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Original Research Article

Investigation of the Earth's Albedo using Meteorological Parameters over Nguru, Nigeria

Akpootu D. O.[1*], Umar M.[1], Abdullahi Z.[2]

[1]Department of Physics, Usmanu Danfodiyo University, Sokoto, Nigeria
[2]Department of Physics, Adamu Augie College of Education, Kebbi State, Nigeria

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***Corresponding author:** Akpootu D. O.
Department of Physics, Usmanu Danfodiyo University, Sokoto, Nigeria

Abstract

Estimation and investigation of an earth's albedo is significant in the evaluation and design of solar energy collectors, atmospheric radiative transfer and studies that relates to atmospheric thermal balance. This study employed the shortwave solar energy balancing at the edge of the Earth's atmosphere to estimate and compare the variation of albedo for Nguru situated in the Sahelian region of Nigeria, using measured monthly mean daily meteorological parameter of global solar radiation obtained from the National Aeronautics and Space Administration (NASA) during the period of thirty-eight years (1984 – 2021). The variation of albedo with surface temperature, maximum wavelength, clearness index, global solar radiation, relative humidity and mean temperature for this location was investigated. The results in this study show that the estimated surface albedo depicts a direct opposite relationship with the clearness index, an inverse relationship with the emitting Earth's surface temperature and a direct relationship with the wavelength for the studied location. The highest and lowest values of albedo for the location was in the months of August and January with 0.4628 and 0.3403 respectively. The emitting Earth surface temperature ranged between 238.5837 K in August and 251.1607 K in January. These values agreed closely to the standard emitting Earth surface temperature value (255.0000 K). The maximum emitting wavelength values for the location revealed that the radiation is longwave and is found within the infrared region of the electromagnetic spectrum.

Keywords: Albedo, earth surface temperature, global solar radiation, maximum wavelength, Nguru.

1. INTRODUCTION

Solar radiation data has been considered as an essential requirement to conduct feasibility studies for solar energy systems [1]. The solar radiation reaching the Earth's surface depends upon the climatic condition of the location, hence, the study of what happens to sunlight as it passes through the atmosphere is crucial to many aspects of science and general knowledge [2]. Over the years, the amount of solar radiation reaching the Earth's surface is being modified through reflection, scattering and absorption in the atmosphere. The fraction of the incident solar radiation that is reflected and scattered back into space is called albedo [3]. Albedo is related to reflection of solar radiation at a surface and therefore defined in terms of it, as the ratio of the reflected solar radiation to the incident solar radiation at the surface, i.e., H_r/H_o. The extraterrestrial radiation, H_o at the edge of the atmosphere, from the sun, is considered the incident solar radiation. Albedo or reflection coefficient is also known as reflectance or reflectivity of a surface; by this, the surface albedo of the Earth is regarded the same as planetary albedo by many scientists [4].

The average overall albedo of the Earth, its planetary albedo, is about 0.3. This fraction of incoming radiation is reflected back into space. The other 0.7 part of the incoming solar radiation is absorbed by our planet [1]. The fraction of the incident radiation that is reflected from the surface is called the albedo. Albedo plays a major role in the energy balance of the earth's surface, as it defines the rate of the absorbed portion of the incident solar radiation [5]. It is assumed however that the reflected radiation, H_r, is both diffuse and specular in nature, that is, it is diffuse if the reflected radiation is uniform or isotropic in all angular directions, and specular if the surface of reflection is smooth with respect to the wavelength of the incident radiation such that the laws of reflection are satisfied [4]. The albedo value ranges from 0 to 1. The value of 0 refers to a blackbody, a theoretical media that absorbs 100% of the incident radiation. Albedo ranging from

0.1–0.2 refers to dark-colored, rough soil surfaces, while the values around 0.4–0.5 represent smooth, light-colored soil surfaces. The albedo of snow cover, especially the fresh, deep snow, can reach as high as 0.9. The value of 1 refers to an ideal reflector surface (an absolute white surface) in which all the energy falling on the surface is reflected [5]. materials with high albedo and emittance attain low temperature when exposed to solar radiation, and therefore reduce transference of heat to their surroundings. Thus, albedo is an important input parameter or quantity in evaluating the total insolation on a building or a solar energy collector. It is also important in the studies dealing with thermal balance in the atmosphere. The Earth's albedo affects the amount of Sun-light the planet absorbs. It plays a major role in the energy balance of the Earth's surface, as it defines the rate of the absorbed portion of the incident solar radiation. Hence, it has a direct effect on Earth's energy budget and, therefore, global temperatures. If the Earth receives more energy from the Sun than it sends back to space, the Earth gets warmer. On the other hand, if the Earth reflects more of the Sun's energy than it absorbs, the Earth gets colder. Some studies on the albedo of the Earth's atmosphere for different locations have been investigated [6]. The observed albedo assumed that the radiation field is isotropic. Albedo, as a property of a surface, therefore, can be used to determine the brightness of a surface [7]. Today, albedo is a major concern for humans worldwide. Albedo is very useful in the studies dealing with thermal balance in the atmosphere. It is an important input parameter or quantity in evaluating the total insolation on a building or a solar energy collector because, materials with high albedo and emittance attain low temperature when exposed to solar radiation, and therefore reduce transference of heat to their surroundings. It is commonly used in astronomy to describe the reflective properties of planets, satellites, and asteroids [8]. Albedo is an important concept in climatology and astronomy, as well as in calculating reflectivity of surfaces in LEED sustainable rating systems for buildings [9].

The purpose of this study is to (i) estimate the value of the earth's albedo at Nguru, Nigeria (ii) compares the emitting earth surface temperature for the study area to the standard value of emitting surface temperature of the earth (iii) to investigate the type of radiation based on the values of the wavelength obtained for the study area (iv) investigate the variation of albedo with the meteorological parameters

2. METHODOLOGY

The monthly mean daily measured global solar radiation, minimum and maximum temperature and relative humidity data used in this study was obtained from the National Aeronautics and Space Administration (NASA). The period under focus was thirty-eight years (1984 – 2021). The mean temperature was obtained by taking the average of the minimum and maximum temperature. The location under study was Nguru, situated across the Sahelian region of Nigeria.

The monthly mean daily extraterrestrial radiation, H_o on a horizontal surface was calculated from the expression given by [10 – 15].

$$H_o = \left(\frac{24}{\pi}\right) I_{sc}\left[1 + 0.033cos\left(\frac{360n}{365}\right)\right]\left[cos\varphi cos\delta sin\omega_S + \left(\frac{2\pi\omega_S}{360}\right) sin\varphi sin\delta\right] \quad (1)$$

where I_{sc} is the solar constant (=1367 Wm^{-2}), φ is the latitude of the site, δ is the solar declination and ω_S is the mean sunrise hour angle for the given month and n is the number of days of the year starting from 1st of January to 31st of December. The solar declination, δ and the mean sunrise hour angle, ω_S was calculated using the following equations [16 – 22].

$$\delta = 23.45 \sin\left\{360\left(\frac{284+n}{365}\right)\right\} \quad (2)$$

$$\omega_S = \cos^{-1}(-tan\varphi tan\delta) \quad (3)$$

The shortwave solar energy balancing at the edge of the Earth's atmosphere was computed using the expression [23].

$$\frac{H_m}{H_o} + \frac{H_a}{H_o} + \frac{H_r}{H_o} = 1 \quad (4)$$

where H_m is the measured global solar radiation (MJm^{-2}day^{-1}), H_o is the extraterrestrial radiation (MJm^{-2}day^{-1}), the ratio $\frac{H_m}{H_o}$ is the fraction of the extraterrestrial radiation, H_o is transmitted through the atmosphere to the ground surface, is known as the clearness index [24, 25]. H_a is the absorbed solar radiation, the ratio $\frac{H_a}{H_o}$ is the solar energy fraction absorbed, and is known as the absorption co-efficient or absorbance, and $\frac{Hr}{Ho}$ would be the solar energy fraction reflected back to space, and is known as the reflection coefficient or reflectance [23] and H_r is the shortwave reflected radiation. According to Babatunde [23] the ratio $\frac{H_a}{H_o}$ is expected to be very small in value when compared with the other ratios given in equation (4) and therefore can be neglected, i.e., $\frac{H_a}{H_o} \ll 1$. Therefore equation (4) becomes

$$\frac{H_m}{H_o} + \frac{H_r}{H_o} \approx 1 \quad (5)$$

From this, an expression for estimating the reflectivity or albedo was obtained as

$$\frac{H_r}{H_o} = 1 - \frac{H_m}{H_o} \quad (6)$$

The flux density of longwave radiation emitted by the Earth, F_E, given by the Stefan-Boltzmann law [26] is expressed as

$$F_E = \sigma T_E^4 \quad (7)$$

where σ is the universal Stefan-Boltzmann constant, σ = 5.67 × 10^{-8} Wm^{-2} K^{-4}, and T_E is the Earth's temperature, in Kelvin (K). F_E is also given [26] as

$$F_E = \frac{\left(1-\frac{H_r}{H_o}\right)F_S}{4} \quad (8)$$

where $\frac{H_r}{H_o}$ is the planetary albedo of the Earth for the study area and F_s is the flux density of solar radiation incident upon the Earth (1368 Wm^{-2}). If equations (7) and (8) are combined together the following equation was obtained and that relates the surface temperature of the Earth, T_E to its albedo for the study locations [26 – 27] as

$$T_E = \left[\left(\frac{\left(1-\frac{H_r}{H_o}\right)F_s}{4\sigma}\right)\right]^{1/4} \quad (9)$$

Equation (9) shows that the temperature T_E decreases as albedo increases. In atmospheric science the term "shortwave" ($\lambda < \mu m$) refers to the wavelength band that carries most of the energy associated with solar radiation and "longwave" ($\lambda > 4\ \mu m$)refers to theband that encompasses most of the terrestrial (Earth-emitted) radiation. In the radiative transfer literature, the spectrum is typically divided into the regions. Shown in figure 1. The relatively narrow visible region, which extends from wavelengths of 0.39 to 0.76μm, is define by the range of wavelengths that the human eye is capable of [26]. The near infrared region, which extends from the boundary of the visible up to ~ 4 μm,which is dominated by solar radiation, whereas the remainder of the infrared region is dominate by terrestrial (i.e., Earth emitted) radiation [26]. Microwave radiation is not important in the Earth's energy balance but it is widely used in remote sensing because it is capable of penetrating through clouds [26]. The maximum wavelength of emission at temperature, T_E was obtained using the Wien's displacement law [26] as

$$\lambda_m = \frac{2897}{T_E} \quad (10)$$

λ_m is expressed in micrometers and T_E in Kelvin.

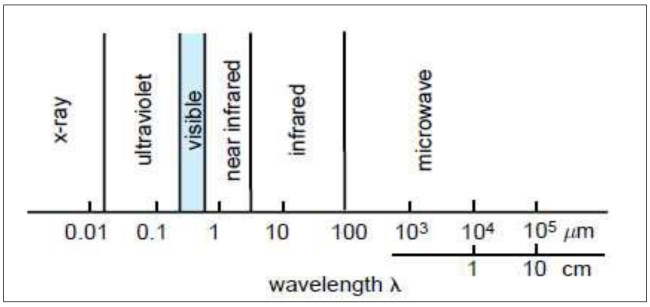

Figure 1: The electromagnetic spectrum [26]

3. RESULTS AND DISCUSSION

Table 1: Monthly average daily albedo, clearness index, short wave reflected radiation, surface temperature and wavelength for Nguru (1984 - 2021)

Month	H_r/H_o	H_m/H_o	H_r(MJm^{-2} d^{-1})	T(K)	Wavelength (μm)
Jan	0.3403	0.6597	20.1988	251.1607	11.5344
Feb	0.3466	0.6534	21.8260	250.5589	11.5622
Mar	0.3542	0.6458	23.4587	249.8220	11.5963
Apr	0.3690	0.6310	23.9703	248.382	11.6635
May	0.3898	0.6102	23.2702	246.3106	11.7616
Jun	0.4122	0.5878	22.2257	244.0124	11.8723
Jul	0.4312	0.5689	21.5128	242.0204	11.9701
Aug	0.4628	0.5371	20.3087	238.5837	12.1425
Sep	0.4114	0.5886	21.6066	244.0998	11.8681
Oct	0.3722	0.6278	21.4181	248.0616	11.6786
Nov	0.3469	0.6531	20.3372	250.5282	11.5636
Dec	0.3450	0.6550	19.3983	250.7124	11.5551

Table 1 above shows the variation of the monthly average daily albedo, clearness index, short wave reflected radiation, surface temperature and wavelength for Nguru study area. The monthly average daily albedo increases from the months of January to August, decreases from months of September to December. The clearness index decreases from the months of January to August, increases from the months of September to December. The short wave reflected radiation increases from the months of January to April, decreases from the months of May to August but slightly increases in the month of September and decreases from the months of October to December. The surface temperature decreases from the months of

January to August and increases from the months of September to December. The wavelength increases from the month of January to August and decreases in the months of September to December indicating that the surface temperature and the maximum wavelength show opposite relationship for Nguru.

3.1 Analysis of the variation of albedo, surface temperature and maximum wavelength for Nguru

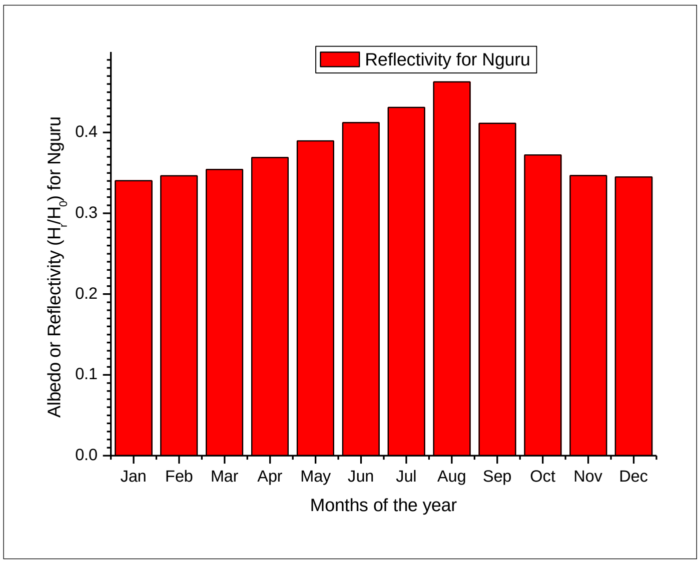

Figure 2: Monthly average daily reflectivity (H_r/H_o) for Nguru (1984-2021)

Figure 2 shows the monthly average daily planetary albedo for the study area (Nguru). The figure stipulates that high values of an albedo were recorded in the months of July, August and September with the highest in August (0.4628) and relatively low values of an albedo were in the months of November, December and January with the lowest values in January (0.3403). The highest value of albedo recorded in the month of August shows that this is the month where there is peak of rainy season in the study area and a predominantly cloudy month, this indicates that reflection of solar radiation by the planet earth in this region are mostly due to clouds, aerosols and air molecules of which cloud is the chief. The surface albedo obtained for the study area ranged between 0.3403 and 0.4628 with the highest values in the month of August (0.4628) during the peak period of rainy season and the lowest in January (0.3403) during the onset of dry season when it was relatively cloudless and dustless. The values of the albedo obtained for this study area under investigation compares favorably well with that of Babatunde *et al.*, [28] where they found the albedo for Ilorin, Nigeria ranging between 0.3610 and 0.6440. The highest value of 0.6440 recorded in their study was found the month of August and the lowest value of 0.3610 recorded was found in the month of November.

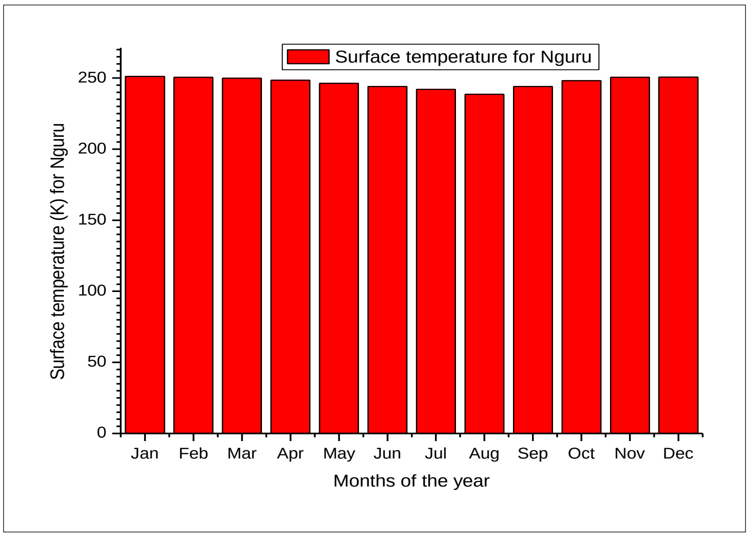

Figure 3: Monthly average daily surface temperature (K) for Nguru (1984-2021)

Figure 3 shows the variation of the radiated temperature by the earth for the study area (Nguru). The highest temperature was recorded in the month of January (251.1607 K) as this is anticipated because the albedo is low during this period, thereby allowing more radiation into the earth which consequently increases the temperature. The lowest temperature was recorded in the month of August (238.5837 K), this is the haziest month for this region, where the rainy season is at its topmost; the low temperature is expected, due to high reflection of solar radiation. In this present study, the surface temperature ranged between the values 238.5837 K –251.1607 K which compares constructively well with standard value for the emitting surface temperature of the earth (255.0000 K). The results revealed that there is an inverse relationship between the earth emitting surface temperature and the planetary albedo.

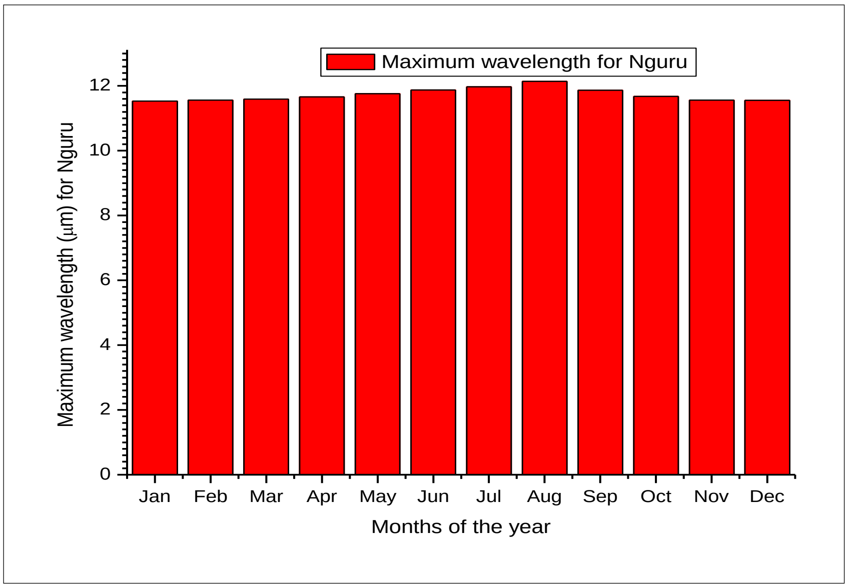

Figure 4: Monthly average daily wavelength (μm) for Nguru (1984-2021)

Figure 4 shows the variation of monthly average daily maximum emitting wavelength for the study area (Nguru). The uppermost peak wavelength was estimated in the month of August (12.1425 μm) and the lowest in the month of January (11.5344 μm). The peak wavelength ranged in the values between 11.5344 μm – 12.1425 μm this value agrees with that reported in radiative transfer literatures [26] that for longwave radiation ($\lambda > 4\ \mu m$). This shows that the radiation is terrestrial (Earth emitted), and therefore within the infrared region.

3.2 Analysis of the variation of reflectivity with clearness index for Nguru

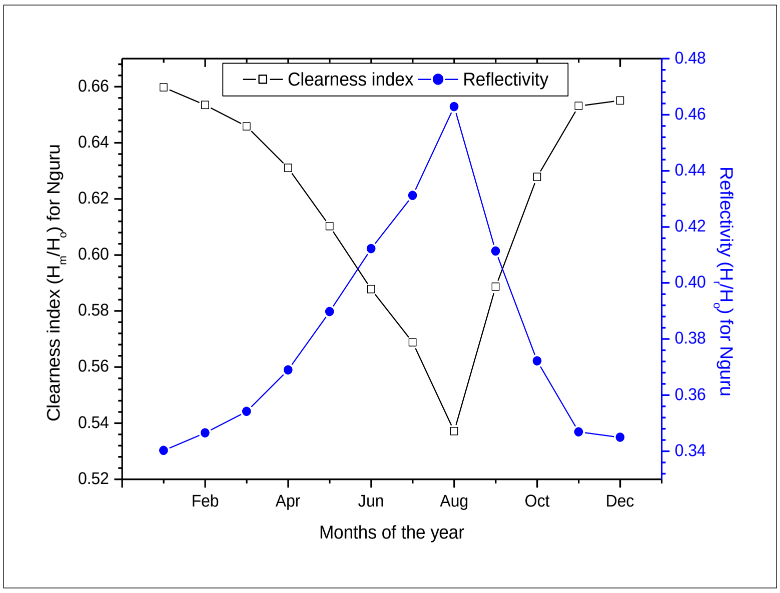

Figure 5: Comparison between reflectivity (H_r/H_o) and clearness index (H_m/H_o) for Nguru (1984-2021)

Figure 5 compares the variation of the albedo and the clearness index for Nguru during the study period. It can be seen from the figure that the reflectance has opposite characteristics to the clearness index. The size of the reflectance or albedo shows the notch of the surface brightness and the amount of the global solar radiation reflected back to space. Thus, when the sky is relatively cloudless, albedo or reflection coefficient would be relatively small, therefore, more radiation would be available to solar energy devices on the Earth. The measured global solar radiation (H_m) and the shortwave reflected radiation (H_r) are fractions of the extraterrestrial radiation (H_o), therefore, the clearness index and reflectance can be compared. The values of the clearness index are more than those of the reflectance, throughout the months for the period under investigation for Nguru, the implication of this, is that, since the global solar radiation is towards the ground surface and the shortwave reflected radiation is towards the space, therefore, the global solar radiation received on the Earth's surface is more than the reflected radiation lost to space throughout the months in the location; signifying the availability of abundant solar radiation in the region. The highest value of albedo and the lowest value of clearness index were found in August. This is where the region is said to have its peak value during the rainy season. The highest and lowest values of clearness index was observed in the months of January and August with 0.6597 and 0.5371 respectively while the highest and lowest values of albedo was recorded in the months of August and January with 0.4628 and 0.3403 respectively confirming their opposite relationship as shown in the figure.

3.3 Variation of reflectivity with meteorological parameters for Nguru

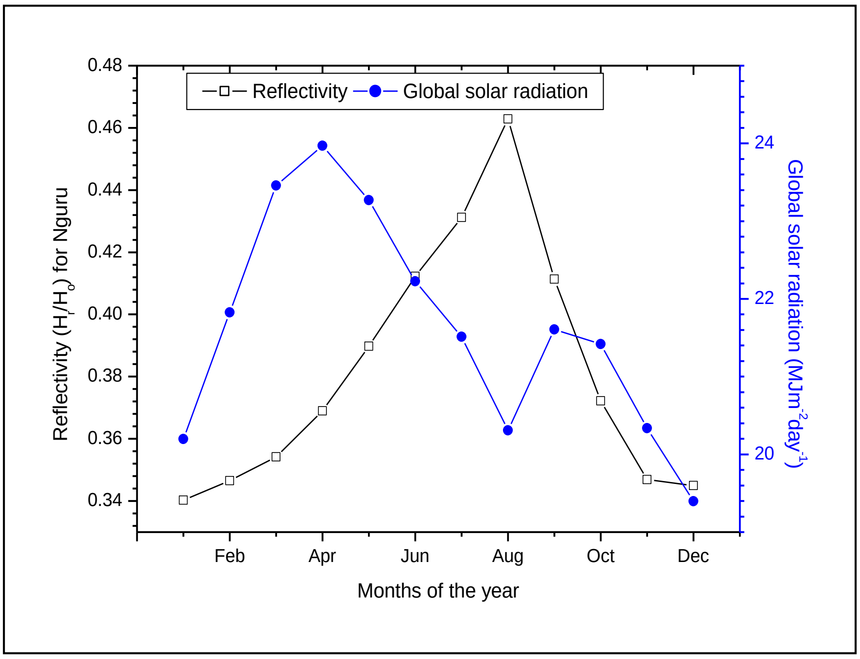

Figure 6: Variation of monthly mean global solar radiation with reflectivity for Nguru (1984-2021)

In Figure 6 the highest reflectivity/albedo of 0.4628 was recorded in the month of August where we have the peak of rainy season in the study area (Nguru) while the lowest solar radiation of 19.3983 MJm^{-2}day^{-1}, was observed in December. The intimation is that possibly more radiation was reflected back to space than received on the surface of the earth in this month which led to low surface temperature of the earth and high albedo. On the other hand, the lowest albedo of 0.3403 was recorded in the month of January whereas the highest solar radiation of 23.9703 MJm^{-2}day^{-1}, was recorded in the month April. However, in general, the result indicated that high values of solar radiation correspond to low values of albedo and low values of solar radiation correspond to high values of albedo. The results also show that the variation of solar radiation with albedo shows almost a direct opposite relationship.

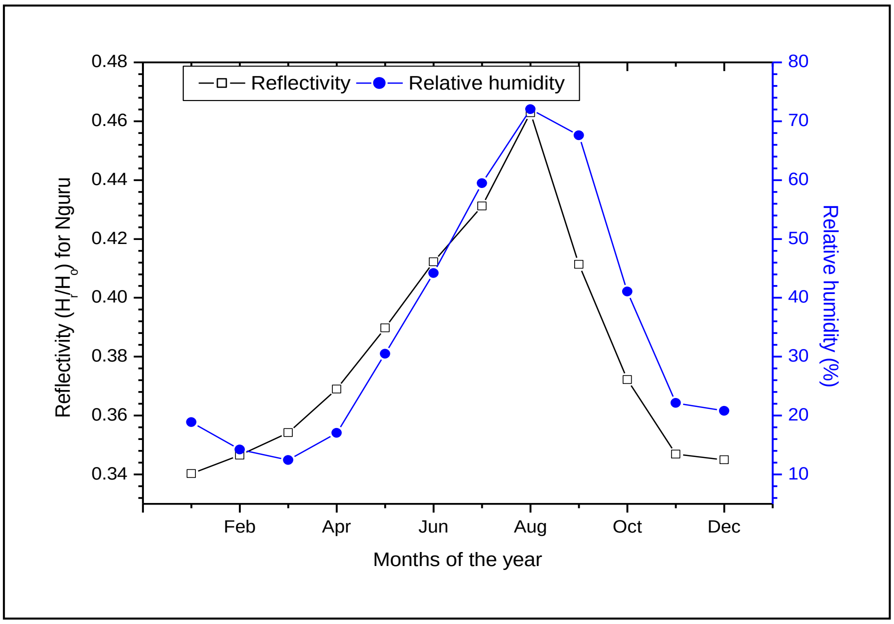

Figure 7: Variation of monthly mean relative humidity (%) with reflectivity (H_r/H_o) for Nguru (1984-2021)

Figure 7 shows the monthly variation of relative humidity with reflectivity for Nguru during the period under investigation. The figure showed the pattern of variation of relative humidity with albedo has almost similar trend. This is an indication that the moisture content in the atmosphere may reliably predict the values of albedo as a direct variation. The relative humidity slightly decreases from January to its respective minimum value in March. The relative humidity and albedo increase subsequently from April until both attained their maximum values of 72.0387 % and 0.4628 in August respectively. The implication is that the highest relative humidity in August corresponds to the highest albedo in the same month. The relative humidity and albedo decrease from August to December. The other implication is that the onset of dry/harmattan season in January corresponds to where we have the lowest albedo for the study area under investigation.

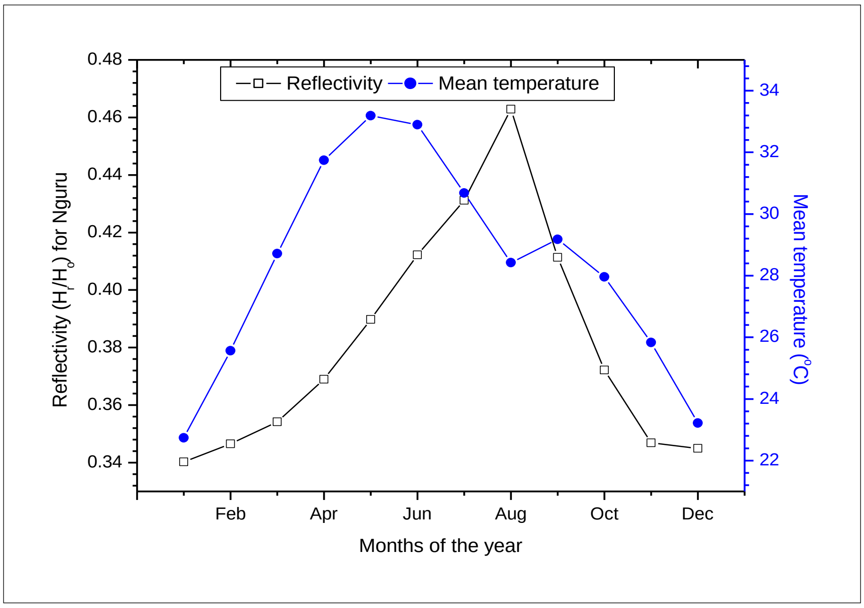

Figure 8: Variation of monthly mean temperature (℃) with reflectivity (H_r/H_o) for Nguru (1984 - 2021)

In Figure 8 the temperature increases from its minimum value of 22.7366 ^{0}C in January and attained its maximum value of 33.1901 ^{0}C in May, the albedo increases from its minimum value of 0.3403 in January to its maximum value of 0.4628 in August and decreases from the months of September to December. Furthermore, the highest albedo observed in August, the decrease in temperature from May to August is an indication of rainy season. Since the rainfall for this region is very inconsistent and unpredictable the season sometimes is from June to October. The result shows that the temperature decreases from the months of June to August, then slightly increases in September and decreases from the months of October to December.

4. CONCLUSION

This study employed the shortwave solar energy balancing at the edge of the Earth's atmosphere to estimate and compare the variation of albedo for Nguru (Latitude 12.88 ° N, Longitude 10.47 ° E and altitude 393.9 m above sea level) situated in Sahelian region of Nigeria, using measured monthly daily meteorological parameters of global solar radiation obtained from the National Aeronautics and Space Administration (NASA) during the period of thirty-eight years (1984-2021). The maximum and minimum values of albedo estimated for Nguru was found in the months of August and January with 0.4628 and 0.3403 respectively. The variation of clearness index with albedo revealed that the clearness index is higher than the albedo throughout the months for Nguru suggesting abundant global solar radiation throughout the years during the study period. The emitting Earth surface temperature for Nguru ranged between 238.5837 K in August and 251.1607 K in January. The maximum emitting wavelength for Nguru ranged between 11 .5344 μm in January and 12.1425 μm in August; these values shows that the radiation in this region is longwave radiation ($\lambda > 4$) as expected and fall within the infrared region of the electromagnetic spectrum.

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