

ATMOSPHERIC TRANSPARENCY UNDER HARMATTAN CONDITIONS

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Abstract

Results of preliminary investigations of the transparency of the atmosphere to direct solar irradiance under two typical harmattan conditions in Akure (7°18'N, 5°15'E) in the spectral interval, 300-1100 nm, are presented for cloud-free conditions. The meteorological effects of the north-south movement of the Inter-Tropical Discontinuity (ITD) during the season over the station has been related to the observed changes in the spectral transmittance. It has been shown, that solar energy arriving at the earth's surface could decrease as much by as 15% of the energy available at the top of the atmosphere within two harmattan regimes. Transmittance characteristics of some spectral bands influenced by water vapour absorption has been used to show that the precipitable water vapour aloft becomes smaller as spell conditions succeed background harmattan conditions at a station. The transmittance of the atmosphere to the direct solar radiation has therefore been shown as being capable of providing useful insights into the drastic changes that could occur in the precipitable water vapour in the atmosphere as the ITD passes over a station.

1. Introduction

Atmospheric aerosols absorb and strongly scatter both solar and infrared radiation and therefore constitute an important climatic factor that perturb the radiation budget of the earth. In the meteorological context, computations of the single scattering albedo, anisotropy factor (or phase function) and the optical depth of the aerosol among other things are considered necessary parameters for the determination of the radiative effects of the aerosols. The attenuating effects of aerosols also have considerable effects on the availability of solar energy at the ground level.

In West Africa, increased turbidity of the lower atmosphere during the harmattan season is mainly due to suspended soil-dust from the Sahara desert. The scattering and absorption of solar irradiance mainly by these dust particles result in remarkable attenuation of the direct component and a significant increase in the diffuse component reaching the ground. This generally results in notable decrease in the total (direct plus diffuse) irradiance arriving at the surface (Adeyefa, 1999). To develop efficient solar energy devices and also estimate their performance under variable harmattan conditions, the knowledge of the spectral distribution of solar irradiance at the earth's surface is crucial.

The meteorological conditions associated with the transport and deposition of harmattan dust particles in West Africa as well as the particle-size distribution

analyses have been discussed by Adedokun *et al.* (1989). Investigations of the deposition and trajectories of Saharan dust in Nigeria have also been conducted by McTainsh (1980) and Adebayo (1989) respectively.

Studies of the attenuation of the solar radiation by Saharan aerosols have been conducted by Cerf (1977), Carlson and Caverly (1977), Oluwafemi (1979), Brinkman and McGregor (1983), Fouquart *et al.* (1987), Tanre *et al.* (1988), Adeyefa and Adedokun (1991) and Haywood *et al.* (2001) and Pinker *et al.* (2001) among others. However, most of the studies deal with the attenuation of harmattan aerosols in wide spectral bands within the UV, visible and infrared regions of the solar spectrum. Furthermore, investigations of the transparency of the atmosphere to the direct solar irradiance under harmattan conditions are significantly limited. Yet, atmospheric transmittance is a very useful meteorological parameter which can serve as a measure of atmospheric contamination (Karras *et al.*, 1990).

Some studies on the transmissivity of the harmattan atmosphere were conducted by Adeyewa (1998) but the paper was based mainly on of the average transmissivity for integrated direct irradiance for harmattan aerosols in some spectral bands at different solar elevations. Based on rigorous analysis of the transmissivity in the integrated bands, the paper also

shows that there were more significant reductions of transmissivity in the visible and infrared regions of the solar spectrum. Spectral analysis of the effect of advected harmattan dust on solar irradiance was also conducted by Adeyefa (1999). However, the study was focussed on the band to band effects and the relationship between the integrated values of the direct-normal, global-horizontal and diffuse-horizontal irradiances in the six spectral bands within the ultraviolet and the infrared spectral regions of the solar spectrum.

In this paper, the meteorological effects of the north-south migrations of the Inter-Tropical Discontinuity (ITD) during the harmattan season is related to the observed increase in aerosol attenuation at Akure and the resulting changes in spectral transmittance. The loss in the transmittance of the direct irradiance in some spectral bands in the changing conditions is also used to study the changes in the bands affected by water vapour attenuation thereby giving some insight into the changes in the precipitable water vapour aloft. The quantitative loss in the solar energy arriving at the surface as a result of the reduction in the atmospheric transparency within harmattan regimes is also discussed.

Measurements of the direct spectral irradiance were carried out on 13th and 14th December 1991 at Akure (7°18'N, 5°15'E), Nigeria during the harmattan period. All the direct-normal irradiance measurements were made in cloud-free conditions. The transparency of the atmosphere to direct solar irradiance varied significantly during this short period in response to the changing harmattan conditions.

2. Instrumentation

The direct component of solar irradiance was measured with a spectral radiometer (trade name, LI-1800, manufactured by LICOR Inc.). The equipment is microprocessor-controlled and automatically handles the acquisition and storage of spectral irradiance data. The LI-1800 spectroradiometer has a spectral range of 300-1100 nm, a spectral resolution of 6 nm and a wavelength accuracy of ± 2 nm. An initial calibration of the equipment was carried out with an optical radiation calibrator (Li-Cor 1800-02) under a controlled laboratory temperature environment for tropical temperature regimes shortly before being shipped to Nigeria. Other details of the spectroradiometer have been given in Adeyefa (1999).

For the measurement of the direct-normal irradiance, a view-limiting tube with a 5° aperture was used in compliance with the recommendations of the World Meteorological Organisation [World Climate Research Programme, WCRP (1986)].

3. Methodology

The attenuation of the spectral solar irradiance, $I(\lambda)$,

reaching the earth's surface (where λ is the wavelength in nm) is given by the familiar Bouguer-Beer-Lambert law:

$$I(\lambda) = I_0(\lambda)DT(\lambda) \quad (1)$$

where $I_0(\lambda)$, is the extraterrestrial spectral solar irradiance at mean earth-sun distance at wavelength λ . D is the correction factor for the sun-earth distance. The extraterrestrial solar irradiance [$I_0(\lambda)$] used here, was obtained from WCRP (1986). This spectrum was a compilation of four extraterrestrial solar spectrum publications.

In equation (1), the parameter $T(\lambda)$ is the total clear sky transmittance function and is given by

$$T(\lambda) = e^{-\tau(\lambda, m_r) m_r} \quad (2)$$

The exponential factor, $\tau(\lambda)$, in equation (2) is the total optical depth comprising the Rayleigh scattering $\tau_R(\lambda)$, aerosol extinction $\tau_A(\lambda)$, ozone optical depth $\tau_{O_3}(\lambda)$, water vapour absorption, $\tau_w(\lambda)$ and the absorption by uniformly mixed atmospheric gases $\tau_U(\lambda)$ (e.g. O₂, CO₂, etc.). The parameter m_r is the relative air mass which has been computed according to the formula of Kasten and Young (1989):

$$m_r = \left[\sin(h) + 0.50572 (h + 6.07995)^{-1.6364} \right]^{-1} \quad (3)$$

where h is the solar elevation angle.

$T(\lambda)$ can be broken down to its different components:

$$T(\lambda) = T_R(\lambda) \cdot T_A(\lambda) \cdot T_W(\lambda) \cdot T_O(\lambda) \cdot T_U(\lambda) \quad (4)$$

where $T_R(\lambda)$, $T_A(\lambda)$, $T_W(\lambda)$, $T_O(\lambda)$ and $T_U(\lambda)$ are the spectral transmittance functions of the atmosphere for Rayleigh scattering, aerosol attenuation, water vapour absorption, ozone absorption and the absorption by the uniformly mixed gases respectively.

The aerosol transmittance function can be expressed as a function of wavelength in the form:

$$T_A(\lambda) = \exp \left[-\beta \lambda^{-\alpha} m_r \right] \quad (5)$$

In this equation, β is the "turbidity coefficient" at $\lambda = 1 \mu\text{m}$ and α is the wavelength exponent which is closely associated to the size of the scattering particles and the frequency of their distribution [Ångström (1929, 1930, 1961)]. The coefficients β and α were computed using the method of linear regressions described by Cachorro *et al.* (1987).

By eliminating the spectral bands affected by the absorptions of water vapour and oxygen, the total optical depth, $\tau(\lambda)$, is made up of the optical depths due to aerosol extinction $\tau_A(\lambda)$, Rayleigh scattering $\tau_R(\lambda)$ and ozone absorption $\tau_{O_3}(\lambda)$:

$$\tau(\lambda) = \tau_A(\lambda) + \tau_R(\lambda) + \tau_{O_3}(\lambda) \quad (6)$$

Therefore, the aerosol optical depth $\tau_A(\lambda)$ is estimated by subtracting $\tau_R(\lambda)$ and $\tau_{O_3}(\lambda)$ from the total optical depth:

$$\tau_A(\lambda) = \tau(\lambda) - \tau_R(\lambda) - \tau_{O_3}(\lambda) \quad (7)$$

Substituting $T(\lambda)$ as expressed in equation 2 into equation 1 and taking the natural logarithm (of equation 1), we have

$$\tau(\lambda) = (1/m_r) [\ln(I_0(\lambda)/I(\lambda)) + \ln D] \quad (8)$$

Since $D = (R_m/R)^2$ where R and R_m are the actual and mean sun-earth distances respectively, substitution of (8) into (7) yields

$$\tau_A(\lambda) = (1/m_r) \left[\ln(I_0(\lambda)/I(\lambda)) + \ln(R_m/R)^2 \right] - \tau_R(\lambda) - \tau_{O_3}(\lambda) \cdot m_{O_3}/m_r \quad (9)$$

Multiplying the ozone optical depth by takes care of the differences in the relative air masses for aerosols/Rayleigh scattering and ozone (O_3).

In equation 9, is the ozone mass as given by Robinson (1966):

$$m_{O_3} = (1 + h_o/6370) / [\cos^2(\theta) + 2h_o/6370]^{0.5} \quad (10)$$

θ is the solar zenith angle and the parameter h_o is the height of maximum ozone concentration (≈ 22 km).

The Rayleigh-scattering optical depth was determined following the formula of Fröhlich and Shaw (1980):

$$\tau_R(\lambda) = (P/P_0) 0.00865 \lambda^{-(3.916+0.074\lambda+0.050/\lambda)} \quad (11)$$

where P is the barometric station pressure and $P_0 = 101.325$ kPa.

The optical depth resulting from ozone absorption $\tau_{O_3}(\lambda)$, has been computed using the equation:

$$\tau_{O_3}(\lambda) = \chi(\lambda) \cdot q \quad (12)$$

where $\chi(\lambda)$ in cm STP^{-1} , is the ozone absorption coefficient as given by Bird and Riordan (1986). Representative total columnar content of O_3 (q in cm STP) for both latitude and month were obtained from Robinson (1966).

The spectral range 350-1038 nm have been used for the computations of the parameters β , α and $\tau_A(\lambda)$, excluding the ranges 560-600, 616-666, 680-746, 754-774, 786-844, and 872-1014 nm. These spectral ranges were excluded because they are more or less influenced by gaseous absorptions of H_2O and O_2 .

4. Result and discussion

To illustrate the general meteorological conditions prevalent during the month of December 1991, the relative latitudinal positions of the Intercontinental Tropical Discontinuity (ITD) over West Africa obtained from meteorological surface charts during the month at 1500 hrs. each day are given in Fig. 1. The ITD was determined by locating the 15°C dewpoint temperature on surface charts and using this position as the southernmost limit of the ITD. The latitudinal positions of the ITD were centred on longitude 5°E which is representative of Akure ($7^\circ 18'\text{N}$, $5^\circ 15'\text{E}$).

Generally, the ITD remained north of Akure (beyond

latitude $7^\circ 18'\text{N}$) earlier in the month until around 13 December. From 14 December, the ITD moved into the Gulf of Guinea and the northern regions beyond latitude 6°N were dominated by the dry and dusty North Easterly harmattan winds. The ITD remained at about 6°N until around 18 December when it began its northward retreat. Table 1 gives the daily mean values of the turbidity parameters β , α and horizontal visibility for Akure during the study period. The mean value of the parameter β was 0.49 on December 13 before the arrival of the dusty winds. It quickly rose to 1.27 on the following day, of December 14. There was an accompanying decrease in the horizontal visibility from about 10 km to about 3 km on the 14th. A significant drop in the value of α from 0.63 to 0.24 also occurred signifying a shift from predominantly smaller aerosols to larger ones. These parameters generally describe the broad meteorological effects of the north-south movement of the ITD during the changing harmattan period. The following discussions on the transparency of the atmosphere during the period should therefore be understood in the light of these conditions.

Direct-normal irradiance spectra measured with the LI-COR LI-1800 spectroradiometer on 13 and 14 Dec., 1991, at Akure, Nigeria at the same solar elevation (42°) and optical air mass (1.5) are shown in Fig. 2. The dips in these curves correspond to regions of absorption by the various atmospheric gases. Although both curves indicate significant attenuation of the direct solar irradiance due to the presence of the harmattan dust, the remarkable reduction in the direct irradiance of 14-12-91 as compared with that of 13-12-91 is notable. The reduction is significant especially in the ultraviolet and visible regions.

Apart from the prevalent turbidity of the harmattan air, the transparency of the atmosphere is also strongly dependent on the elevation angle of the sun. Hence, to contrast the atmospheric transmission characteristics in the two harmattan conditions, measurements made at the same solar elevation (42°) and optical air mass ($m_r = 1.5$) have been used. Figure 3 shows transmittance curves for such harmattan conditions [13-12-91 ($\beta = 0.5$) and 14-12-91 ($\beta = 1.3$)] at the same air mass ($m_r = 1.5$). The large reduction in atmospheric transparency for 14-12-91 compared to 13-12-91 is easily noticed. The two curves (same air mass range) represent cloud-free conditions during the measurement (see also Fig. 2). It can be seen that transmissivity increases strongly with wavelength in the UV and visible regions. Regions of absorption of solar radiation by various minor atmospheric gasses have characteristically low transmittances. Finger prints of water vapour bands for instance (centred at 720, 810, 942, and 1100 nm) and oxygen bands (630, 690, and 760 nm) are clearly seen in the figure (Fig. 3).

Transmissivity is seen to increase strongly with wavelength in both cases. But the 14-12-91 curve is flat relative to that of the 13-12-91. Atmospheric transparency to solar radiation is therefore significantly reduced and is less dependent on wavelength as turbidity increases notably under harmattan spell conditions.

A brief band to band comparison of atmospheric transmittance for the Saharan aerosol in the two harmattan regimes at the same instantaneous air mass conditions have been carried out in the following spectral bands: UVB (300-320 nm), UVA (320-400 nm), UV (300-400 nm), VIS (400-700 nm), IR (700-1000 nm) and Total (300-1100 nm). The outer limits of 300 and 1100 nm correspond to the spectral limits of the spectroradiometer. Table 2 gives the integrated spectral transmissivity for harmattan aerosols for the designated spectral bands at a solar elevation angle of 42 ° for 13 and 14 December, 1991. Please note that solar elevation was the same for the two cases in the table. The prevalent atmospheric turbidities are shown as well as percentage increase or decrease relative to 13th December, 1991.

Compared to background harmattan conditions typified by 13-12-91, the instantaneous reduction in transmittance in the very turbid spell conditions of 14-12-91 at the specified solar elevation is about 50% in the UVB, 64% in the UVA and 67% in the entire UV region (300 - 400 nm).

The decrease was about 68% in the visible region, 69% in the infrared and 68% in the within the whole range (300-1100 nm). It could therefore be seen from Table 2 that the the reduction in atmospheric transmittance so direct solar irradiance has its greatest effect on the visible and infrared regions. Please note that these computations were based on the instantaneous measurements at same elevation angle of the sun (42 °). Detailed band to band analyses for all the spectral measurements for the period are given in Adeyewa (1998). Also, it has to be noted that the highest errors of measurement for the spectroradiometer, which is about 20%, occur in the UV region so that the results in this band should be treated with due caution (Riordan et al., 1989; Myers, 1989).

Fouquart *et al.* (1987) in an experiment in Niger (December, 1980), obtained aerosol optical thickness (at 550 nm) which varied from 0.2 on very clear days to 1.5 during a so-called "dry haze" period which can be interpreted as harmattan dust spell. In their study, large changes in the parameter $\tau_A(\lambda)$ were observed. The increases in aerosol optical depth were associated with small α (roughly $\alpha \approx 0.2$), while for the clearest days, α reached its standard continental value ($\alpha \approx 1.3$). They interpreted such variations as denoting changes in the size distribution with a shift toward larger particles for the haziest days. The

present results have good agreement with their observations.

Estimating the quantitative loss in the direct solar irradiance within the whole spectral interval under consideration as a result of the reduction in the atmospheric transparency in the two harmattan regimes, a value of 210 Watts/m² was obtained. This value which corresponds to 68% decrease relative to the background value, translates to about 15.4% of the energy available at the top of the earth's atmosphere (solar constant). Conducting solar radiation measurements in the Cape Verde Islands during the 1974 GATE project, Carlson and Caverly (1977) estimated that the depletion of the energy reaching the surface over the eastern equatorial Atlantic region by Saharan aerosol amounted to about 20% of the solar constant. Note however, that the value obtained in the present study is just within one harmattan regime and the other.

For urban aerosols in Spain, Lorente *et al.* (1994) found that the effects in the reduction of the direct irradiance transmittance for was more significant in the UV region. Karras *et al.* (1990) also presented some broad-band direct solar irradiance values for Athens. Their results were better even for low solar elevation angles than the transmittance shown for the harmattan aerosol.

The spectral variations of the aerosol optical depth ($\tau_A(\lambda)$) for the two harmattan conditions [13-12-91 and 14-12-91] at the same air mass ($m_r = 1.5$) are shown in Fig. 4.

The figure also shows the spectral portions that have been omitted in the analysis due to the complexities introduced by the absorption bands. The significant differences between the two series indicate the notable differences in the turbidity regimes between the two consecutive days. While $\tau_A(\lambda)$ decreased gradually from about 1.0 at 350 nm to 0.5 at 1038 nm on 13-12-91, it rose to about 1.6 at 350 nm decreasing to 1.2 at 1038 nm on 14-12-91. The percentage increase in $\tau_A(\lambda)$ on 14-12-91 relative to 13-12-91 is as shown in Fig. 5. The aerosol optical depth rose steadily from about 60% in the UV region (350 nm) to about 160% in the infrared region (1038 nm) within the short (24 hours) time interval. The sharp increase in atmospheric turbidity especially in the infrared regions explains the dramatic decrease (almost 70%) in the transparency of the atmosphere to direct solar irradiance in the region relative to the background harmattan conditions of 13-12-91 as shown in Table 2.

It is imperative to compare relatively, the transmission of the direct irradiance in the bands affected by water vapour attenuation with those barely influenced by it. This was done by taking the ratio of the irradiance at the 942 nm (IR H₂O band) to that at a typical absorption-free wavelength (862 nm). In Fig. 6, the transmission ratios (942 nm/862 nm) as a function of

the optical air mass for 13-12-91 and 14-12-91 are presented. The ratio varied between 0.24 to 0.28 on 13-12-91 but increased on 14-12-91 to values ranging between 0.33 and 0.36. Indirectly, this reveals that the precipitable water vapour aloft on 13-12-91 was higher than that of 14-12-91. This can be explained thus: the Inter-Tropical Discontinuity (ITD) which was located north of Akure on 13-12-91 was more humid on that day due to the presence of the relatively moist south westerly current.

By 14-12-91, however, the ITD had moved south of the station as stated earlier thereby bringing a drier but dust-laden wind over the station. The figure therefore indicates the changes in the atmospheric water vapour aloft within the two harmattan regimes.

5. Conclusion

This paper has related the observed changes in spectral aerosol attenuation within two harmattan regimes to the meteorological effects of the north-south movements of the ITD during the season. It has been shown, that the resulting changes in spectral transmittance affects the (direct) solar energy arriving at the earth's surface which could decrease as much as 15% of the solar constant within two harmattan regimes within a short period. Atmospheric transmittance has been used to show that drastic changes in the precipitable water vapour in the atmosphere occur as the ITD passes over a station. It has therefore been shown, that studying the transmittance characteristics of the direct irradiance in some spectral bands influenced by water vapour extinction could provide useful insights into the changes in the atmospheric water vapour in the atmosphere in the absence of clouds.

Nomenclature

The following symbols and acronyms used in the paper are as defined below:

D	$(R_m / R)^2$
$I_0(\lambda)$	The spectral flux of the solar radiation at the top of the earth's atmosphere
h	Height above ground surface (km)
h_0	The height of maximum ozone concentration (km)
m_r	Relative air mass (dimensionless)
$\chi(\lambda)$	Ozone absorption coefficient (cm STP-1)
m_{O_3}	Ozone optical mass (dimensionless)
$\tau_{O_3}(\lambda)$	Ozone optical depth
γ	Elevation angle of the sun
α	Wavelength exponent in Ångström's turbidity formula (dimensionless), instrument temperature coefficient
β	Ångström's turbidity parameter centered at 1 μ (dimensionless)
θ	Zenith angle of the sun
$\tau(\lambda)$	Total optical depth
$\tau(\lambda, m_r)$	Total optical depth as a function of wavelength λ and relative air mass m_r
$\tau_A(\lambda)$	Aerosol extinction (optical depth due to

	aerosols)
$\tau_G(\lambda)$	Extinction caused by the absorption by other atmospheric gases (e.g. O_2 , CO_2 , etc.)
γ_{ob}	Observed elevation angle of the sun (in degrees)
$\tau_R(\lambda)$	Rayleigh scattering optical depth
$\tau_w(\lambda)$	Optical depth due to water vapour absorption
GATE	GARP Atlantic Tropical Experiment
I	Intensity of the direct solar beam, at a given wavelength, λ ; energy
IR	integrated transmittance for the range, 700-1000 nm
ITD	Inter-Tropical Discontinuity
LI-1800	LI-COR solar spectroradiometer
NIP	Normal Incidence Pyrheliometer
P	Station barometric pressure
PAR	Photosynthetically Active Radiation
Po	Standard pressure at ground level (1013.25 hPa)
q	Total O_3 columnar content of the atmosphere (cm STP)
R	Actual sun-earth distance, ratio of the limiting aperture (mm)
Ro	Mean sun-earth distance (= 149.6×10^6 km).
T(λ)	Total spectral transmittance function
$T_A(\lambda)$	spectral transmittance function for aerosol attenuation
$T_O(\lambda)$	spectral transmittance function for ozone absorption
Total	integrated transmittance for the range, 300-1100 nm.
$T_R(\lambda)$	spectral transmittance function for Rayleigh scattering
$T_U(\lambda)$	spectral transmittance function for the absorption by the uniformly mixed gases.
$T_W(\lambda)$	spectral transmittance function for water vapour absorption
UV	Ultraviolet radiation; integrated transmittance for the range, 300-400 nm
UVA	integrated transmittance for the range, 320-400 nm
UVB	integrated transmittance for the range, 300-320 nm
VIS	integrated transmittance for the range, 400-700 nm
WCRP	World Climate Research Programme
WMO	World Meteorological Organization.

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Table 1: Daily mean values of turbidity parameters β and α and horizontal visibility for AKURE (13-14 December, 1991).

Day	December 13th, 1991	December 14th, 1991
β	0.49 ± 0.05	1.27 ± 0.03
α	0.63 ± 0.11	0.24 ± 0.01
Vis (km)	10	3

Table 2: Instantaneous atmospheric transparency to direct solar irradiance for two harmattan conditions (13 and 14 December, 1991) for UVB to IR spectral bands.

Days	13-12-91	14-12-91	% Change
Elevation	42 °	42 °	Nil
Air Mass	1.5	1.5	Nil
β	0.5	1.3	+160
α	0.7	0.2	-71
UVB			
300-320 nm	0.02	0.01	-50
UVA			
320-400 nm	0.11	0.04	-64
UV			
300-400 nm	0.09	0.03	-67
VIS			
400-700 nm	0.28	0.09	-68
IR			
700-1000 nm	0.36	0.11	-69
TOTAL			
300-1100 nm	0.31	0.10	-68

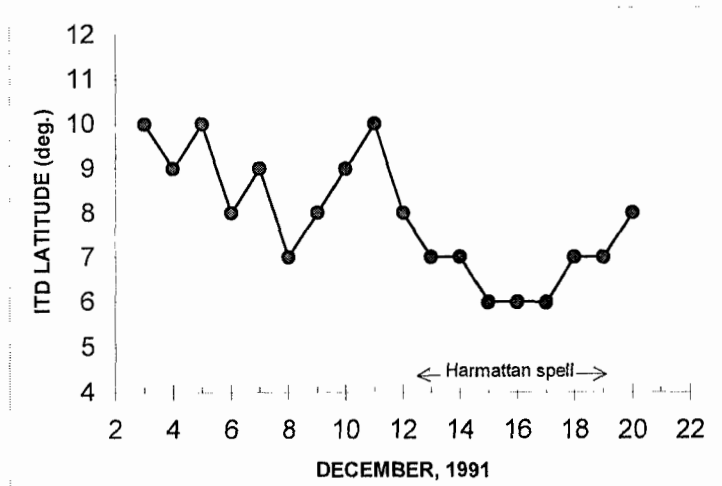


Fig. 1: Daily relative positions of the ITD at 1500 hrs. centred on longitude 5 °E in December, 1991.

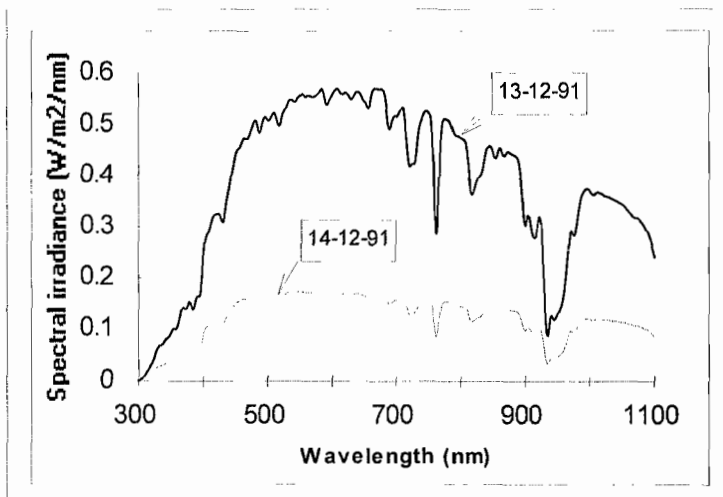


Fig. 2: Direct-normal irradiance spectra measured with the LI-COR LI-1800 spectroradiometer on 13 and 14 December, 1991, Akure, Nigeria at the same solar elevation (42 °) and optical air mass (1.5).

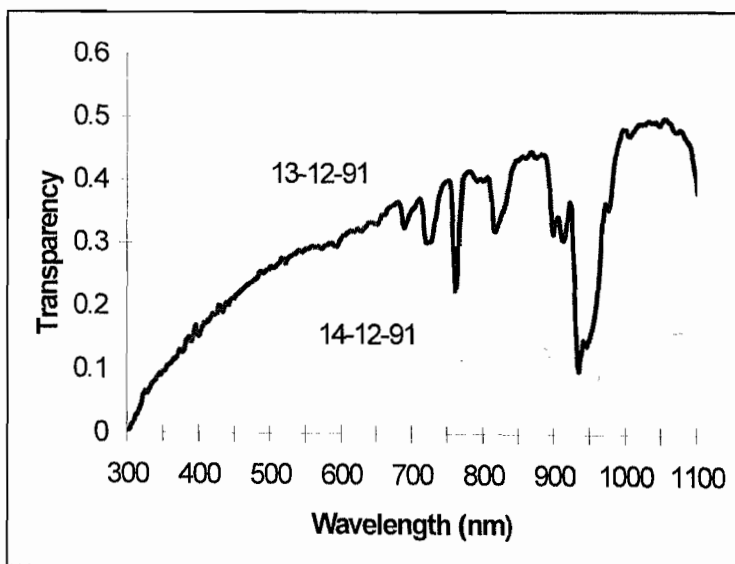


Fig. 3: Solar Irradiance transparency for the two harmattan conditions [less turbid day: 13-12-91 ($\beta = 0.5$) and turbid day: 14-12-91 ($\beta = 1.3$)] at same air mass ($m_r = 1.5$).

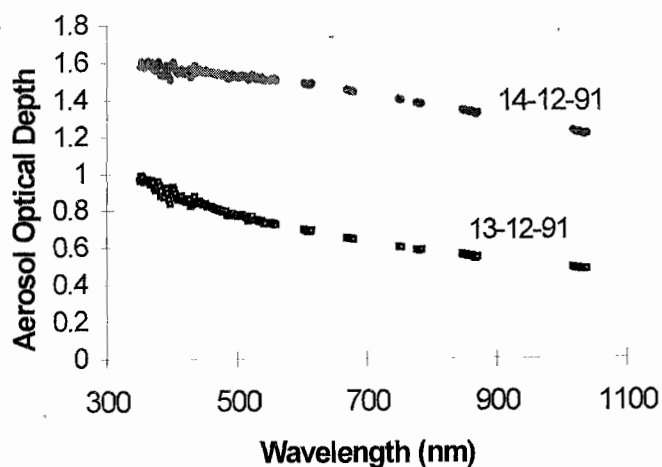


Fig. 4: Spectral variations of the aerosol optical depth (instantaneous values at $m_r = 1.5$) for two harmattan conditions [13-12-91 and 14-12-91]. Note the significant difference between the two series.

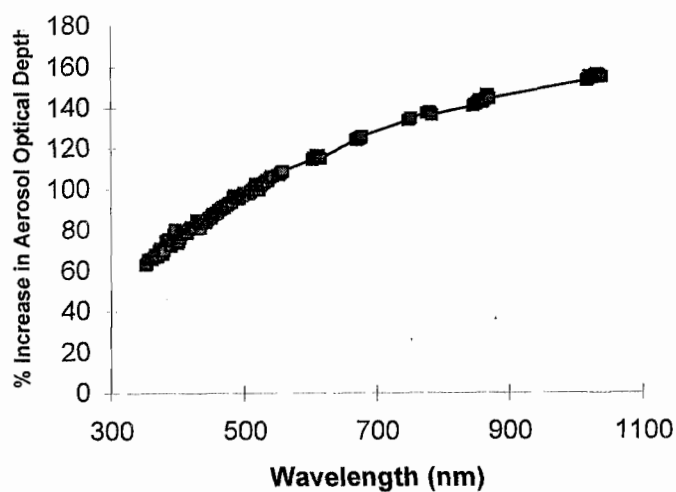


Fig. 5: Spectral percentage increase in the Aerosol Optical Depth on 14-12-91 relative to 13-12-91.

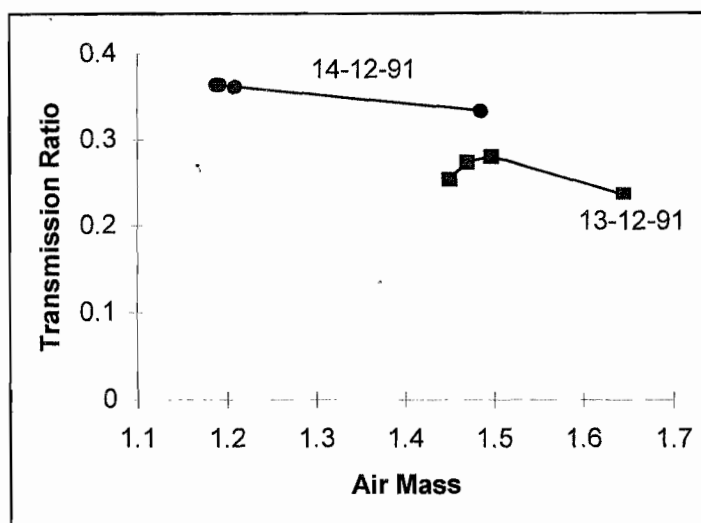


Fig. 6: Transmission ratio (942 nm/862 nm) versus the optical air mass on 13-12-91 and 14-12-91.