, because the long-term average soil temperature is theoretically equal for all depths. In order to demonstrate the accuracy of FR, diurnal variations of soil heat fluxes were simulated for the data set used in this work at the depth of 0.05 m where the parameters for the modelled equation were available (Figure 1). The values $c_v = 1.76 \times 10^6$ and $k=0.968$ were obtained from work.
of Otunla and Oladiran [15] carried out at the same experimental site. The damping depth $\Delta z$ is calculated from the formula given by Stull [16] as:

$$\Delta z = \frac{k \omega}{\sqrt{2c_v}}$$

where $\omega = \frac{2\pi}{P}$ ($P = 24$ hours). Figure 2 indicated coefficient of determination ($R^2$) of 0.89, slope of 0.90, intercept of 3.53 W/m$^2$ which are within required and acceptable accuracy (Figure 2). Further statistics of comparison indicated Root mean squared error (RMSE) of 16.07 W/m$^2$, mean bias error (MBE) of 4.06 W/m$^2$, and mean percentage error (MPE) of -12.71 W/m$^2$. With this level of accuracy, FR method was then adopted to generate time series of ground heat flux ($G_o$) values at the surface.

Figure 1: Time series comparison of modeled soil heat flux $G$ (at a 0.05 depth) using Force restore method (FR) and Measured Soil Heat Flux $G$ (same depth) for days February 24 to February 28 2004.
Figure 2: Scatter plot for estimated Soil Heat Flux \( G \) for FR method and measured soil heat flux at the depth of 0.05 m, from February 24 to February 28 2004.

Four other methods with varying degree of simplicity and data requirements were then used to simulate the ground heat fluxes \( (G_0) \) at the surface and the results were compared with FR using times series plots of the diurnal variations for all the days considered and, \( R^2 \), Intercept, slope, RMSE and MBE statistics. The methods are listed as follows:

2.2 Simple Measurement (SM)

\[
G_0 = G_p(t) + c_v \cdot z_p \cdot \frac{T_i - T_{s}(t - \Delta t) + 0.5[\Delta T(t - \Delta t) - \Delta T(t)\Delta t]}{\Delta t}
\]

[2] where \( G_p \) is the soil heat flux measured with a heat flux plate at the depth \( z_p \) (for this experiment, \( z_p = 0.05 \) m), \( T_i \) is the soil temperature at \( z_p \), \( \Delta t \) is the time step of the soil temperature record (for our experiment, \( \Delta t = 30 \) min) and \( \Delta T \) is the temperature difference between the surface and \( z_p \) and \( c_v = 1.76 \times 10^6 \)
2.3 Percentage of Net Radiation (PR)

There are several papers where the $G_0$ was estimated as a fraction $p$ of the net radiation ([17-18], [3],[5]).

That is, $G_0(t) = -p \cdot Q'(t)$  \hspace{1cm} (4)

2.4 Universal Function of Net Radiation (UR)

Santanello and Friedl [6] modified the percentage of net radiation method as

$$G_0(t) = A \cos \left[ \frac{2\pi(t+10800)}{R} \right] Q'(t)$$  \hspace{1cm} (5)

$A$ and $B$ are the so-called universal parameters and are quantified as $A = 0.0074(\Delta T_s) + 0.088$ and $B = 1729(\Delta T_s) + 65013$ respectively. $\Delta T_s$ is the daily range of surface temperature.

2.5 Linear Function of Net Radiation (LR)

Ground heat flux had also been quantified as a linear function of net radiation. That is,

$$G_0(t) = a_{LR} Q^*(t + \Delta t_g) + b_{LR}.$$  \hspace{1cm} (6)

The time offset $\Delta t_g = 4h$ was found from our data set. The parameters of the linear function ($a_{LR} = -0.02$, $b_{LR} = -26.031$) were found through linear regression between $G_0$ estimated by the FR method, reference $G_0$, and the net radiation $Q^*$. Examples of this method can be found in Fuchs and Hadas [17] and Idso et al. [18].

2.6 Method of Analysis

Analysis was done using the slope, intercept, $R^2$, Root Mean Square Error (RMSE) and Mean Bias Error (MBE). The closer the slope and $R^2$ values to one the more accurate is the comparison, the smaller the intercept, MBE and RMSE the more accurate is the result. Positive sign of intercept and MBE indicates overestimation in the calculated values, while negative sign indicates underestimation.

$$R^2 = \left( \frac{n(\Sigma g_{obs} - g_{est}) - (\Sigma g_{obs})(\Sigma g_{est})}{\sqrt{n^2(\Sigma g_{obs})^2 - (\Sigma g_{obs})^2}(n^2(\Sigma g_{est})^2 - (\Sigma g_{est})^2)} \right)^2$$  \hspace{1cm} (7)

$$MBE = \frac{1}{n} \sum_{1}^{n} (G_{est} - G_{obs})$$  \hspace{1cm} (8)
\[ RMSE = \left[ \frac{1}{n} \sum_{1}^{n} (G_{est} - G_{obs})^2 \right]^{1/2} \]  

(9)

Where \( G_{obs} \) and \( G_{est} \) are respectively the measured and estimated values of \( G_0 \) and \( n \) is the number of observations.

3. Results and Discussion

The temporal structure of the FR estimates of \( G_0 \) data is closely matched by the \( G_0 \) estimated from SM method (Figure 3a). The scatter plot (Figure 5a) indicated a very good agreement between FR and SM estimates of \( G_0 \) (\( R^2 = 0.85 \) and slope = 0.87). The simple measurement method (SM) generated the lowest RMSE (32.69 W/m\(^2\)) when compared with other methods. In addition, the modelled crests (i.e. Noon-time values) and the troughs (i.e. the night-time values) of the diurnal variations of the \( G_0 \) wave (Figure 3a) have the lowest underestimations as indicated by the values of the intercept and MBE of -3.43 and -3.70 W/m\(^2\) respectively (Table 1). In contrast to other methods investigated in this work, the SM method requires continuous soil temperature measurements, but this further measurement effort is rewarded with unrestricted temporal applicability with no restriction of site-specific calibrations.

For PR method, diurnal variations of \( p \) were taken into account by using different values for day-time and, early morning and night-time. For day time (\( p = 0.27 \): from 7:00 UTC to 19:00 UTC) and, early morning hours and night, \( p = 1.15 \): from 00:00 UTC – 06:30 UTC and 19:30 UTC – 23:30 UTC. From the scatter plot in Figure 5b, the PR method gave \( R^2 \) value of 0.61 and slope of 0.57 which were lower in comparison with the SM method. Moreover, a larger RMSE value of 54.97 W/m\(^2\) was obtained using PR method when compared with the SM method. All these indicated that the PR method is not as good as the SM method. A close inspection of Figure 3b indicated overestimation of both the crests and troughs of \( G_0 \) waves. These were captured by the positive values of the intercept and MBE listed in Table 1.

Figure 4a showed the time series variations of both the reference and estimated \( G_0 \). The scatter plot in Figure 6a gave values \( R^2 \) (i.e 0.60) and slope (i.e 0.51) which are lower compared with PR method (Table1). Highest value of RMSE
(i.e 60.69 W/m²) indicating a poorer performance was also obtained with this method. The $G_0$ waves crests and troughs were overestimated even though a close inspection of Figure 6a indicated the troughs which represent the night-time were more overestimated. These biases were captured with positive and higher magnitudes of intercept and MBE values when compared with both SM and PR methods (Table 1).

The linear function of net radiation (LR) method generated $G_0$ waves which match better, the variations of reference $G_0$ obtained from the FR method among all the methods that relied on net radiation measurements (Figure 5b). This fact is easily corroborated with $R^2$ value of 0.60, slope of 0.58 (Figure 6b) and RMSE of 53.81 W/m² (Table 1). The overestimations of $G_0$ wave crests and troughs obtained from this method were the least among all the methods that used net radiation measurements (see the intercept and MBE values for LR method in Table 1).
Figure 3: Comparison of the time series of estimated Ground Heat Flux $G_o$ from Force restore method (FR) with (a) Simple measurement method (SM) and (b) Percentage of net radiation method (PR) at the surface (depth of 0 m) from February 24 to February 28 2004.
Figure 4: Comparison of the time series of estimated Ground Heat Flux $G_o$ from Force restore method (FR) with (a) Universal function of net radiation (UR) and (b) Linear function of net radiation (LR) at the surface (depth of 0 m) from February 24 to February 28 2004.
Figure 5: Scatter plot of estimates of Ground Heat Flux $G_o$ from FR with (a) SM method and (b) PR at the surface from February 24 – February 28 2004.

Figure 6: Scatter plot of estimates Ground Heat Flux $G_o$ from FR with (a) Universal function of net radiation (UR) and (b) Linear function of net radiation (LR) methods at the surface from February 24 – February 28 2004.
Table 1: Statistical comparison of Ground heat flux ($G_0$) estimates from Force Restore Method and Simple Measurement (SM), Percentage of net radiation (PR), Universal function of net radiation (UR) and Linear function of net radiation (LR) methods.

| Methods     | $R^2$ | Slope | Intercept (W/m$^2$) | RMSE (W/m$^2$) | MBE (W/m$^2$) |
|-------------|-------|-------|---------------------|----------------|--------------|
| SM          | 0.85  | 0.87  | -3.43               | 32.69          | -3.70        |
| PR          | 0.61  | 0.57  | 10.47               | 54.97          | 14.11        |
| UR          | 0.60  | 0.51  | 28.21               | 60.69          | 26.94        |
| LR          | 0.60  | 0.58  | 4.55                | 53.81          | 3.60         |

4. Conclusion

In this study, the performances of the simple measurement method (SM), percentage of net radiation (PR), universal function of net radiation (UR) and linear function of net radiation (LR) for estimating the ground heat flux were examined and the main finding is as follows:

The simple measurement method reproduced the day-time and night-time variations of Ground heat flux ($G_0$) better, using force restore method as the reference, than all the methods that parameterized $G_0$ as a function of net radiation ($R^2$, slope, intercept, RMSE and MBE values of 0.85, 0.87, 3.43W/m$^2$, 32.69, W/m$^2$, -3.70 W/m$^2$ respectively). Hence, the best estimates of $G_0$ in this study was obtained from simple measurement method. This method worked well independently of soil characteristics and meteorological conditions. However, the method requires measurement of two parameters.

The method that parameterized ground heat flux as a linear function (LR) of the net radiation generated the best estimates of $G_0$ out of all the methods that utilized net radiation measurements ($R^2$, slope, intercept, RMSE and MBE values are 0.60, 0.58, 4.55 W/m$^2$, 53.81 W/m$^2$ and 3.60 W/m$^2$ respectively). This method is closely
followed by percentage of net radiation method (PR). The method that parameterized G0 as a universal function (UR) was found to be the worst in this study. Both LR and PR methods have the advantage of utilizing only few data and only one measured parameter. However, the calibration of the PR and LR methods turned out to vary with time and space. Hence, they can only be used for short time estimations at a specific site and are thus ideal for gap-filling.

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