Estimation of the Ground Heat Flux from Percentage of Net Radiation in Ile-Ife, Osun State, Nigeria

Usman, A[1]; Sunday, J. A.[1] and Sunmonu, L.A[2]

[1]*Department of Science Laboratory Technology (Physics/Electronics Unit), Kwara State Polytechnic, Ilorin, Nigeria*
[2]*Department of Physics, Obafemi Awolowo University, Ile-Ife, Osun, Nigeria*
*Corresponding Author**

Abstract: **Some results and measurement of analysis used to determine ground heat flux, have been evaluated with field data in Ile-Ife, Osun state, Nigeria. For the field observations, an instrumented meteorological mast was set up at an experimental site ($7^0 33'$N, $4^0 35'$E) located at Obafemi Awolowo University campus, Ile-Ife, Nigeria for a period of two weeks (31st May-14th June, 2013). The soil heat flux, net radiation and soil temperature from the soil heat flux plate; an all-wave net radiometer, and soil thermometer were recorded every 10 seconds and averaged over 2 minutes interval. The sampled data was stored in the datalogger (Campbell Scientific, Model CR10X) storage module. After the removal of spurious measurement values (Quality Assurance and Quality Control), the data stored was further reduced to 30 minutes averages using the Microcal Origin (version 7.0) data analysis software. The estimated ground heat flux, PR was compared with the actual measurements, $H_{G,C}$ and remarkably good agreement have been obtained with the MBE = -0.01 Wm^{-2}; RMSE = 0.13 Wm^{-2}, and r = 0.75. Hence, in the absence of direct measurement of the ground heat flux, the parameterization considered in this study is capable of yielding good result for ground heat flux even with a small set of measured net radiation data.**

Key words: **Conductivity, infrared radiation, sky, solar radiation and sun.**

I. INTRODUCTION

Ground heat flux measurements is important in micrometeorology, for instance a higher H_G usually causes higher soil temperatures that in turn can cause higher evaporation and dry the soil. Higher evaporation may enhance cloud formation and at the same time, higher soil temperatures can increase sensible heat transport to the atmosphere (Liebethal, 2005). The magnitude of H_G controls soil temperature, it also affects soil physical processes such as soil evaporation and aeration, chemical reactions in the soil and biological processes such as seed germination, seedling emergence and growth, root development and microbial activity. Thus, changes in ground heat flux are most important not only in micrometeorology but also in a number of related scientific fields (Liebethal, 2005).

Ground heat flux is normally measured with heat flow sensors and soil temperature probes buried beneath the soil surface. But, since H_G is highly dependent on surface conditions (wet or dry and bare or vegetated), it cannot be reliably approximated for large areas. On a daily basis, H_G is generally small relative to the other fluxes and sometimes has been ignored in energy balance models (Hatfield *et al.*, 1984).

The ground surface (including plants and urban areas) is heated during the day by the incoming shortwave radiation. During the night, the surface cools due to long-wave up-welling radiation, and is cooler than the air and the deeper soil layers. High gradients of temperature are observed in layers only a few millimeters thick (Foken, 2008).

Net radiation (R_n) at the surface is given as the algebraic sum of the downward flux of emitted solar radiation (R_{sd}) from sun and sky (i.e. global radiation), the downward infrared or thermal radiation flux (R_{id}) from the atmosphere, the upward flux of reflected solar radiation (R_{su}), and the upward infrared radiation flux (R_{iu}) from the surface (Jegede *et al.*, 2006).

It is intended in this research to present some results of measurements and analysis of ground heat flux over grass covered surface at Ile-Ife and to develop a parametric equation for estimating ground heat flux from percentage of net radiation measurements.

II. MATERIALS AND METHODS

Theoretical background

The ground heat flux, H_G, is based mainly on molecular heat transfer and is proportional to the temperature gradient times the thermal molecular conductivity a_G.

$$H_G = a_G \frac{\partial T}{\partial Z} \quad (1)$$

This molecular heat transfer is so weak that during the day only the upper decimeters are heated. When considering the annual cycle of ground temperature, maximum temperature is at the surface during the summer, but 10–15 m below the surface during winter (Lehmann and Kalb, 1993). On a summer day, the ground heat flux is about 50–100 Wm^{-2}. A simple but not reliable calculation (Liebethal and Foken, 2006) is: $H_G = -0.1R_n$ or $H_G = 0.3 R_n$ (Stull, 1988). The determination of the ground heat flux according to Eq. (1) is not practicable because the temperature profile must be extrapolated to the surface to determine the partial derivative there.

However, the ground heat flux (H_G) at the surface can be estimated as the sum of the soil heat flux measured at some depth using soil heat flux-plates and the heat storage in the layer between the surface and the plate:

$$H_G = SHF + \Delta S \qquad (2)$$

Where SHF is the soil heat flux and ΔS is the storage term.

The storage term ΔS is given as

$$\Delta S = \frac{\Delta T_s C_s d}{t} \qquad (3)$$

Where, ΔT_s is the change in soil temperature, C_s is the heat capacity of the soil, d is the depth and t is the output interval.

The net radiation flux R_N is a result of radiation balance between shortwave (R_S) and longwave (R_L) radiatons at or near the surface, which can be written as

$$R_N = R_S + R_L \qquad (4)$$

where R_S is the shortwave radiation flux and R_L is the longwave radiation flux.

However, expressing shortwave and longwave radiation balance terms as

$$R_S = R_S{\downarrow} - R_S{\uparrow} \qquad (5)$$

$$R_L = R_L{\downarrow} - R_L{\uparrow} \qquad (6)$$

where $R_S{\downarrow}$ = downward shortwave radiation

$R_S{\uparrow}$ = upward shortwave radiation

$R_L{\downarrow}$ = downward longwave radiation

$R_L{\uparrow}$ = upward longwave radiation

Therefore, the net (overall) radiation balance can also be written in another form by substituting equations (5) and (6) into equation (4) as

$$R_N = (R_S{\downarrow} - R_S{\uparrow}) + (R_L{\downarrow} - R_L{\uparrow}) \qquad (7)$$

where the downward and upward arrows stand for incoming and outgoing radiation components respectively.

The incoming shortwave radiation ($R_S{\downarrow}$) consists of both the direct (beam) solar radiation and the diffuse radiation. It is also called insolation at the ground. It has strong diurnal variation (almost sinusoidal) in the absence of fog and clouds. Diffuse solar irradiance is measured by a pyranometer, with its glass dome shaded from the Sun's beam. The shading is accomplished either by an occulting disc or a shading arm attached to a solar tracker.

The outgoing shortwave radiation ($R_S{\uparrow}$) is actually the fraction of $R_S{\uparrow}$ that is reflected by the surface and it is given as

$$R_S{\uparrow} = -a\, R_S{\downarrow} \qquad (8)$$

where 'a' is the surface albedo

Thus, for a given surface, the net shortwave radiation may be written as

$$R_S{\uparrow} = (1 - a)\, R_S{\downarrow} \qquad (9)$$

The incoming longwave radiation ($R_L{\downarrow}$) from the atmosphere in the absence of clouds depends primarily on the distributions of temperature, water vapour and carbon dioxide. It does not show a significant diurnal variation.

The outgoing terrestrial radiation ($R_L{\uparrow}$) being proportional to the fourth power of the surface temperature in absolute units, shows stronger diurnal variation, with its maximum value in the afternoon and minimum at the dawn. It can be expressed by Stefan- Boltzmann law as:

$$R_L{\uparrow} = \sigma T^4 \qquad (10)$$

Where $R_L{\uparrow}$ = upward longwave radiation (Wm^{-2})

σ = Stefan- Boltzmann constant = 5.67 x 10^{-8} Wm^{-2} K^{-4}

T = Atmospheric temperature (K)

Percentage of net radiation (PR)

This approach determines H_G as a fixed percentage of R_N (PR), expressed in Eq. 11. Several papers dealing with the PR approach propose values for the percentage α lying between 0.10 and 0.50 (Fuchs and Hadas, 1972; Idso *et al.*, 1975; De Bruin and Holtslag, 1982; Clothier *et al.*, 1986; Kustas and Daughtry, 1990).

$$H_{G,PR} = -\alpha R_N \qquad (11)$$

α is different for daytime and nighttime, because during the daytime the energy provided by R_N is shared between H_G and the turbulent heat fluxes. While these are nearly negligible during night time and H_G makes up the largest part of R_N. Even within the daytime and the nighttime period, α is not constant but continuously changes due to changing atmospheric processes (Liebethal and Foken, 2006). Here, the PR approach is tested for the full 24 h period. There are several papers dealing with this type of parameterization, showing values for α lying between 0.10 and 0.50 (Fuchs and Hadas, 1972; Idso *et al.*, 1975; Clothier *et al.*, 1986; Kustas and Daughtry, 1990) and Liebethal and Foken, 2006 used 0.14. For this study, we chose not to take a α value from literature but to fit it to the calibration data set, leading to α =0.20.

III. METHODOLOGY

An all-wave net radiometer (Kipp and Zonen, model NR-LITE), two soil thermometers (Campbell Scientific, model T108) and a soil heat flux plate (Campbell Scientific, model HFP01) was set up on site to measure net radiation, soil temperature and soil heat flux respectively over grass covered surface. The instruments were set up at an experimental site near the Sports Complex in Obafemi Awolowo University, Ile-Ife for a period of two weeks (31st May-14th June, 2013). The NR-LITE net radiometer was mounted on a 2.7 m tall mast and aligned at 1.41 m above the grass-covered surface. One of the T108 soil thermometers was buried at 2 cm and the other was buried together with the soil heat flux plate at 10 cm below the soil surface. Measurements was taken every 10 seconds and averaged over 2 min intervals. The sampled data was then stored in the datalogger (Campbell scientific, model CR10X) storage module. The data stored was further reduced by using the Microcal Origin (version 7.0) data analysis software.

IV. RESULTS AND DISCUSSION

Ground heat flux estimate

The diurnal variation in α is not taken into account with a constant α = 0.20 (Eq.11), the PR approach parameterizes throughout the entire field work. The results of the PR approach against $H_{G,C}$ (Fig. 1). The figure shows that they were closely related. i.e they portray satisfactory agreements with each other, where the correlation coefficient is 0.75 and a low value of mean bias error -0.01 (Wm^{-2}).

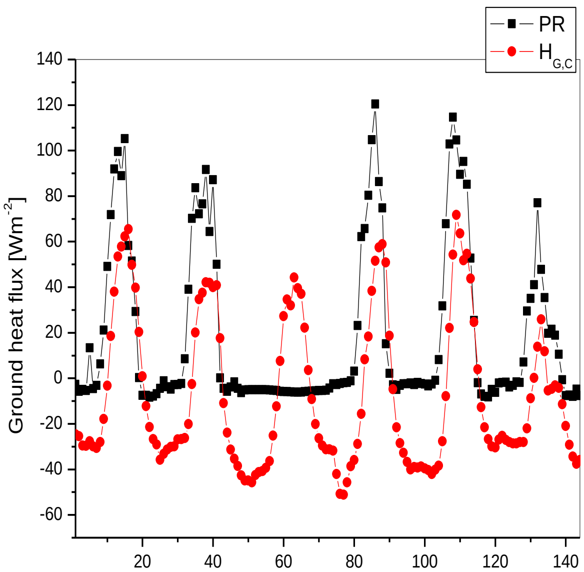

Figure 1: Results of the tested parameterization approach PR compared to the calculated $H_{G,C}$ for the data.

The scatter plot (Fig. 5) reveal the overestimation of PR approach by $H_{G,C}$ can originate from either the higher soil moisture or the height of the grass. To find out which of the factors is more important, we compared the data of May 31 with those of June 8 (Fig. 3 and 4). Both days face nearly the same soil moisture, whereas the crop height is considerably different. It turns out that the PR approach works very for June 8 while it slightly overestimate $H_{G,C}$ for May 31.

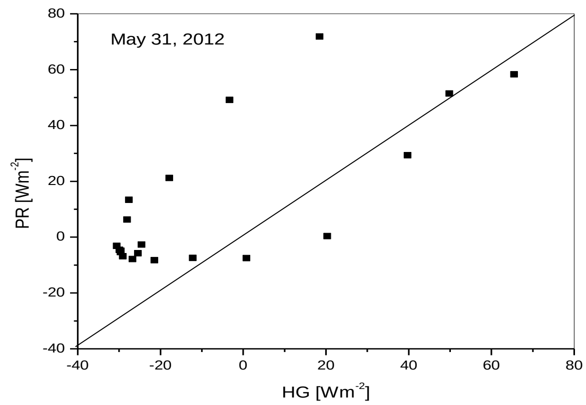

Figure 3: Scatter plot showing the tested parameterization approach PR vs. the calculated $H_{G,C}$ data.

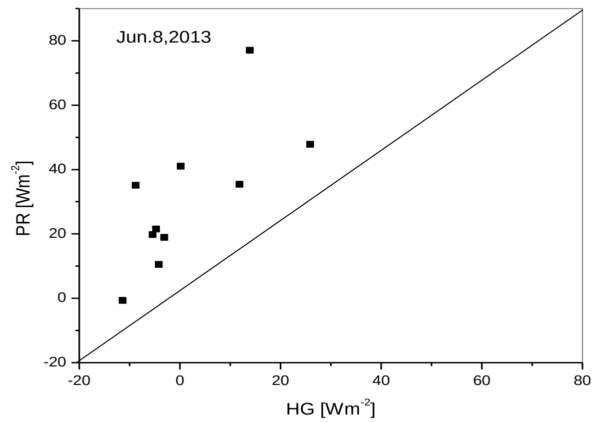

Figure 4: Scatter plot showing the tested parameterization approach PR vs. the calculated $H_{G,C}$ data.

We conclude that the crop height influences the ratio of $H_{G,C}$ and R_N much more strongly than soil moisture. Finally, the PR is overestimate of $H_{G,C}$ (Fig. 5)

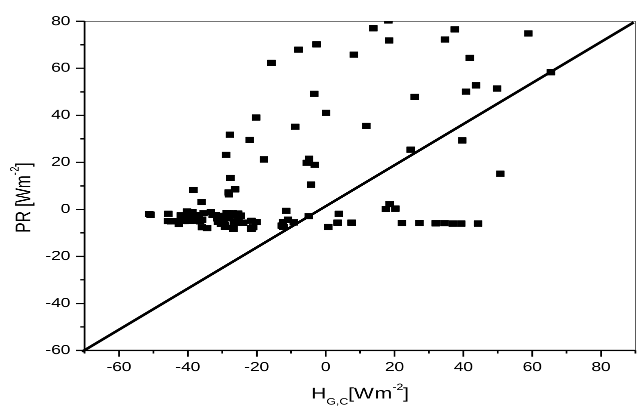

Figure 5: Scatter plot showing the tested parameterization approach PR vs. the calculated $H_{G,C}$ data

V. CONCLUSION

Continuous measurements of soil heat flux, soil temperature and downward shortwave radiation, upward shortwave radiation, downward longwave radiation, upward longwave radiation and net radiation at an experimental site ($7^0 33^{'}$N, $4^0 35^{'}$E) located at Obafemi Awolowo University campus, Ile-Ife, Nigeria, have been carried out between May 27th and June 14th, 2013. Using the direct measurement technique, these datasets have been used to investigate determine ground heat flux from percentage of net radiation. Six days (May 31st, June 3rd, 4th, 5th, 6th and 8th) from the observation period were selected and studied for the fluxes.

The results showed that determination of ground heat flux from percentage net radiation worked well in this study with some limitations and quality loss: the PR approach turned out to vary in time and space. Hence, it can only be used for short-time parameterizations at a specific site and thus ideal for gap filling.

In general, parameterization approach tested here is capable of saving sensors, time and costs for recording ground heat flux. The results of this study reveal that it is possible to get good parameterization results for $H_{G,C}$ even with a small set of measured data.

ACKNOWLEDGEMENT

The Authors are grateful to the leader, Professor O.O. Jegede and members of Atmospheric Research Group, Department of Physics, Obafemi Awolowo University, Ile-Ife, Nigeria for making available the equipment used for this research.

REFERENCES

[1] Campbell Scientific, (2010): Net Radiometer model NR-Lite Measurement and Control Module Instruction Manual. Campbell Scientist Ltd. Leicester-shire, UK.

[2] Clothier, B.E., Clawson, K.L., Pinter, P.J., Moran, M.S., Reginato, R.J. and Jackson, R.D. (1986): Estimation of soil heat flux from net radiation during the growth of alfalfa. Agric. For. Meteorol., Vol. 37, pp. 319-329.

[3] De Bruin, H. A. R. and Holtslag, A. A. M. (1982): A simple parameterization of the surface fluxes of sensible and latent heat during daytime compared with the Penman–Monteith concept .J. Appl. Meteor., Vol. 21, pp. 1610–1621.

[4] Foken, T. (2008): Micrometeorology. Springer-Verlag Berlin Heidelberg, pp. 11.

[5] Fuchs, M. and Hadas, A. (1972): The heat flux density in a non-homogeneous bare loessial soil. Bound-Layer Meteor., Vol. 3, pp. 191–200

[6] Hatfield, J.L., Perrier, A. and Jackson, R.D. (1984): Estimation of evapotranspiration at one time-of-day using remotely sensed surface temperatures. Agric. Water Manage, Vol. 7, pp. 341-350.

[7] Idso, S. B., Aase, J. K. and Jackson, R. D. (1975): Net radiation-soil heat flux relations as influences by soil water content variations, Boundary-Layer Meteorol. Vol. 9, pp. 113-122.

[8] Jegede, O.O., Ogolo, E.O., and Aregbesola, T. O. (2006): Estimating Net Radiation Using Routine Meteorological Data At A Tropical Location In Nigeria. International Journal of Sustainable Energy, Vol. 25, No. 2 pp. 107-115.

[9] Kustas, W. P. and Daughtry, C.S.T. (1990): Estimation of the soil heat flux/net radiation ratio from spectral data. Agric. For. Meteorol. Vol. 49, pp. 205-223.

[10] Lehmann, A and Kalb, M. (1993): 100 Jahre meteorologische Beobachtungen an der Säkularstation Potsdam 1893-1992. Deutscher Wetterdienst, Offenbach, pp. 32.

[11] Liebethal, C. (2005): On the determination of the ground heat flux in micrometeorology and its influence on the energy balance closure, PhD Thesis, University of Bayreuth, pp.152.

[12] Liebethal, C. and Foken, T. (2006): Evaluation of six parameterization approaches for the ground heat flux. Theor. Appl. Climatol. Vol. 88, pp.43-56

[13] Stull, R.B. (1988): An Introduction to Boundary Layer Meteorology. Kluwer Academic Pub., pp. 666.

APPENDIX I

Synoptic Observation of Some Selected Days at the Site during 31st May To 14th June 2013

DATE	TIME	WEATHER REMARKS
01-06-2013	7hr	Cloudy, No isolation
	9hr	Cloudy, No isolation
	12hr	Rainy, Partly Cloudy, No insolation
	15hr	Partly Cloudy, Dry Air
	18hr	Partly Cloudy, Dry Air
03-06-2013	7hr	Cloudy, No insolation
	9hr	Clear Skies, High insolation
	12hr	Partly Cloudy, Little insolation
	15hr	Partly Cloudy, Little insolation
	18hr	Cloudy, No insolation
04-06-2013	7hrs	No rain, Partly Cloudy, no insolation
	9hrs	No rain, Partly Cloudy, sun is dimly visible
	12hrs	No rain, Partly Cloudy, sun is dimly visible
	15hrs	No rain, Cloudy, Little insolation
	18hrs	No rain, Partly Cloudy, Little insolation
05-06-2013	7hrs	No rain, Cloudy, no insolation
	9hrs	No rain, Partly Cloudy, sun is dimly visible
	12hrs	No rain, Partly Cloudy, Little insolation
	15hrs	No rain, Cloudy, high insolation
	18hrs	No rain, Cloudy, No insolation