Theor. Appl. Climatol. 61, 77–84 (1998)

Theoretical and Applied Climatology

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The Diffuse Fraction of Global Solar Irradiance at a Tropical Location

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With 7 Figures

Received February 5, 1998
Revised May 12, 1998

Summary

The annual and monthly mean diurnal variations of the diffuse fraction of global solar irradiance arriving on the ground at a tropical station in Sub-Sahel Africa is here been reported. The monthly mean hourly values of the diffuse fraction (K_d) for such clear-sky months as February, March and November at this location, which approach a minimum at about local noon, are observed to lie generally below 0.50 during the period from 11:00 to 15:00 hrs (LST). Consequently, solar concentrators utilising parabolic mirrors are expected to have high performance during these months in this region. Like the mainly-cloudy and wet months (June to August) in which monthly mean hourly values of K_d higher than 0.62 have been recorded, the corresponding diffuse fraction for dust-haze months (mostly December and January) with high turbidity coefficients were generally above 0.50. Monthly mean hourly values of K_d for less cloudy months (April, May, September and October) ranged between 0.48 and 0.77 during the period from 11:00 to 15:00 hrs (LST). The effects of atmospheric dust-haze, clouds and albedo on the monthly mean diurnal variation of the diffuse fraction has been discussed. Also reported are the characteristic values of K_d for sets of months with relatively similar atmospheric and sky conditions at this location. The annual variations of the monthly mean daily values of K_d which exhibit strong seasonal dependence showed a peak in August for both years. Except for the months of February and March, the monthly mean daily totals of K_d exhibited similar annual marches during both years. The major discrepancy in the values of the monthly mean daily totals of K_d in both years were recorded in the months of February, November and December, with the corresponding K_d values for these months in both years agreeing only to within 32.9% in February, 15.4% in November and 16.2% in December. Apart from the aforementioned months, the corresponding monthly mean daily totals of K_d for the remaining nine months in both years agreed mostly to within less than 8.4%. The least monthly mean daily ratios of K_d were obtained in the relatively clear month of November for both years being 0.43 in 1993 and 0.49 in 1994. On an annual average, the diffuse component was found to constitute 59.6% of the global solar irradiance arriving on the ground at this region in 1993 and 60.9% in 1994. The results been reported here have been compared with a few others emanating from other tropical stations.

1. Introduction

The proportion of downwelling shortwave radiation that is absorbed by the earth's surface provides the source of energy for all exchange processes occurring at the earth-atmosphere interface. There is an increasing demand for information on this parameter to meet diverse needs. In particular, the knowledge of the diffuse fraction of global solar irradiance (K_d) is a major requirement in assessing the climatological potential of a locality for solar energy utilisation and in estimating the long term averages or expected values of the output of concentrating solar collectors. Moreover, the dependence of the diffuse fraction on the clearness index provides a fundamental input to techniques for estimating the irradiation on inclined surfaces and plays an important role in thermal and biological processes on the earth's surface. In their pioneering work, Liu and Jordan (1960), expressed the monthly diffuse fraction K_d (ratio of the monthly diffuse to monthly global radiation on a horizontal surface) as a well-behaved function of the monthly global transmissivity of the atmosphere thus proposing the relationship:

$$\frac{\bar{G}_d}{\bar{G}} = 1.39 - 4.027\,\bar{K}_T + 5.531\,\bar{K}_T^2 - 3.108\,\bar{K}_T^3 \quad (0.3 < \bar{K}_T < 0.7) \qquad (1)$$

where $\bar{K}_T$ is the monthly averages of the clearness index (ratio of the global to extraterrestrial radiation), $\bar{G}_d$ and $\bar{G}$ (in MJm^{-2}day^{-2}) denote respectively daily diffuse and global radiation incident on a horizontal surface. Following this fundamental work, a number of studies have been conducted by divers investigators including (Orgill and Hollands, 1977; Iqbal, 1978; Erbs et al., 1982; Vignola and McDaniels, 1984; Desnica et al., 1984; Hollands, 1985; Zeroual et al., 1996; Jacovides et al., 1996) to examine the overall validity of Liu and Jordan's result as well as to propose similar models for various locations and climates. Most of these studies have revealed that the dependence of diffuse fraction on K_T is not entirely deterministic. This is expected on physical grounds as varying combinations of cloud cover, aerosol content, air mass, surface albedo yielding the same value of K_T may not necessarily result in a unique value of K_d. Liu and Jordan (1960) indicated that their models would be practically applicable at stations with similar atmospheric conditions and surface albedo as those for which their equations were developed. However, the applicability of Liu and Jordan models is further limited by the major constraints that K_T is assumed to vary primarily due to cloudiness and that the relationship between K_T and K_d is independent of cloud type. Given that the general form of the parameterized clear sky direct irradiance G_b incident on a horizontal surface at the ground is

$$G_b = G_o \cos\Theta_z \tau_a \tau_w \tau_{R_1} \tau_{R_2} \tau_M \qquad (2)$$

(where G_o is the extraterrestrial solar irradiance (in Wm^{-2}) corrected for earth-sun distance, Θ_z is local solar zenith angle, τ_a,τ_w,τ_{R_1}, $\tau_{R_2}\tau_M$, (dimensionless) are the transmittances in the atmosphere after the extinction due to absorption by fixed gases (a), absorption by water vapour (w), Rayleigh scattering by fixed gases (R_1), Rayleigh scattering by variable gases (R_2) and Mie scattering by particles (M) respectively), the diffuse irradiance G_d can be approximated as

$$G_d = f_R(G_{w1} - G_b) + f_M(G_{w2} - G_b) + f_A \qquad (3)$$

where f_R is the forward scatter fraction from Rayleigh scattering, f_M is the forward scatter fraction from Mie scattering, f_A is a correction to account for surface albedos other than 0.25, G_{w1} and G_{w2} are the direct radiative components in the absence of Rayleigh scattering and Mie scattering respectively. Hence generally speaking, broad band diffuse irradiance G_d on a horizontal surface comprises of the Rayleigh-scattered diffuse irradiance G_{dr}, the aerosol-scattered diffuse irradiance G_{da} and the downward irradiance due to multiple reflections between the ground and the atmosphere G_{da}. Explicit expressions for G_{dr}, G_{da} and G_{da} have been deduced by Iqbal (1986).

Although a number of formulae developed to estimate hourly, daily and monthly values of K_d do exhibit similar trends in their dependence on K_T, and are often assumed to be valid over large geographical areas, these models often differ in some respect from one another. In addition to the seasonal and locational variations in the $K_d(K_T)$ relations, lack of agreement between various proposed models can be attributed to variations in the precision and duration of data, lack of regular inspection and maintenance of measuring instruments, changes in local meso-scale climates, variations in the temporal and spatial grouping and averaging of data, and the way of defining transmittances, forward scatter ratios and corrections. A novel approach for calculating the monthly average daily fraction of diffuse solar radiation has been reported by Kudish et al. (1982). In addition to K_T, later studies examining the general validity of Liu and Jordan's result have suggested the dependence of K_d on variables including cloud cover, surface albedo, relative sunshine, geographical location, relative humidity and turbidity coefficient. Nonetheless, the actual simultaneous measurements of diffuse and global solar irradiance over a considerably long period and the subsequent computation of K_d and K_T provides the basis for either formulating new 'Liu and Jordan-like' models or validating existing ones. In view of its obvious utility and the fact that the sky condition and diffuse fraction have been seldom studied over a long period in West-Africa, the object of this paper is to report the characteristic variations of the diffuse fraction of global solar irradiance at a tropical station situated in Nigeria, West Africa.

2. Instrumentation, Meteorological Features and Data Analysis

With the aid of a shaded and calibrated Eppley 'Black and White' star pyranometer, the hourly diffuse solar irradiance incident on a horizontal surface atop a tower 350 m above sea level, have been measured for two years (February 1993 to January 1995). The geometry of the shadow band is 0.241. This geometry lies well within the limit $b/r \leq 0.333$ proposed by Gueymard (1986) where b and r are the respective width and radius of the band. In addition to the measured hourly diffuse solar irradiance G_d, a second pyranometer (Eppley Precision Spectral Pyranometer) which has been previously calibrated at NOAA, Boulder Colorado, U.S.A., was installed close to the shaded pyranometer to measure the corresponding global solar irradiance G. Both pyranometers were regularly inspected and cleaned. The site for this measurement is located on the campus of University of Ilorin (8°32′ N, 4°46′ E) positioned at the upper tip of the Guinea Savannah zone. This observing site which affords optimum exposure to the global and diffuse radiation sensors has been reported by Miskolczi et al. (1997) to be ideally suited for studying the effect of dust on surface radiative fluxes. Situated close to the centre of Nigeria in West Africa, this location is affected by the annual alternating southward and northward passage of the Inter-tropical Convergence Zone (ITCZ). During the northern hemisphere summer, the African monsoon provides West Africa with rainfall with the large scale flow been characterised by low level south-westerly winds and an upper level easterly flow. The average annual rainfall in Nigeria is about 870 mm. Two easterly wind maxima between 10° N and 15° N, with one in the upper troposphere near 200 hPa (tropical easterly jet) and the other in the mid-troposphere (African easterly jet) at 700–600 hPa have been observed here. The wave-like disturbance (African waves) in the wind field that moves from east to west during the summer have been reported (Burpee, 1975) to posses an average period of 3.5 days.

During the northern hemisphere winter, the Inter-Tropical Discontinuity (ITD) is positioned North of the equator. At this time, West Africa becomes influenced by north-easterly trade winds which prevails to an elevation of about 3 km (Adeyefa and Holmgren, 1996) carrying with it dry, cold, tropical continental dust-haze air-masses from the Sahara desert (Oluwafemi, 1988; Iziomon and Aro, 1995). The dust which affects a greater part of West Africa in winter south of latitude 15° N, especially the Nigerian zone, has been reported to come mainly from the North-eastern Sahara usually along the alluvian plain of Bilma (18° N, 12° E) in Southern Niger, and Faya Lageau (18° N, 19° E) Chad, off the Western slope of the Tibesti Massif (Wilson, 1971). The dust particles are then transported by strong north-easterly trade winds mainly at 900 and 850 hPa particularly north of the ITD towards the Gulf of Guinea and subsequently to Nigeria. In view of the foregoing, Nigeria is usually characterised by wet season from about March to October and by dry season from November to February, although slight variations in these periods occur from year to year. An estimate of sixty to two hundred tons per year of sahara dust constitutes a significant component of tropospheric aerosols at least in the tropics. During spring and autumn, dust is transferred from the Arabian and African deserts over Cyprus desert depressions (Jacovides et al., 1996).

When diffuse solar irradiance is measured by shadow-band method, a portion of the diffuse radiation is screened from the sensor by the shadow band. Consequently, the value of the measured diffuse solar irradiance G_{dm} is to be increased by the loss δG_{dm} in order to obtain the corrected value of diffuse solar irradiance. For a hypothetical isotropic distribution of sky radiance, the isotropic correction function (f_{is}) was given by Drummond (1956) as:

$$f_{is} = \frac{1}{1 - \left(\frac{2}{\pi}\right) \cdot \left(\frac{b}{r}\right) \cdot \cos^3 \delta (w_0 \cdot \sin\phi \cdot \sin\delta + \sin w_0 \cdot \cos\phi \cdot \cos\delta)} \quad (4)$$

where δ is the solar declination in degrees, ϕ is the latitude of location and w_0 is the sunset hour angle expressed as

$$w_0 = \cos^{-1}(-\tan\phi \cdot \tan\delta) \tag{5}$$

Given that the actual anisotropy of the sky radiance distribution caused by sky cloudiness and atmospheric turbidity is accounted for by an additional anisotropic correction factor f_{an}, the overall correction factor is given by:

$$F = f_{is} \cdot f_{an} \tag{6}$$

Applying Eq. (4), daily isotropic correction factors were computed. The corresponding anisotropic correction factors were deduced according to (Kasten, 1986). The overall correction factors were then obtained and the measured hourly data of diffuse solar irradiance corrected. Plots of daily isotropic correction factors for the period between February and Decmber 1993 during the first year of measurement, is presented in Fig 1. The maximum isotropic factors were obtained about the vernal and autumnal equinoxes when the earth axis is perpendicular to the sun rays and the envelope of the solar ray cone becomes a flat surface parallel to the equatorial plane (δ=0). There is a close agreement between the isotropic correction factors reported here and those obtained by Iniechen et al. (1983) and Coulson (1975), the latter been reported only for each 10° of latitude, from the equator to the pole in the Northern hemisphere.

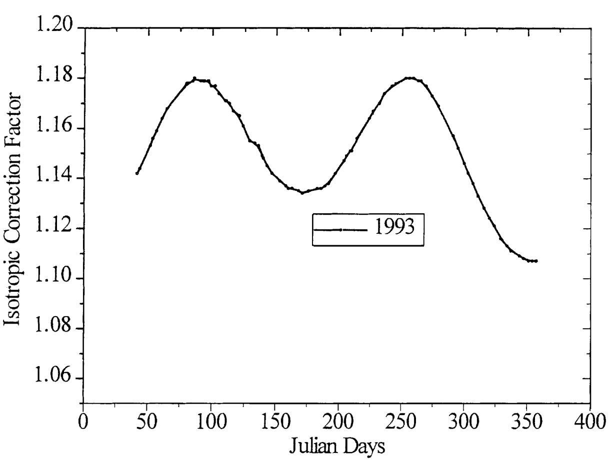

Fig. 1. Diffuse irradiance isotropic correction factors for shadow band as a function of Julian Days

3. Results and Discussions

Estimates of the monthly average fraction of diffuse solar irradiance are required in predicting and determining the energy conversion efficiency of concentrating solar collectors in relation to flat plate solar collectors at a location. The diffuse ratio K_d mirrors the effectiveness of the sky and atmosphere in scattering downwelling short-wave radiation. Lower values of K_d resulting from Rayleigh scattering of solar radiation by atmospheric particles, whose diameters are small compared to the wavelength of the incoming radiation, is required for high performance of solar concentrators. Since the Rayleigh scattering coefficient varies as λ^{-4} (where λ is the wavelength of the incoming radiation), the spectral transmittance of air molecules rapidly increases with wavelength and decreases with increasing optical air mass. Iqbal (1986) gave the complete transmittance by Rayleigh scattering as:

$$\tau_{R\lambda} = \exp\left(-0.008735\lambda^{-4.08}(P/P_0)M_a\right) \tag{7}$$

where M_a is the relative optical air mass, P is the surface pressure and P_0 is the standard air pressure of 1013 hPa. Generally speaking, the sky and atmospheric conditions in Nigeria can be classified as either clear sky condition (usually the case during the early period and towards the end of the rain season), cloudy sky condition (usually the case for most part of the rain season) and dust-haze atmosphere (usually the case during the middle of the dry season). Monthly mean diurnal variations of the diffuse fraction (K_d) for months that are characteristically cloudy, clear and hazy at this location are presented in Figs. 2 to 4.

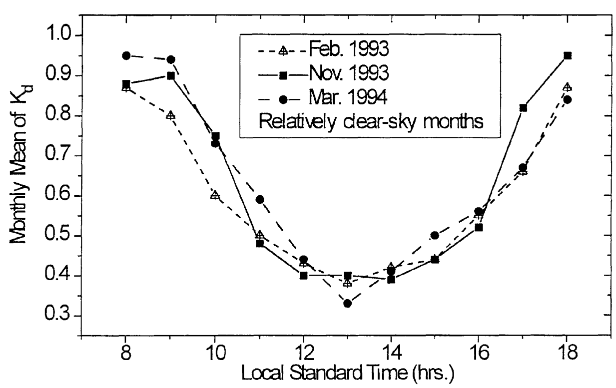

Fig. 2. Monthly mean diurnal variation of K_d during relatively clear sky months

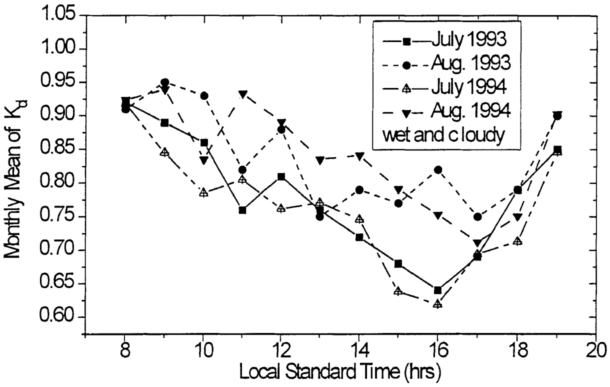

Fig. 3. Monthly mean diurnal variation of K_d during cloudy and wet months

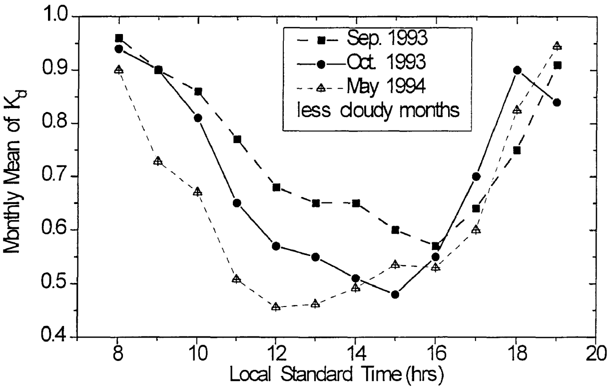

Fig. 4. Monthly mean diurnal variation of K_d during less cloudy months

Figure 2 shows these variations for the clear sky months of February and November 1993 and March 1994. The monthly mean hourly values of K_d is seen to fall to a minimum at about local noon. Futhermore these values are generally less than 0.50 from about 11:00 to 15:00 hrs (LST) of these months signifying that on a monthly average, the direct (beam) component constitute the bulk of the global solar irradiance reaching the ground. The diffuse irradiance arriving on the ground during these times is mainly due to the constant background of molecular scattering and to a much lesser extent, the surface albedo. Consequently, solar concentrators utilising parabolic mirrors are expected to have high performance during these months at this tropical location. However, in the event of an appreciable albedo, the radiation reflected from the underlying surface and scattered by the atmosphere in the direction of this surface would cause a notable rise in the incoming diffuse radiation.

The monthly mean diurnal variation of K_d for cloudy and wet months of July and August are presented in Fig. 3. These months fall within the rain season when the clearness index K_T ranges from about 0.35 to about 0.48. The monthly mean hourly values of K_d are found to be generally greater than 0.62 during the day thus signifying the high proportion of the diffuse sky irradiance arriving on the ground during these months in comparison to the beam irradiance. The irregularity in the monthly mean variation of K_d for these cloudy and wet months is conditioned by the varying forms and intensity of cloudiness characterising these months. Higher monthly mean values of K_d were obtained in August in relation to July. The magnitude of the diffuse fraction obtained under a cloudy sky is essentially dependent on the amount of and form of cloudiness. Generally speaking, cloudiness results in a significant increase of the diffuse fraction (K_d) since clouds are largely made up of coarse scatterers in the form of water droplets or ice crystals which act as strong centres of radiation scattering. In the presence of cirrus, cirrocumulus, altostratus and altocumulus clouds, the diffuse fraction has here been observed to increase with increasing cloudiness. As shown in Fig. 4, the monthly mean hourly values of K_d for less cloudy months ranged between 0.48 and 0.77 during the period from 11:00 to 15:00 hrs (LST).

In Fig. 5 is shown the monthly mean diurnal variations of K_d for the aerosols laded (dust-haze) months of December 1993 and January

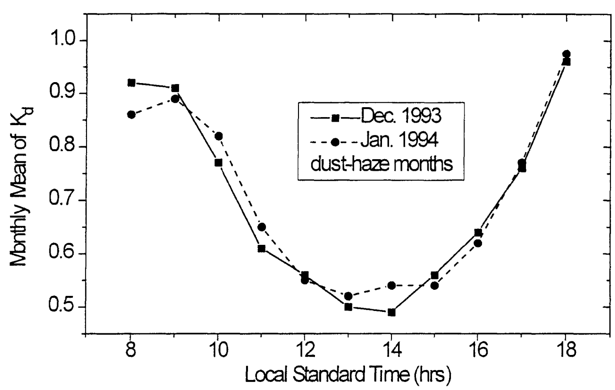

Fig. 5. Monthly mean diurnal variation of K_d during dust-haze months

1994. Aerosols have a significant impact on climate through their direct effect on radiation and their influence on cloud formation and thus also on radiation. In particular, the optical thickness, single scattering albedo and the asymmetry parameter of aerosols are important in the atmospheric correction procedures. The monthly mean hourly values of K_d which are generally greater than 0.50 are reflective of the seasonal atmospheric turbidity and sky conditions that characterise these months in Nigeria. Predominantly in December and January of each year, sizeable amounts of dust particles produced in the Saharan desert due to its aridity, the high temperature attained by its soil, and the resulting intense diurnal thermic turbulence, are transported by a cold dry wind called Harmattan towards the Gulf of Guinea across Nigeria. These fine opalescent Harmattan dust particles are airborne giving rise to a dusty atmosphere and a poor visibility often less than 1 km. The rising of the dust is probably caused by the steep pressure gradient developed along the North-South direction across the Sahara which gives rise to a strong easterly current. Carlson and Carverly (1976) showed that aerosol concentration and Mie extinction are linearly related for Sahara dust. It is therefore expected that visibility will be similarly related with turbidity. In addition to the dusty atmosphere usually observed during Harmattan season, the obtained fractional values of K_d during the Harmattan months at this location are a consequence of other features such as smoke from bush burning activities, low relative humidity and marked diurnal extremes of temperatures. In particular, the optical depths are usually at their maximum during the Harmattan season. Based on Angstrom's turbidity formula, aerosol transmittance is given by

$$\tau_{A\lambda} = \exp\left(-\beta \cdot \lambda^{-\alpha} \cdot M_a\right) \quad (8)$$

where β and α are the Angstrom's turbidity coefficient and wavelength exponent respectively with the latter been related to the size distribution of the aerosol particles. The monthly mean hourly values of K_d in the hazy months of December and January with high turbidity coefficients are seen to be higher than those obtained in the clear-sky months of November 1993 and March 1994. Furthermore, the mean diffuse ratios for sets of months with relatively similar atmospheric and sky conditions at this location were estimated and are been presented in Fig. 6. The mean K_d values varies from 53% for set of relatively clear months to 58% for set of dust-haze months and 71% for mainly cloudy and wet months.

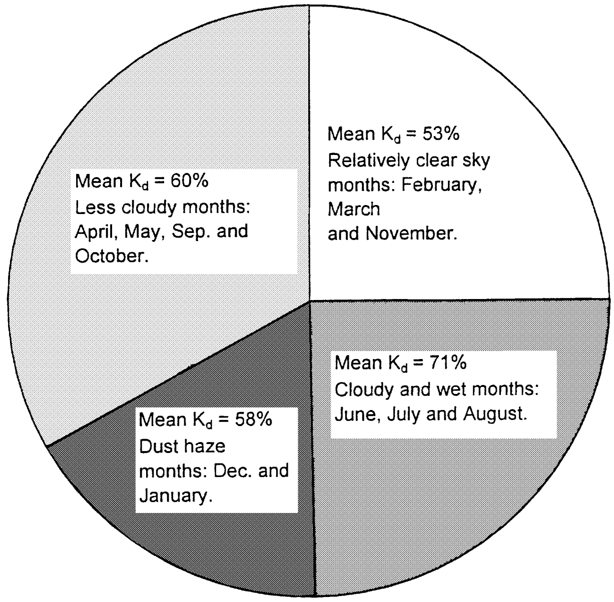

Fig. 6. Mean diffuse ratios for months with relatively similar atmospheric and sky conditions

Presented in Fig. 7 are the annual variations of the monthly mean daily values of K_d for 1993 and 1994. Interestingly, these variations which exhibit a strong seasonal dependence show virtually

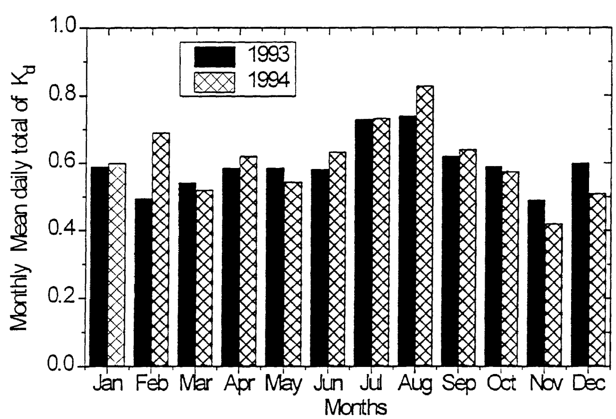

Fig. 7. Annual variation of monthly mean daily totals of K_d

the same trend for both years with a peak in August. Except for the months of February and March, the monthly mean daily totals of K_d exhibited similar annual marches during both years. The major discrepancy in the values of the monthly mean daily totals of K_d in both years were recorded in the months of February, November and December, with the corresponding K_d values for these months in both years agreeing only to within 32.9% in February, 15.4% in November and 16.2% in December. The relatively high monthly mean daily total of K_d obtained for February 1994 can be attributed mainly to forward scattering of downwelling solar radiation by continuous thin cirrus and altostratus clouds, and partly due to atmospheric turbidity. Apart from the aforementioned months, the corresponding monthly mean daily totals of K_d for the remaining nine months in both years agreed mostly to within less than 8.4%. We have chosen to substitute the result of January 1995 for January 1993, for which no diffuse radiation data was available, to provide a complete data set for 1993. In this way, it has become possible to compare fully the results obtained in 1993 and 1994 and to restrict analysis to these two years. The highest monthly mean daily ratios of K_d in 1993 and 1994 at this location are 0.74 and 0.82 respectively, obtained in the cloudy month of August. Hence August is seen to stand out as the month of the least average monthly clearness index during the rainy season in this region. These results are in agreement with those obtained by Ideriah and Suleman (1989), Bamiro (1983), Adeyefa et al. (1997) and Adedokun et al. (1994). The least monthly mean daily values of K_d are obtained in the relatively clear month of November being 0.43 and 0.49 for 1993 and 1994 respectively. On an annual average, the diffuse component has been found to constitute 59.6% in 1993 and 60.9% in 1994 of the global solar irradiance arriving on the ground at this tropical station. These experimental results confirm to a large extent the average diffuse fraction range of 65–70% predicted by Bamiro (1983) for south-western Nigeria. Furthermore, Modi and Sukhatme (1979) have reported similarly high diffuse ratios for 12 Indian stations. It is highly improbable that low annually averaged diffuse fraction and high clearness indices are attainable in the equatorial regions of the World.

4. Conclusion

Based on a two-year period measurement of hourly diffuse and global solar irradiance arriving on the ground at a tropical station in Sub-Sahel Africa, the annual and monthly mean diurnal variations of the diffuse ratio of global solar irradiance has been reported. The monthly mean hourly values of the diffuse fraction (K_d) for such clear-sky months as February, March and November at this location, which approach a minimum at about local noon, are observed to lie generally below 0.50 during the period from 11:00 to 15:00 hrs (LST). Consequently, solar concentrators utilising parabolic mirrors are expected to have high performance during these months in this region. Like the mainly-cloudy and wet months (June to August) in which monthly mean hourly values of K_d higher than 0.62 have been recorded, the corresponding diffuse fraction for dust-haze months (mostly December and January) with high turbidity coefficients were generally above 0.50. Monthly mean hourly values of K_d for less cloudy months (April, May, September and October) ranged between 0.48 and 0.77 during the period from 11:00 to 15:00 hrs (LST). The effects of atmospheric dust-haze, clouds and albedo on the monthly mean diurnal variation of the diffuse fraction has been discussed. Also reported are the characteristic values of K_d for sets of months with relatively similar atmospheric and sky conditions at this location. The annual variations of the monthly mean daily values of K_d which exhibit strong seasonal dependence showed a peak in August for both years. Except for the months of February and March, the monthly mean daily totals of K_d exhibited similar annual marches during both years. The major discrepancy in the values of the monthly mean daily totals of K_d in both years were recorded in the months of February, November and December, with the corresponding K_d values for these months in both years agreeing only to within 32.9% in February, 15.4% in November and 16.2% in December. Apart from the aforementioned months, the corresponding monthly mean daily totals of K_d for the remaining nine months in both years agreed mostly to within less than 8.4%. The least monthly mean daily ratios of K_d were obtained in the relatively clear month of

November for both years being 0.43 in 1993 and 0.49 in 1994. On an annual average, the diffuse component was found to constitute 59.6% of the global solar irradiance arriving on the ground at this region in 1993 and 60.9% in 1994. These experimental results which compare favourably with the diffuse ratios reported by Modi and Sukhatme (1979), Ideriah and Suleman (1989), Adeyefa et al. (1997) and Adedokun et al. (1994) also confirm to a large extent, the annual average diffuse fraction range of 65–70%, predicted by Bamiro (1979) for south-western Nigeria.

Acknowledgements

This work was partly funded through the Senate Research Grant administered by the University of Ilorin, Ilorin, Nigeria. We are indebted to Prof. R. T. Pinker, Department of Meteorology, University of Maryland at College Park, U.S.A. for her assistance in procuring some of the measuring equipments used and to Dr. F. Miskolczi for providing the calibration data. Dr. S. Udo analysed the Global irradiance data for the months May–August 1994.

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