



Diurnal and seasonal variations of the incoming solar radiation flux at a tropical station, Ile-Ife, Nigeria



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ABSTRACT

The diurnal and seasonal variations of the incoming solar radiation have been studied by analysing two years data measured between January, 2016 to December, 2017 at a Tropical station, Ile-Ife (7.53°N; 4.54°E), Nigeria. The maximum incoming solar radiation flux which occurs between 13:00 – 14:00 LT and varies in the course of the year from $639.5 \pm 171.6 \text{ Wm}^{-2}$ (with large fluctuations) in the wet months (March – October) to $700.7 \pm 105.2 \text{ Wm}^{-2}$ in the dry months (November – February). The large differences in the values, diurnal and seasonal variation of the measured incoming solar radiation between the dry and wet seasons are attributed to the attenuation of the flux by aerosol particles in the dry season and increased cloudiness and humidity in the wet season. The monthly maximum values of 760.3 Wm^{-2} and 732.8 Wm^{-2} indicated a double peak from March to May and October to November respectively while a minimum of about 492.7 Wm^{-2} was recorded from July to August. Similarly, the daytime average had a double peak of 412.5 Wm^{-2} and 361.3 Wm^{-2} in March/April/May and October/November respectively, equally a minimum value of about 249.8 Wm^{-2} was recorded in July/August. The maximum value of the air temperature (which occurs around 15:00 LT) was observed to lag behind the maximum value of the incoming solar radiation (which occurs around 13:00 LT) by 2 hours at the study site. The statistical analysis of the monthly daytime averages of the incoming solar radiation showed that the intensity of the flux received at Ile-Ife (a tropical location) is high (about 67% of the incoming solar radiation are between the interval 325 and 400 Wm^{-2}) throughout the year.

1. Introduction

The incoming solar radiation flux which is a radiant energy, is the sum of the diffused (the incoming shortwave in the shade) and direct radiations incident on the earth's surface in the form of shortwave radiation. This energy is the major means and primary source of energy that drives the hydrological cycle (Iqbal, 1983; Geiger et al., 1995). It also determines the total amount of energy that is available at the earth's surface for life-giving processes on the earth planet, environmental, physical and biological processes (such as photosynthesis, warming of the soil and air, moisture evaporation, evapotranspiration) (Iqbal, 1983).

Several factors such as the time of the day, season, cloud cover, gas molecules, atmospheric aerosols, surface temperature, atmospheric and geographic features, conditions and types of the surface (bare, vegetated, water and so on) usually influenced the intensity of solar radiation received at different parts of the earth's surface (Matzinger et al., 2003; Jegede et al., 2006; Ayoola et al., 2014). Knowledge of the incoming solar

radiation is very important in determining its major contribution to the surface radiation energy balance and its usefulness in solar electrical and direct thermal applications, solar voltaic technology, studying of land-surface processes, validation of crop growth simulation models. As a result of these, a number of investigations on the incoming solar radiation at the earth's surface have been carried out all over the globe by several authors. However in the developing countries such as the tropical region, Nigeria inclusive where large amount of incoming solar radiative flux is received throughout the year, the study and continuous measurements of the flux is still very few despite the relatively simple instrumentation available for measuring it (Jegede, 1997a, 1997b; Ayoola et al., 2014). This is due to technological, electrical and institutional limitations, government interests, high cost of purchasing and maintaining the necessary equipment (Chiemeka, 2008). Due to these challenges, a lot of empirical models which are developed for other geographical locations with atmospheric conditions different from those of the Tropics have been used to estimate the flux at the Tropical

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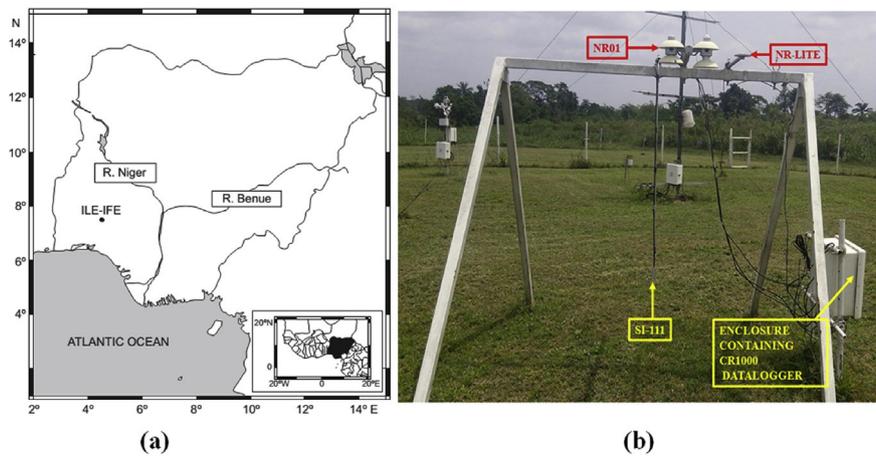


Fig. 1. (a) The outline map of Nigeria showing the location of Ile-Ife, and (b) The arrangements of the sensors at the meteorological site within Obafemi Awolowo University, Ile-Ife.

locations. This led to difficulties in quantifying and understanding the characteristics (diurnal and seasonal variation) and annual abundance of the flux which can form a basis for harnessing it and using it in solar electrical applications and other areas. A number of studies on radiative flux have been carried out by several authors in Nigeria. Some of these studies include, Adeyefa and Adedokun (1991); Adedokun et al. (1995); Iziomon and Aro (1998, 1999); Jegede (1997a, 1997b, 1997c); Jegede et al. (2006); Falodun and Ogolo (2007), Ogolo et al. (2009); Adeniyi et al. (2012); Oladosu et al. (2012); Akpootu and Aruna (2013), Ayoola et al. (2014); Adedoja et al. (2015) just to mention a few. The results from these studies revealed that the incoming solar radiation were attenuated (that is, scattered and absorbed) slightly in the dry months due to significant increase in the turbidity of the lower atmosphere by aerosol particles (such as Harmattan dust) and substantially by high amount of cloud cover and precipitable water molecules during the wet seasons.

The objectives of this paper are to: (a) measure the incoming solar radiation flux and air temperature at Ile-Ife (7.53°N; 4.54°E), Nigeria for a period of two years (January, 2016 to December, 2017) to accomplish the research gaps mentioned above; (b) study in details the diurnal, monthly and seasonal variations and characteristics of the incoming solar radiation and (c) compare the annual mean of the incoming solar radiation with the air temperature.

2. Methodology

The measurement of the incoming solar radiation flux was conducted in an open space at the Teaching and Research (T&R) Farm, Obafemi Awolowo University (O.A.U), Ile-Ife (7.53°N; 4.54°E; altitude 300 m above the sea level, a.s.l), Nigeria (Fig. 1). According to the Köppen's classification, the measurement site is situated within the tropical wet and dry zone of West Africa (Griffiths, 1974) and is characterised as alternating wet and dry periods spanning between March/April to October and November to February, respectively. The measurement site has an area of 50 m × 100 m square and it was covered by grass (*Axonopus fissifolius*) which changed from leafy-green during the wet season to dry twigs during the dry season. Cowpea, Maize and cassava were planted at an appreciable distance from the measurement area. In this area, the relative humidity in the early mornings is usually about 80% except for the dry season when the values sometimes drop to about 70% or even less (Griffiths, 1974). The daytime temperatures ranged between 24.5 °C and 37.7 °C, with the mean temperature, above 26.0 °C. The average annual rainfall ranges between 1000 and 1500 mm coupled with weak surface wind flow that is less than 1.5 ms⁻¹ which is generally a prominent feature in the Tropical area (Hayward and Oguntoyinbo, 1987; Jegede, 1998; Ayoola et al., 2014). The intensity of the incoming

solar radiation received at the surface in Ile-Ife is high all year round due to its proximity to the equator with maxima values of 1100 and 800 Wm⁻² at about 13:00 LT for March and August respectively (Balogun et al., 2003).

The net radiation at the earth's surface can be expressed as:

$$R_N = S_i - S_r + L_d - L_u \quad (1)$$

where R_N is the net radiation, S_i is the incoming solar radiation, S_r is the reflected solar radiation, L_d is the downwelling longwave radiation from the atmosphere and L_u is the upwelling longwave from the earth's surface (Jegede et al., 2006; Ayoola et al., 2014).

Two meteorological mast of heights 1.75 m (triangular-shaped) and 6 m were installed at the measurement site. On the 6 m mast, a temperature and relative humidity Probe (model HMP45C) was placed at a height of 2.0 m above the ground level to measure the air temperature and relative humidity. Also installed on the mast are pyranometer, rain gauge, two cup anemometers, wind vane and a NR-LITE double-dome net radiometer. On the 1.75 m mast, a four-component net radiometer (model NR01, Hukseflux Inc., USA) was mounted at a height of 1.72 m to measure the components of net radiation among the other devices (e.g. NR-LITE net radiometer and SI-111 precision infrared thermometer sensors). The incoming solar radiation flux (Wm⁻²) was measured with a pyranometer (type SR01, ISO-class, sensitivity – 15.74 μV/Wm⁻²) that faces upward contained in the NR01 sensor. The specifications (sensitivities and calibration constants) provided by the manufacturers were used for each sensor. All the sensors were calibrated before and after measurements and no significant drift was observed in the calibration constants of the instruments after the measurement period. All the sensors were connected directly by cables to dedicated dataloggers (model CR1000, Campbell Scientific, USA) using a differential voltage measurement to reject noise, enhance better accuracy and quality data and to measure the output signals as low level voltages of about ±50 mV (Fig. 1). The raw data was sampled at 10 seconds interval and subsequently stored as 1-minute average in the datalogger. The output data was subjected to standardised quality control and assurance (QC/QA) procedures to ensure data consistency and for removal of spurious data and replacement of missing values. After this, the dataset was sorted into daily (24-hours) data files, reduced from 1-minute average to 1-hour averages and subjected to further analysis using proprietary software. The incoming solar radiation measurements acquired for this study covered the period from January, 2016 to December, 2017 along with visual records of the weather conditions. At Ile-Ife (approximately: 7.5°N), the sunrise and sunset times are around 07:00 and 19:00 LT (GMT +1), respectively.

2016

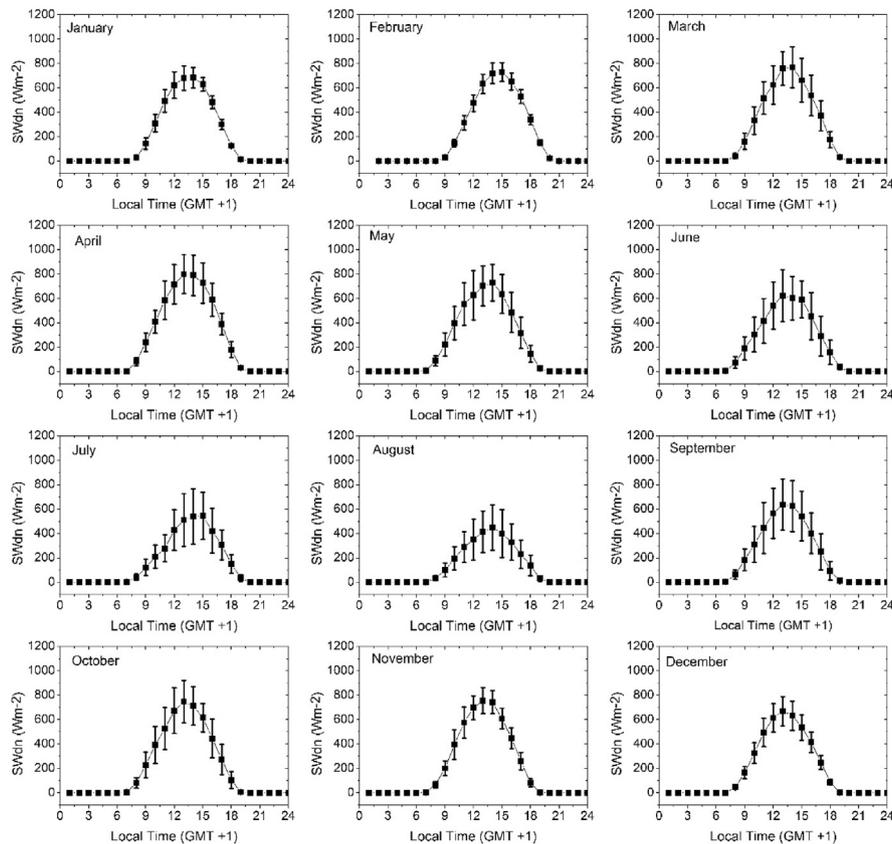


Fig. 2. Diurnal variation of the monthly mean of the incoming solar radiation flux (SWdn) at Ile-Ife, Nigeria for January to December, 2016.

3. Results and discussion

The diurnal variation of the incoming solar radiation flux measured at the study site from January, 2016 to December, 2017 is presented in Figs. 2 and 3. The 1-hr average values of the radiative fluxes together with the corresponding standard deviation (SD) are plotted in these figures. Figs. 2 and 3 show that the trend of the incoming solar radiation observed for all the months was positive throughout the period of observation. In the morning at sunrise between 07:00 LT and 08:00 LT, the incoming solar radiative flux increases steadily from zero to positive values and reaches a local maxima at about 13:00 to 14:00 LT (local noon). In the late afternoon periods as the sun begins to set, the values of the incoming solar radiation steadily decrease and drop to zero from about 20:00 LT and throughout the evening and night periods.

In Figs. 2 and 3, the diurnal patterns and the values of the hourly averaged incoming solar radiation from January to December, 2016 and 2017 vary in accordance with the change of dry (November to February) to wet (March/April to October) season.

The maximum values of the incoming solar radiation for the months of January and December which are the peaks of the dry season at the location were $666.4 \pm 88.4 \text{ Wm}^{-2}$ (at 14:00 LT) and $664.9 \pm 119.9 \text{ Wm}^{-2}$ (at 13:00 LT) respectively. The low values of the incoming solar radiation recorded in January and December can be attributed to the high turbidity of the atmosphere. The high aerosol loading at the study site arises from the prevalence of wind-blown dust of Saharan origin (north-easterly surface wind) known locally as harmattan dust (Okogbue et al., 2009; Falaiye et al., 2014). In addition, the low values recorded in January and December are due to the prevalence of particulates such as biomass burning aerosol (which arise from bush burning activities) at this time of the year. As from the month of February which marks the beginning of transition from dry to wet season, the maximum values of the incoming

solar radiation increased from $725.0 \pm 71.8 \text{ Wm}^{-2}$ (at 14:00 LT) to $776.6 \pm 139.1 \text{ Wm}^{-2}$ (around 14:00 LT) in March. The increasing values of the incoming solar radiation can be attributed to lowering of the turbidity in the atmosphere due to the removal of the suspended aerosol particles by showers of rain in these months when compared to January and December. As such, there is less attenuation of the incoming solar radiation and increase in the amount of direct solar radiation that reaches the earth's surface in February and March than in January and December. Also, the same figures show that the maximum values for the incoming solar radiation decreased to about $547.7 \pm 208.5 \text{ Wm}^{-2}$ and $437.7 \pm 171.9 \text{ Wm}^{-2}$ in July and August which are the peak of the wet season respectively. The decrease in the values of the incoming solar radiation observed in July and August can be attributed to the high amount of cloudiness, increase in relative humidity, precipitable water molecules in the atmosphere and frequent thunderstorm activities (Ayoola et al., 2014).

It can be observed from Figs. 2 and 3 that the fluctuations of the incoming solar radiation (standard deviation, SD) in the dry months is less than 145 Wm^{-2} and up to about 225 Wm^{-2} in the wet months. The large fluctuations observed in the wet months can be attributed to the attenuating effects of clouds and water vapour (which vary temporally and spatially) on the incoming solar radiation. In the dry months, the absence of cloud and the attenuating effects of aerosols on the incoming solar radiation is more pronounced (Iqbal, 1983; Jegede, 1997b, 1997c; Jegede et al., 2006; Adeniyi et al., 2012; Ayoola et al., 2014). The peak values of the incoming solar radiation (ranging $437.7 \pm 171.9 \text{ Wm}^{-2}$ and $776.6 \pm 139.1 \text{ Wm}^{-2}$) obtained in this study is comparable with the range of values (404.8 ± 54 to $750.3 \pm 41 \text{ Wm}^{-2}$) obtained at the International Institute of Tropical Agriculture, Ibadan (7.38° N , 3.93° E) between 1997 – 2001 by Adeniyi et al. (2012). The peak value of $725.0 \pm 71.8 \text{ Wm}^{-2}$ obtained for the measured incoming solar radiation in February falls within the range of values 600 Wm^{-2} and 800 Wm^{-2} as reported at Ile-Ife

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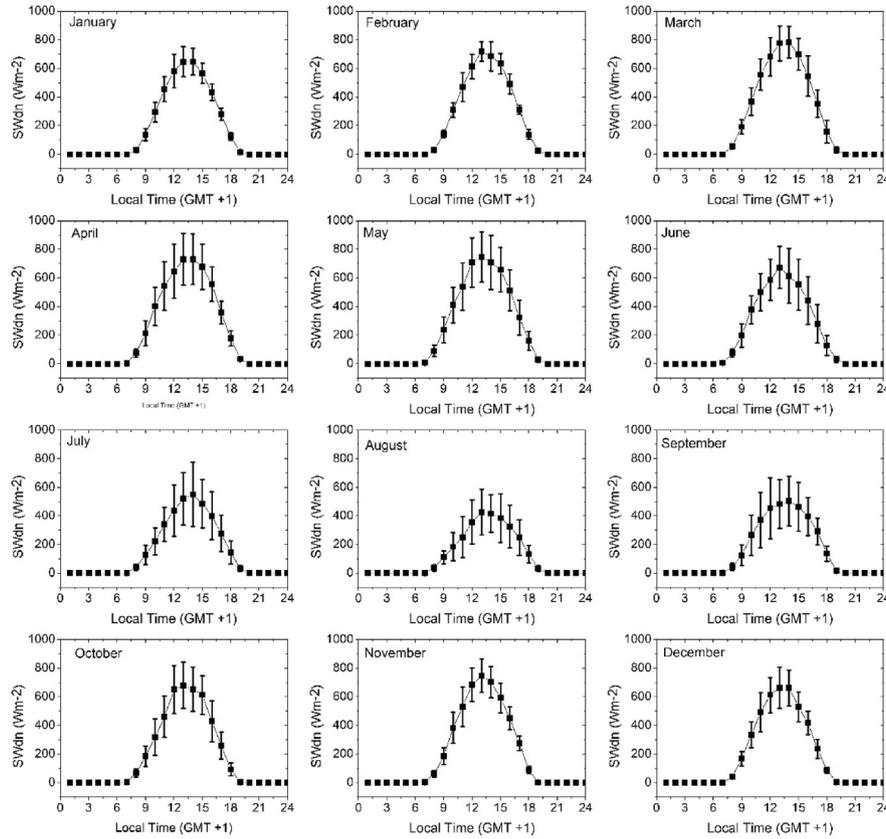


Fig. 3. Diurnal variation of the monthly mean of the incoming solar radiation flux (SWdn) at Ile-Ife, Nigeria for January to December, 2017.

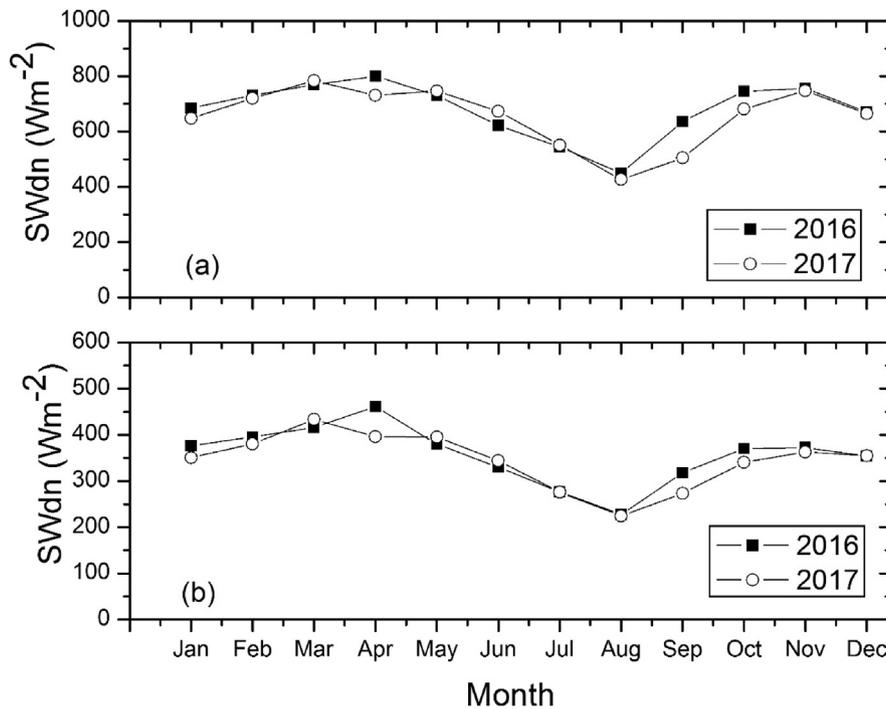


Fig. 4. Variation of (a) maximum diurnal values and (b) daytime monthly mean of the incoming solar radiation flux (SWdn) at Ile-Ife, Nigeria for January – December, 2016 and 2017.

by Jegede et al. (2004).

The variation of the monthly maximum and daytime monthly mean of

the incoming solar radiation flux at the study site from January to December, 2016 and 2017 is presented in Fig. 4. It was observed that the

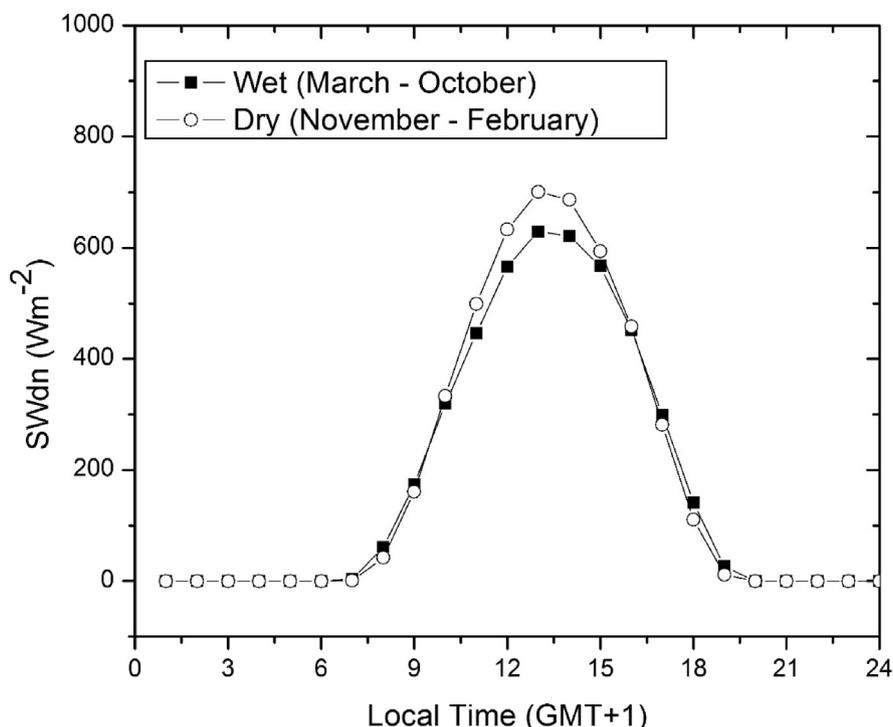


Fig. 5. Diurnal variation of the incoming solar radiation flux (SWdn) at Ile-Ife, Nigeria for both the wet (March – October) and dry (November – February) seasons, covering the period of January, 2016 to December, 2017.

Table 1

Diurnal variation of the incoming solar radiation flux (SWdn) with the corresponding standard deviation measured at Ile-Ife, Nigeria for January, 2016 – December, 2017.

Local Time (GMT +1)	2016 SWdn (Wm ⁻²)	2017 SWdn (Wm ⁻²)	Period Mean SWdn (Wm ⁻²)
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	2.5 ± 1.7	2.6 ± 1.5	2.5 ± 1.6
8	56.7 ± 27.8	54.2 ± 22.5	55.5 ± 25.1
9	175.5 ± 70.0	168.4 ± 62.1	171.9 ± 66.1
10	324.5 ± 109.2	323.0 ± 102.7	323.7 ± 105.9
11	470.7 ± 139.0	459.8 ± 136.9	465.2 ± 137.9
12	591.5 ± 153.3	585.0 ± 149.8	588.2 ± 151.5
13	668.5 ± 154.7	651.3 ± 144.3	659.9 ± 149.5
14	667.5 ± 151.1	638.8 ± 148.6	653.1 ± 149.9
15	595.4 ± 140.0	572.0 ± 133.3	583.7 ± 136.6
16	461.8 ± 133.3	450.4 ± 121.0	456.1 ± 127.2
17	298.6 ± 101.9	291.4 ± 88.5	295.0 ± 95.2
18	132.6 ± 58.5	130.8 ± 51.3	131.7 ± 54.9
19	21.1 ± 12.5	21.4 ± 12.2	21.3 ± 12.3
20	0	0	0
21	0	0	0
22	0	0	0
23	0	0	0
24	0	0	0
Mean	186.1 ± 52.2	181.2 ± 48.9	183.7 ± 50.6

values of both the maximum and daytime monthly mean of the incoming solar radiation flux were higher as expected with similar trend. As shown in Fig. 4 (a), a double peak values of 760.3 Wm⁻² and 732.8 Wm⁻² were observed around March/April/May and October/November respectively while a minimum of about 492.7 Wm⁻² was observed in July/August (the peak of the rainy season). Similarly in Fig. 4 (b), a double peak values of about 412.5 Wm⁻² and 361.3 Wm⁻² were observed in March/April/May

and October/November respectively while a minimum of about 249.8 Wm⁻² was observed in July/August. The minimum values reported in July/August can be attributed to the attenuating effect of clouds (and possibly aerosol particles) on the incoming solar radiation over the study site which are highly variable on the temporal and spatial scales (Jegade, 1997c).

The diurnal variation of the incoming solar radiation flux over the wet (March – October) and dry (November – February) seasons at the study site from January, 2016 to December, 2017 is presented in Fig. 5. As shown in the figure, the diurnal patterns and trends of the two seasons are similar except that the values of the incoming solar radiation were lower during the wet season than the dry season. The maximum value of the incoming solar radiation of about 700.7 ± 105.2 Wm⁻² and 639.5 ± 171.6 Wm⁻² were recorded for the dry and wet seasons respectively. The large differences in the diurnal variation of the incoming solar radiation between the dry and wet seasons show that clouds attenuate the flux more than the hazy conditions arising from the harmattan dust of the dry season (Jegade, 1997b, 1997c; Adeniyi et al., 2012; Oladosu et al., 2012).

The hourly mean of the incoming solar radiation flux measured at Ile-Ife for the month of January to December, 2016 and 2017 is presented in Table 1. As shown in the table, the maximum value (>650 ± 140 Wm⁻²) of the incoming solar radiation was observed to occur around the local noon (13:00 LT). However, the minimum values of zero were recorded in the midnight hours up to the early morning with the obvious implication that there is absence of direct solar radiation at the surface during these periods.

The diurnal variation of the incoming solar radiation flux and air temperature from January to December, 2016 and 2017 is presented in Fig. 6. As shown in the figure, the diurnal patterns and trends of the two variables are similar. The maximum value of the incoming solar radiation was observed around 13:00 LT while the maximum value of the air temperature was observed around 15:00 LT which shows a time lag of about 2 hours between the time of occurrence of the two variables. The lag between the maximum time of the incoming solar radiation and the air temperature implies that there is usually a delay in the heating of the atmospheric column – which starts at the ground, by the incoming solar radiation (Garratt, 1992). Jegede (1997b) observed that the time lag

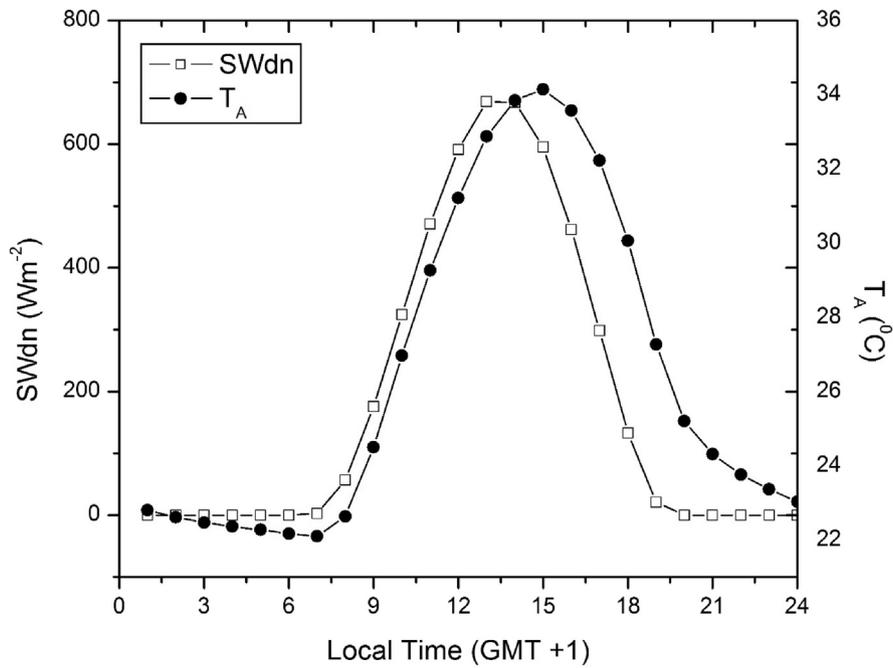


Fig. 6. Daily variation of the incoming solar radiation flux (SWdn) and air temperature (T_A) at Ile-Ife, Nigeria for January, 2016 to December, 2017.

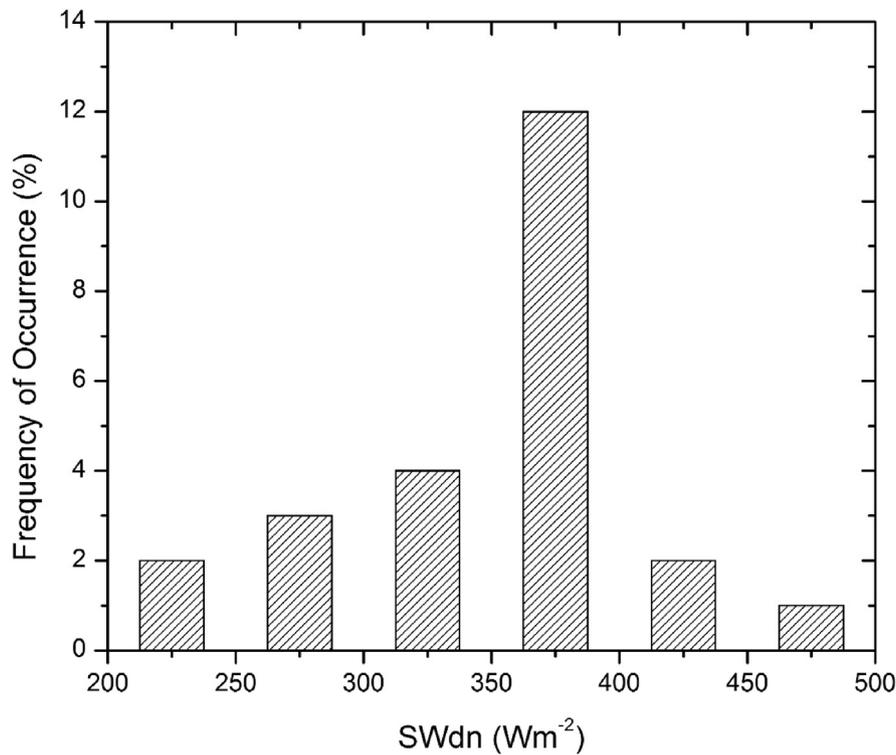


Fig. 7. Frequency distribution of the monthly averages of the daytime incoming solar radiation flux (SWdn) at Ile-Ife, Nigeria for January, 2016 – December, 2017.

between the time of maximum net radiation and that of the air temperature at Osu (7.43° N, 4.58° E) a nearby tropical station is about 2 hours. A time lag of about 3 hours was observed between the incoming solar radiation and air temperature in Ibadan (7.38° N, 3.93° E) by Adeniyi et al. (2012).

The frequency of occurrence of the monthly daytime averages of the incoming solar radiation for January, 2016 – December, 2017 is presented in Fig. 7 and Table 2. As shown in the figure and table, the

distribution of the incoming solar radiation has a high value (about 50%) between 375 and 400 Wm⁻² and more than half of the value of the incoming solar radiation which is about 67% are between interval 325 and 400 Wm⁻². These show that the intensity of the incoming solar radiation received at Ile-Ife (a tropical location) is high almost throughout the year due to its proximity to the equator (Balogun et al., 2003; Oladosu et al., 2012).

Table 2

Frequency distribution of the monthly daytime averages of the incoming solar radiation flux (SWdn) at Ile-Ife, Nigeria for January, 2016 – December, 2017.

SWdn (Wm^{-2}) Interval	Frequency of Occurrence	Percentage Frequency (%)
225–250	2	8.3
275–300	3	12.5
325–350	4	16.7
375–400	12	50.0
425–450	2	8.3
475–500	1	4.2
Total	24	100

4. Conclusion

The diurnal, seasonal and annual variations of the incoming solar (shortwave) radiation flux measured at Ile-Ife (7.53°N ; 4.54°E), Nigeria between January, 2016 – December, 2017 have been presented in this work. The diurnal range of the incoming solar radiation during the dry months ($700.7 \pm 105.2 \text{ Wm}^{-2}$) was found to be higher than the range during the wet months ($639.5 \pm 171.6 \text{ Wm}^{-2}$). The monthly maximum has double peak values of 760.3 Wm^{-2} and 732.8 Wm^{-2} recorded in March/April/May and October/November respectively and a minimum of about 492.7 Wm^{-2} around July/August. The daytime mean has double peak values of 412.5 Wm^{-2} and 361.3 Wm^{-2} recorded in March/April/May and October/November respectively and a minimum of about 249.8 Wm^{-2} around July/August. The monthly mean values of the incoming solar radiation varied seasonally and its annual variation showed a bimodal distribution. The large differences in the values of the diurnal and seasonal variation of the measured incoming solar radiation between the dry and wet seasons are attributed to the attenuation of the flux by aerosol particles in the dry season and increased cloudiness and humidity in the wet season. The time of occurrence of the maximum air temperature and the maximum incoming solar radiation showed a lag of about 2 hours for the observation periods. The statistical analysis (frequency distribution) of the monthly daytime averages of the incoming solar radiation showed that the intensity of the flux received at Ile-Ife (a tropical location) is high (about 67% of the incoming solar radiation are between interval 325 and 400 Wm^{-2}) almost throughout the year.

Declarations

Author contribution statement

O. O. Soneye: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed analysis tools or data; and Wrote the paper.

M. A. Ayoola: Performed the experiments; Contributed analysis tools or data.

I. A. Ajao: Performed the experiments.

O. O. Jegede: Conceived and designed the experiments; Performed the experiments; Contributed analysis tools or data tools.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

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