***Original Research Article***

# Determining Global Solar Radiation Incident on Tilted Surfaces with Different Tilt Angles at the Department Of Physics Makerere University

**KEY WORDS; 1) GLOBAL SOLAR RADIATION; 2) TILTED SURFACES; 3) DIFFERENT TILT ANGLES**


## ABSTRACT

Solar radiation data at horizontal level, tilted surfaces and in the atmosphere is an important feature in solar energy applications such as photovoltaic systems for electricity generation, solar collectors for heating and passive solar devices. This study presents an investigation of the dependence of global solar radiation incident on a tilted surface on some meteorological parameters for different tilt angles based on measured meteorological data of sunshine hours, relative humidity and temperature at Makerere University. **Empirical models** relating global solar radiation on tilted surfaces and meteorological data were formulated using data of six months. The empirical model for the estimation of daily global solar radiation on the tilted surfaces of $15^0$, $22.5^0$ and $30^0$, whose assessment is based on the statistical analysis with the Mean Bias and Root Mean Square difference that is in good agreement with the measured data on a tilted surface is $\frac{H_t}{H_{o\beta}} = -0.2614 - 0.2386(RH) + 1.5822\left(\frac{T_{\max}}{65}\right) + 0.1065\left(\frac{T_{\max}}{T_{\min}}\right)$

The model yielded a RMSE of 4.2654, with a low correlation coefficient of 0.3743 at a 95% confidence interval and MBE of 1.5801. Analysis of data for global solar radiation data attained over a period of 3 years, towards the verification of Akoba's model [15] at a tilt angle of $22.5^0$ recommends a new model $\frac{H_t}{H_{o\beta}} = -0.9227 - 0.1405\left(\frac{n}{N}\right) - 0.0335(RH) + 3.2826\left(\frac{T_{\max}}{65}\right)$ that capitulated a RMSE of 2.5985, with a correlation coefficient of 0.8863 at a 95% confidence interval and MBE of 2.3391.


## 1. INTRODUCTION

### 1.1 Background of the Study

Uganda is endowed with many forms of energy sources that include large hydro, small hydro, geothermal, biogas, biomass, biomass-based cogeneration, wind, solar and more recently, petroleum, which is being explored in the Rift Valley region. However, sustainable use of these resources has been declining due to a number of factors. First are the numerous civil wars, which not only affected the country's economic growth but also other development sectors like energy. The wars in the country affected the policy framework and implementation arms of government. National Association of Professional Environmentalists [1], noted that, each of the energy sub-sectors was seriously affected by the economic decline of the 1970s and early 1980s characterized by deforestation, inadequate maintenance, low investment, distorted pricing mechanisms and environmentally unsustainable policies and laws. The country is still experiencing the shock and the distortions that took place in the energy sector. The first reason has inter-alia led to a second reason of dependency on biomass energy.

Secondly, unsustainable utilization and dependency on biomass energy sources has led to many environmental problems and to scares of desertification. This energy consumption pattern is a major threat to the country's economic development. Ministry of Energy and Mineral Development [MEMD] [2], noted that over 90% of the national energy demand is met from wood fuel. Today the country is facing serious denudation and degradation of its forests and woodlands, which is leading to severe environmental consequences. According to FAO estimates (*ibid*) Uganda is losing 50.000 ha (0.8%) of its forestland per year through deforestation, most of which occurs in woodlands outside the protected areas.

According to MEMD [2], Uganda is a resource rich country and has a very high potential of renewable energy resources as earlier noted. Some of these renewable energy resources have never been developed while others are not fully developed. Developing and harnessing of the country's renewable energy potential is required if the country's energy needs are to be met.

Kamese [3] cites that according to [2], Uganda's per capita energy consumption of 0.3 toe (12.72 GJ) is among the lowest in the world. Few people have access to modern energy supplies such as electricity and petroleum products. The energy consumption rate stands at about 5 million toes per year of which approximately 93% is biomass (wood, charcoal and agricultural residue). The access to grid electricity stands at 6% for the whole country and about 1% for the rural areas. Uganda's energy consumption is low compared to countries in Europe and America, which have an average of 5.0 tonnes per annum. In terms of per capita of total energy. Uganda's average consumption in 1994 was 25 kg compared to 34 kg for Tanzania, and 110 kg for Kenya, while South Africa had 2,146 kg per head. In 1995, the domestic energy consumption was estimated at 12 million tonnes (about 1 toe), and demand was projected to increase by 65% by the year 2000. The majority of the communities both urban and rural largely depend on fuel wood and charcoal for their energy. MEMD [4] categorizes that about 72% of the total grid-supplied electricity is consumed by only 12% of the domestic population concentrated in Kampala, and nearby cosmopolitan towns. Domestic electricity consumption can be categorized as follows, residences (55%), industries (20%), commercial end-users (24%) and street lighting (1%).

Uganda has considerable renewable energy resources for energy production and the provision of energy services, yet they remain unexploited, largely due to the perceived technical and financial risks. These resources include: biomass, geothermal, large scale hydro, mini/micro/pico hydro, wind and solar energy. However, with the exception of biomass, whose contribution is very significant, the remaining renewable sources (including large hydros), contribute only about 5% of the country's total energy consumption. This limits the scope and productivity of economic activities that can be undertaken in any part of the country. Thus it is imperative that the use of these abundant resources should be enhanced [4]. Existing solar data clearly show that the solar energy resource in Uganda is high throughout the year. The mean solar radiation is 5.1 $KWh/m^2$ per day, on a horizontal surface. This level of insolation is quite favorable, for the application of a number of solar technologies. These include; solar water heating; and solar photovoltaic systems for supply of basic electricity in rural institutions and households as well as areas not connected to the grid.

Knowledge of global solar radiation is essential in the prediction, study and design of economically viable systems which use solar energy. Information on global solar radiation received at any site (preferably gained over a long period) should be useful not only to the locality where the radiation data is collected but also for the wider world community. A global study of the world distribution of global solar radiation requires knowledge of the radiation data in various countries and for the purpose of worldwide marketing, the designers and manufacturers of solar equipment will need to know the average global solar radiation available in different and specific regions.

Measured data is the best form of this knowledge. Unfortunately, there are very few meteorological stations that measure global solar radiation, especially in developing countries like Uganda. In places where no measured values are available, common practice has been to determine this parameter by appropriate correlations which are empirically established using the measured data. Several empirical models have been used to calculate solar radiation, utilizing available meteorological, geographical and climatological parameters such as sunshine hours [5], [6], [7] air temperature, latitude, precipitation, relative humidity and cloudiness, [8]. The most commonly used parameter for estimating global solar radiation is sunshine duration. For proper, economical, and efficient development and utilization of solar energy, knowledge of the availability and variability of solar radiation intensity both in time and spatial domain is very crucial. Unfortunately, for many developing countries, solar radiation measurements are not easily available because the measurement equipments and techniques involved are not easily acquired. Measurements of solar radiation in Uganda are quite scanty today. Solar collectors are not mounted horizontally, as a case of solar water heaters. The collector requires an incline to the horizontal to cater for the convection heat transference in the fluid. On the other hand, it is convenient to have solar photovoltaic panels mounted along the roof of the house so that they too assume the slope of the roof (flash roof), or in the open with a certain angle of tilt. This slope allows the panel to keep clean and free of foreign bodies. Stationary solar systems (both flat plate collectors and PV) have to be tilted towards the sun to maximize the amount of solar radiation incident on the collector surface [9]. This presents a challenge to engineers engaged in installation of thermal collectors. They rely on available data on horizontal surfaces. To enhance the viability of this power technology in Uganda, up to date information on solar radiation on tilted surfaces is required.

In Uganda, Otiti [10] has made an attempt to calculate the global solar radiation on tilted surfaces, using the method given by Liu and Jordan [11], for Entebbe (Latitude $00^0$ 03' N, Elevation 1147m) and Gulu (Latitude 02° 45' N, Elevation 1107m). His calculated values for the two sites have not been validated by comparing the estimated values with actual measured values. Measurements of solar radiation have been carried out by Otiti [10],Luwalira [12] and Mubiru [13] in separate studies for a few locations. The locations include; Makerere (Latitude $00^0$ 19' N, altitude = 1220m), Mbarara (Latitude = 00° 36' 48 S, altitude = 1402m), Lira (Latitude = 00° 14' 56 S, altitude = 2490m), Tororo (Latitude = 02° 41' 06 N, altitude = 1483m) , Kabale (Latitude = 01° 15' S, altitude = 1867 m), Gulu (Latitude 02° 45' N, altitude 1107m), Soroti (Latitude = 01° 43' N, altitude = 1127m) and Entebbe (Latitude $00^0$ 03' N, Elevation 1147m). These measurements were done on horizontal surfaces. Using an empirical model, validated by experimental data of global solar radiation, Mubiru et al [14] have arrived at global solar radiation map for Uganda. Akoba [15] has investigated an empirical model for global solar radiation on a tilted surface which has been validated using measured solar radiation at a single tilt angle and at one location. She suggested that measurements at several titled angles were needed to obtain the optimal tilt for different months and stations.

In this study, the amount of solar energy incident on tilted surfaces for different tilt angles was measured at Makerere University using Kipp and Zonen CM6B pyranometers. The readings were processed and correlated with values predicted from models based on horizontal surface meteorological data. It is expected that the results are to be useful in the prediction of solar radiation on tilted surfaces facing the equator and those with arbitrary orientation for a number of locations in Uganda.

### 1.2 Statement of the Problem

Solar radiation data is a fundamental input for solar energy applications such as photovoltaic, solar–thermal systems and passive solar design. The data should be reliable and readily available for design, optimization and performance evaluation of solar technologies for any particular location. Unfortunately, for many developing countries like Uganda, solar radiation measurements are not easily available because of not being able to afford the measuring equipments and techniques involved yet designers of solar energy devices and field technicians need information on solar radiation incident on such collectors at given localities, for sizing and installation purposes respectively. Therefore, it is necessary to develop methods to estimate the solar radiation on the basis of the more readily available meteorological data. Many models have been developed to estimate the amount of global solar radiation on horizontal surfaces using various climatic parameters, such as sunshine duration, cloud cover, humidity, maximum and minimum ambient temperatures, wind speed, etc. Currently to the best of our knowledge little work has been done namely by Otiti [10] and Akoba [15] towards the measurement and prediction of the global, diffuse and beam radiation incident on tilted surfaces in Uganda. Solar data exists but only for horizontal surfaces. There is need for more data of solar radiation on a tilted surface, since most solar collector installations require tilted surfaces, and for establishing the amount of global solar radiation incident on a tilted surface at various locations in Uganda with similar climatological conditions by carrying out measurements on tilted surfaces for different tilt angles and correlating them with data generated by empirical models.

### 1.3 General Objective

The general objective of the study was to determine the global solar radiation incident on tilted surfaces in Uganda.

### 1.4 Specific Objectives

i) To measure the global solar radiation on a tilted surface at Makerere University for different tilt angles.

ii) To investigate the correlation between the tilted surface radiation and sunshine hours, temperature and relative humidity for different tilt angles.

iii) To develop an empirical model for predicting global solar radiation on tilted surfaces and to validate the model using the experimental data of global solar radiation on tilted surfaces.

### 1.4 Scope of the Study

The study was conducted at the Department of Physics Makerere University because there is an observatory site at the department and the location is characteristic of regions around Lake Victoria. In the vicinity of the Department of Physics there is a meteorological station in the Department of Geography, Makerere University where meteorological data is currently being measured. The study involved measurements of global solar radiation on tilted surfaces for three angles of tilt, global solar radiation on horizontal surface, sunshine hours, maximum and minimum temperature and relative humidity.

### 1.6 Justification

i) The sun is an inexhaustible source of energy. Quantitative assessment of solar radiation incident on a tilt plane is very important to engineers designing solar energy collecting devices, to architects designing buildings, and to agronomists studying insolation on vegetation on mountain slopes.

ii) Solar radiation reaching the earth's surface varies significantly with location, atmospheric conditions including cloud cover, aerosol content, and ozone layer condition, and time of day, earth/sun distance, solar rotation and activity. Since the solar spectra depend on so many variables, standard spectra are to be developed to provide a basis for theoretical evaluation of the effects of solar radiation and as a basis for simulator design.

iii) The amount of solar radiation received by a given surface is controlled, at the global scale, by the geometry of the earth, atmospheric transmittance, and the relative location of the sun. At the local scale, radiation is additionally controlled by surface slope, characteristics and elevation. Estimation of clear sky solar radiation for sloped surfaces is important in remote sensing applications involving energy balance and extraterrestrial estimation, which need an estimation of total energy striking a given surface.

## 2. MATERIAL AND METHODS

### 2.1 Study Area

Solar radiation measurements were carried out at the Kampala station at the Department of Physics, Makerere University, located at latitude 00° 19’ N, longitude 32° 40’ E and altitude 1220 m above sea level. The data of temperature and relative humidity was obtained from the meteorological section of the Department of Geography, Makerere University.

## 2.2 Data Structure

Primary data included global solar radiation on tilted surfaces and global solar radiation on a horizontal surface. These were measured using Kipp and Zonen CM6B pyranometers. Data was gathered for a period of six months (Dec - 2012 to May - 2013). Secondary data of sunshine duration, relative humidity, maximum and minimum temperature was obtained from already installed instruments. The sunshine duration is being measured at the Department of Physics by using a CSDI sunshine duration sensor. Relative humidity is being measured at the Meteorological section using two thermometers (dry and wet bulb thermometers). Secondary data for a period of six months (Dec – 2012 to May – 2013) was considered. This secondary data was useful in the development of the required model. All the above instruments recorded data on an hourly basis. The data was summed up to obtain average data.

## 2.3 Data Collection

### *2.3.1 Measurement of Global Solar Radiation*

*2.3.1.1. Pyranometer*

A pyranometer is an instrument for measurement of global (beam + diffuse) irradiance arriving from the whole hemisphere. This hemisphere is usually the complete sky dome. A pyranometer can be used in a tilted position as well, in which case it will also receive the ground-reflected radiation, [16] and [17].

*2.3.1.2 Radiation Sensors*

An instrument that measures radiant energy is generally called a radiometer. The heart of a radiometer is its sensor, also called a detector. The functioning of a radiometer depends on the method of radiation detection used. Unlike pyrheliometer detectors, the sensing elements of pyranometers are based on the thermoelectric, thermo mechanical or the photovoltaic principles and have flat surfaces compared to conical absorbers of some of the pyrheliometers.

*2.3.1.3 Kipp and Zonen Pyranometers*

Pyranometers are radiometers designed for measuring the irradiance on a plane surface, resulting from radiant fluxes in the wavelength range from 0.3 to 3.0μm, normally from solar radiation.

## 2.4 Measurement of Global Solar Radiation on a Titled Surface

The pyranometer was mounted securely on a stand in the open such that the plane containing the sensor was inclined at angles to the horizontal and facing southwards towards the equator. From the mounting stand to the ground is a height of 6.85m. The pyranometer were connected to a Campbell CR10X Data logger. The chosen site was ideal for the measurement of solar radiation since there was no shading by nearby buildings or structures on the radiometer. The daily global radiation incident a tilted surface was recorded and stored by the Data logger.

## 2.5 Measurement of Global Solar Radiation on a Horizontal Surface

Another pyranometer (Kipp and Zonen CM 6B) was placed horizontally in the open. This has a sensitivity of $16.56 \times 10^{-6}$ V/Wm$^2$. The daily global solar radiation incident on a horizontal surface was recorded and stored in a Campbell CR10X Data logger.

## 2.6 Parameters Used in the Estimation and Analysis of Global Solar Radiation

To be able to formulate an appropriate empirical model for solar radiation on tilted surfaces, extraterrestrial parameters were required. These parameters included: Sun's Sunset or sunrise hour angle, Daily extraterrestrial solar radiation on a tilted day length surface and Noon solar height. The parameters were calculated using an expression adapted from Iqbal [17] and Duffie and Beckman [16]. A computer program was written in MATLAB which enabled the computation of the parameters for the different days. To use the computer program, initial entries such as Julian's day number, solar constant, latitude and tilt angle are required. Eqn (1) was used to compute the sun's declination.

$$\delta = \begin{Bmatrix} 0.006918 - 0.399912\cos d + 0.07025\sin d \\ -0.006758\cos 2d + 0.000907\sin 2d \\ -0.002697\cos 3d + 0.00148\sin 3d \end{Bmatrix} \left(\frac{180}{\pi}\right). \quad (1)$$

This equation was used because it estimates δ with a maximum error of 0.0006 rad. The hour angle was computed from

$\omega_s = \cos^{-1}\left(-\tan(\phi)\tan(\delta)\right)$ and the daily extraterrestrial solar radiation on a tilted surface was computed using eqn (2)

$$I_{o\beta} = \frac{12x3600}{\pi} G_{sc}\left[1 + 0.033\cos\left(\frac{360 d_n}{365}\right)\right]\left[\cos(\phi - \beta)\cos\delta\sin\omega_1 + \frac{2\pi\omega_1}{360}\sin(\phi - \beta)\sin\delta\right] \quad (2)$$

at the characteristic declination. The characteristic extraterrestrial solar radiation on a tilted surface was computed using eqn (3)

$$H_{o\beta} = \frac{24x3600 G_{sc}}{\pi}\left[1 + 0.033\cos\left(\frac{360 d_n}{365}\right)\right]\left[\cos(\phi - \beta)\cos\delta\sin\omega_s + \frac{2\pi\omega_s}{360}\sin(\phi - \beta)\sin\delta\right] \quad (3)$$

The monthly average daily extraterrestrial solar radiation was also calculated from the same equation of the characteristic extraterrestrial solar radiation on a tilted surface and was found to agree with the characteristic one. The day length is given by Eqn.(4) by Duffie and Beckman [16].

$$N = \frac{2}{15}\omega_s \quad (4)$$

The mean sine of solar height $(\sin(h))$ is calculated using eqn (5) by Diez – Mediavilla et al [18].

$$\sin(h) = \frac{\left\{\sin\phi\sin\delta + \frac{24}{\pi}\cos\phi\cos\delta\left(1 - \left(\frac{\tan\phi\tan\delta}{\cos\phi\cos\delta}\right)\right)^2\right\}}{N} \quad (5)$$

where $\phi$ and $\delta$ are the latitude and solar declination, respectively.

## 2.7 Collection of Meteorological Data

### *2.7.1 Measurement of Sunshine Hours*

WMO [19] defined sunshine duration as the period during which direct solar irradiance exceeds a threshold value of 120 $Wm^{-2}$. This value is equivalent to the level of solar irradiance shortly after sunrise or shortly before sunset in cloud-free conditions. It was determined by comparing the sunshine duration recorded using a Campbell-Stokes sunshine recorder (CSDI) with the actual direct solar irradiance.

## 2.8 Measurement of Temperature

Daily minimum and maximum temperature data for a period of six months was collected from the meteorological section in the Department of Geography, Makerere University. Six's thermometers were used to measure temperature in this Department. In order to measure the temperature of air near the earth's surface, the thermometer was placed in air and the temperature was read off.

### 2.9 Measurement of Relative Humidity

Relative humidity is a measure of the amount of water vapor present in an air sample, compared to its value if the air were saturated with water constitute. By monitoring water constitute amount in the atmosphere, the climate of a given location may be classified as arid (dry) or humid (moist). Without this water constitute, clouds are not possible. World Meteorological Organization [20] defines relative humidity of an air-water mixture as the ratio of the partial pressure of water vapor in the mixture to the saturated vapor pressure of water at a prescribed temperature. Relative humidity is normally expressed as a percentage and is given by Eqn. (6)

$$RH = \frac{p(H_2O)}{p^*(H_2O)} x100\% . \qquad (6)$$

### 3.10 Data Analysis

The data collected was compiled using Microsoft Excel and then imported to MATLAB, using a script, for analysis. The collected data was subjected to least squares regression analysis to obtain the empirical dependence of global solar radiation on the meteorological factors. The models formulated were validated by statistical tests. Different methods were used to evaluate the performance of the models. Comparison tests performed were; the Maximum Absolute Error (MAE), the Mean Bias Error (MBE) and the Root Mean Square Error (RMSE). The correlation coefficient (r) between the measured and estimated values was also computed. The MBE is defined by $MBE = \frac{\sum_{i=1}^{N}(y_i - x_i)}{N}$ (7)

where i is an index, $y_i = i^{th}$ estimated value, $x_i = i^{th}$ measured value and N the number of observations. A positive MBE signifies an overestimation and a negative MBE stands for an under estimation. A low MBE is desirable. The RMSE is defined by

$$RMSE = \left( \frac{\sum_{i=1}^{N}(y_i - x_i)}{N} \right)^{1/2} \qquad (8)$$

The smaller the RMSE is, the better the performance of the model. The correlation coefficient, r, between the estimated and measured radiation values is defined by

$$r = \frac{\sum_{i=1}^{N}(y_i - \bar{y})(x_i - \bar{x})}{\sqrt{\left[\sum_{i=1}^{N}(y_i - \bar{y})^2\right]\left[\sum_{i=1}^{N}(x_i - \bar{x})^2\right]}} \qquad (9)$$

where, $\bar{y}$ is the estimated mean value and $\bar{x}$ is the measured mean value of the global solar radiation. The definitions in Eqns. (7), (8), and (9) were adapted from Iqbal [17]. In the modeling formulation the ratio of global solar radiation to extraterrestrial radiation $\frac{H}{H_{o\beta}}$ was expressed as a function of the meteorological parameters such as; clearness index $\frac{n}{N}$, relative humidity (RH), relative temperatures; $\frac{T_{Max}}{65}$, $\frac{T_{Min}}{65}$, $\frac{T_{Mean}}{65}$, ratio of maximum temperature to minimum temperature $\frac{T_{Max}}{T_{Min}}$ and the difference between the maximum temperature and minimum temperature, $T_{Max} - T_{Min}$ where 65 is the maximum temperature the thermometer can measure. The parameters used for the model formulation were of; 1D ($1^{st}$ order and second order), 2D (double parameters) and 3D (three parameters). a, b, c and d are constants introduced that were to be determined. A sample rank sum test was performed to identify the best of the models formulated. The ranking method proposed by Mubiru et al [14] was used to rank the different models. In their method, the MBE and the RMSE were each divided by the average of the actual total solar radiation values and then summed up. The ranking process was based on the rank sum. A model with the smallest rank sum was ranked first. Data for a period of six months was collected. This data was filtered, as the study considered data of the months when the pyranometers were fully functional to obtain high quality data. Three quarters of the data was used in model formulation and the rest was used in model testing.

## 3. RESULTS AND DISCUSSION

### *3.1 Distribution of Global Solar radiation on a Horizontal and tilted surfaces*

The daily global solar radiation on a horizontal surface varied from a lowest 2.13$MJm^{-2}$ to a highest 23.70$MJm^{-2}$ that were observed on the 30th Jan 2013 and 26th Feb 2013 respectively. For a surface with a $30^0$ tilt, 1.85 $MJm^{-2}$ was the lowest and 24.29 $MJm^{-2}$ was the highest observed on $30^{th}$ Jan 2013 and $20^{th}$ Dec 2012 respectively, For the $22.5^0$ tilt angle, it is observed that the lowest daily global radiation was 1.97 $MJm^{-2}$ on $30^{th}$ Jan 2013 and the highest was 23.94 $MJm^{-2}$ on $20^{th}$ of Dec 2012. For the $15^0$ tilt angle the lowest daily global radiation was 1.97 $MJm^{-2}$ and the highest was 23.86 $MJm^{-2}$ observed on $30^{th}$ Jan 2013 and $26^{th}$ Feb 2013 respectively. The results showed generally that the lowest daily global solar radiation was received on $30^{th}$ Jan 2013 for both horizontal and tilted surfaces probably due to clouds. The highest for the $30^0$ and $22.5^0$ were observed on $20^{th}$ Dec 2012 while that of $15^0$ coincided with that received on the on the horizontal being the same day $26^{th}$ Feb 2013.

The ratio of daily global solar radiation on a tilted surface to the extraterrestrial solar radiation on a tilted surface $\left(\frac{H_t}{H_{o\beta}}\right)$ and that on a horizontal surface $\left(\frac{H}{H_o}\right)$ were plotted in figure.1. It is observed that more global solar radiation $(H_t)$ is received on tilted surface as the angles decreased; hence the horizontal surface $(H)$ received the highest global radiation $(H)$ as shown by the results. Thus $(H)$ was greater than $(H_t)$ for the tilt angles of $15^0$, $22.5^0$ and $30^0$ investigated. This is attributed to the fact that the location of the site is approximately at the equator so the low angles of tilt approximate near normal incidence. The solar radiation received will decrease with increasing angle of tilt.

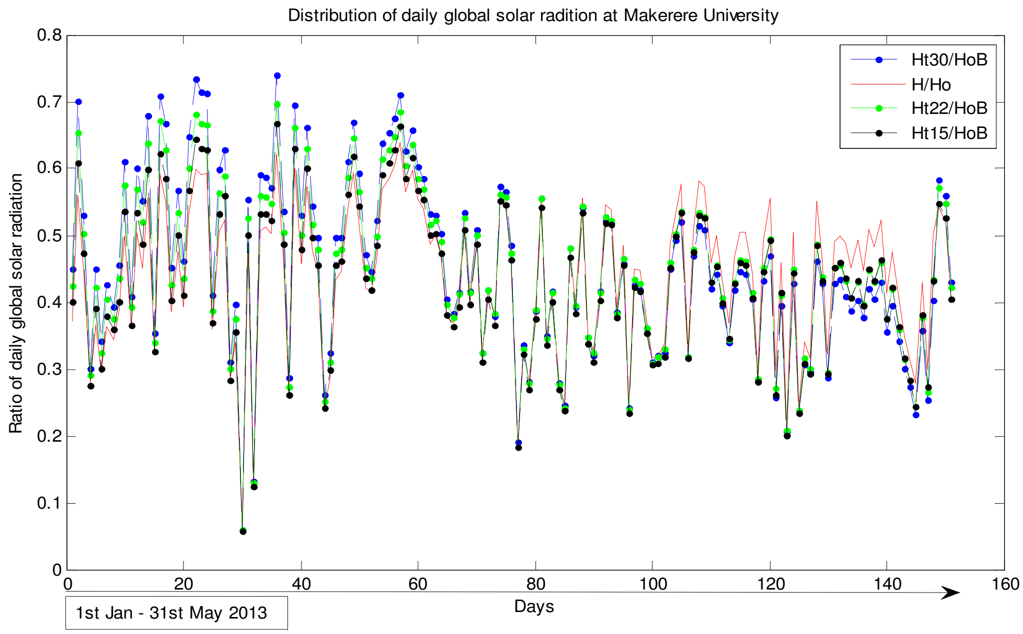



*Figure.1: Distribution of the ratio of global solar radiation to extra-terrestrial solar radiation on surfaces at Department of Physics, Makerere University.*

### 3.2 Distribution of Ambient Temperature

The maximum and minimum recorded temperatures measured by the meteorological section of the Department of Geography, Makerere University, during the six month are plotted in figure. 2. The maximum recorded temperature was $33.2^0$ on 30th of March 2013 in agreement with the earlier measurements by Akoba [15] where the maximum recorded temperature was observed on 27th of March. The lowest recorded temperature was $13.1^0$ on 21st of February 2013. Past temperature records Mubiru et al [14] show that, the month of March is characterized by essentially constant daily high temperatures, with daily high temperatures exceeding 26℃ throughout the month and this agrees with the results obtained in the study, implying that the atmosphere was clean and clear, resulting in drier weather.

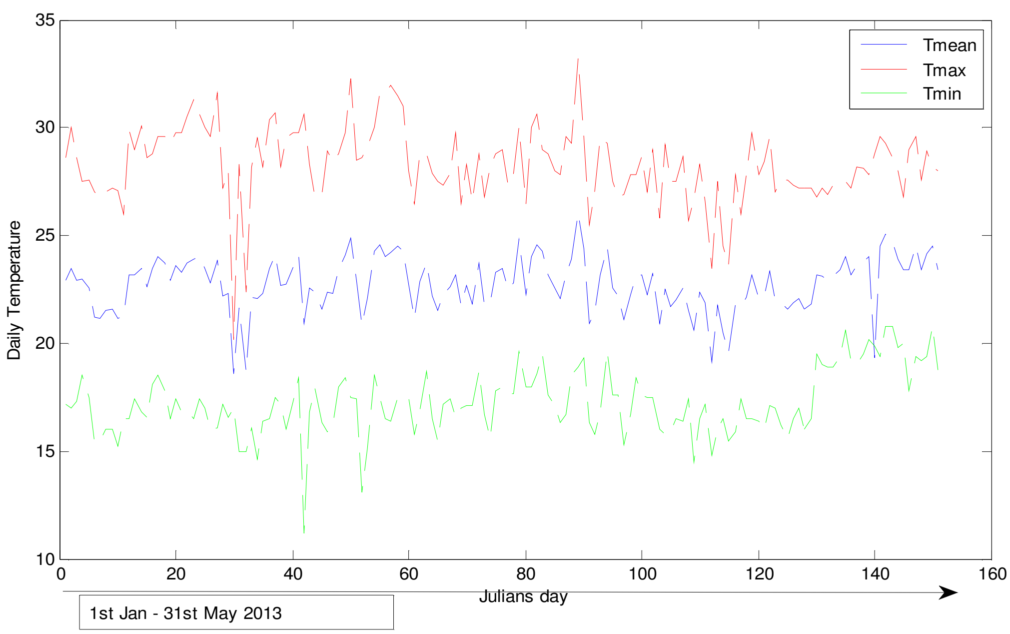


*Figure.2: Distribution of daily Temperature at the Department of geography, Makerere University.*

### 3.3 Distribution of Relative Humidity

Relative humidity (RH) was recorded at the meteorological section of the Department of Geography, Makerere University for the same period as that during which the maximum and minimum temperatures were recorded. This was recorded twice a day at 9:00 am and at 3:00 pm local time. The daily values of the relative humidity are plotted in figure.3. It is observed that the highest value of the daily relative humidity was recorded on 31st of January 2013 as 92%. The lowest was recorded twice on 21st January and 6th March of 2013. According to the past records Mubiru et al [14], the months of December and January are always known to be dry hot seasons with relatively low humidity conditions (66% January 2013) implying that there were a small number of water molecules in the atmosphere [21]. The discrepancy is attributed to weather changes as January was characterized with some rains during the month.

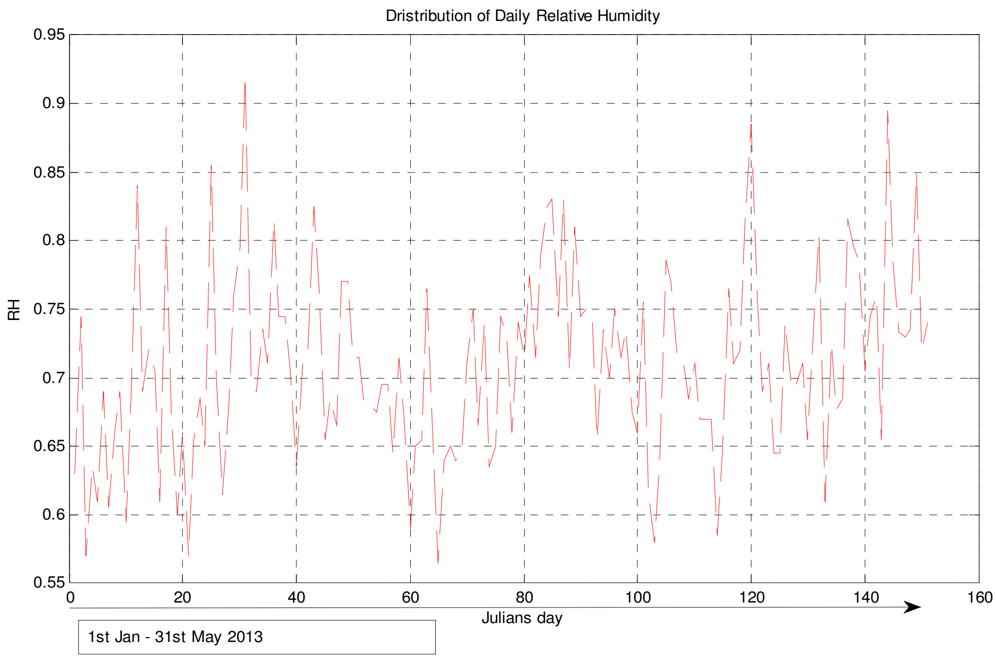



*Figure 3: Distribution of daily Relative Humidity at the Department of Geography Makerere University*

### 3.4 Variations of Global Solar Radiation on a Tilted Surface with Sunshine Hours, Temperature and Relative Humidity.

The scatter diagrams showing ratios of global solar radiation to the extraterrestrial solar radiation and selected climatological parameters such as sunshine hours (n), ratio of Maximum to minimum temperature $\left(\frac{T_{\max}}{T_{\min}}\right)$ and Relative humidity are shown in the figures 4, 5 and 6.

(a).

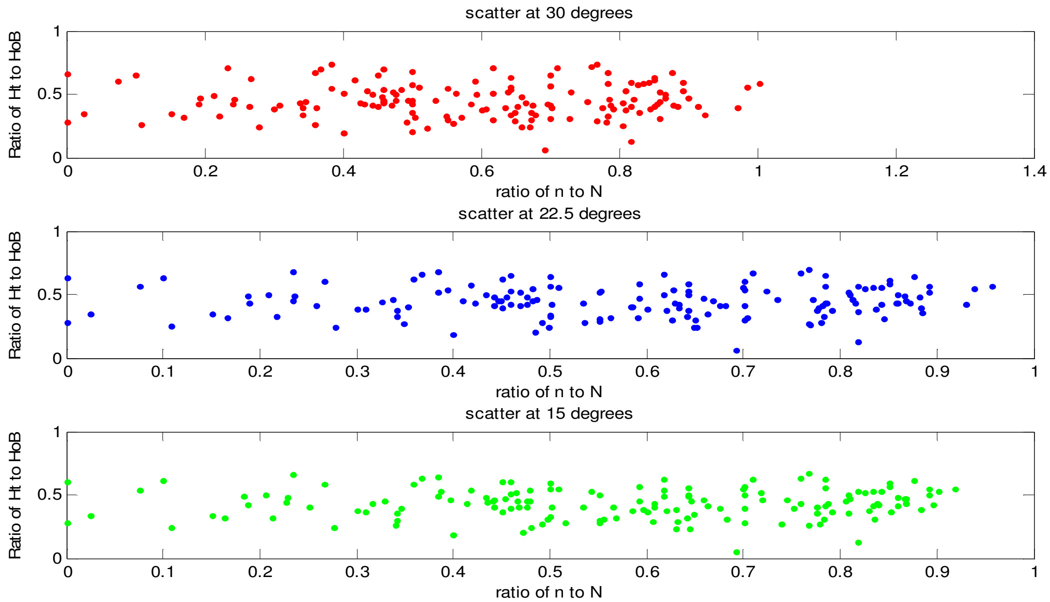



*Figure.4: Variation of the ratio of global solar radiation to extraterrestrial solar radiation on a tilted surface with the ratio of the Daily sun shine hours to the day length for the three tilt angles*

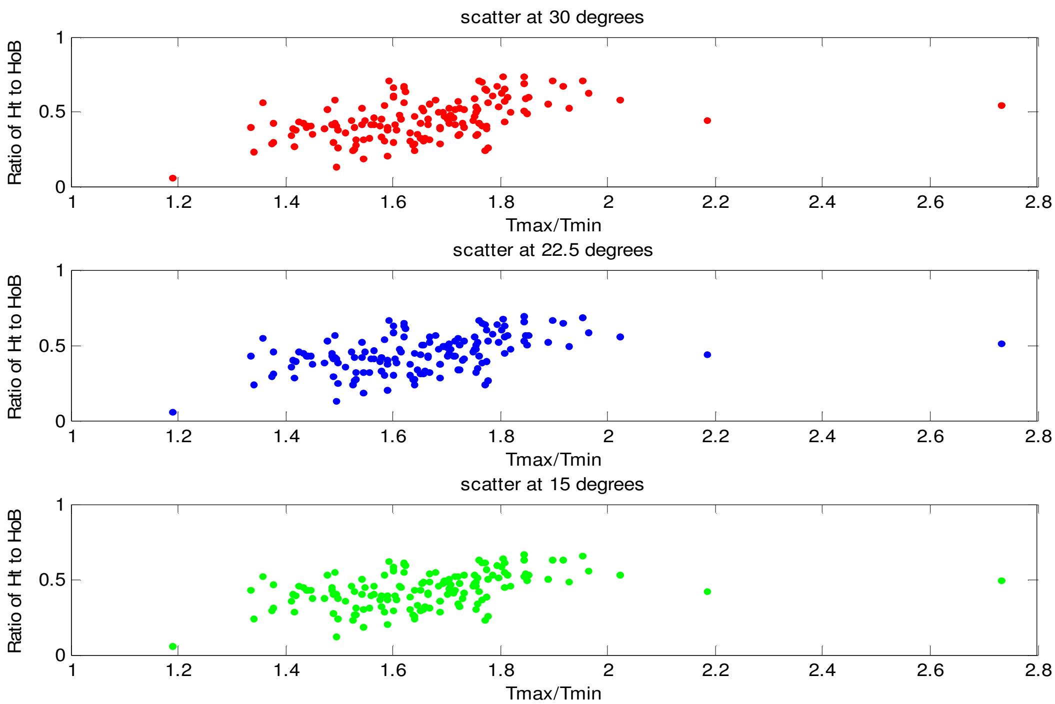



*Figure 5: Variation of the ratio of global solar radiation to extraterrestrial solar radiation on a tilted surface with the ratio the maximum temperature to minimum temperature for the three tilt angles*

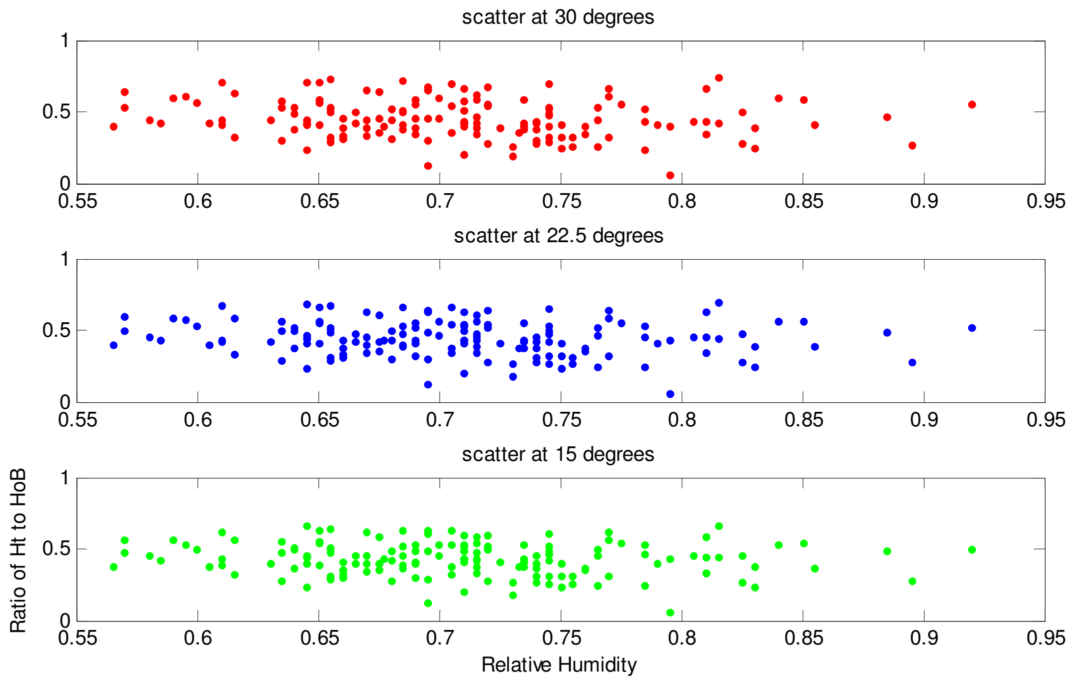



*Figure 6: Variation of the ratio of global solar radiation to extraterrestrial solar radiation on a tilted surface with the Daily relative Humidity for the three tilt angles*

The scatter plots shown in *Figure 4, 5 and 6* depict a positive relationship with a poor correlation between $\frac{H_t}{H_o}$ and the climatological parameters clearness index, temperature variations and Relative humidity. Hence it can be inferred from figure 4 and 5 that the poor correlation between the clearness index and the ambient temperature is because of the masking of the clearness index by water constitute molecules particularly in the rainy seasons for the month of February to May. The results agree with those of Aubient [22] who reported that the infra-red sky radiations are strongly dependent on sky temperature, which in turn correlates well with the vapour pressure, ambient temperature and clearness index.

3.4.1 *Variation of the ratio of global solar radiation to extraterrestrial solar radiation on a tilted surface versus the global solar radiations received on the different tilt angles.*

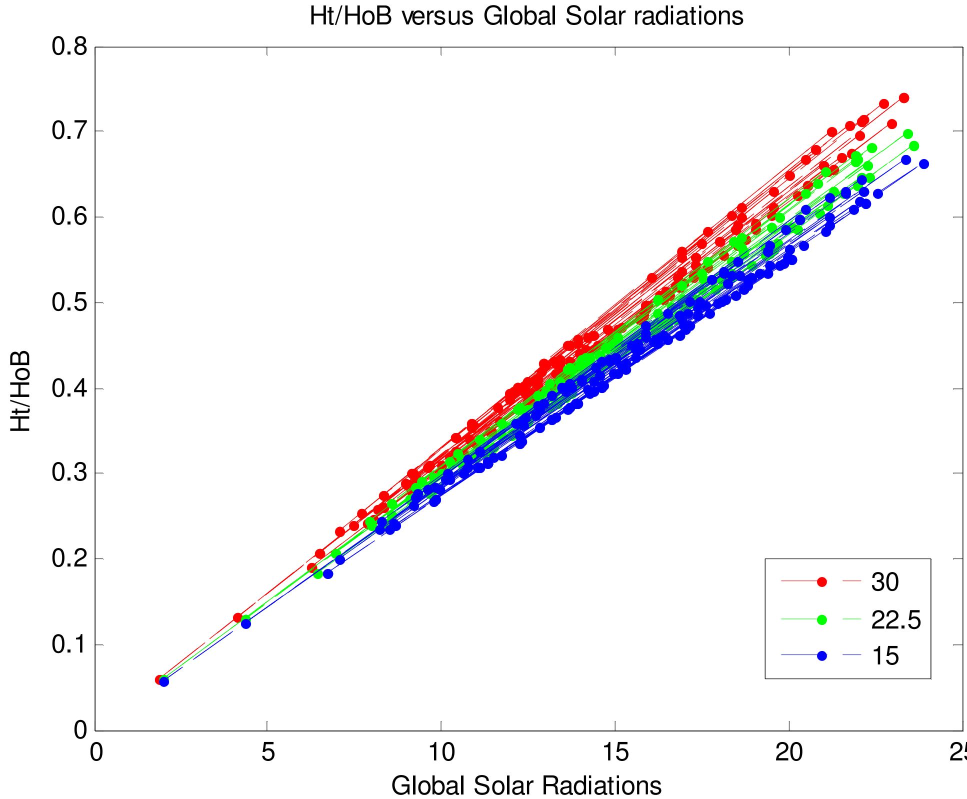



*Figure.7: Variation of the ratio of global solar radiation to extraterrestrial solar radiation on a tilted surface versus the global solar radiations*

*Figure.7* shows that there is a linear relationship between *the ratio of global solar radiation to extraterrestrial solar radiation and* global solar radiation, increasing and decreasing trend of global solar radiations and clearness index are tentatively similar implying that there is a strong correlation between them. it is expected that when the skies are clear, then more global radiation is expected due to less scattering by clouds, aerosols etc.

### 3.5 Model Formulation

Data gathered for a period of six month was cleaned and utilized for model formulation. Out of the 183 data points, 151 were used for model formulation and the rest were used in model testing. The scatter diagrams facilitated the visual interpretation in each case. The scatter diagrams for the global radiation with the climatological parameters such as relative humidity (RH), mean temperature $\left(T_{mean}\right)$, maximum temperature $\left(T_{\max}\right)$ and the ratio of maximum to minimum temperature $\left(\frac{T_{\max}}{T_{\min}}\right)$ in terms of single parameter or multiple parameters were investigated in finding the best empirical model of the global solar radiation on a tilted surface. Single parameters, double and three parameters can be used in the formulation of a better model [23]. The different empirical models considered are represented below

$$\frac{H_t}{H_{o\beta}} = a + b\left(\frac{n}{N}\right) \quad \text{(i)}$$

$$\frac{H_t}{H_{o\beta}} = a + b\left(RH\right) \quad \text{(ii)}$$

$$\frac{H_t}{H_{o\beta}} = a + b\left(\frac{T_{\max}}{T_{\min}}\right) \quad \text{(iii)}$$

$$\frac{H_t}{H_{o\beta}} = a + b\left(T_{\max} - T_{\min}\right) \quad \text{(iv)}$$

$$\frac{H_t}{H_{o\beta}} = a + b\left(\frac{n}{N}\right) + c\left(\frac{T_{\max}}{65}\right) \quad \text{(v)}$$

$$\frac{H_t}{H_{o\beta}} = a + b\left(\frac{n}{N}\right) + c\left(\frac{T_{\max}}{T_{\min}}\right) \quad \text{(vi)}$$

$$\frac{H_t}{H_{o\beta}} = a + b\left(RH\right) + c\left(\frac{T_{mean}}{65}\right) \quad \text{(vii)}$$

$$\frac{H_t}{H_{o\beta}} = a + b\left(\frac{n}{N}\right) + c\left(T_{\max} - T_{\min}\right) \quad \text{(viii)}$$

$$\frac{H_t}{H_{o\beta}} = a + b\left(\frac{T_{\max}}{65}\right) + c\left(T_{\max} - T_{\min}\right) \quad \text{(ix)}$$

$$\frac{H_t}{H_{o\beta}} = a + b\left(\frac{n}{N}\right) + c\left(RH\right) + d\left(T_{\max} - T_{\min}\right) \quad \text{(x)}$$

$$\frac{H_t}{H_{o\beta}} = a + b\left(\frac{n}{N}\right) + c\left(RH\right) + d\left(\frac{T_{\max}}{65}\right) \quad \text{(xi)}$$

$$\frac{H_t}{H_{o\beta}} = a + b\left(\frac{n}{N}\right) + c\left(RH\right) + d\left(\frac{T_{\max}}{T_{\min}}\right) \quad \text{(xii)}$$

$$\frac{H_t}{H_{o\beta}} = a + b\left(RH\right) + c\left(\frac{T_{mean}}{65}\right) + d\left(\frac{T_{\max}}{T_{\min}}\right) \quad \text{(xiii)}$$

$$\frac{H_t}{H_{o\beta}} = a + b\left(\frac{T_{\max}}{T_{\min}}\right) + c\left(\frac{T_{\max}}{T_{\min}}\right)^2 \quad \text{(xiv)}$$

$$\frac{H_t}{H_{o\beta}} = a + b\left(\frac{T_{\max}}{65}\right) + c\left(\frac{T_{\max}}{65}\right)^2 \quad \text{(xv)}$$

$$\frac{H_t}{H_{o\beta}} = a + b\left(\frac{T_{mean}}{65}\right) + c\left(\frac{T_{mean}}{65}\right)^2 \quad \text{(xvi)}$$

$$\frac{H_t}{H_{o\beta}} = a + b\left(T_{\max} - T_{\min}\right) + c\left(T_{\max} - T_{\min}\right)^2 \quad \text{(xvii)}$$

$$\frac{H_t}{H_{o\beta}} = a + b\left(\frac{n}{N}\right) + c\left(\frac{n}{N}\right)^2 \quad \text{(xviii)}$$

$$\frac{H_t}{H_{o\beta}} = a + b\left(\frac{n}{N}\right) + c\left(\frac{T_{mean}}{65}\right)^2 \quad \text{(xix)}$$

$$\frac{H_t}{H_{o\beta}} = a + b\left(\frac{n}{N}\right) + c\left(\frac{T_{max}}{T_{min}}\right) + d\left(\frac{T_{max}}{65}\right) \qquad \text{(xx)}$$

where a, b, c and d are regression coefficients. These regression coefficients were computed by carrying out a least square fit. The script that was developed was used to compute the coefficients obtained in each model created:

### 3.6 Validation of Empirical Models Developed

December 2012 data points were randomly selected and used to test the formulated models. The model results were evaluated using maximum absolute error (MAE), Mean bias error (MBE), root mean square error (RMSE) and the correlation coefficient (r). Table 1, gives the models' statistical results with the correlation coefficient for each tilt angle, where r is the correlation coefficient of the experimental data versus calculated values. The correlation coefficient gives an evaluation of the experimental data by the model, while the MBE and RMSE provide information about the tendency to over – or under estimate in a particular range. These were used to evaluate the model's performances. The statistical results allowed for the recognition of differences between the experimental data and the model estimates and the existence of systematic over – or under estimation tendencies respectively.

Mubiru et al [14] proposed a ranking method of different models, in which the MBE and RMSE are each divided by the average of the actual solar radiation values and the summed up. The ranking processing is based on the rank sum. A model with the smallest rank sum is ranked first. This was done for the 20 models formulated to identify the best model. The data results showed for the three tilt angles of $15^0$, $22.5^0$ and $30^0$ that model (xiii) with the relative humidity (RH), maximum temperature $\left(\frac{T_{max}}{65}\right)$ and the ratio of Maximum to minimum temperature $\left(\frac{T_{max}}{T_{min}}\right)$ as inputs ranked number one at 95% confidence interval. Table 1 shows a summary of the MBE, RMSE and Correlation Coefficients $(r)$ for the different tilt angles.

Table 1: **MBE, RMSE and Correlation Coefficient of the Model (xiii) at different tilt angles**

| Tilt angle | MBE | RMSE | R |
|---|---|---|---|
| $30^0$ | 2.7530 | 5.0718 | 0.3661 |
| $22.5^0$ | 2.2409 | 4.7300 | 0.3707 |
| $15^0$ | 1.5801 | 4.2654 | 0.3743 |

Generally, it is observed that models with rank sum ranging from 1 – 3 for the different tilt angles were the better performing models with the input parameters; $RH$ , $\frac{T_{max}}{65}$ $\frac{T_{max}}{T_{min}}$ ; $\frac{n}{N}$ , $RH$ , $\frac{T_{max}}{T_{min}}$ and $\frac{T_{max}}{T_{min}}$ respectively. According to the results in table 1, the recommend model eqns (10, 11 and 12) are;

$$\frac{H_t}{H_{o\beta}} = -0.3942 - 0.3201(RH) + 1.8754\left(\frac{T_{max}}{65}\right) + 0.1573\left(\frac{T_{max}}{T_{min}}\right) \text{ tilted at } 30^0 \quad (10)$$

$$\frac{H_t}{H_{o\beta}} = -0.2970 - 0.2690(RH) + 1.6798\left(\frac{T_{max}}{65}\right) + 0.1239\left(\frac{T_{max}}{T_{min}}\right) \text{ tilted at } 22.5^0 \quad (11)$$

$$\frac{H_t}{H_{o\beta}} = -0.2614 - 0.2386(RH) + 1.5822\left(\frac{T_{\max}}{65}\right) + 0.1065\left(\frac{T_{\max}}{T_{\min}}\right) \text{ tilted at } 15^0 \quad (12)$$

The results of the empirical model developed do not concer with Mubiru et al's [14] conclusion that sunshine hours and the maximum temperature have a strong influence on the prediction of global solar radiation on a surface use sunshine hours as a climatological parameter is not reflected in the model. Estimates of global solar radiation on tilted surfaces were computed using the model with the smallest rank sum (xiii) and then compared with the measured values. Estimated and measured values of global solar radiation on tilted surfaces show that on some days there is slightly under and over estimation of the global solar radiation, as pointed out by Akoba [15], this study emphasizes that this could be due to the linear tendency of an empirical model, which slightly fails to cope with the global solar radiation.

### 3.7: Comparison of Global Solar Radiation on a Tilted Surfaces With that Measured on a Horizontal Surface

The variation of the ratio of global solar radiation on tilted surfaces to that of global solar radiation on a horizontal solar radiation versus time is shown in figure 7.

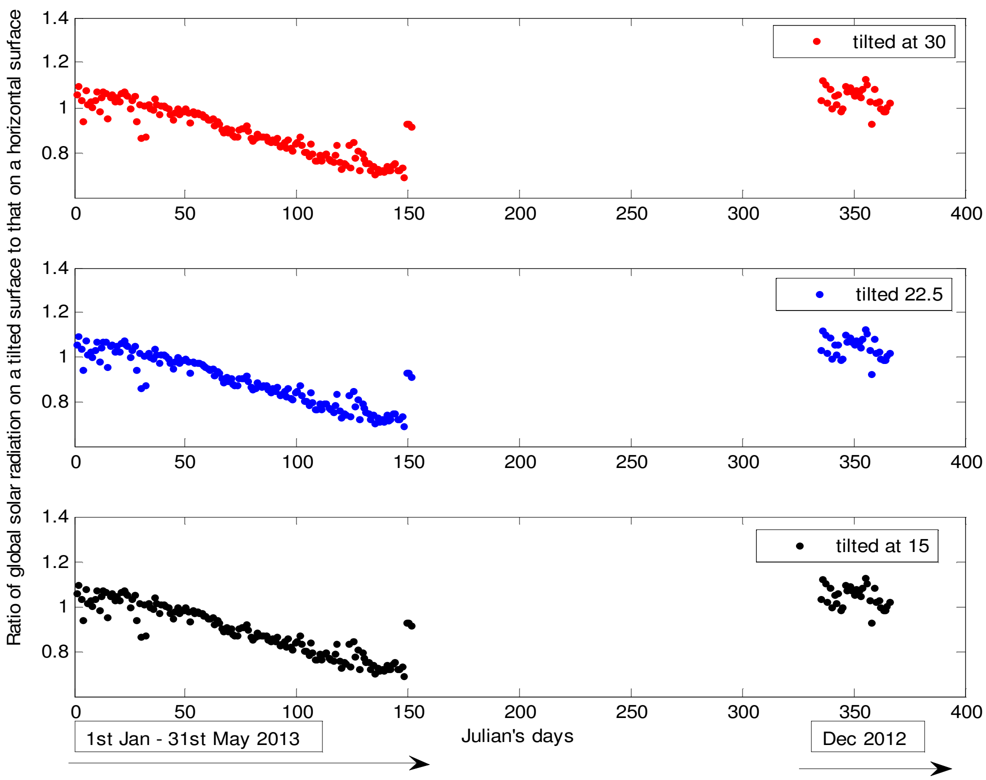



*Figure 8. : A plot of the ratio of tilted to horizontal global solar radiation against time for the study period*

From 1st December – 2012 to 14th Feburary 2013 the ratio is above unity as earlier observed by Akoba [15]. The results of this study show that the tilted surface recieves more solar radiation than horizontal surface during this period. In the period from 22nd of Feburary 2013 to 31st of May 2013 the daily global radiation received on horizontal surface is greater than that on tilted surface. This was attributed to the skies being clear and their accompanying weather patterns could not limit the solar radiation to the Earth's surface. Gopinathan [24] observed the ratio being above unity as a consequence of the sun's position in the sky according to the time of the day and time of the year. The other reason could be that the view angles of the tilted surfaces cut out a limited solid angle of the sky unlike the horizontal surface which views the entire hemisphere. Since there is a relationship between $\frac{H_t}{H_{o\beta}}$ and $\frac{H}{H_o}$ then one can develop a relationship between the two as suggested by Olmo et al [23] who describe a model that it requires only the global irradiance, and not the direct irradiance value to calculate the global irradiance on an inclined plane.

### 3.8 Analysis of Solar radiation data for the angle of tilt $\beta = 22.5^0$ collected over for a period of three years

In an attempt to achieve a better and a more reliable model for the estimation of global solar radiation on a $22.5^0$ tilt angle, solar radiation data for a period of three years from 1st January 2010 to 31st December 2012 has been used to check Akoba's [15] model developed using the meteorological parameters of sun shine, relative humidity and temperature. Data for the months of October and November 2012 were not included since the data logger was not functioning during that period. The results of the measurements were computed and plotted in figure 9. It is observed that in January 2010 and 2011, the ratio of daily global solar radiation on a tilted surface to the extraterrestrial solar radiation on a tilted surface $\left(\dfrac{H_t}{H_{o\beta}}\right)$ and that on a horizontal surface $\left(\dfrac{H}{H_o}\right)$ exhibited highest values of 0.49 for both. During February 2011 the value was 0.52. The variation in available solar insolation was the result of variation in clouds and their accompanying weather patterns which are among the most important atmospheric phenomena limiting solar radiation at the Earth's surface during the different months of the year.

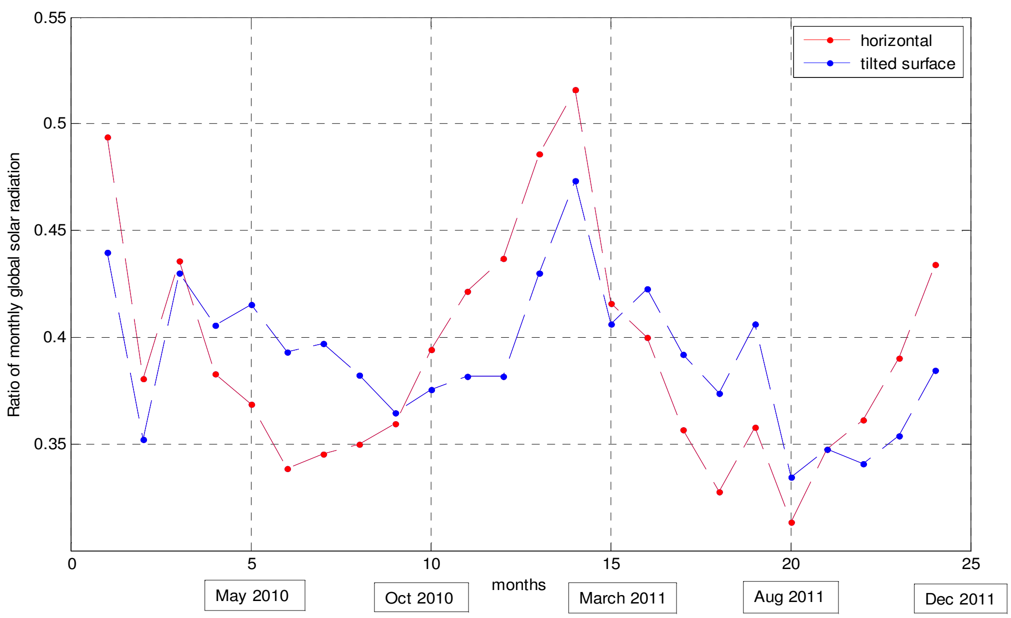



Figure 9*: Distribution of the ratio of global solar radiation to the extraterrestrial solar on surfaces at the Department of Physics, Makerere University*

#### 3.8.1 Regression Coefficients for the Justification of Akoba's Model (2009) Using the Models developed in Section 3.5

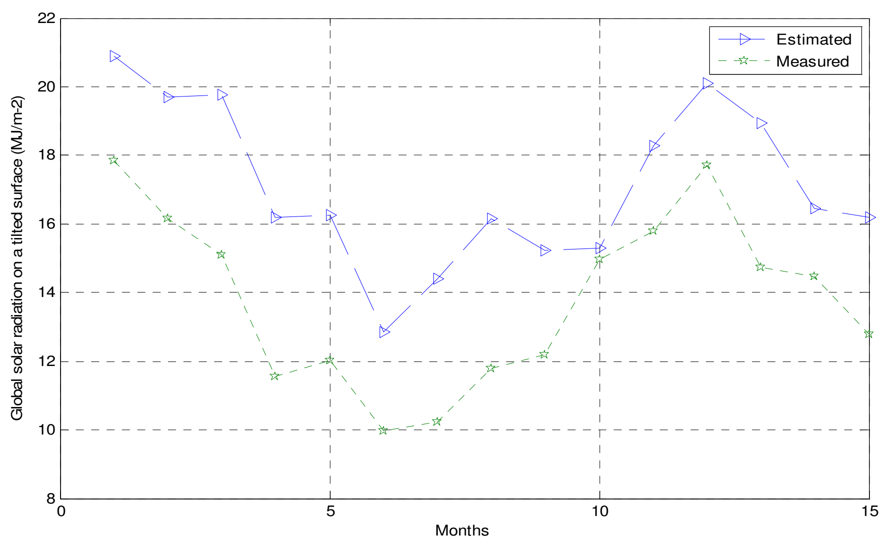
Data gathered for a period of three years was cleaned and utilized for model formulation. The data points were for the verification of Akoba's model (15) formulated that was developed on the data points of one year.

### 3.8.2 Model Validation using monthly data averages for the angle of tilt $\beta = 22.5^0$ obtained over a period of three years

A quarter of the monthly data averages (15 monthly average points) were used to test the models formulated in section 3.5. The procedure for validation follows that carried out in section 3.6. The statistical findings carried out showed that model (xi); with Sunshine hours, relative humidity and maximum temperature as input parameters ranked the best. The model showed a $MBE = 2.3391, RMSE = 2.5985$ and $r = 0.8863$ at a 95% confidence level. The results provided new evidence that model (xi), eqn (13) performed better.

$$\frac{H_t}{H_{o\beta}} = -0.9227 - 0.1405\left(\frac{n}{N}\right) - 0.0335(RH) + 3.2826\left(\frac{T_{\max}}{65}\right) \quad (13)$$

The model is in disagreement with Akoba's [15] which is now ranked 3rd for data gathered for a period of three years. The study findings are in agreement with the assertion by Mubiru et al [14] that sunshine hours and maximum temperature have got a strong influence on the prediction of global solar radiation on a surface. Figure 10 shows estimates of global solar radiation of the monthly averages on a tilted surface computed using equation (13) (the best model). It is observed that the model over estimates global solar radiation. This could be due to the multiplicity of parameters that are linearly dependent. The study findings also agree with those of Ruiz et al [25] who verified Olmo et al's model [23] and found that the model over estimated the solar radiation incident on tilted surfaces and the Root Mean Square Error (RMSE) has a minimum of 21.5%. He concluded that the values of the hourly global solar radiation and those computed were practically identical; with relative error estimation distributed like a Gaussian noise which was less than 10% for 70% of the




data.

*Figure 10: Comparison of measured and estimated values of Global Solar Radiation on a tilted surface*

Figure 10 depicts the comparison of the global solar radiation on a tilted surface with that measured on the horizontal surface on a monthly basis. For the months of November, December, January and February for the period of study the ratios were above unity meaning that the tilted surfaces received more solar radiation than the horizontal surface. These findings agree with those of Akoba [15] who cites Mubiru et al [24] who suggested that this may be a consequence of the sun's position in the sky according to the time of the day and time of the year. The ratios being above unity can be ascribed to water and relative humidity being low in the atmosphere at these times (Jan 2010_1.04; Nov 2010_1.02; Dec 2010_1.95; Jan 2011_1.04; Feb 2011_1.01; Nov 2011_1.03; Dec 2011_1.04; Jan 2012_1.05; Dec 2012_1.06; Jan 2013_1.04 and Feb 2013_1.01. This is the reason why we had clearness index greater than unity as more global solar radiation will be reaching the earth. The more the atmosphere is clean and clear, the greater is the value of the clearness index and the drier the weather is. However, the reverse is true in the case of clearness index below unity that means there is abundant presence of all sorts of scattering agents particularly heavy aerosol particles which aid forward scattering. The scattering activities that occur in the atmosphere favour greater value of diffuse radiation hence lower clearness index.

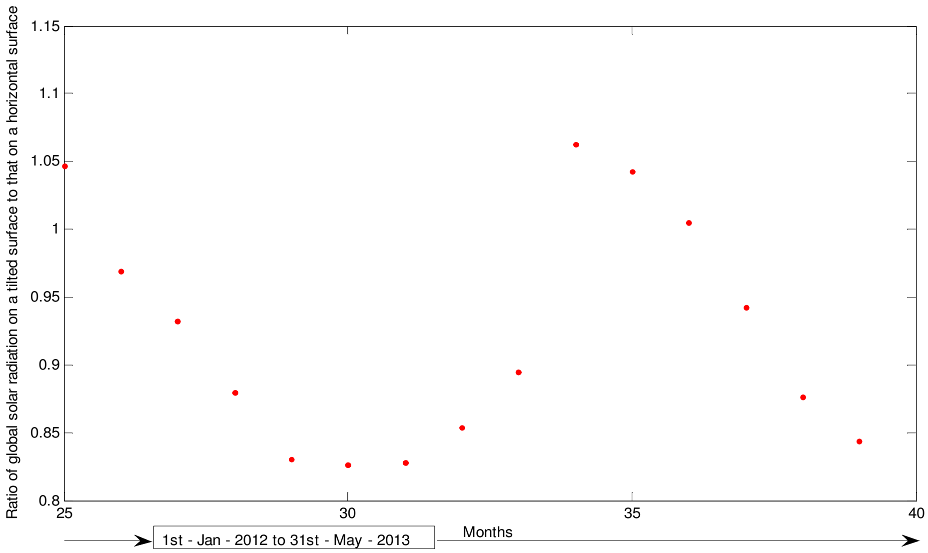



*Figure 11: A plot of the ratio of tilted* $(\beta = 22.5)$ *to horizontal global solar radiation for average monthly period from Jan 2012 to May 2013*

In the period of two years as shown in Fig 11, it is known that solar radiation at the Earth's surface is not constant over time but rather varies considerably over decades. This is then referred to the changes in the amount of total solar radiation and this is due to solar activity. Solar activity relates to climate change in that cosmic rays can aid the formation of clouds. Clouds can have a significant effect on Earth's climate as they change the albedo of the earth and enhance the greenhouse trapping effect. According to Svensmark et al. (28), clouds in the lower atmosphere contain less liquid water during times of low cosmic ray fluxes. Besides, the relative abundance of aerosols decreases during such periods, providing for a causal mechanism between solar activity and cloud formation. Svensmark et al. (28) state that total cloud cover exerts a net negative radiative force on the meteorological parameters such as temperature, atmospheric pressure, direction and force of wind, relative air humidity and precipitation of the climate system, because the reflection of solar radiation due to increased cloudiness is stronger than the cloud-enhanced greenhouse effect in the Infra-red part of the spectrum causing a change in the temperatures. Solar activity minima tend to be correlated with colder temperatures, and longer than average solar cycles tend to be correlated with hotter temperatures. The increase or decrease of the temperature can be explained only by an unperiodical variation of the climate at a micro regional scale. Because the climatic changes are produced on a very large time scale, this tendency of the temperature is more probably not an expression of the global climatic changes but a meteorological variation.

## 4.0. Conclusions

The global solar radiation incident on inclined surfaces is estimated from the meteorological parameters. This work presents the outcome of an attempt to predict the global solar radiation on a tilted surface based on measured values of sunshine hours, temperatures and relative humidity only. This is important because sunshine hours, temperature and relative humidity are commonly available parameters, while global solar radiation on a tilted surface is rare, costly to measure and requires continuous attention by skilled manpower. Data for Makerere University between December 2012 and May 2013 was used for developing an empirical model. Findings show that a model which uses relative humidity, relative maximum temperature and the ratio of Maximum temperature to minimum temperature outperforms the other empirical models developed. It gives values of MBE, RMSE and a poor correlation coefficient shown in table 1. Results of the current study show that the best model differs from those obtained by the previous studies for the estimation of daily solar radiation on a tilted surface in Makerere and other areas with similar pattern of meteorological factors.

This means that the models of equations (10), (11) and (12) give good estimates for the global solar radiation in Makerere University during the time period covered by the current study. Comparisons between the measured and calculated values of the global solar radiation along with the values of mean base error (MBE) and root mean square error (RMSE) were obtained and the low values of the (RMSE) for all models indicate fairly good agreement between measured and calculated values of global solar radiation, the correlation coefficients themselves do not provide strong evidence. It is evident from scatter diagrams in section 3.4 that there were no clear cut relationships between the ratio of global solar radiation on a tilted surface and individual meteorological parameters. The high values of MBE and RMSE and low value of correlation coefficient obtained emphasize the need for data gathered for a long period.

Findings of model validation using monthly data averages for the angle of tilt $\beta = 22.5^0$ obtained over a period of three years are in disagreement with Akoba's model [15]. The present study comes up with a new model that utilizes sun shine hours, relative humidity and relative maximum temperature as input parameters that outperform the other empirical models developed for the period of three years. A model recommended by the study is

$$\frac{H_t}{H_{o\beta}} = -0.9227 - 0.1405\left(\frac{n}{N}\right) - 0.0335(RH) + 3.2826\left(\frac{T_{\max}}{65}\right)$$

It is possible that this model equally will applies to the $15^0$ and $30^0$ tilt angles

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## DEFINITIONS, ACRONYMS, ABBREVIATIONS

NEAP – National Environment Action Plan
NEMA – National Environment management Authority
MEMD – Ministry of Energy and Mineral Development
WMO – World Metrological Organisation