Calculation of direct and diffuse solar irradiance components using a Slob Algorithm model in Gauteng conditions.

L.C. Nethwadzi and H. Winkler

University of Johannesburg, Physics Department, PO Box 524, 2006 Auckland Park, Johannesburg, South Africa

E-mail: thwadzi@gmail.com

Abstract. Most solar radiation measuring devices only determine the total irradiance on a horizontal surface, but for various applications diffuse and direct components are also needed. Because of this, several models have been developed to establish the correlations between the diffuse fraction and various predictors. This paper analyses the measured global irridiance at a Gauteng location as a function of the relative solar position. An equation is presented to estimate both components from the measured daily global solar irradiance only. In this equation, the diffuse component is related to the product of the cosine of the zenith angle and the Linke turbidity factor. The analysis attempts to reproduce the measured irradiance through basic modelling of the spectral opacity of the atmosphere in terms of the Linke Turbidity. This includes estimating direct beam attenuation and the diffuse component, which are then combined with the module spectral response in an attempt to match the measured and modelled energy yield. The performance of the model has been graphically and statistically analyzed by two established methods, namely; Mean Bias Error (MBE) and Root Mean Square Error (RMSE).

1. Introduction

Solar irradiance is abundant in South Africa. Therefore, reliable models predicting solar irradiance and the corresponding solar energy generated is of great importance. Modules utilize total irradiance, which consists of two components, direct and diffuse. Models are required for estimating both these components. In the past, many correlations between these quantities have been developed and the majority of these project the diffuse fraction using the clearness index ($K_T = G_h/I_0$), which is expressed by the ratio of global to extraterrestrial solar irradiance [1, 2, 3]. Some models also consider the effect of variables like solar zenith angle (θ_Z) (the angle the Sun makes with the zenith), air mass, Rayleigh optical thickness and the Linke turbidity factor. This study uses the Slob algorithm, which estimates the global irradiance component on a horizontal surface under cloud free conditions from the solar zenith angle in conjunction with the Linke turbidity factor [4]. In this study, new coefficients for this model have been found and then used to estimate solar irradiance over Gauteng.

2. Theory

When solar radiation traverse the Earth's atmosphere, some of its incident energy get absorbed and scattered, both this affects the solar spectrum reaching the ground level [5]. The radiation that reaches the surface consists of a direct normal component (B_N) from the Sun, i.e. the solar beam, and a diffuse component (D_h) from all other directions. The sum of these as measured by a horizontal surface is defined as the global horizontal irradiance.

The Linke turbidity factor (T_{LK}) quantifies the concentration of particles that reduce the incoming irradiance in cloud-free conditions. It is defined as the number of clear dry atmospheres necessary to produce the observed attenuation, and was introduced in 1922 [6] to quantify atmospheric aerosol [7]. It is a common parameter used to model the atmospheric absorption and scattering of solar irradiance under cloud free conditions. It may be expressed as follows:

$$T_{LK} = -\left(\frac{1}{\delta_R \times m_a}\right) \ln\left(\frac{B_N}{I_0}\right) \tag{1}$$

where δ_R is the Rayleigh optical thickness of a water and aerosol free atmosphere (clear and dry atmosphere), m_a is the relative optical airmass, B_N is the direct normal irradiance ($B_N = B_h/\cos\theta_Z$), and I_0 is the solar constant corrected for the Earth-Sun distance. The latter is given by $I_0 = I_{SC} \times [1 + 0.033 \times \cos\left(\frac{360\times n}{365}\right)]$, where $I_{SC} \approx 1367$ W/m^2 and n is the day number of the year, starting from 1 January [8]. Relative optical airmass is defined as the pathlength in terms of atmospheres along which solar irradiance travels through the Earth's atmosphere. It is given by $m_a = \sec\theta_Z$ if the Earth curvature and refraction are ignored, but it becomes more complex if those factors are considered [9]. Rayleigh optical thickness (δ_R) is a parameter used in solar energy research to determine the fraction of solar light able to traverse the atmosphere. In this study, the Linke turbidity factor will be determined using the classical method based on the Kasten and Young formulas [10] for the optical airmass and the improved Kasten formula for Rayleigh optical thickness as shown below:

$$\delta_{R1} = \frac{1}{[9.4 + 0.9 \times m_a]} \tag{2}$$

and

$$\delta_{R2} = \frac{1}{[a_0 + a_1 \times m_a - a_2 \times {m_a}^2 + a_3 \times {m_a}^3 - a_4 \times {m_a}^4]} \tag{3}$$

[9, 11], and where constants a_0, a_1, a_2, a_3 and a_4 are 6.6296, 1.7513, 0.1202, 0.0065 and 0.00013, respectively.

3. Method

The study proposes to analyze global irradiance in a typical Gauteng environment to determine the local Linke turbidity factor (T_{LK}) and then use this to estimate the solar irradiance. The global irradiance data were provided for several days collected by Sinetech in Randburg (latitude 26°5′11″S and longitude 27°58′28″E). The site is an urban and light industrial area which might experience moderate smog from traffic activities particularly during the morning and afternoon rush hour. These measurements were collected at intervals of 15 minutes on an ongoing basis from sunrise to sunset.

To improve the calculations of the Linke turbidibity values, irradiance data was linear interpolated for every minute. Global solar data for the dates 18 and 27 September, and 22 November 2015 are used in this work.

We have considered a NOAA [12] solar model to determine the relative position of the Sun at any particular time of the day using the latitude and longitude coordinates of the chosen site in Gauteng Province. To calculate the amount of solar energy delivered on the horizontal surface, the solar zenith angle was calculated using $\theta_Z = \cos^{-1}[\cos(\phi) \times \cos(\sigma) \times \cos(\omega) + \sin(\phi) \times \sin(\sigma)]$. Here ϕ is the geographical latitude, σ is the solar declination angle and ω is the solar hour angle from the meridian in degrees expressed by: $\omega = (Solar\ Time\ (h) - 12) \times 15°$, being negative in the morning and positive in the afternoon. The solar declination angle is defined as the angle between the equator and the direction of the Sun's rays, and is sufficiently accurately estimated by $\sigma = 23.45° \times \sin[360(284 + n)/365]$.

In this adopted model, an extraterrestrial solar irradiance (I_0) corrected for the Earth-Sun distance and global solar irradiance (G_h) are used as an input to calculate the T_{LK} values for a site. The T_{LK} values were calculated using equation (1) with the use of standard (δ_{R1}) and adjusted (δ_{R2}) models of Rayleigh optical thickness defined by equations (2) and (3), respectively. While the estimation of the beam irradiance component is more precise, the key difference from various models presented in the writings distinguish themselves in the handling of the diffuse component [13].

To calculate the diffuse irradiance, the first step procedure consists of estimating the minute clearness index (K_T), followed by defining the diffuse fraction as predicted by one variable (K_T) not to be more than 1/3 [1] of the global irradiance. This is important because the turbidity specifically quantifies cloudless atmospheric environments. In view of the limited information available from our data, the following adopted linear equation proved to be reasonably good for prediction of the minute average daily diffuse solar irradiance over the chosen Gauteng location:

$$\frac{D_h}{G_h} = 0.331 - 0.2333K_T \tag{4}$$

[14, 15]. More importantly, the present model proposed by equation (4) does not require the clearness index to be classified into sub-intervals, which then allowed for greater flexibility when altering the relationship to accommodate for location differences, since it was tested in different locations with different altitudes. The calculations for the clearness index assumes that the terrain surrounding the site is a perfect horizontal surface meaning the incoming solar irradiance is unhindered by topographical structures. In the South African interior winter months usually exhibit clearer skies for most locations [16].

Through the ratio of D_h/G_h, it is possible to compute diffuse (D_h) and direct irradiance components on a minute-by-minute basis using $G_h = B_h + D_h$. The direct normal irradiance (B_N) component is evaluated from the difference between the G_h and D_h using the expression $B_N = B_h/\cos\theta_Z = (G_h - D_h)/\cos\theta_Z$. T_{LK} values can be calculated through equation (1) in every locality where G_h is measured [17]. Once the T_{LK} values of the atmosphere were known, they were then used to calculate the global solar irradiance components. Equation (1) was rearranged to become $B_h = I_0\ \cos\theta_Z\ \exp\ (-T_{LK}\ \delta_R\ m_a)$ so that the direct irradiance model associated with the T_{LK} could be approximated.

The diffuse component was estimated by the Slob Algorithm model expressed by $D_{h1} = X + Y\cos\theta_Z T_{LK}$ [4], which describes the diffuse irradiance component for cloudless conditions, where X and Y are coefficients found from linear regression fits for diffuse solar irradiance components applied to the above mentioned datasets obtained using equation (4). This was valid for the Linke turbidity factors less than 12.5. The formula was derived by making an assumption that the diffuse component is directly proportional to the product of $\cos\theta_Z T_{LK}$ (=z). However, the Slob Algorithm model results were improved with the use of quadratic function of the form $D_{h2} = az^2 + bz + c$. The figures below illustrate linear and quadratic fittings of the data:

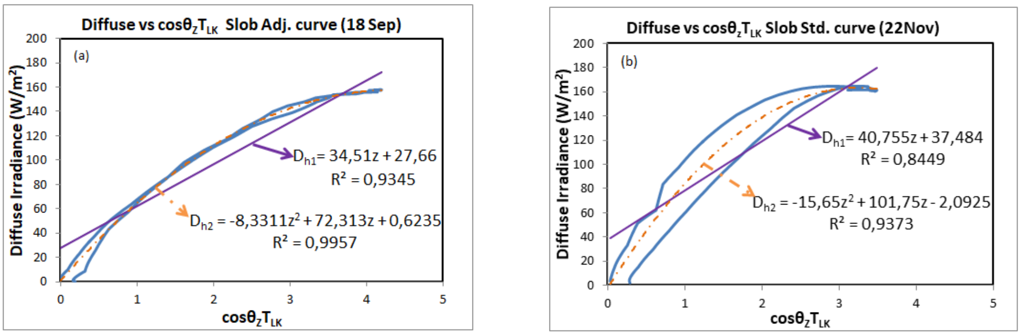

Figure 1. Represents the diffuse components D_{h1} (linear fit) and D_{h2} (quadratic fit) for (a) 18 September 2015 data and (b) 22 November 2015 data.

After the calculations of the direct and diffuse components, they were then added to give the global solar irradiance which was then compared with the measured global solar data. The performance of the model have been graphically and statistically analyzed by two established methods, namely; Mean Bias Error (MBE) and Root Mean Square Error (RMSE) [18]. The time varying errors were all analyzed for each minute of each hour, and then averaged within the same hour, over all days. The MBE describes the overall bias of a model and its value should be small. A percentage error between $\pm 10\%$ is considered acceptable [19]. In general, if this value is negative, the model underestimates compared to the observed values and percentage error. The RMSE is a good indicator of how accurate the model estimates the measured values [20]. The model performs best for the smallest possible values of RMSE. The latter are defined by the following expressions; $MBE = \frac{\sum_{i=1}^{N}(G_{(model)i} - G_{(meas)i})}{\sum_{i=1}^{N} G_{(meas)i}}$ and $RMSE = \frac{\sqrt{(1/N)\sum_{i=1}^{N}(G_{(model)i} - G_{(meas)i})^2}}{(1/N)\sum_{i=1}^{N} G_{(meas)i}}$, where $G_{(model)i}$ is the estimated value from a model, $G_{(meas)i}$ is the corresponding measured value and N is the number of values used in the series [18]. A greater positive RMSE means a huge deviation in the estimated value from the measured value and zero represents the ideal case.

4. Results and Discussion

The results of the measured and modelled global solar irradiance using Slob Algorithm (standard) model equation are shown in figures below

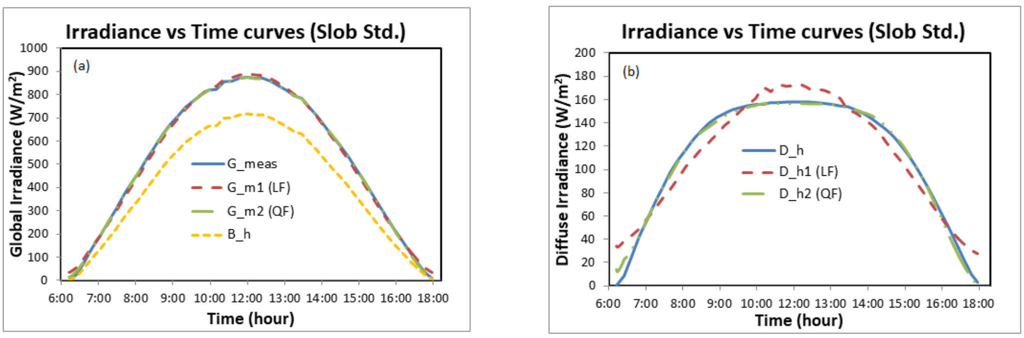

Figure 2. Represents results of Slob Algorithm standard model-measurements intercomparison. (a) global (G_{meas} (measured), G_{m1}(LF) (linear fit) and G_{m2}(QF) (Quadratic fit)) and direct (B_h), and (b) diffuse (D_h (model), D_{h1}(LF) (linear fit) and D_{h2}(QF) (Quadratic fit) irradiances with 18 September 2015 data.

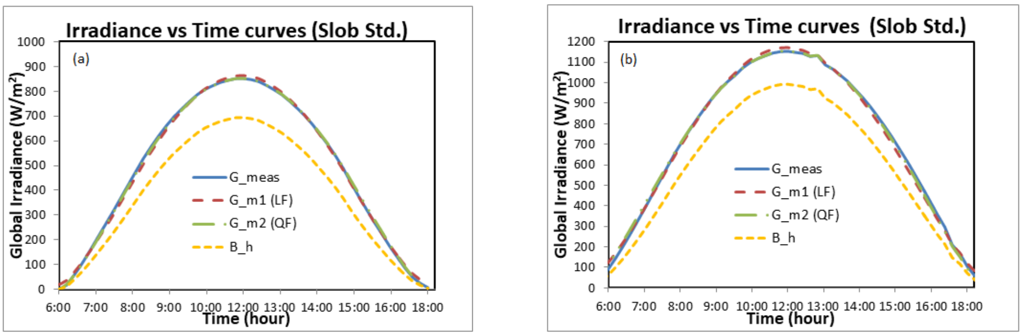

Figure 3. Represents results of Slob Algorithm standard model-measurements intercomparison of global (G_{meas} (measured), G_{m1}(LF) (linear fit) and G_{m2}(QF) (Quadratic fit)) and direct (B_h) irradiances with (a) 27 September and (b) 22 November 2015 data.

Figures 2 and 3 indicate that the total irradiance and modeled diffuse component are in agreement with the measurements performed at Randburg for clear sky conditions. While the measured and modeled daily global irradiance values have been equated through $G_h = B_h + D_h$, the corresponding values of global irradiance are not necessarily the same for each hour as illustrated in the figures. The quadratic fitting has improved the diffuse component as shown by D_{h2} and G_{m2} in figures 2 and 3. Hence, the quadratic relationship has caused the modeled global (G_{m2}) to be superimposed with the measured data. It is also found that diffuse fraction of the total irradiance is strongly correlated with the clearness index. This is consistent with the expectation that when the atmosphere is clearer, a smaller fraction of the radiation is scattered [21]. Using the standard model of Rayleigh optical thickness equation (2) resulted in higher values of T_{LK} compared to the values obtained using the adjusted model equation (3).

Table 1. The averaged performance evaluation by certain error parameters of the proposed Slob Algorithm standard model for each day considered.

n	G_{meas}(W/m^2)	G_{model}(W/m^2)	MBE(%)	RMSE(%)
261	531.1	532.6	0.007	2.35
270	500.1	500.1	-0.001	2.17
326	703.5	703.5	-0.0004	2.72

Table 2 shows the statistical performance of the model and the percentage values of MBE and RMSE are very low indicating a reasonably agreement between the modeled and measured data. The negative values of MBE indicate that the proposed model slightly underestimates the global irradiance. It was noted that there appear to be systematic discrepancies between the measured and computed values around sunrise and sunset. This may have resulted due to the model's intrinsic limitations, or of decreased measurement accuracy, which is expected when global solar irradiance is low. This analysis was done for the chosen days of the year to investigate seasonal variations in model error.

5. Conclusions

The diffuse irradiance versus the product of $\cos\theta_Z T_{LK}$ curves indicate that the quadratic relationship is the best fit for both diffuse and global solar irradiance results. The results of the model used here for the clear sky conditions over Randburg in Gauteng Province were found to be in par with the measurements. The proposed model can be considered as consistent and efficient tool to estimate solar irradiance spatially and temporally. Future studies will try to test some irradiance models for the clear sky conditions and some models for diffuse irradiance in order to calculate the solar irradiance components. T_{LK} calculation and verification, and δ_R parameterization are key issue for further improvements in modelling performance.

Acknowledgment
The authors gratefully thank Sinetech Solar Company for making available their diurnal measured global solar irradiance data.

References

[1] Gama A, et al, 2010, Determination of atmospheric turbidity using solar radiation measurements for two Algerian sites, 2nd International conference on Nuclear and Renewable Energy Resources, 4-7 July 2010, Ankara Turkey, *ResearchGate*, 1-6.

[2] Liu B Y H, et al, 1960, The interrelationship and characteristics distribution of direct, diffuse, and total solar radiation, *Solar Energy*, **4**, 1-19.

[3] Gueymard C A, 2001, Parameterized Transmittance model for Direct Beam and Circumsolar spectral irradiance, *Solar Energy*, **71**, 325-346.

[4] Hinssen Y B L, 2006, Comparison of different methods for the determination of sunshine duration, *Scientific Report*, **WR-2006**, 1-76.

[5] Gard H P, et al, 1993, Fundamentals and characteristics of solar radiation, *Renewable Energy*, **3**, 305-319.

[6] Linke F, 1922, Transmissions-Koeffizient und Trübungsfaktor, *Beitr. Phys. fr. Atmos.*, **10**, 91-103.

[7] Bason F, 2004, Diffuse solar irradiance and atmospheric turbidity, In Eurosun 2004 conference proceedings, Freiburg, Germany, June 2004, 1-7.

[8] Iqbal M, 1983, An introduction to solar radiation, New York, USA, Academic Press, 2nd Edition.

[9] Winkler H, 2012, Appropriate air mass and solar radiation attenuation parameterization for Southern Africa, Proceedings of the 2012 South African Instute of Physics annual conference, 9-13 July 2012, UP, (events.saip.org.za), 1-6.

[10] Kasten F, et al, 1989, Revised optical air mass tables and approximation formula, *Applied Optics*, **28**, 4735-4738.

[11] Kasten F, 1996, The Linke turbidity factor based on improved values of the Integral Rayleigh Optical thickness, *Solar Energy*, **56**, 239-244.

[12] NOAA, 2011, National Oceanic and Atmospheric Administration solar calculations spreadsheet, NOAA, *Silver Spring*, MD, USA, (ftp://ftp.srrb.noaa.gov/pub/data/surfrad/).

[13] Perez R, et al, 1987, A new simplified version of the Perez diffuse irradiance model for tilted surfaces, *Solar Energy*, **39**, 221-231.

[14] Tiwari G, et al, 2015, Study and analysis of solar radiation models, *Internal Journal of Current Engineering and Technology*, **5**, 3544-3559.

[15] Aras H, et al, 2006, Estimating the horizontal diffuse solar radiation over the Central Anatolia Region of Turkey, *Energy Conversion and Management*, **47**, 2240-2249.

[16] Boland J, et al, 2001, Modelling the diffuse fraction of global solar radiation on a horizontal surface, *Environmetrics*, **12**, 103-116.

[17] Cucumo M, et al, 2000, A calculation method for the estimation of the Linke turbidity factor, *Renewable Energy*, **19**, 249-258.

[18] Badescu V, 1997, Verification of some very simple clear and cloudy sky models to evaluate global solar irradiance, *Solar Energy*, **61**, 251-264.

[19] Khalil S A, 2013, A comparative study of total, direct and diffuse solar by using different models on horizontal and inclined surfaces for Cairo, Egypt, *Renewable and Sustainable Energy Reviews*, **27**, 853-863.

[20] Hoff T E, et al, 2013, Reporting of irradiance modeling relative prediction errors, *Progress in Photovoltaics: Research and Applications*, **21**, 1514-1519.

[21] Erbs D G, et al, 1992, Estimation of the diffuse radiation fraction for hourly, daily, and monthly-average global radiation, *Solar Energy*, **28**, 293-302.