A NEW MODEL FOR CLEAR SKY DOWNWARD LONGWAVE RADIATION OBTAINED FROM A TROPICAL CLIMATE

Chendo M.A.C.[1] and Obot N.I. [2*]

[1] Physics Department, University of Lagos, Lagos State, Nigeria.

[2] Department of Science Lab. Tech., Federal Polytechnic Ilaro, Ogun State, Nigeria.

*Corresponding author, obot4ever@yahoo.com

Abstract

Though some equations are general in nature, some are locality biased and need to be tested before use in another location. In this work some exiting equations of clear sky downward longwave are tested to see if they significantly predict the measured irradiation beside their correlation. At $K_T \geq 0.62$, only 39 cases were found in a 2-year data of daily irradiation from September, 1992 to August, 1994 measured in the tropics - Ilorin, Nigeria (8° 32[1]N, 4° 34[1]E). Out of 12 equations, only the original Swinbank (1963) and Brunt (1932) models estimations were found to be statistically significant, having R values of 0.608 and 0.939 respectively. They performed even better when their constants were localised. However from $K_T \geq 0.60$ with over 70 cases, only the Swinbank (1963) model predicted the irradiation significantly but with a low positive correlation; R = 0.386. By least square method via theoretical modelling, a new equation is presented which mimics the Swinbank's model but in cooperate water vapour term. It predicts significantly with high positive correlation at $K_T \geq 0.60$, when tested.

1.0 Introdution

Longwave radiation (designated downward if radiation is coming down from the sky or upward if radiation is from the earth surface) continues to be received even at nights when the sun is not seen. Downward longwave radiation is radiation from the atmosphere and it ranges from about 4-100μm. It is an important energy flux that accounts for the highest source of heat on the earth's surface [1-2]. The instrument for measuring longwave radiation is relatively expensive, dedicate and mostly mounted by experts; those accumulating to scarcity of data. Even where data are available, accessibility is another hurdle in some parts of the developing countries.

In literature, there are several works that has been done in this field and downward lonwave radiation data for scientific, architectural, engineering and agricultural uses cannot be overemphasised [e.g. 3-5]. So to get around data acquisition, estimations are usually made from equations derived from the ground truth. Simulations from satellite are also streamlined with the ground truth.

It is not only expected that equations or any other methods should merely be used to obtain data but accuracy is desired. Also many of these equations are locality biased and performance is enhanced when their constants are localised [6-7]

Longwave radiation depends on a lot of other atmospheric parameters like cloud cover, temperature, water vapour and also on geographical parameters like altitude [7-8]. Efficiency of solar energy appliances is better guaranteed under clear sky than cloudy sky and daily mean values are less prone to error than the hourly (solar irradiance) values [9]. There are various statistical tools that are used to test the applicability of a model. However, in most cases the t-test, t_s which depicts whether or not a model estimates the measured value statistically significant is not used. In this work some existing clear skies equations are tested using statistical tools like t-test and a new equation for the location is put forward.

2.0 Method

The site of this work is Ilorin (8 32^{o}N, 4 34^{o}E) in Nigeria and the data measurement from September, 1992 to August, 1994and collection have previously been reported in [10-11].Clear skies criteria [12] are used to pick out daily mean clear sky irradiation. At $K_T \geq 0.62$, 39cases of daily mean longwave radiation were found and subsequently calculated values were generated from some chosen clear sky models [13-23]. Using statistical tools like Mean Bias Error (MSE), Root Mean Square Error (RMSE), correlation co-efficient (R) and most importantly the t-test, (t_s) the performance of the models are evaluated. Furthermore the clearness index was lower to $K_T \geq 0.60$ where a total of 82 clear skies days were found.

A statistics t_s, which serves to depict the level of adjustment between calculated and measured data proposed by Stone, 1993[24] and has been used by [25-28] is given as;

$$t_s = \sqrt[2]{\frac{(n-1)MBE^2}{RMSE^2 - MBE^2}} \qquad (1)$$

$$MBE = \frac{\sum(Lm - Lc)}{n} \qquad (2)$$

$$MABE = \frac{\sum[Lm - Lc]}{n} \qquad (3)$$

$$RMSE = \sqrt[2]{\frac{\sum(Lm - Lc)^2}{n}} \qquad (4)$$

Where *Lm* is measured data, *Lc* is calculated data and *n* is the number of data.

The t-test, t_s if when compared to the critical t, $t_{c(\alpha/N-2)}$ and t_s is less than $t_{c(\alpha/N-2)}$, then the ascertained that the calculated data estimated the measured data to be statistically significant is accepted. Otherwise if t_s is greater than $t_{c(\alpha/N-2)}$, then the hypothesis that it did not estimate the measured data to be statistically significant is accepted. Where α is the level of significance at N – 2 degrees of freedom. In most cases $\alpha = 0.05$ implying 95% confidence level, likewise for this work.

The general form for most expressions of clear skies downward longwave radiation can be given as;

$$L \downarrow = \mathcal{E}\sigma T^4 \tag{5}$$

where $\mathcal{E}$ is the emissivity, σ is the Stefan Boltzmann constant and T^4 is the screen level temperature in Kelvin. The emissivity in most cases is the changing expression that differentiates one form of equation from another (see equations 6-17).

$$Brunt\ (1932) \quad = \left(0.605 + 0.048e^{1/2}\right)\sigma T^4 \tag{6}$$

$$Efimova\ (1961) \quad = (0.746 + 0.0066e)\sigma T^4 \tag{7}$$

$$Swinbank\ (1963) \quad = (5.31 * 10^{-13})T^6 \tag{8}$$

$$Idso\ \&\ Jackson\ (1965) = (1 - 0.261 \exp(-7.77 * (273 - T)^2))\ \sigma T^4 \tag{9}$$

$$\text{Maykut}\ \&\ Church\ (1973) = 0.7855\ \sigma T^4 \tag{10}$$

$$\text{Brusaret (1975)} \quad = \quad 1.24(\text{e/T})^{1/7}\ \sigma T^4 \tag{11}$$

$$\text{Satterlund (1979)} = 1.08\left[1 - \exp\left(\text{e}^{\text{T}/2016}\right)\right]\sigma T^4 \tag{12}$$

$$\text{Idso 1 (1981)} \quad = \ 0.179\left[\text{e}^{1/7}\exp(350/\text{T})\right]\sigma T^4 \tag{13}$$

$$\text{Idso 2 (1981)} \quad = [0.70 + 5.95 * 10^{-5}\text{e}\ \exp(1500/\text{T}^4)]\sigma T^4 \tag{14}$$

$$\text{Guest (1998)} \quad = \sigma T^4\ - 85.6 \tag{15}$$

$$\text{Plata (1996)} \quad = \ [1 - (((1 + 46.7(\text{e/T})) * \exp(-(1.2 + 3 * 46.7 * \text{e/T})^{1/2})]\ \sigma T^4 \tag{16}$$

$$\text{Konig} - \text{Lango}\ \&\ Augstein\ (1994) = 0.765\sigma T^4 \tag{17}$$

3.0 Results and Discussion

The selected models can be segmented into two classes of; (1) those with both temperature and water vapour variables; and (2) those with only temperature variable. At $K_T \geq 0.62$ (table 1), the models with both temperature and water vapour terms are better than those with only temperature term. The former have their correlation co-efficient values being very high, that is the values falls into the range from 0.90-1.0, except for Satterlund whose value stands at 0.893.

Those models with only temperature variable e.g. Guest (1999) and Idso & Jackson (1965) have their R values ranging from 0.574 – 0.608. The models that statistically estimates the measured data significantly are those of Brunt (1932) and Swinbank (1965) models, each of them belonging to the different classes of model with both temperature and water vapour terms and only temperature term respectively. At 95% confidence level, the critical $t_{c(\alpha/N-2)}$ is 2.021 and those models have their ts values as 0.022 and 1.44 respectively, which are less than the critical $t_{c(\alpha/N-2)}$ value. The Brunt model performs better in all ramifications when localised, however the Swinbank model has mixed behaviour - it improves in the MSE value as it lowers from 4.172 to 0.295 but the R value lessens from 0.608 to 0.572 (table 2).

Table 1; Results for $K_T \geq 0.62$, where $n = 39$

Models	MBE	MABE	RMSE	t_s	R
Brunt (1932)	0.987	5.951	7.850	0.781	0.939
Efimova (1961)	-26.908	26.908	27.829	23.362	0.952
Swinbank (1963)	-4.172	14.433	18.384	1.436	0.608
Idso & Jackson (1965)	-10.595	15.236	21.253	3.544	0.574
Maykut & Church (1973)	23.847	28.259	30.592	7.671	0.574
Brusaret (1975)	-7.657	9.236	10.566	6.483	0.957
Satterlund (1979)	-11.774	12.433	16.044	6.659	0.893
Idso 1 (1981)	-25.543	25.544	26.495	22.359	0.959
Idso 2 (1981)	-28.644	28.644	30.296	17.894	0.956
Guest (1998)	7.777	17.813	20.233	2.567	0.578
Plata (1996)	-7.567	8.546	10.509	8.617	0.946
Konig-Lango & Augstein (1994)	33.329	34.892	38.473	10.690	0.574

Table 2; Results for localised models at $K_T \geq 0.62$; Brunt localised = $(0.593 + 0.052e^{1/2})\,\sigma T^4$, localised Swinbank = $5.25 * 10^{-13}\,T^6$

Models	MBE	MABE	RMSE	t_s	R
Brunt(localised)	0.108	5.635	7.159	0.093	0.948
Swinbank(localised)	0.295	15.023	18.457	0.099	0.572

Table 3; Results for $K_T \geq 0.60$, where $n = 82$

Models	MBE	MABE	RMSE	t_s	R
Brunt (1932)	-4.631	7.779	9.982	4.713	0.904
Efimova (1961)	24.519	24.519	26.159	24.205	0.912
Swinbank (1963)	2.769	15.856	19.571	1.286	0.386
Idso 1 (1981)	22.791	22.791	24.392	23.600	0.921
Idso 2 (1981)	22.514	22.514	27.536	12.781	0.931
Idso & Jackson (1965)	6.91	16.065	20.555	3.213	0.386
Maykut & Church (1973)	-24.313	27.403	30.947	11.428	0.387
Brusaret (1975)	5.047	8.357	10.268	5.080	0.910
Satterlund (1979)	8.007	11.724	14.843	5.766	0.814
Guest (1998)	-11.123	19.307	22.028	5.265	0.387
Plata (1996)	3.919	7.634	9.656	3.997	0.904
Konig-Lango & Augstein (1994)	-33.656	34.484	38.811	15.672	0.387

At $K_T \geq 0.60$(table 3), the values of error terms are more than at $K_T \geq 0.62$ (table1) cases. The correlation values also drop for both classes of equations. R falls slightly in magnitude in the first class (of the order of 0.04) but those of the temperature models are of the order of 0.223. For instance, the R value falls from 0.608 for $K_T \geq 0.62$ to 0.387 for $K_T \geq 0.60$ for the Swinbank equation. Nonetheless, Swinbank's model still estimates the measured data significantly while Brunt model no longer statistically estimate the measured data to be significant. The $t_{c(\alpha/N-2)}$ from the standard students t-tables for degree of freedom of about 60 to 120 data at 95% confidence level is 1.980. From table 2.0, the t_s value for Swinbank is 1.286, which is less than that $t_{c(\alpha/N-2)}$ of 1.980.

4.0 New model for clear skies longwave radiation

The clearness index for clear skies starts from 0.60 and from the fore going, at $K_T \geq 0.60$ the only model that statistically estimates the measured data but correlates rather low is the Swinbank. When the clearness index is taken higher to 0.62, fewer data are recorded with two models now statistically estimating the measured data significantly. The other model which is the Brunt model has a water vapour term. Although some most of the models with both temperature and water vapour terms correlate vey high with the measured data, yet they are found wanting with respect to t-test. There is need for new model (s) that could correlate relatively high with the measured data and also estimated the measured data to be statistically significant even at $K_T \geq 0.60$.

It is reported in Iziomon et al 2003[7], that DIN-VIN 1999[29] claims that the Swinbank model which is based on theory of radiative transfer based approximation for clear sky longwave irradiance and also that another literature Llebot and Jorge 1984[30] claims the model to be theoretically justified in terms of the 6.3um absorption band of water vapour. Downward longwave radiation is a composite function of both temperature and water content of the atmosphere [31].

In literature, there are works that have expressed downward longwave radiation in straight forward linear and multiple linear models with parameters like temperature, water vapour and relative humidity [10, 32].

Traditionally in modelling of clear skies longwave equations, the dependent variable(s) is expressed in term of the emissivity Ɛ after accounting for σT^4 in the Stefan Boltmann's expression (equation 5). Ɛ approximately ranges from 0.7- 0.9. When the equations are extended to all skies, then the cloud cover is included.

While still adopting equation 5, the T^2 is spiced up with water vapour (e) so that eventually the total power of temperature T is somewhat in the power of 6 as in Swinbank model. The nature log of eT^2 gives values in a range comparable to Ɛ. From the foregoing the theoretical modelling method is used [33].

The clear skies data from $K_T \geq 0.60$ were partitioned into two in the ration of 3:1. Care was taken to accommodate the two seasons (dry and raining) in both sets of data. While the larger set was used to get the constant, some data from the larger set were used also with data of the smaller set for validation. It was believed that this procedure would make the model applicable elsewhere.

Thus from the expression $\mathcal{E} = a \ln(eT^2) + b$ and by least square method whereby the straight line passes through the origin, the constants a and b are 0.058 and 0 respectively. The new equation is of the from;

$$L\downarrow = (0.058 \ln eT^2)\sigma T^4 \qquad (18)$$

From the new model, the results are for n = 74, MBE = -0.693, MABE = 9.165, RMSE = 11.560, ts = 0.513, R= 0.865 respectively. The critical t ($t_{c(\alpha/N-2)}$) at the this number of data and at 95% confidence level is 1.980 and the new model has its t_s value to be less than the critical value, hence it estimates the measured data significantly. However the correlation value R which is 0.865 is high, not very high. The range of 0.9 – 1.0 is considered very high.

5.0 Conclusion

It's been shown that at clearness index of 0.60 for clear skies downward longwave radiation, only the Swinbank (1963) model for estimating the irradiation statistically estimates the measured data significantly but has a rather low correlation with the measured data. However, those models that even correlate very high with the measured data fail to statistically estimate the measured data significantly. A model which has a water vapour term and overall temperature term of somewhat in T^6(K) does estimates downward longwave radiation significantly and also correlate positively high in this region under study. This assertion should be tested elsewhere. The new model is an improvement on Swinbank's model, though more work should be done to improve on the correlation value to be very high.

References

[1] W.D. Sellers, (1965). Physical Climatology. Chicago University.

[2] A. Ohmura, Journal of Applied Meteorology 40, (2001), 753-761

[3] J.I. Jimenez, L. Alados-Arboledas,Y. Castro-Diez, G. Ballester. Theoretical and Applied Climatology, 38(1987) 37- 42

[4] J. Sedlar, R. Hock, The Cryoshpere, 3 (2009), 75- 84

[5] J. Sedlar, R. Hock, The Cryosphere Dicussions, 2 (2008), 487-511

[6] C.C. Alvarez, C. G. Garcia, Atmosfer , 3 (1990), 291-304

[7] M.G. Iziomona, H. Mayerb, A. Matzarakisb, Journal of Atmosphere and Solar-Terrestrial Physics, 65(2003), 1107– 1116

[8] K. Yang, J. He, W. Tang , J. C.C.K. Qin, Agricultural and Forest Meteorology 40(2010), 756-761

[9] C. A. Gueymard, Solar Energy 74(2003), 355 - 379

[10] S.O. Udo, Turkey Journal of Physics 27(2003), 61- 67

[11] Obot, N., Chendo, M., Erusafe, E. and Olutayo O., 10th World Renewable Energy Congress and Exhibition, Scotland (2008), 2023- 2027

[12] M. Aubinet.. Solar Energy 53(2) (1994),147- 151

[13] D. Brunt, Quarterly Journal of the Royal Meteorological Society 58(1932), 389–418
[14] W. Brutsaert, Water Resources Research 11(1975), 742–744
[15]W. C. Swinbank, Quarterly Journal of the Royal Meteorological Society 89 (1963), 339–348.
[16] S.B Idso and R.D. Jackson, Journal of Geophysical Research 74(1969), 5397– 5403
[17] A.J. Prata, Quarterly Journal of the Royal Meteorological Society 122 (1996), 1127–1151.
[18] S. B. Idso, Water Resources Research ,17(2) (1981), 295-304
[19] P. S. Guest, Journal of Geophysical Research, 103 (1998), 30761-30771
[20] G. A. Maykut, and P. E. Church, Journal of applied Meteorology 12 (1973), 620 - 638
[21] D. R. Satterlund, Water Resources Research 15(6) (1979), 1649 -1650
[22] N. A. Efimova, *Meteorol.Gidrol.*, 10 (1961), 28-33
[23] G. König-Langlo, and E. Augstein, *Meteorol. Z.*, 3 (1994), 343-347
[24] R.J. Stone Solar Energy 51(1995), 289-291
[25] Soares, J., Oliveira, A. P., Boznar, M. Z., Mlakar, P., Escobedo, J. A. and Machado, A. J. Applied Energy 79 (2004), 201-214
[26] C.P. Jacovides, and H. Kontoyiannis, Agricultural and Water Management 27, (1995). 365-371
[27]I.T Togrul,., H. Togrul, and H.Evin, Renewable Energy 21 (2000), 231-246
[28] J. Almororox, M. Benito,. and C. Hontoria, Interciencia 33 (2008), 280 – 283
[29] DIN-VIN Handbook 333 (1999) cited in [7]
[30] J.E. Llebot and J. Jorge (1984) cited in [7]
[31] C.H. Reitan, Journal of Applied Meteorology 2(6) (1963), 776-779
[32] A.R.T. Golaka and R.H.B.Excell, Substainable Energy and Enviroment (SES) (2004), 38-41
[33] D. Edwards and M. Hamson, (1989). Macmillan Education Ltd, London.