PREDICTING GLOBAL SOLAR RADIATION ON A HORIZONTAL SURFACE A CASE STUDY FOR ZAMBIA

[1]Chisala Kapumpu*, [2] Paul Chisale, [3]Nicholus Kwendakwema and [3]Edwin Luwaya
[1]MEng Student in Thermofluids, Department of Mechanical Engineering,
School of Engineering, University of Zambia
Email: kapumpuc@zra.org.zm; kapumpuc@gmail.com
[2] Faculty of Engineering, Namibia University of Science & Technology,
Private Bag 13388, Windhoek, Namibia.
[3]Department of Mechanical Engineering, School of Engineering,
University of Zambia

ABSTRACT

Insolation models have been recognized for many years in solar energy systems as important tools to determine radiations for locations lacking insolation data base. Unfortunately, for most geographical areas in Zambia, the insolation data is not available. Correlations between the daily measurements of global solar radiation and the meteorological parameters were presented in tabular form for the selected locations. A common relationship to estimate global solar radiation for the all Zambia is also established. The values of correlation coefficients established varied from 53% to 97% and the errors of estimation were between 0.24 and 0.0.84.

Key Words: Solar Radiation; Regression Analysis; Extraterrestrial Solar Radiation

INTRODUCTION

As sources of the petroleum and natural gas are gradually depleted, renewable energy sources such as wind, biomass, photovoltaic and geothermal energy may become more important in the future (Borman, et al., 2007). Energy is essential for development; yet two billion people world over currently go without it, condemning them to remain in the poverty trap. The fundamental dilemma is that, despite energy being a vital ingredient for growth, sustainable development and for the vast majority of economic activities, its production and use, contributes to global warming. Therefore, the greatest challenge facing the world energy sector today is how to meet the rising demand for energy, while at the same time reducing emissions of greenhouse gases (WEC, 2007).

The annual solar radiation in Zambia is amongst the highest in the world. The radiation across the country is equitably uniform, in the range of 6,600-7,700 MJ/m^2 (5.27- 6.09kWh/m^2) (Rask, et al., 2005). Therefore, it is expected that the application of solar energy engineering especially; solar water heaters, lighting and refrigeration of medicines at rural health centers will become widespread in the near future. This paper looks at the estimation of solar radiations for locations in Zambia especially, where this resource is not directly measured.

NOMENCLATURE

H_0	[MJ/m^2]	Mean daily monthly extraterrestrial solar radiation,
R_h	[%]	Mean daily monthly relative humidity,
T_{max}	[^{0}C]	Mean daily monthly maximum air temperature
$T_{dp,max}$	[^{0}C]	Mean daily monthly maximum dew point temperature
P	[bars]	Mean daily monthly atmospheric pressure
	[^{0}]	Solar declination angle
C	[Oktas]	Cloud cover,
	[MJ/m^2]	Mean daily monthly global solar radiation at earth's surface
n/N		Average daily ratio of sunshine duration,
n	[h]	Hours of measured sunshine
n^*		Day of year
N	[h]	Potential astronomical sunshine hours
I_{sc}	[W/m^2]	Solar constant
I_{sn}	[W/m^2]	Extraterrestrial solar radiation
	[^{0}]	Latitude
	[^{0}]	Hour angle
	[^{0}]	Sunset hour angle
a,b,c,e,f,g,h		Regression Coefficients

SOLAR RADIATION

Everything in nature emits electromagnetic energy, and solar radiation is energy emitted by the sun. The energy of extraterrestrial solar radiation is distributed over a wide continuous spectrum ranging from ultraviolet to infrared rays. The incoming irradiation from the sun, at any given point, takes different shapes, depending on the geometry of the earth, its distance from the sun, geographical location of any point on the earth's surface, astronomical coordinates, and the atmosphere composition. A considerable amount of the solar radiation is absorbed, scattered and reflected by molecules, aerosols, water vapor and clouds as it passes through the atmosphere and consequently the solar energy balance of the earth remains the same (Sen, 2008). The rate at which this solar energy is emitted from the sun is equivalent to the energy coming from a furnace at a temperature of about 6,000 K (10,340ºF) (William, et al., 2001).

Radiation is the transfer of energy via electromagnetic waves that travel at the speed of light. The velocity of light in a vacuum is approximately 3 x 108 m/s. The time it takes light from the sun to reach the Earth is 8 minutes and 20 seconds. Heat transfer by electromagnetic radiation can travel through empty space. Any body above the temperature of absolute zero (-273.15 ^{o}C) radiate energy to its surrounding environment. The many different types of radiation are defined by their wavelength. The electromagnetic radiation can vary widely (Beckman, et al., 2013).

The designers of solar energy collection systems are interested in knowing how much solar energy has fallen on a collector over a period of time such as a day, week or year. This summation is called *solar radiation or irradiation* (William, et al., 2001).

METHOD

The whole solar radiation modelling procedure revolves around the plausible estimation of the model parameters from a given set of data (Sen, 2008). The data for solar radiation energy can be obtained through two different methods. The first method, which is more reliable, is the direct measurement of solar radiation components using Pyranometers and Pyrheliometers (El-Sebaii, et al., 2005). Systematic measuring of diffuse solar energy and the global (total) irradiation incident on a horizontal surface are usually undertaken by national agencies, which are the national meteorological offices in many countries. At several locations direct or beam irradiation is measured by a pyrheliometer with a fast-response multi-junction thermopile (Sen, 2008).

The second approach relies on empirical-analytical relationships that can predict the solar radiation components as a function of time, latitude, altitude, zenith angle, clear sky conditions, hours of measured sunshine, etc. The latter can be used in locations with similar meteorological and geographical characteristics where experimental data on solar radiation energy is not available due to limited coverage of radiation measuring networks (El-Sebaii, et al., 2005). This method uses regression analysis and can be applied to estimate solar radiation to most parts of Zambia where it is not measured.

In this research, the general procedure for developing mathematical models for solar radiations are achieved by correlating the measured data sets of solar radiations and geographical, geometrical, astronomical and meteorological (GGAM) parameters for the seven locations where solar radiation is measured in Zambia. These locations were namely; Mansa, Mfuwe, Ndola, Livingstone, Kasama, Mongu, and Lusaka. The data sets for the daily measurements of GGAM parameters and global solar radiations collected for each site were: the cloud cover; sunshine hours; dew point temperature; humidity; maximum temperature; atmospheric pressure; solar radiation; Using linear regression analysis the proposed solar radiation models take the form as:

Table 1: Locations of considered stations and regression and correlation coefficients of estimate for the models (1-8)

Location	Latitude (^{o}) S	Longitude (^{o}) E	*a*	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	CC%	SE
Kasama	10.2117	31.1178	2218.7757	0.5994	0.0945	8.1852	0.0475	-0.0975	0.3582	-2.5546	-2.5266	0.9752	0.2413
Livingstone	17.8500	25.8667	61.7375	17.8513	1.6572	-10.4440	-0.5887	-2.2468	1.5870		-2.6337	0.7855	0.6827
Lusaka	15.4167	28.2833	-585.6600	-11.6302	0.4990	21.7918	0.2025	-0.2900	0.0473	0.6585	-2.3639	0.8735	0.5850
Mansa	11.2000	28.8833	-53.8110	0.5958	0.5000	0.8100	0.3214	1.0400	0.0456	0.0229	-3.4939	0.8738	0.5575
Mfuwe	13.2586	31.9364	195.6132	-3.0681	0.3809	26.8869	0.0642	-0.2344	0.1169	-0.2329	-0.2243	0.8229	0.5504
Mongu	15.2775	23.1319	-1293.9995	0.5195	0.3711	-10.4984	0.3583	1.5675	-0.4234	1.3970	-1.4918	0.5290	0.8364
Ndola	12.9667	28.6333	-4134.0024	14.9040	1.5428	-15.9948	-0.4630	0.3769	1.6686	4.6917	0.5053	0.7087	0.7360
All Zambia	15.4167	28.9364	-86.9255	0.3439	0.5144	12.1276	0.0049	0.0368	0.1402	0.0917	-0.8268	0.7633	0.5949

RESULTS AND DISCUSSION

Monthly mean daily global solar radiation (H), ratio of bright sunshine (n/N), mean daily relative humidity (R_h), mean daily maximum air temperature (T_{max}), mean daily maximum dew point temperature (T_{dp}) sine of the solar declination angle (Sinδ) and Cloud cover (C) at selected locations in Zambia where collected, analysed and presented in graphical forms as:

The figures below give the daily monthly mean variations of the considered parameters: T_{max}; $T_{dpmax;}$ H; n/N; $R_{h;}$ c and P at the selected stations in Zambia.

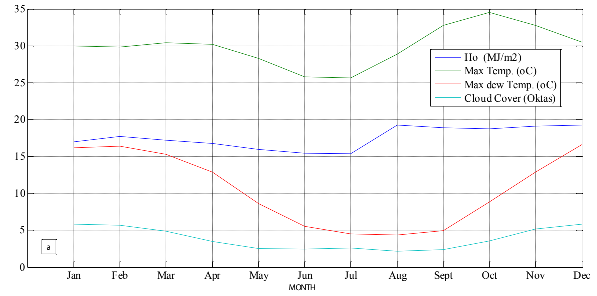


Figure 2: Monthly mean variations of the considered parameters (a) T_{max}, Cloud Cover C, $T_{dp\ max}$ and H_o (b) H/H_o and n/N at **LIVINGSTONE** Station.

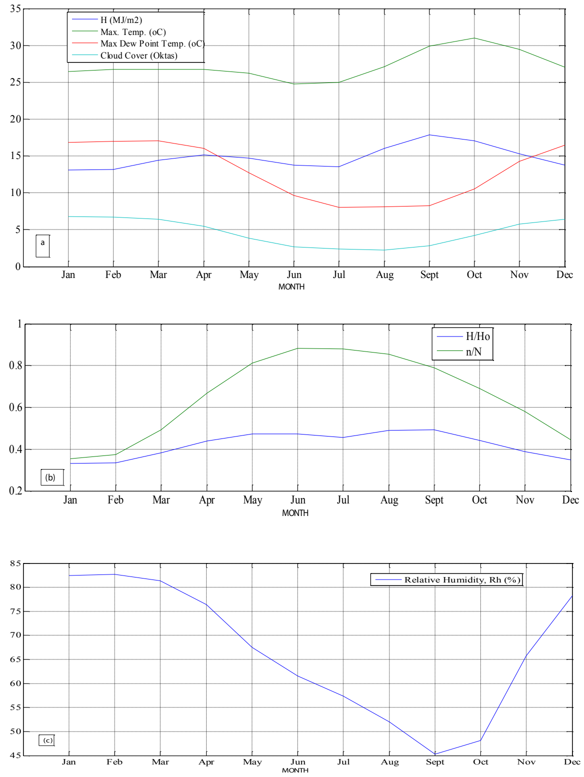
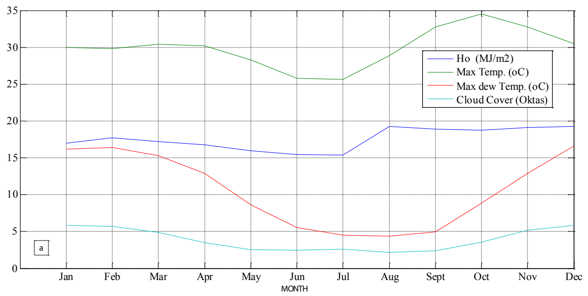


Figure 1: Monthly mean variations of the considered parameters (a) T_{max}, Cloud Cover C, T_{dpmax} and H_o (b) H/H_o and n/N, and (c) Relative Humidity, Rh at **KASAMA** Station.



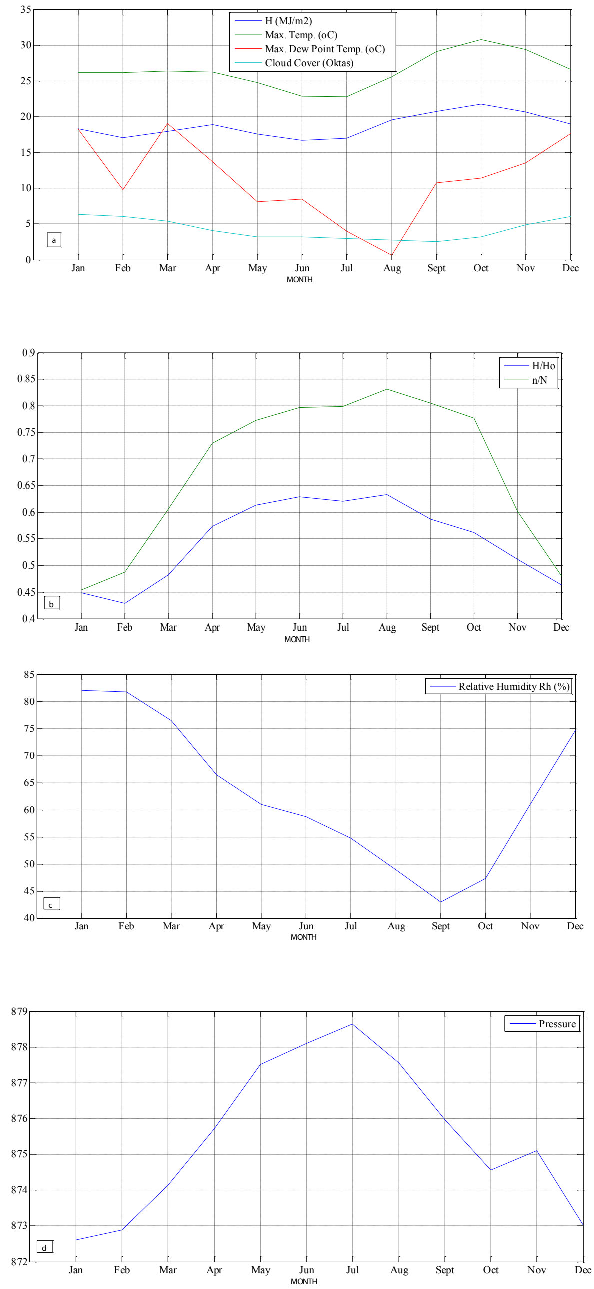


Figure 3: Monthly mean variations of the considered parameters (a) T_{max}, Cloud Cover C, $T_{dp\ max}$ and H_o (b) H/H_o and n/N (c) Relative Humidity, Rh and (d) Pressure at **LUSAKA** Station

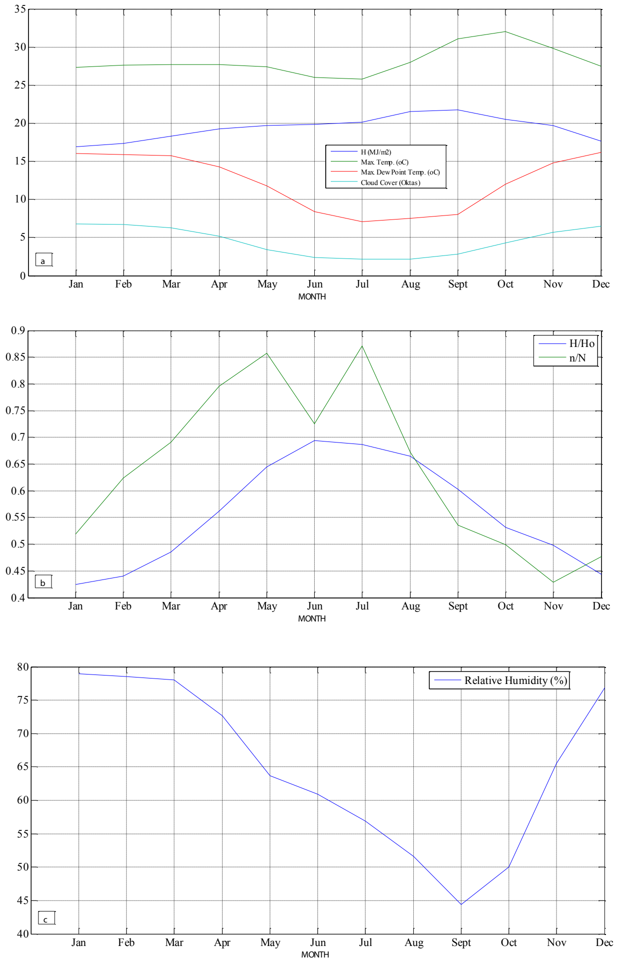
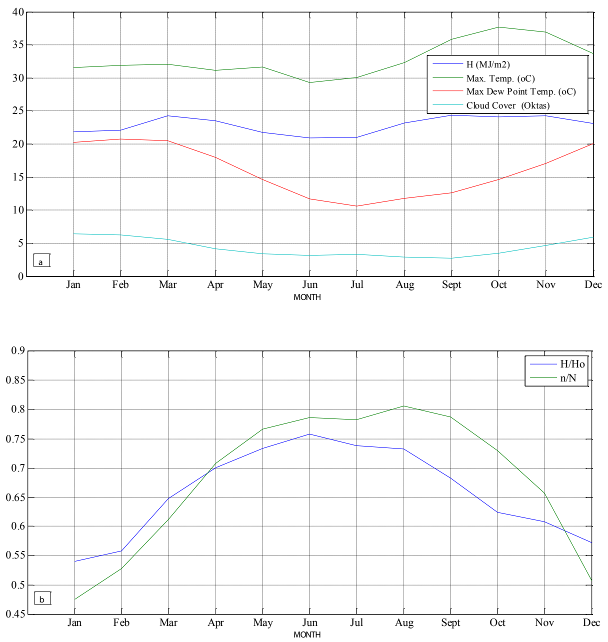


Figure 4: Monthly mean variations of the considered parameters (a) T_{max}, Cloud Cover C, $T_{dp\ max}$ and H_o (b) H/H_o and n/N and (c) Relative Humidity, R_h at **MANSA** Station



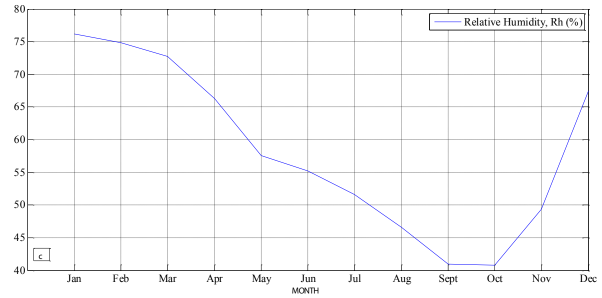


Figure 5: Monthly mean variations of the considered parameters (a) $T_{max,}$ Cloud Cover C, $T_{dp\ max}$ and H_o (b) H/H_o and n/N (c) Relative Humidity, R_h at **MFUWE** Station

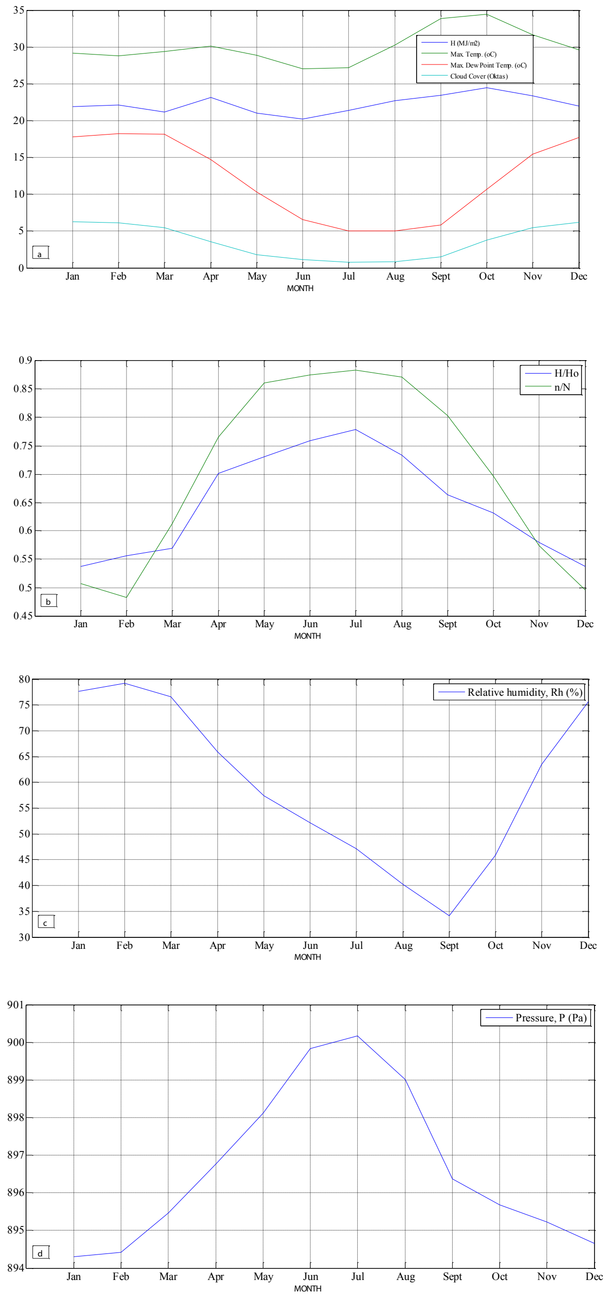
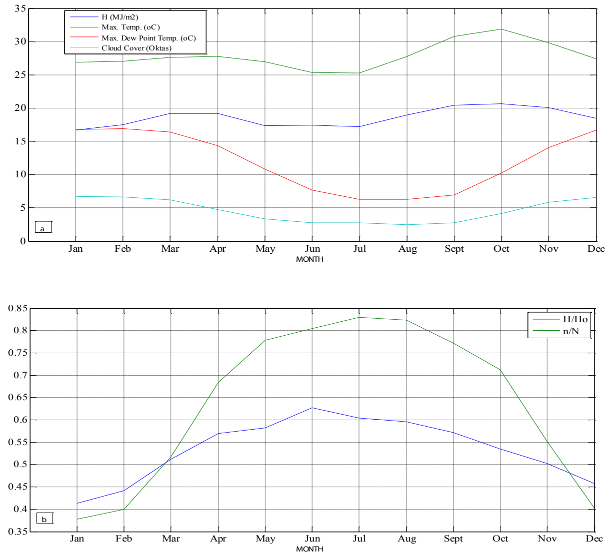


Figure 6: Monthly mean variations of the considered parameters (a) T_{max}, Cloud Cover C, T_{dpmax} and H_o (b) H/H_o and n/N (c) Relative Humidity, Rh and (d) Pressure at **MONGU** Station



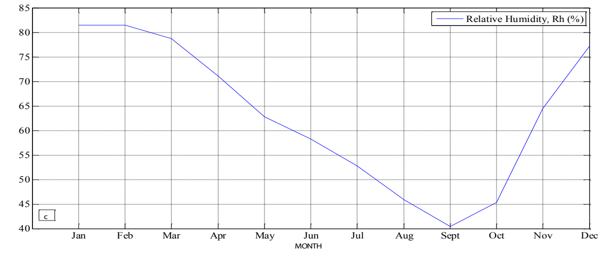


Figure 7: Monthly mean variations of the considered parameters (a) T_{max}, Cloud Cover C, T_{dpmax} and H_o (b) H/H_o and n/N (c) Relative Humidity, R_h at **NDOLA** Station

From Table 1, the formulae of empirical models investigated can be written as follows.

1. **Kasama Model**

$$\bar{H} = 2218.7757 + 0.5994 \sin\delta + 0.0945H_o + 8.1852\, {}^{n}/_{N} + 0.0475 - 0.0975T_{max} + 0.3582T_{dp,max} - 2.5546P - 2.5266C$$

Eqn. 1

2. **Livingstone Model**

$$\bar{H} = 61.7375 + 17.8513 \sin\delta + 1.6572H_o - 10.4440\, {}^{n}/_{N} - 0.5887R_h - 2.2468T_{max} + 1.5870T_{dp,max} - 2.6337C$$

Eqn. 2

3. **Lusaka Model**

$$\bar{H} = -585.6600 - 11.6302 \sin\delta + 0.4990H_o + 21.7918\, {}^{n}/_{N} + 0.2025R_h - 0.2900T_{max} + 0.0473T_{dp,max} + 0.6585P - 2.3639C$$

Eqn. 3

4. **Mansa Model**

$$\bar{H} = 53.8110 + 0.5958\sin\delta + 0.5000H_o + 0.8100\, {}^{n}/_{N} + 0.3214R_h + 1.0400T_{max} + 0.0456T_{dp,max} + 0.0229P - 3.4939C$$

Eqn. 4

5. **Mfuwe Model**

$$\bar{H} = 195.6132 - 3.0681 \sin\delta + 0.3809H_o + 26.8869\, {}^{n}/_{N} + 0.0642R_h - 0.2344T_{max} + 0.1169T_{dp,max} - 0.2329P - 0.2243C$$

qn. 5

6. **Mongu Model**

$$\bar{H} = -1293.9995 + 0.5195 \sin\delta + 0.3711H_o - 10.4984\, {}^{n}/_{N} + 0.3583R_h + 1.5675T_{max} - 0.4234T_{dp,max} + 1.3970P - 1.4918C$$

Eqn. 6

7. **Ndola Model**

$$\bar{H} = -4134.9924 + 14.9040 \sin\delta + 1.5428H_o - 15.9948\, {}^{n}/_{N} - 0.4630R_h + 0.3769T_{max} + 1.6686T_{dp,max} + 4.6917P + 0.5053C$$

Eqn. 7

8. **Model for all Zambia**

$$\bar{H} = -86.9255 + 0.3439 \sin\delta + 0.5144H_o + 12.1276\, {}^{n}/_{N} + 0.0049R_h + 0.0368T_{max} + 0.1402T_{dp,max} + 0.0917P - 0.8268C$$

Eqn. 8

Measured Global Solar Radiation and GGAM Parameters

Figures 1 – 7 show the plots for the monthly mean variations of the considered parameters: maximum temperature; maximum dew point temperature; relative humidity; pressure sunshine hours; cloud cover and ground measured global solar radiation at selected stations in Zambia.

(a) Global Solar Radiation Measurements

The maximum values of global solar radiation at all considered locations appear in October, while the minimum values are in June. The average annual daily values for the global solar radiation on horizontal surface at Kasama is 14.82 MJ/m^2/day, at Livingstone is 17.56 MJ/m^2/day, at Lusaka is 18.76 MJ/m^2/day, at Mansa is 19.39 MJ/m^2/day, at Mfuwe is 22.87 MJ/m^2/day, at Mongu is 22.23 MJ/m^2/day and at Ndola is 18.60 MJ/m^2/day. The values of global solar radiation at Mfuwe and Mongu (south Zambia) are higher than those in Livingstone, Lusaka and Ndola (middle Zambia), Mansa and Kasama (northern Zambia). This is due to the fact that the daily mean number of hours of the bright sunshine in the south is higher than in the middle and the north, where the values of annual mean of the number of sunshine hours in Mfuwe is 8.1h and Mongu is 8.37 h, in Livingstone is 9.10 h, in Lusaka is 8.10 h, in Kasama is 7.75 h, in Mansa is 7.64 h and in Ndola 7.59 h.

(b) Maximum Temperature (T_{max})

The maximum monthly daily mean temperature values are higher in October and lower in July at all locations. The annual mean values of the maximum temperatures are 27.27, 29.96, 26.40, 24.06, 28.17, 32.85, 30.02 and 27.87 ^{o}C at Kasama, Livingstone, Lusaka, Mansa, Mfuwe, Mongu and Ndola respectively. The values increase as one moves from the north toward south because the solar declination angle at the north is smaller than at the middle and the south of Zambia.

(c) Relative Humidity as a Percentage (R_h)

Plots of the relative humidity for Kasama, Livingstone, Lusaka, Mansa, Mongu and Ndola stations are shown in figure 2. The graphs have the same trend where the maximum values were in January/ February and the minimum values were in September. This is because of the rain season in January and dry season in October. The annual mean values of the relative humidity are 66.58, 55.67, 63.01, 64.84, 58.30, 59.62 and 63.32% at Kasama, Livingstone, Lusaka, Mansa, Mfuwe, Mongu and Ndola respectively.

(d) Cloud Cover, (C)

Cloud Cover has maximum values in January and December while the minimum values occur in July for all the selected locations.

(e) Maximum Dew Temperature (T_{dp})

The variations of monthly maximum dew point temperature have the same trend, where the maximum values for each were in January and December and the minimum values were in July and August.

(f) Pressure

The variations of monthly maximum values of Pressure were in June and July at all locations, while the minimum values were in January and February.

Table 1, shows that the correlation coefficient for Kasama is the best, where its value is 97.5% and the standard error of estimation (SE) is 0.241. The lowest value of CC is 55.89% at Mongu and SE is 0.836. CC and SE have the values 78.5% and 0.68, 87.4% and 0.585, 87.5% and 0.557, 82.3% and 0.55, 82.3% and 0.73 and at Livingstone, Lusaka, Mansa, Mfuwe and Ndola espectively. For the all locations in Zambia, correlation coefficient (CC) is 70.9 and standard error (SE) is 0.59.

Comparison between ground measured and estimated values of global solar radiation at selected locations

The values of global solar radiation calculated in the models in Eqn. 1 – Eqn.7 were compared with the corresponding measured values as given in Table 9 and Figures 8 – 14.

Table 9: **Comparisons of ground measured and estimated values of global solar radiation at selected locations (MJ/m2).**

Months	Selected Locations													
	Kasama		Livingstone		Lusaka		Mansa		Mfuwe		Mongu		Ndola	
	Measured Mean	Estimated	Measured Mean	Estimated	Measured Mean	Estimated	Measured Mean	Estimated	Measured Mean	Estimated	Measured Mean	Estimated	Measured Mean	Estimated
January	13.092	12.872	16.958	17.038	18.328	18.256	16.909	17.196	21.815	21.965	21.921	21.876	16.677	16.608
February	13.159	13.407	17.710	17.950	17.055	17.267	17.356	17.529	22.094	22.119	22.098	21.987	17.497	17.450
March	14.382	14.355	17.236	17.121	17.942	18.196	18.296	18.257	24.255	24.333	21.178	21.231	19.206	19.318
April	15.149	15.145	16.775	17.060	18.905	18.890	19.259	19.121	23.554	23.612	23.149	23.114	19.214	19.334
May	14.684	14.790	15.948	16.003	17.599	17.566	19.717	19.871	21.757	21.781	21.013	21.200	17.366	17.411
June	13.784	13.724	15.480	15.345	16.670	16.766	19.866	19.945	20.922	20.811	20.193	20.154	17.418	17.519
July	13.563	13.684	15.400	15.541	16.973	17.023	20.154	20.121	20.970	20.826	21.378	21.371	17.241	17.333
August	16.039	16.082	19.238	19.222	19.568	19.423	21.547	21.608	23.227	23.351	22.685	22.878	18.952	18.789
September	17.863	17.829	18.929	19.033	20.713	20.596	21.741	21.701	24.374	24.125	23.422	23.464	20.457	20.466
October	17.070	17.169	18.731	18.879	21.754	21.891	20.508	20.611	24.115	24.239	24.437	24.479	20.672	20.498
November	15.274	15.252	19.080	19.222	20.660	20.641	19.707	19.667	24.315	24.398	23.388	23.412	20.060	20.100
December	13.771	13.966	19.243	19.440	18.947	18.968	17.617	17.662	23.064	23.085	21.957	21.941	18.423	18.500

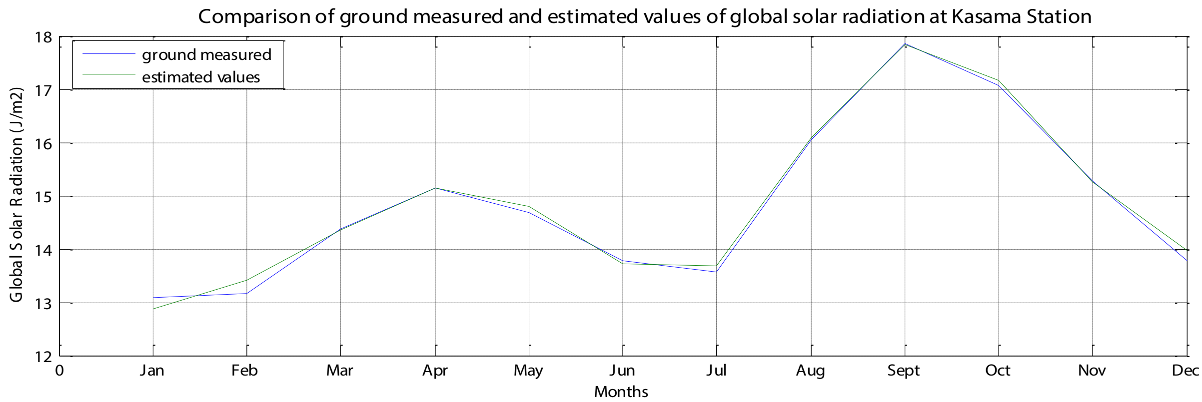


Figure 8: Comparisons of ground measured with estimated values of global solar radiation data sets at Kasama.

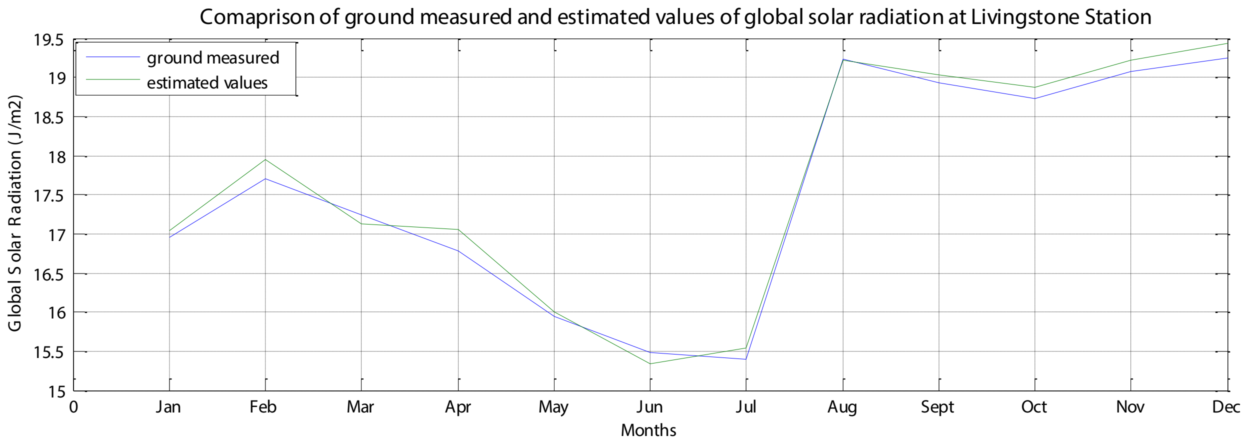


Figure 9: **Comparisons of ground measured with estimated values of global solar radiation data sets at Livingstone.**

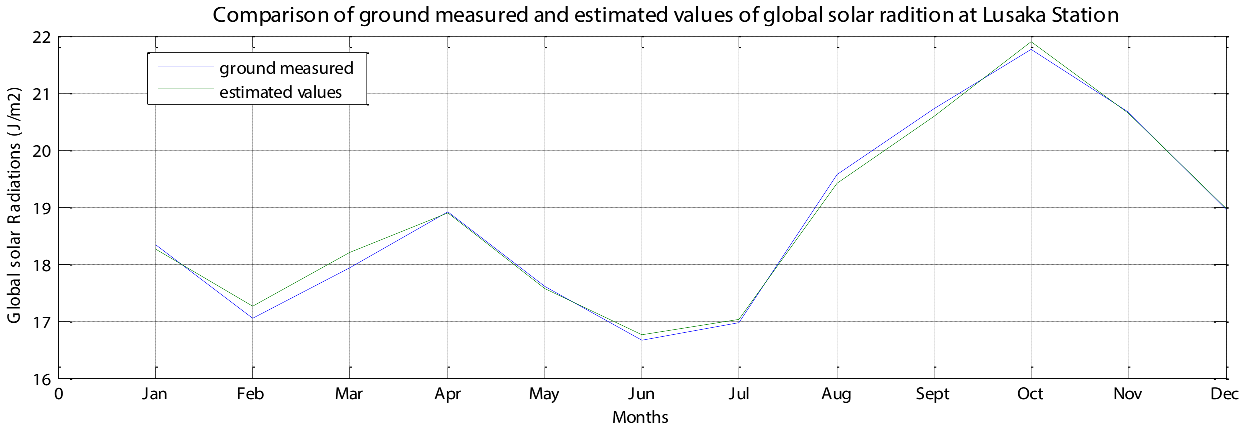


Figure 10: Comparisons of ground measured with satellite estimated values of solar radiation data sets at Lusaka.

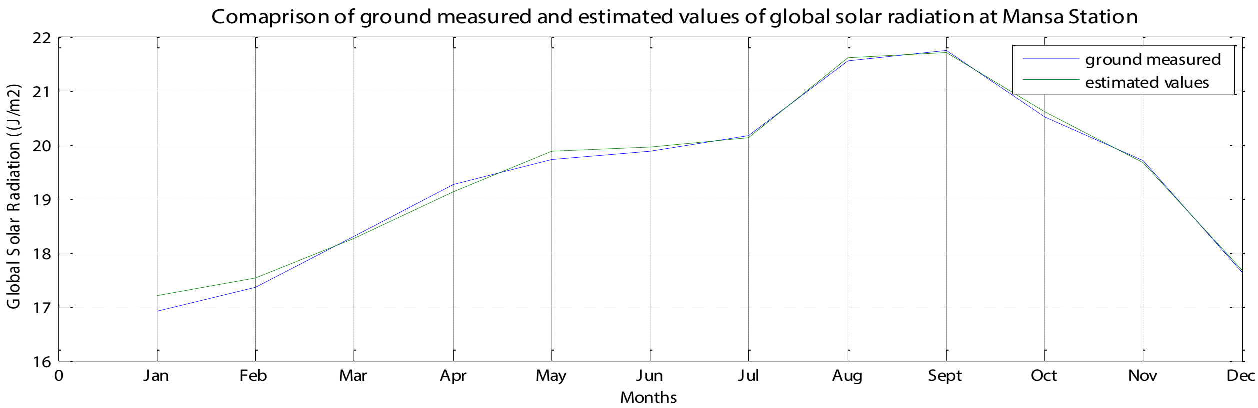


Figure 11: Comparisons of ground measured with estimated values of global solar radiation data sets at Mansa.

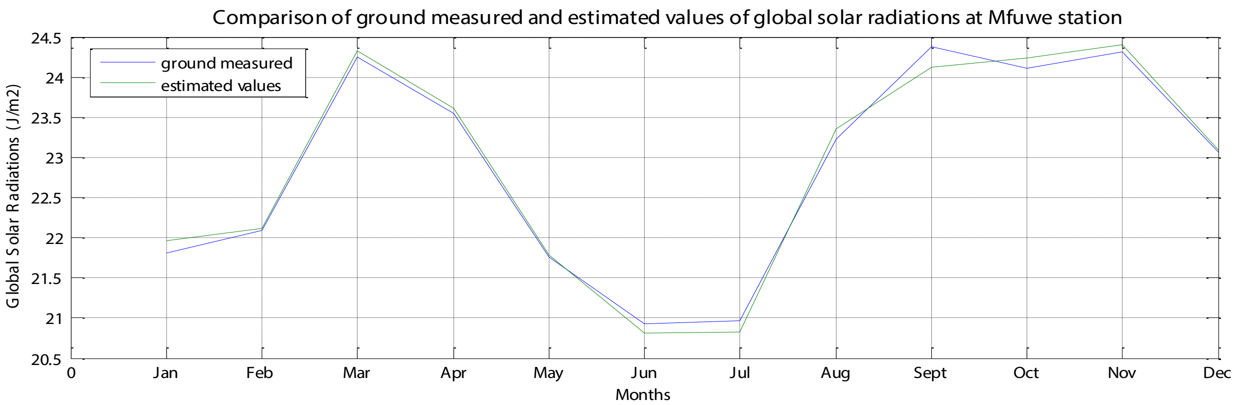


Figure 12 Comparisons of ground measured with estimated values of global solar radiation data sets at Mfuwe

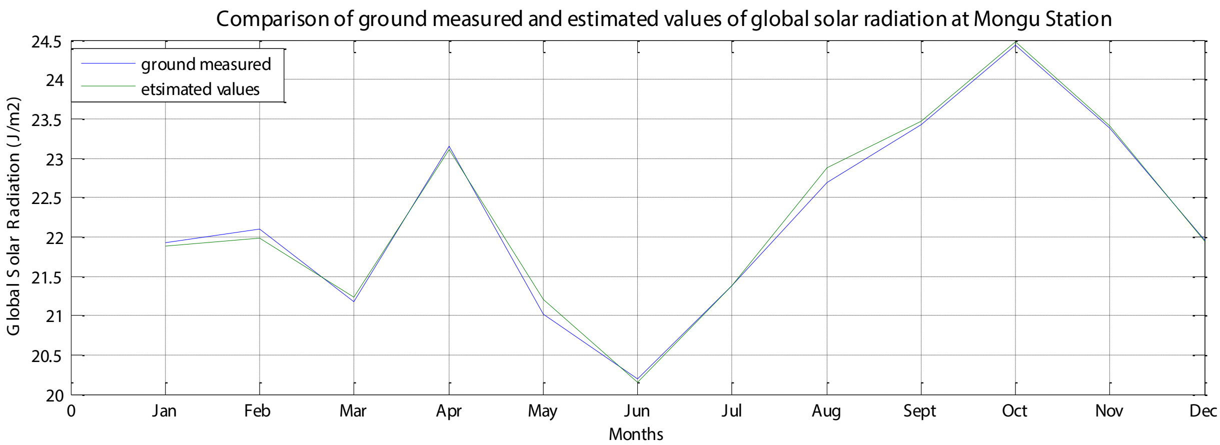


Figure 13 Comparisons of ground measured with estimated values of global solar radiation data sets at Mongu

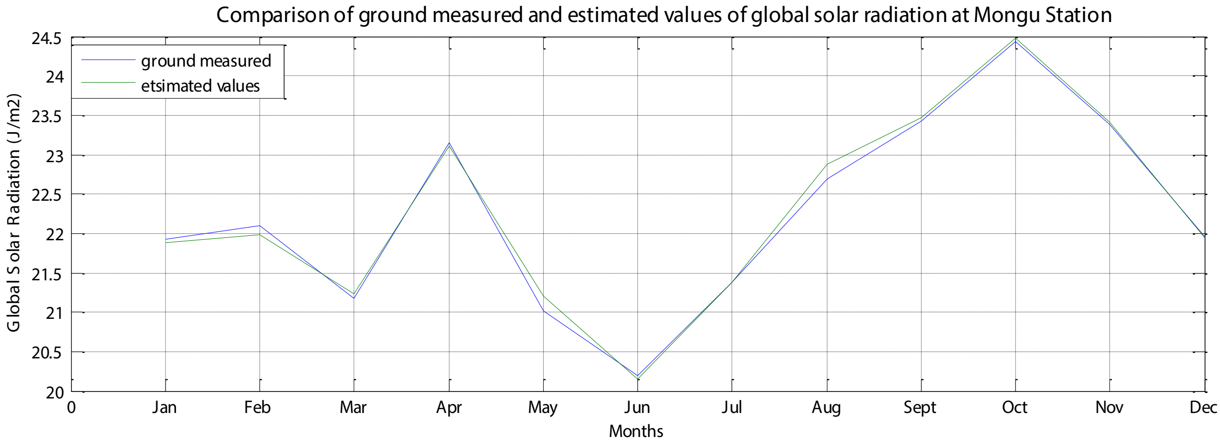


Figure 14 Comparisons of ground measured with estimated values of global solar radiation data sets at Ndola.

From the figures 8 – 14, the deviations between the measured and calculated values are very small. This implies that the models are suitable in calculating the solar radiations at any location in Zambia.

CONCLUSION

The variations of monthly global solar radiation and different meteorological parameters such as sunshine duration, maximum temperature, relative humidity, maximum dew point temperature, cloud cover and pressure were presented and analyzed for the seven selected representative locations in Zambia. The correlation and regression coefficients for each location and also for the whole Zambia were calculated. From the results and considerations, the values of correlation coefficients vary between 97.5% at Kasama and 55.89 % at Mongu and the error did not exceed 0.836. Equations 1 – 7 are used with considerable accuracy to estimate the global solar radiation at the selected locations and Equation 8 for the whole Zambia.

REFERENCES

Beckman W A, Duffie John Solar, 2013. *Engineering of Thermal Processes*, John Wiley & Sons, New Jersey.

Borman, L. G, Ragland, W. L, 2007. *Combustion Engineering*, McGraw-Hil, Singapore.

El-Sebaii, A. A, Trabea, A. A, 2005. *Estimation of Global Solar Radiation on Horizontal Surfaces over Egypt*, Egypt J Solids 28 (1).

Rask Gron Helen, Nixon Chisonga, 2005. *Terminal Evaluation of the UNEP/ GEF Project Renewable Energy- based Electricity Generation*, United Nations Enviroment Prgramme (UNEP).

Sen Z, 2008. *Solar Energy Fundamentals and Modeling Techniques: Amosphere, Enviroment, Climate Change and Renewable Energy*, Springer, Instanbul.

World Energy Council, 2007. *Survey of Energy Resources,* World Energy Council, London.

William B, Geyser M, 2001. *Power from the Sun*, Power of Sun.net.