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Decomposition Model for Estimating Diffuse Solar Radiation

M. Harhash[1,*], *W. Dawoud*[2], *A. H. Oraby*[2] *and M. M. Abdel Wahab*[1]

[1] Astronomy, Space Science and Meteorology Department, Faculty of Science, Cairo University, Giza, Egypt
[2] Physics Department, Faculty of Science, Mansoura University, Mansoura, Egypt

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Abstract: In this paper, a regressive model based on the sigmoid function is presented for estimating the diffuse component of surface solar irradiance from the global irradiance. We consider the correlations between global solar radiation and its diffuse component measured on horizontal incident. The regression equation was tested outside the measurement period (2016) with a root mean square error of about 0.1 and a relative mean bias error of $-14.6 \pm 0.8\%$. Results show that the sigmoid behaviour provides more reliable estimates for values of diffuse solar irradiance.

Keywords: Regression coefficient, decomposition model, solar radiation, clearness index, surface solar irradiance

1 Introduction

Solar energy in the form of radiation received at the earth's surface is essential to life. It provides the energy required in many natural processes from photosynthesis to atmospheric circulations [1]. On the other hand, energy resources are essential to improve human standard of living and ensure a high quality of life. Because of the cost of fossil fuels and their environmental and health impact, governments and non-governmental organizations are usually interested in fulfilling their energy demands via solar energy as a sustainable renewable energy source. Hence, solar radiation data are in demand by scientists, architects, and solar engineers to be used in climate research, energy-efficient building designs, and solar energy systems developments [2, 3].

The amount of solar radiation received on a horizontal plane at the ground per unit area is known as the global solar irradiance. It is divided into two components; direct and diffuse. In rural areas and developing countries, long-term records of direct and diffuse solar radiation data may be available only at few locations due to the cost of the equipment used for the measurements, their maintenance, and the calibration requirements. Therefore, several empirical methods that can measure global solar irradiance had been proposed in many locations and used for estimating both components [4, 5, 6]. These models are based on ordinary least square regressions fitted linearly or with a polynomial function with a given order [7, 8].

In the 60's of the last century, the Egyptian Meteorological Authority Radiation Network (EMA-RN) was established to provide solar irradiance data for monitoring and detecting important changes in the surface radiation balance. Currently, EMA-RN provides radiation data at almost 10 sites at high accuracy and high temporal frequency (minute to hourly). These few stations cannot offer a synoptic view of the solar radiation over Egypt. Consequently, for mapping the solar radiation, different methods arose to estimate the diffuse and direct components in Egypt [9]

The objective of the present study is to investigate the characteristic of the measured solar radiation in terms of correlation between the global and diffuse components. Based on this correlation, a new regressive model has been developed to predict the diffuse component from the measured global irradiance for Cairo.

2 Methodology

2.1 Database

The data used in this study is composed of global, direct, and diffuse solar irradiances measurements. The hourly

* Corresponding author e-mail: maha.harhash@cu.edu.eg

solar radiation data were measured by the Egyptian Meteorological Authority, EMA, from January 2004 to December 2010 at Cairo mega city, Egypt. The global irradiance, G, received on a horizontal plane was measured using pyranometers. Other pyranometers equipped with shading disks, in order to shield the direct component of solar irradiance, were used to record the diffuse irradiance, D, received on a horizontal plane. The direct beam of solar radiation, B_n, incident on a normal plane was measured using pyrheliometers . The measurements of EMA radiometric network are traceable to the world radiometric reference standards for solar data, where spare instruments are calibrated every five years in Davos, Switzerland, with an accuracy of about 3% to 4% [10]. However, during the measurement, systematic errors (instrumental errors) or random errors may occur due to operational issues (maintenance, reading) [11]. Therefore, it is very important to apply restricted procedures of quality control on each measurement before processing and providing the data. The solar irradiances measurements are subjected to quality check procedures to revoke any erroneous data; the conditions to pass are as follow:

$$G > max(0.03E,\ 1Wm^{-2}) \tag{1}$$

$$G < min(E,\ 1.2E_n,\ 1.5E\ \cos(\theta_z)^{0.2} + 100Wm^{-2},\ 1.2E\ \cos(\theta_z)^{0.2} + 50Wm^{-2}) \tag{2}$$

$$D > max(0.03E,\ 1Wm^{-2}) \tag{3}$$

$$D < min(0.8E_n,\ 0.95E\ \cos(\theta_z)^{0.2} + 50Wm^{-2},\ 0.75E\ \cos(\theta_z)^{0.2} + 30Wm^{-2}) \tag{4}$$

$$B_n > 1Wm^{-2} \tag{5}$$

$$B_n < min(E_n,\ 0.95E_n\ \cos(\theta_z)^{0.2} + 10Wm^{-2}) \tag{6}$$

$$0.92 \le (G\ /\ B_n \cos(\theta_z) + D) \le 1.08,\ \text{for}\ \theta_z < 75^o \tag{7}$$

$$0.85 \le (G\ /\ B_n \cos(\theta_z) + D) \le 1.15,\ \text{for}\ \theta_z > 75^o \tag{8}$$

where E and E_n denote hourly mean irradiance of the extraterrestrial solar radiation received horizontally at and normal to the top of the atmosphere, respectively, while θ_z is the solar zenith angle. The solar zenith angle is the complementary angle of the sun altitude angle above the horizon [12]. After passing the quality control, a statistical outliers analysis has been applied. For every hour in the same month over the entire period, the mean (μ) and standard deviation (σ) of the global and diffuse solar irradiance are calculated. The percentages of the statistical envelops of $\pm1\sigma$,$\pm2\sigma$, and $\pm3\sigma$ applied to the data shows that the surface solar irradiance follows a normal distribution as shown also in the annual diurnal cycle, Fig. 1. However, values within $\pm1\sigma$ from the mean are only considered for this study.

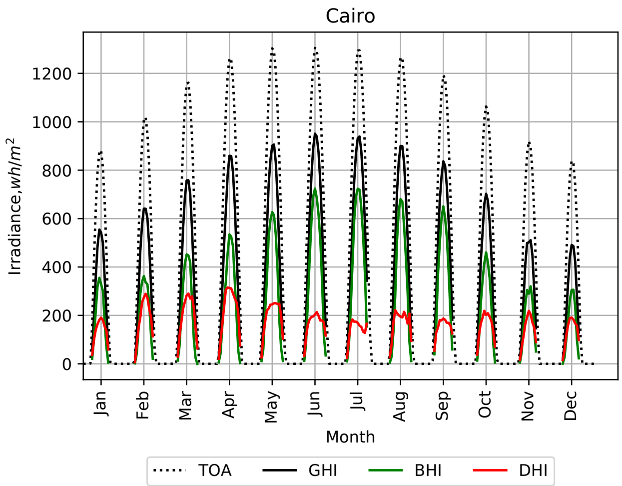

Fig. 1: Annual variation in diurnal cycle based on monthly averages of hourly surface solar irradiance components (global, direct, and diffuse) after quality control at Cairo in the time period 2004 – 2010.

2.2 Solar radiation model

Using the hourly measurements of the radiation data, the ratio of hourly global irradiance on a horizontal surface (G) to the extraterrestrial irradiance on a horizontal surface (E) during the same hour, known as the clearness index ($K_T = G/E$), is calculated. Similarly, for each hour the ratio of hourly diffuse (D) to global (G) irradiance on a horizontal surface, known as the diffuse fraction ($K_d = D/G$), is calculated. The hourly extraterrestrial solar radiation incident on a horizontal surface is calculated using the following equation [12]:

$$E = e_o\ I_{sc}\ (\sin\delta\ \sin\phi\ +\ \cos\delta\ \cos\phi\ \cos H) \tag{9}$$

where e_o is the eccentricity correction factor, I_{sc} is the solar constant ($1367Wm^{-2}$), δ is the solar declination angle, ϕ is the latitude angle, and H is the solar hour angle.

A logistic regression using the fitting method of Newton-Conjugate gradient (ncg) has been applied for the sigmoid function:

$$y = \frac{1}{1 + \exp[-(y_0 + m(x - x_0))]} \tag{10}$$

where x_0 is the mid point of the sigmoid curve on the x-axis, while m and y_0 represent the slop and the intercept of the straight line representing the logistic function:

$$logit(y) = ln(y/1 - y) = y_0 + mx \tag{11}$$

where the slope controls its sharpness, while the sign of y_0 determines its shape (positive y_0 indicates s-shape curve, while negative represents a z-shape curve).

3 Results

Cairo is selected in this study as it is one of the mega cities. From the analysis of the solar radiation data for the period from 2004 to 2010, interrelationship is obtained to express the diffuse fraction of the global solar irradiance in terms of the clearness index. The scatter plot of the diffuse fraction versus the clearness index shown in Fig. 2 has been obtained using high-quality assured solar irradiance data. A total number of 5,284 (about 23% of the available data) passes the quality control procedures of Equations (1) - (8), as listed in Table 1. As noted from these table, the high number of gaps in the measured direct component B_n affects the number that passed the consistency check (Equations (7) and (8)). The obtained values of the regression parameters of Equation (10) after applying the quality control and then considering the statistical envelop of $(\pm 1\sigma)$ from the mean are respectively as following:

$$K_d = \frac{1}{1+\exp(7.77K_T - 4.36)} \quad (12)$$

$$K_d = \frac{1}{1+\exp(7.01K_T - 3.83)} \quad (13)$$

Using a recent data for the same location, the new model's performance has been tested, in addition to the coefficient of determination R^2, by means of the following statistical indices:

–the root mean square error $RMSE = \sqrt{\frac{1}{n}\sum(\hat{x}-x)^2}$

–the mean bias error $MBE = \frac{1}{n}\sum(\hat{x}-x)$

Table 1: Data summary of the surface solar irradiance components (global, diffuse, and direct) at Cairo. Including are the number of total samples and the number of valid data after quality control, percentages are given in brackets.

	G	D	B_n
total	30669	30669	30669
gaps [1]	7446 (24.28%)	8586 (28%)	17366 (56.62%)
available	23223	22083	13303
QC_{ssi} [2]	21609 (93.05%)	20374 (92.26%)	11034 (82.94%)
QC [2]	5284 (22.75%)	5284 (23.93%)	5284 (39.72%)
$\mu \pm 1\sigma$ [3]	3827 (72.43%)	3560 (67.37%)	3470 (65.67%)
$\mu \pm 2\sigma$ [3]	5033 (95.25%)	5089 (96.31%)	5121 (96.92%)
$\mu \pm 3\sigma$ [3]	5232 (99.02%)	5262 (99.58%)	5264 (99.62%)

[1] Relative to the total number of measurements.
[2] Relative to the number of available points.
[3] Relative to the number of points that passed the QC.

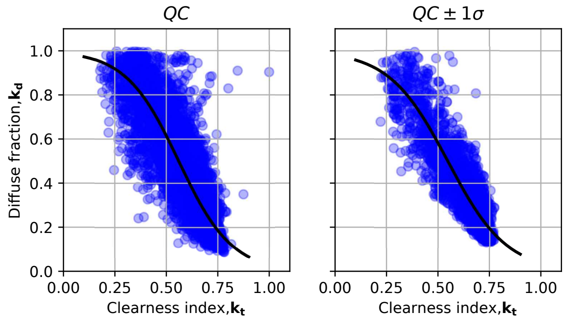

Fig. 2: Scatter plot of diffuse fraction vs. clearness index and fitting curve (solid line) using a sigmoid function in the time interval 2004 – 2010 for Cairo station after applying the quality control procedures to the raw data (left), and then $\mu \pm 1\sigma$ envelop (right).

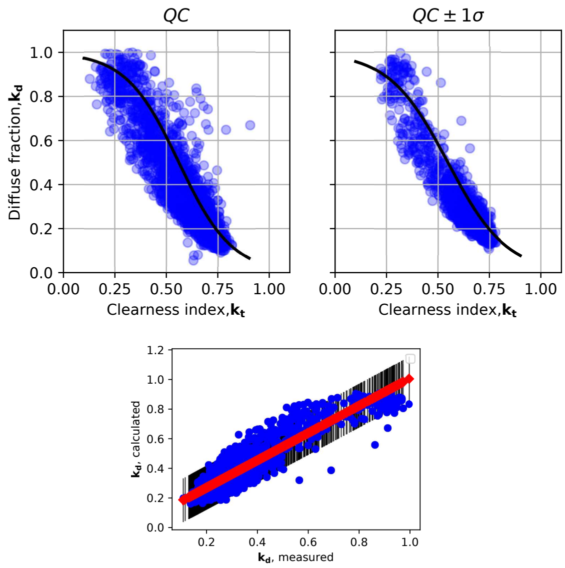

Fig. 3: Scatter plot of diffuse fraction vs. clearness index and fitting curve (solid line) using a sigmoid function for Cairo station in 2016 after applying the quality control procedures to the raw data (upper left), and then considering the statistical envelop of $(\mu \pm 1\sigma)$ (upper right). Down left and right is the validation of the estimated K_d in each case.

–the relative mean bias error $rMBE = \frac{1}{n}\sum(\frac{\hat{x}-x}{x})100\%$

where $\hat{x}$ is the calculated value (model output), x is the measured value, and n is the total number of measurements.

The upper part of Fig. 3 shows a scatter plot of the diffuse fraction versus the clearness index for Cairo location from solar radiation data recorded in 2016. A total number of 2291 points passed the quality control procedures, 1267 existed in the statistical envelop of

Table 2: Comparison of the estimated diffuse fraction to the measurements at Cairo for solar radiation data of 2016.

	QC	*QC* and $\mu \pm 1\sigma$
total no.	2291	1267
R^2	0.81	0.85
RMSE	0.13	0.097
MBE	-0.065	-0.06
rMBE %	-13.69	-15.44

($\mu \pm 1\sigma$). The accuracy of the estimated diffuse fraction from the proposed model, Equations (12) and (13), is shown in Fig. 3 in the lower part. As shown in Table 2, the negative *MBE* shows underestimated values with 13.69% and 15.44% associated with coefficients of determination ranging 81% and 85% respectively; depending on the outliers after quality control. The *RMSE*, which is a measure of the accuracy of estimate, have been found to be about 0.1.

4 Perspective

The availability of surface solar irradiance and the diffuse fraction of solar radiation are necessary to assess the performance of solar energy systems and to the air quality. Therefore, estimates of data failing the quality test criteria or even initially lacking is highly desired. Generally, any of the three components of the solar irradiance can be directly calculated from the relation $G = D + B_n \cos\theta_z$ whenever two components are measured and passed the quality control procedures. When only one irradiance component is measured, some empirical models exist to estimate the missing component and then use that relation to derive the third component.

In this study, a new regressive model is proposed for estimating the hourly diffuse solar irradiance when only the global irradiance is measured. The model relies on the existence of logistic correlation (based on a sigmoid function) between the diffuse fraction and the clearness index. The model's performance had been evaluated using a recent data set (2016) taken from out of the measuring period (2004–2010) for the same location. Results show that the new proposed model provides better estimates in terms of root mean square and mean bias errors (relative *MBE*), 0.12 and -0.065 (-13.69%) respectively.

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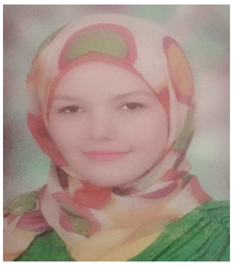
M. Harhash received the MSc degree in Meteorology at Cairo University, Egypt. Her research interests are in the areas of atmospheric science including mathematical physics, remote sensing, and numerical models for weather and climate research. She has participated in published research articles in reputed international journals of energy and atmospheric sciences.



W. Dawoud received the BSc degree in physics at Mansoura university, Egypt. Her research interests are in the areas of mathematical physics and theoretical physics.

A. H. Oraby, graduated 1971, obtained his MSc degree 1976 and Phd 1983 in electronics from Osaka University, Japan. He was appointed to the position of professor in experimental physics in 1997. he founded a scientific school in experimental physics at Mansoura University where 30 students obtained their master degrees and 20 students have had their doctorate degrees. He has more than 48 worldwide research publications included in Scopus website with more than 376 citations and h-index 12.

M. M. Abdel Wahab has over 35 years of experience in the field of meteorology and atmospheric science. He is specialized in weather modelling, climate change and air pollution. He is currently teaching and consulting in these fields. He has been a Principle Investigator and co-Director of many scientific projects including the establishing of an Earth Observation satellite data receiving station at Cairo University (funded by NATO Science for Peace program). He was leading some international projects with co-partners from Italy, France, Switzerland, USA (NCAR) and Purdue University. Recently Dr. Wahab has been engaged with ionospheric physics simulations and space weather problems. He is a member in Third National Communication Report Team. He is the responsible for the Adaptation Strategy INDCs.