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Modeling of Infrared Radiation for all Skies from Easy-to-Measure Meteorological Parameters at Tropical Location: Ilorin, Nigeria

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Abstract

Downward infrared radiation (L) and some easy-to-measure meteorological variables (relative humidity, clearness index and vapour pressure) were collected for a period of two years at Ilorin. Downward infrared radiation data were obtained using a pyrgeometer (Eppley-PIR), while data for relative humidity and vapour pressure for Ilorin were obtained from the Nigerian Meteorological Services, Lagos. Based on these data, using statistical regression analysis, empirical models (seven one-variable and nine two-variable) for predicting daily mean infrared radiation, from both clear and cloudy skies, were tested. Their advantage is that they only make use of easily measured meteorological parameters.

The best one-variable model is the one based on vapour pressure, with correlation coefficient R = 0.973 and standard error of estimate $\sigma = 0.3354$ MJm^{-2}. The best two-variable model is the one involving vapour pressure and clearness index, with R = 0.979 and $\sigma = 0.3017$ MJm^{-2}. Hence, from this result, the use of the multiple-variable model is only slightly justified, as the one-variable model already gives reasonable estimations.

The applicability of some existing clear sky models to the Ilorin environment was also tested. While some of them were adequate for estimation of infrared radiation under clear sky conditions, others were not. Models that include both temperature and vapour pressure terms performed better.

1. Introduction

A qualitative understanding of infrared sky radiation is necessary for the design of radiant cooling systems. For example, the ability to predict infrared sky radiation accurately, along with knowledge of radiative and other heat transfer characteristics of surfaces, can be used to design buildings that remain cool without mechanical conditioners [1].

Hence, as emphasized by Catalanotti et al. [2] and others, the use of the cold sky as a heat sink for radiating bodies on the earth's surface may provide a promising alternative to conventional cooling techniques. Additionally, down-welling thermal radiation is an important element of the energy balance of buildings, greenhouses, swimming polls, solar collectors, vegetation leaves, etc. Its quantification is necessary to estimate correctly the radiative losses of these systems. Unfortunately, this important radiation component is not routinely measured worldwide. Sometimes the available data are of very poor quality. The instruments used in measuring infrared radiation, whether directly (pyrgeometer) or indirectly (pyrradiometer), are expensive and delicate. Hence before now, they were not used for routine weather measurements. Under the leadership of the WMO/WCRP, a Baseline Surface Radiation Network (BSRN) is being established for long term monitoring of surface radiation balance components; and measurement of infrared radiation using pyrgeometers is one of the many routine instruments used. Even with this, there are still relatively few radiation measuring centres, especially in Tropical Africa.

To estimate infrared sky radiation, models exist for predicting daily thermal radiation from both clear [1,3-8] both clear and cloudy, i.e, all sky, conditions [1, 9-12]. Some of the models are fundamental, and are of little use for practical applications, while others are empirical in nature. As also opined by Aubinet [12] for Belgium, the formulas for clear skies are of little use for countries like Nigeria, where occurrences of entirely clear days are rather rare. However, their applicability to this location will still be examined.

For the cloudy sky models, the inputs are sky emittance, cloud cover, air temperature, vapour pressure (or dew point), clearness index, global and diffuse solar radiation, etc. Clearness index is the ratio of global solar radiation to extraterrestrial radiation; it gives the percentage depletion by the sky of the incoming radiation and therefore indicates both the level of availability of solar radiation and changes in the atmospheric conditions in a given locality.

In this article, the relationship between infrared sky radiation and "objective" ground measured meteorological variables like vapour pressure, relative humidity and clearness index is examined under both cloudy and clear sky conditions. The applicability of some clear sky models to Ilorin, a Tropical location, is also examined. Similar analysis had been carried out on global solar radiation at this station [13].

2. Instruments and Methods

Infrared sky radiation was measured using a pyrgeometer (Eppley-PIR). The device has a temperature compensation circuit that works to correct for the heating by direct and diffuse solar radiation and to eliminate deviations from calibration under conditions where the ambient temperature varies widely. Hence, two thermistor circuits were built into the pyrgeometer for the sake of monitoring the dome and body temperatures so as to take care of dome heating effect. Other details concerning this instrument can be obtained elsewhere [14, 15].

Originally, data were sampled every 2 seconds with an integration time of 3 minutes. In the present paper, mainly daily or monthly mean data are used. The data set covered a period of two years (September 1992 - August 1993).

Values of vapour pressure (mb) and relative humidity were obtained from the Nigerian Meteorological Services, Oshodi, Lagos and are for Ilorin International Airport, located about 12 km from the site of this project. The weather conditions at Ilorin [16] show that within this distance these parameters can be extrapolated, especially considering that daily and monthly means are used. The values of clearness index are as contained in Udo [17].

Because energy budgets are typically established on a monthly basis, monthly correlations are primarily considered, although correlations on other periods are discussed. Whenever the prediction efficiencies of the predictive equations are to be compared, mean bias error (MBE), mean absolute bias error (MABE), root mean square error (RMSE) (as defined in Akinoglu and Ecevit [18], or standard errors of estimate are used.

While some authors (e.g., Aubinet, 1994 [12]) investigate relations between infrared sky radiation and other meteorological variables by studying the relations between dependent variables that describe infrared sky radiation (e.g., sky emittance, emittance of a gray body at air temperature) and independent variables that can be measured easily at ground level, others use the directly measured infrared flux (e.g., Brunt, [4]) or the sky-to-earth radiation deficit (Ineichen et al., 1984). The method of Brunt [4] is used here. Moreover, models that use the dependent variable and one or two independent variables are described.

The clear-sky models that are tested in this work are those of Swinbank [8], Brutstaert [5], Brunt [4], Idso and Jackson [7], Idso 1 and 2 [6] [Equations (1) - (6), respectively]. The equations were used with the original values of their coefficients (except that of Brunt, which uses the values a = 0.605 and b = 0.048 that Sellers [19] obtained as a median of 22 evaluations) and are listed below

$$L = 5.31 \times 10^{-13} T^6 \tag{1}$$

$$L = 1.24 \sigma T^4 (e/T_0)^{1/7} \tag{2}$$

$$L = (0.605 + 0.048e^2)\sigma T^4 \tag{3}$$

$$L = \sigma T^4 < 1 - \{0.26 \exp[-7.77 \times 10^{-4}(273 - T)^2]\} > \tag{4}$$

$$L = 0.179\sigma T^4 e^{1/7} \exp(350/T) \tag{5}$$

$$L = \sigma T^4\{0.70 + 5.95 \times 10^{-5} e \exp(1500/T)\} \tag{6}$$

In these equations, σ is the Stefan - Boltman constant, T is the screen-level air temperature (K), and e the screen-level vapour pressure (mb). Equations (1) and (2) are analytically derived, while the rest are empirical.

The criteria for a day to be selected as having clear sky conditions were:

(i) The clearness index, $K_{T,}$ must be greater than or equal to 0.62; and

(ii) The long-wave radiation must be stable during the day. To effectively evaluate this criterion, the following equation is used:

$$L_{24h} - L_{night} < 10W/m^{-2},$$

where the indexes (24 h, night) refer to average values for the period considered. According to Aubinet [12], in using these criteria it is ensured that no significant cloud passage occurs during the night and no fog appears before the sunset.

3. Geography of the Site

Ilorin, the town in which the study site is located, is situated at about the mid-point of Nigeria.

The prevailing winds in Ilorin, as in the whole West-African sub-region, are the South-Westerly (SW) and the North-Easterly (NE) trade winds. The SW wind blows from the Atlantic Ocean and brings rain to the West African Coast, including Nigeria from about April to October (this is the rainy season period). The NE wind, a very dry wind, blows across the country between November and March, bringing Harmattan dust with it (this is the dry season period). The dry season period at Ilorin can be classified into two main groups:

(i) The Harmattan period, when cold and dust-laden North-Easterly trade winds from the Sahara desert keep the atmosphere over Ilorin and its environs heavily overcast for days, with characteristic hazy and cloud free weather conditions with low relative humidity, degradation of visibility [20], depletion of solar radiation [21], attenuation of radio signals, and discomfort to the respiratory system and associated ailments [22]. This condition applies mainly to the months of December and January.

(ii) The cloud and dust - free period (November, February and March) of mainly high solar radiation and clear weather conditions.

3.1. Results and Discussion

3.1.1. Daily Correlation

Estimation of IR from RH

When the daily mean values of infrared radiation were regressed with the respective relative humidity values for the two-year period, except for the months of November 1993 and May 1994, where data were not available (see Fig. 1a), it was found that the two parameters were weakly correlated positively, with a correlation coefficient of $R = 0.552$. When the data were separated into seasonal sets, dry and wet, the wet season set showed very poor correlation ($R = 0.002$, while the dry season regression gave a weak positive correlation of $R = 0.583$ (see Fig. 1b, c).

Carrying out the analysis for each month showed that strong and positive correlations existed between these two parameters for the months for February 1993, March 1993, December 1993 and January 1994, with R = 0.925, 0.911 and 0.902 respectively. These months with highest R all fall into the dry season. Examples of strong and poor correlation on this basis are shown in Fig. 1d and *e* respectively.

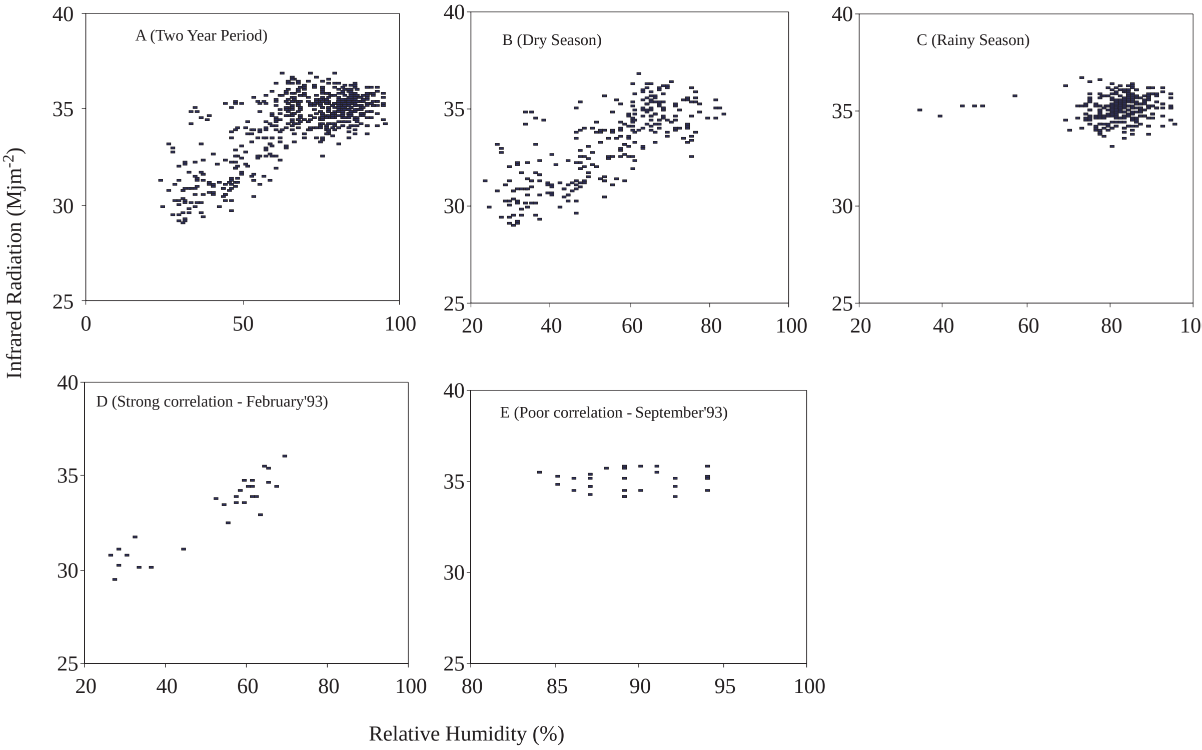

Figure 1. Relationship between daily infrared radiation (MJm^{-2}) and relative humidity (%) for the various situations indicated.

The poor correlation within the rainy season is obvious. This is because although there is a wide range of relative humidity values within this period (between 68.2 and 85.5% for April and October), the value of infrared sky radiation remains almost constant (see Table 3 for L-values). This seems to indicate that there is an optimum level of humidity in the atmosphere beyond which its increase has no effect on the amount of infrared sky radiation received. Hence, water vapour looks like a better estimator of downward infrared radiation (L) at this stage. For the dry season period, the range of variation of relative humidity matches the range of variation of L. The daily mean value of L for the two-year period was 34.3 MJm^{-2} (excluding November 1993 and May 1994).

3.1.2. Monthly Correlation

(i) One-variable models. The various one-variable models are presented in Table 1 with the corresponding empirical forms, correlation coefficients R, and standard errors of estimate, σ.

The results in Table 1 suggest that the best one-parameter models are the $L(e)$ models with no significant differences among them. Next in performance are the $L(RH)$ models, with the logarithmic form being slightly better than the linear one.

The L (K_T) models are found to be inadequate; and it has been shown elsewhere [17] that, in general, the two parameters are poorly correlated, except within very wet and cloudy months (June - October), when R was found to be as high as 0.909.

Table 1. The empirical form, correlation coefficients R and standard errors of estimate σ of the various one parameter models.

	Equation Form	R	σ (MJm^{-2})
	L(K$_T$) models		
i.	L = 40.2 - 1.9K$_T$	0.497	1.245
ii.	L = 46.3 - 7.3 exp(K$_T$)	0.495	1.246
	L(RH) models		
iii.	L = 28.8 + 0.1RH	0.895	0.6748
iv.	L = 12.8 + 5.11n(RH)	0.929	0.5579
	L(e) models		
v.	L = 27.8 + 0.3e	0.971	0.3450
vi.	L = 17.5 + 5.4lne	0.971	0.3452
vii.	L = 22.5 + 2.5(e)^2	0.973	0.3354

These results look a bit surprising, but this is because of the masking of the clearness index by vapour pressure, as explained by Aubinet [12]. He showed that at constant temperature (the rainy season temperature remains almost constant at this location), a low clearness index implies wet weather and so a higher vapour pressure. He further showed that in Belgium, where the relative humidity is constantly high (as in Ilorin), vapour pressure depends highly on air temperature.

(ii) **Two - variables models**

Nine equations were tested: Three L $(RH,\ K_T)$ models and six $L(e, K_T)$ models (Table 2). Generally, it appears that these models clearly give better results than the one - variable models, except for the $L(e)$ models. The$L(e)$ one - variable models perform better than the $L(RH, K_T)$ two-variable models. The $L(e, K_T)$ models are better than the $L(RH, K_T)$ models. However, within the $L(e, K_T)$ models, no significant differences exist among models. It should be noted that the inclusion of K_T to $L(e)$ models only slightly improves their performances.

Table 2. Same as Table 1 but for two-variable models.

	Equation Form	R	σ (MJm^{-2})
	L(RH, K$_T$) models		
i.	L = 29.6 + 0.1RH + 1.9lnK$_T$	0911	0.6400
ii.	L = 24.0 + 0.1RH + 7.22K$_T$	0.917	0.6396
iii.	L = 7.07 + 5.9ln(RH) + 5.1K$_T$	0.942	0.5383
	L(e, K$_T$) models		
iv.	L = 30.6 + 0.26e - 1.5exp(K$_T$)	0.975	0.3361
v.	L = 29.4 + 0.3e - 2.5K$_T$	0.975	0.3346
vi.	L = 19.5 + 5.1lne + 1.7ln(1-K$_T$)	0.979	0.3110
vii.	L = 27.2 + 0.3e - 1.1ln(K$_T$)	0.979	0.3106
viii.	L = 21.8 + 5.0lne - 2.08exp(K$_T$)	0.979	0.3070
ix.	L = 20.1 + 5.1lne - 3.4K$_T$	0.979	0.3017

The predictive abilities of Equations (viii) and (ix) in Table 2, which appear to be the best with no significant difference between them, are tested by comparing the predicted values with measurements. The MBE, MABE and RMSE are also determined. Results are as presented in Table 3. A dependence test was used because new data were not available.

The results show that the error terms are almost the same, not minding the obvious limitation impose by a dependent test, except for the fact that MBE values are smaller in Eq. (viii) than in Eq. (ix) implying that in the long term, Eq. (ix) outperforms Eq. (viii) in this regard.

3.2. Clear-Sky Models

On applying the two criteria used in selecting clear-sky days (section 2), only 39 days (for the two-year period) conform to them; the second criterion had no significant effect on the selection, as only two days were eliminated based on it.

Comparisons of the calculated values of infrared radiation with measured values are plotted in Fig. 2, while the error values are presented in Table 4.

Table 3. Measured and calculated infrared sky radiation for Equations (viii) and (ix) in Table 2 and their respective MBE, MABE and RMSE.

Month	Measured (MJm^{-2})	Calculated (MJm^{-2})	
		Equation (viii)	Equation (ix)
January	31.1	31.0	30.8
February	33.0	33.0	32.8
March	34.2	34.0	33.8
April	35.4	34.8	34.5
May	35.3	35.2	35
June	35.2	35.2	34.9
July	35.3	35.3	35.0
August	35.5	35.2	35.0
September	35.0	35.2	34.9
October	34.6	35.0	34.8
November	34.5	34.8	34.5
December	32.7	32.9	32.6
MBE		-0.02	-0.3
MABE		0.2	0.3
RMSE		0.4	0.4

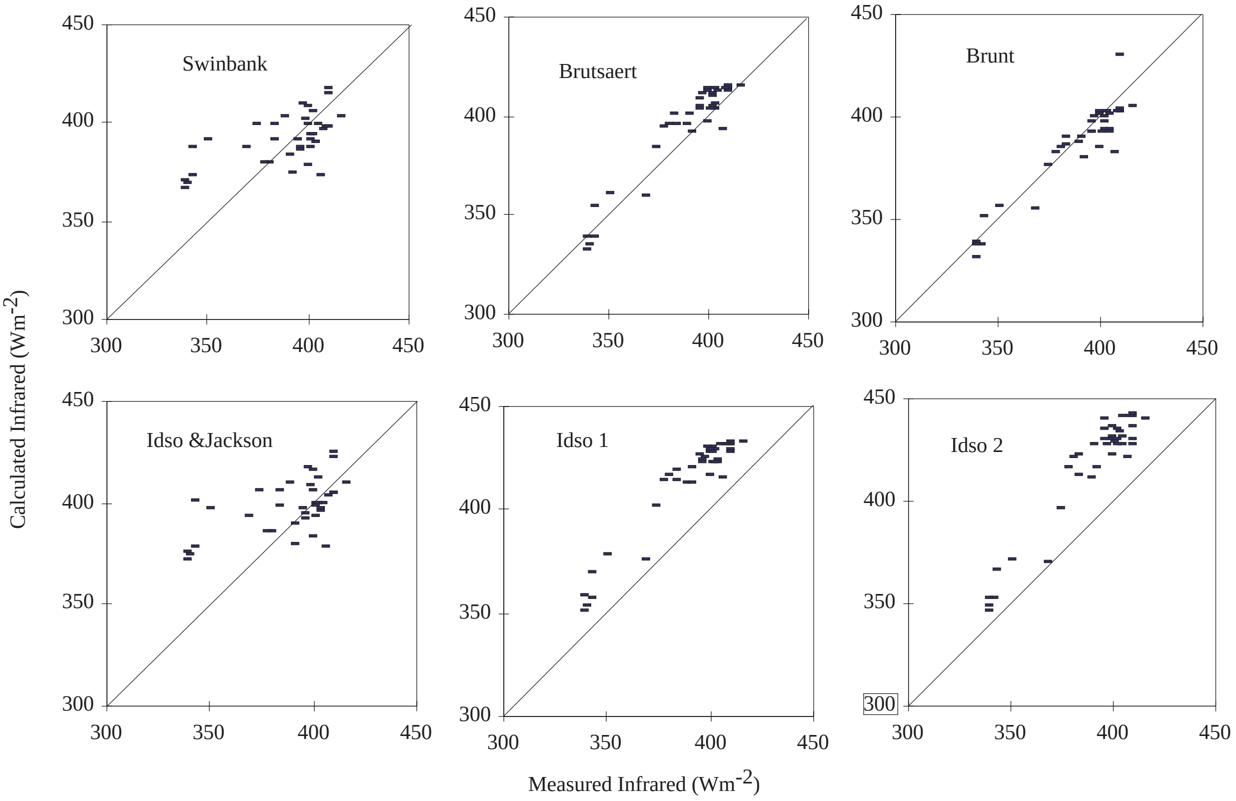

Figure 2. Comparison of daily measured and calculated infrared radiation (Wm^{-2}) for different models.

Results show that the Brunt model performs better than the others; though it slightly underestimates the measurements. Those of Brutstaert, Swinbank, and Idso and Jackson closely follow it. The models of Idso 1 and Idso 2 clearly have tendencies to overestimation.

Table 4. Error values (Wm^{-2}) for the six clear-sky models (see section 2).

Error term	Equations					
	(1)	(2)	(3)	(4)	(5)	(6)
MBE	4.162	7.403	-1.690	10.590	25.544	28.313
MABE	14.449	8.982	5.469	15.241	25.544	28.313
RMSE	18.389	10.262	6.988	21.248	26.495	30.500

According to Jimenez et al. [23], Idso indicates that his formulae were derived from data obtained at Phoenix, Arizona, which is a very dusty site; and since the variations in atmospheric dust content can significantly alter the flux of long-wave radiation from the atmosphere, he suggested that it may be convenient to modify the value of the constant 0.70 in his formula for those locations that have a different amount of dust than is normal for Phoenix. This is probably the reason for the poor performance of these models at this location. In this analysis only two days had characteristics which are probably similar to Phoenix ; and these were recorded during the Harmattan period (Section 3).

Results obtained here are similar to those reported by Jimenez et al. [23] for data with screen level temperatures above 0°C.

Culf and Gash [24] reported that the adjusted Brutsaert equation described their data excellently, illustrating the fact that its analytical derivation makes it more easily adaptable than other similar, but empirically derived, equations. However, in this work the Brunt equation, though empirically derived, performs better, showing that although the Culf and Gash assertion is true, some of the empirically derived equations are equally good and could be applied universally. According to Culf and Gash, Brutsaert earlier showed that his equation compared favourably to Brunt and Swinbank, although he made no comparison with observed data.

Even with these results, caution is generally needed when using these types of models. For example, when compared with measured values, some values were 50 Wm^{-2} too large, although for the Burnt model, they were generally below 10 Wm^{-2}. According to Berdahl and Fromberg [1], the net radiation loss of a surface at ambient temperature under clear skies is about 70 Wm^{-2}. Thus, a 50 Wm^{-2} error is really a serious matter if the net cooling power of a surface is to be determined. This caution is also necessary even while taking measurements.

4. Summary and Conclusion

Several equations were used to describe the dependence of the downward infrared sky radiation on vapour pressure (e), relatively humidity (RH) and clearness index (K_T). Four forms of equations were tested, including linear, logarithmic, power law and exponential. The best one-variable models show that this radiation can best be estimated from vapour pressure.

For the two - variable regression analysis, several models were tested. Their qualities depend essentially on the choice of the independent variables. The greater the number of variables, of course, the better the equations work. With equal number of independent variables, the $L(e, K_T)$ models are better than the $L(RH, K_T)$ models. The one-variable models of $L(e)$ were found to perform better than the two - variable models of $L(RH, K_T)$. This again shows that vapour pressure is a single variable that can be used to estimate infrared sky radiation. The inclusion of other variables is only slightly justified. The advantage of this model, as also opined by Aubinet [12], is that it requires only one measurement that is easy to obtain.

Using these new correlations, it is possible to evaluate, on a daily or monthly basis, the infrared sky radiation if clearness index, water vapour pressure and relative humidity (these are all easy-to-measure meteorological parameters) are known at a location. It is hoped that these results will be useful at locations with similar climates, if not globally.

On clear sky models, results show that those that include both temperature and vapour pressure terms perform better, apart from Idso 1 and 2, which were derived under conditions which were quite different from those at Ilorin.

Moreover, although it is important to exercise care when applying any empirical equation to different sites and seasons than those for which they were developed, because they utilize local empirical coefficients, some of them are quite good and could be applied globally. In this study, the Brunt equation performed better than the Brutsaert and Swinbank equations, although it is empirical.

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