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PYRHELIOMETRIC DETERMINATION OF ATMOSPHERIC TURBIDITY IN HARMATTAN OVER ILE-IFE, NIGERIA *

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ABSTRACT

Measurements of direct solar radiation intensity, using an Angstrom compensation pyrheliometer carried out over three harmattan seasons (1985–1987) at Ile-Ife (7.29N, 4.34E) Nigeria, have been used to determine atmospheric turbidity based on five different models of turbidity, viz: Schuepp (B), Angstrom (β), Kastrov (C), Unsworth (τ_a) and Linke (T).

The five parameters indicate high aerosol loading of the atmosphere during the period and high correlation is established between them: ($0.919 \leq r \leq 0.999$). An inverse relationship has been noticed between horizontal visibility and atmospheric turbidity: ($-0.80 \leq r \leq -0.76$).

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1 Introduction

The determination of atmospheric turbidity parameters is very important in climatological studies and especially, in atmospheric radiative model formulations (Tomasi et Al.1983) .

In the West African region, the advent of the dust-ladden harmattan winds is an annual event, particularly between November and the following March . This period witnesses the invasion of the region by the North Easterly winds blowing from the Sahara, giving rise to high atmospheric turbidity and consequently, poor visibility .

Many studies of the Saharan dust transport monitored over the Atlantic (e.g. Shutz 1980 and Shutz et Al 1981), over Europe (e.g. Prodi and Fea 1979, Prodi and Tomasi (1983) and Tomasi et Al 1983) ,around the Sahel region (e.g. Kalu 1979, McTainsh (1980), Brinkman and Mcgregor (1983) and D'Almeida (1986)) and south of the region (Hamilton and Archbold (1945), Balogun (1974), Oluwafemi (1979,1980,1981), Adepetu et Al 1988 and Adedokun et Al 1989) have established the fact that the Sahara is a source region of millions of tons (per year) of atmospheric aerosol, mainly quartz, that have significant climatological effects on the solar radiation absorption over a wide area of the globe .

The present study examines the variation in atmospheric turbidity due to the Saharan dust monitored through pyrheliometric measurement of direct solar radiation over Ile-Ife (7.29N,4.34E), about 2,000 km southwest of the source region, during the harmattan seasons of 1985-1987 .

A comprehensive examination of five different models of atmospheric turbidity : Schuepp (B) , Angstrom (β) , Kastrov (C) , Unsworth (τ) and Linke (T) show that the parameters were all unanimous in depicting high aerosol loading of the atmosphere over the region.

2 Data Collection

An Angstrom Compensation Pyrheliometer, calibrated against a standard pyrheliometer at the Swedish Meteorological and Hydrological Institute (SMHI) Norrkoping Sweden (courtesy Dr Lars Dahlgren) was loaned to us for the purpose of these measurements.

The pyrheliometer was manually operated to make measurements of direct solar radiation during conditions when the sun's disk was not covered by clouds. In particular, thin cirrus cloud if over the sun's disk, make the readings unreliable as measurements so taken refer to a re- radiation or transmission of the sun's radiation by the cirrus intermediary . Three Schott filters : yellow (OG1), Red (RG2) and dark red (RG8) were also used in

the measurements whenever suitable conditions permitted . Each filter has a Davos certified reduction factor DR valid for filter temperature range 10^0 to $35^0 C$.

The measurements were carried out on a 20m high building at Obafemi Awolowo University campus, Ile-Ife Nigeria. Other conventional surface data taken before and after the measurements include dry bulb and wet bulb temperatures, horizontal visibility, cloud amount and cloud types.

Apart from the fact that data were only taken when suitable weather conditions allowed , the unreliable power supply in the country (power cuts were not predictable) served as constraints on the amount of data obtainable. Most of the data were taken at 10 GMT (11 LST) although some special days existed when data were taken virtually round the clock .

3 Techniques For Deriving Atmospheric Turbidity

Solar radiation traversing the atmosphere experiences significant attenuation given by the Lambert-Beer-Bouguer law :

$$I = \int_0^\infty I(\lambda)\, d\lambda = s^{-1} \int_0^\infty I_0(\lambda) \exp(-ma(\lambda))\, d\lambda \qquad (1)$$

where I is the direct solar radiation intensity at the earth's surface , $I(\lambda)$ is the intensity of the normal incidence radiation at the observing station as a function of wave length , $I_0(\lambda)$ is the extra terrestrial normal incidence radiation intensity at the mean earth-sun distance similarly expressed as a function of wave length , $s = R^2/R_m^2$ is the correction factor to allow for the variation in the actual earth-sun distance R from the orbital mean , R_m and $\exp(-ma(\lambda))$ is the transmission factor for solar radiation of wavelength λ .

The total attenuation coefficient $a(\lambda)$ may be split into three separate components as follows :

$$a(\lambda) = a_R(\lambda) + a_D(\lambda) + a_W(\lambda) \qquad (2)$$

where a_R is attenuation of solar radiation in clean dry air according to Rayleigh's theory of scattering by air molecules, a_D is the attenuation by the atmospheric aerosol content and a_W is the attenuation due to water vapour.

Several models have been derived for parameterization the turbidity of the atmosphere. Five of such models, described below, have been used in our computations :

(a) *Linke's Turbidity Coefficient T*

Linke's turbidity coefficient T , introduced by Linke (1922) , is a measure of haze and water vapour content of the atmosphere. It is defined as :

$$T = P(m)(\log I_o - \log I - \log S) \tag{3}$$

where

$$P(m) = (ma_R(m)\log e)^{-1}$$

and m is the absolute air mass number .

(b) *Angstrom's Turbidity Coefficient* β

The attenuation of solar radiation by aerosols has been represented by a turbidity coefficient β and a wavelength exponent α by Angstrom (1929, 1930) thus :

$$a_D(\lambda) = \beta\lambda^{-\alpha} \tag{4}$$

where λ is wavelength in micrometers . The exponent α is a measure of the particle size and it varies between $\alpha = 0$ for very large particles (where scattering and absorption are independent of wavelength) and $\alpha = 4$ for very small Rayleigh particles (gas particles) . β is a measure of the quantity of haze suspended in the air .

(c) *Schuepp Turbidity Coefficient B*

Schuepp (1949) also developed a method which has the same theoretical basis as Angstrom's but he replaced β by B which refers to a decimal base (dedadic coefficient). The relationship between β and B is given by the equation :

$$\exp^{-\beta/\lambda^{\alpha}} = 10^{-B/(2\lambda)^{\alpha}}$$

or , if written in another form ,

$$B = \beta 2^{\alpha}\log e \tag{5}$$

Schuepp's B refers to a wavelength $\lambda = 0.5\mu m$ which represents the central part of the visible spectrum while Angstrom's β refers to the wavelength $\lambda = 1.0\mu m$.

(d) *Kastrov Turbidity Coefficient C*

Kastrov (1928) obtained a simple formula for the integral solar radiation at the surface level :

$$S_m = S_0/(1 + Cm)$$

from which we obtain :

$$C = 1/m(S_0/S_m - 1) \tag{6}$$

where C is a quantitative characteristic of atmospheric transparency, S_0 is the extraterrestrial intensity of the normal incidence irradiance (solar constant) at mean earth-sun distance, and S_m , the measured direct flux at the surface level .

Although it has been shown that the coefficient C is not a unique value because of its dependence on atmospheric air mass m and consequently on the height of the sun , Kondratyev (1969) and others have noted that in the interval from $m = 3$ before noon to $m = 3$ in the afternoon , the coefficient C may be considered practically constant, independent of atmospheric air mass. Now, since most essential calculations of C are done within this interval when $m \leq 3$, the use of C for computing atmospheric turbidity is quite feasible.

(e) *Unsworth Turbidity Coefficient* τ_a

Unsworth (1975) has suggested a measure of atmospheric turbidity which is a function of atmospheric aerosol content only. This coefficient was defined by :

$$\tau_a = -m_h^{-1}\ln(IS/I^*) \tag{7}$$

where $m_h = \csc\theta$ is defined as the relative air mass , θ is the apparent elevation of the sun above the horizon and I^* is defined as the normal incidence irradiance (for mean solar distance) at the bottom of an aerosol - free atmosphere which includes a specified amount of water vapour.

4 Computation Of Turbidity Parameters

The measured intensities have been reduced to mean solar distance by the factor R^2/R_m^2 , using table (3) in the appendix of the IGY instruction manual (CSAGI 1958) for the neccessary percentage corrections .

The Linke turbidity factor T was computed according to equation (3) using values of $P(m)$ revised after Feussner and Dubois (1930) and valid for $I_0 = 1380Wm^{-2}$ available from table (6) in the appendix of the IGY instruction manual .

For the Schuepp coefficients B , use was made of the new tables compiled by Valko (1971) . This is an extended table based on $\lambda < 630nm$ which was applicable for values of $B \leq 0.700$. The B values so computed were then used to obtain β values from the relation in equation (5) for days with $B \leq 0.700$.

Strictly speaking, the table is valid for a mean precipitable water W value of $1cm$. (For other values of W, a correction scheme attached to the table was followed).The B values were based on $\alpha = 1.5$.

For our estimation of W, in the absence of radiosonde data, use was made of the Ojo (1970) technique of deriving precipitable water from surface dew -point temperatures t_d: .

$$\ln W = 0.0279 - 0.6225t_d \tag{8}$$

where t_d was expressed in ^{0}F .

As confirmed by Adedokun (1989) this technique is suitable for the harmattan season although a power law relationship has been found to suit the raining season period(Adedokun 1986 , 1989) .

Computation of Angstrom's coefficient β_0 was facilitated by application of table 7 in the IGY instruction manual . This table has been compiled for the short wave component of radiation $I_b(\lambda < 0.630\mu m)$ obtainable as the difference between the total direct radiation I_t and the radiation I_R measured after transmission through the red filter Schott RG2 thus:

$$I_b = I_t - DR_2 I_R \tag{9}$$

where DR_2 is the red filter reduction factor. Many occasions of β_0 values that were higher than those obtainable from the said table were encountered.

Derivation of both β_0 and B is followed by estimation of turbidity coefficients β_r , β_y , β_{ry} and β_{rr} facilitated by use of a table by Angstrom (1964) . Here β_r refers to the short wave radiation derived from measurements with $RG2$ filter , β_y , to the short wave radiation given by measurement with the $OG1$ filter while β_{ry} and β_{rr} refer to bands defined as differences between $RG2$ and $OG1$ and $RG8$ and $RG2$ respectively. Table (1) gives the values obtained on some selected days. It is to be noted that although β_0 derivation was based on a table built up under the assumption that $\alpha = 1.3$, an extension of the table using $\alpha = 1.5$ and 1.6 have been adapted for deriving B. We have here found this technique justified in that the ratio β/β_0 is approximately unity in all cases treated in table (1) .

Kastrov's turbidity coefficients, C were calculated in accordance with equation (6). The values of S_0 were obtained from a table compiled by Kastrov for solar radiant fluxes as applicable to a dry and clean atmosphere (Kondratyev 1969) .

The computation of Unsworth's turbidity coefficient, τ_a requires the knowledge of precipitable water vapour W .Hence, for reasons explained above, equation (8) was used and estimates made for Ile-Ife were compared with those obtained for Lagos radiosonde station some 200 km away and found to be realistic . Then, Unsworth (1975) table of I^* as a function of both relative air mass m_h and the precipitable water content of the atmosphere was utilised for the calculation of τ_a .

For calculating the energy absorbed by water vapour, we have used McDonald (1960) result to obtain :

$$A = 106.26(Wm)^{0.30} \tag{10}$$

where Wm is equivalent to the amount of precipitable water along the path of the sun's rays .

5 Results and Discussions

Shown in figs (1),(2) and (3) are graphs of the daily variations of T,C,τ_a indicating the pulsations in atmospheric turbidity and, consequently harmattan intensity. The gaps evident on the diagrams are indicative of occasions when data could not be taken either due to power cuts or adverse weather conditions .

Fig 4 shows the frequency distribution of B and β measured during the experiment. The mean and standard deviation of each of the parameters are are also shown in the figure.

To examine the comparison between the various turbidity models we have plotted in figs (5) to (13) the graphs of τ_a against C , τ_a against T and C against T as obtained over each of the seasons 1984/85 , 1985/86 and 1986/87 respectively . It can be found that a high correlation exists between the various models indicating that they are unanimous in depicting a high aerosol loading of the atmosphere during the harmattan . In general the correlation coefficients $(0.919 \leq r \leq 0.999)$ are all significant. We have shown the regression output for each pair of parameters below the figures.

5.1 Seasonal Variation in Turbidity

Monthly means $(\bar{X})$ of the parameters C and T have been computed for each of the seasons as depicted in table (2). Similarly computed were the standard deviation (σ), the confidence interval (CI) and the confidence limits $\bar{X}_{LL}$ and $\bar{X}_{UL}$ (for the lower and upper confidence limits respectively). The 95 percent confidence level was employed, implying that 95 percent of the observations lies within the interval $\bar{X}_{UL}$ and $\bar{X}_{LL}$ (Balsey (1972) and Wang (1952)).

This procedure was repeated for parameters τ_a and the energy absorbed by water vapour A (equation (10)) and the results shown in table (3).Also in table (4), we have similar calculations done for parameters α_0, B and β.

The November and December columns in the 1984/85 harmattan season were left blank because our measurements commenced in January of that season. The data sample (N) were unavoidably small in some of the seasons due to the aforesaid observation constraints.

5.2 Atmospheric Turbidity and Visibility

To investigate how turbidity varies with visibility, we have plotted the Linke turbidity factor T against observed visibility in figs.(14) and (15) for the 1985/86 and 1986/87 seasons, respectively . An inverse relationship can be found between atmospheric turbidity and visibility $(-0.80 \leq r\ le - 0.76)$.

The more turbid the atmosphere, the shorter the horizontal visibility .

Poor visibility, often caused by thick harmattan haze, frequently results in disruption of aviation schedules and, sometimes, aviation accidents over the region .

6 Conclusions

The time series of the atmospheric turbidity parameters, here obtained, clearly show the existence of harmattan 'spells' that occurred periodically during the season. This confirms the observation of Adebayo (1979) and Adedokun et Al. (1989).

A strong association can be found between the various turbidity parameters: $(0.919 \leq r \leq 0.999)$, indicating that they all agree in depicting the nature and intensity of the harmattan. Not only do they indicate similar periods for the 'spell' occurrence but they also show that a high atmospheric loading characterizes the harmattan seasons. This agrees with the finding of Oluwafemi (1979) who, using a Volz- type photometer, recorded a rise in atmospheric optical density over Lagos during the harmattan months of December 1977 and January 1978. In a similar manner, Brinkman and Mcgregor (1983), using an Eppley normal incidence pyrheliometer, recorded high values of an integral turbidity r (first used by Unsworth and Monteith (1972)) in their measurement at Zaria, in northern Nigeria.

The mean value of the wavelength exponent, α which is a measure of particle size has been shown in table (4) to be between 1.5 and 1.6 , the latter been more predominant for many months. This value is an indication of the fact that the nature of the harmattan dust monitored over the station is predominantly small. This corroborates the results of Adedokun et Al.(1989).

Our results have shown that a negative but high correlation exists between atmospheric turbidity and horizontal visibility $(-0.80 \leq r \leq -0.76)$. This is in agreement with the results of D'Almeida (1986) who obtained a negative but high correlation $r \approx -0.96$ between β and visibility in his measurement carried out over the Sahel region.

The monthly and seasonal means of atmospheric turbidity showed that the 1984/85 harmattan season was the most turbid while the 1985/86 season was the least. The months of December and January were shown to be more turbid than the other months in the season while April was shown to be the least turbid. This is in line with the usual expectation as the rains often begin again in April following the dry season.

Although the scope of this study has been somewhat limited by data availability, we believe that the results have given some illumination on the nature and variability of atmospheric turbidity in harmattan in the region and its crucial effect on horizontal visibility.

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TABLE 1

SCHÜEPP AND ANGSTRÖM'S TURBIDITY PARAMETERS

MONTH	DAY	B	β	β_o	α	β_r	β_g	β_{rr}	β_{rg}	β/β_o
NOV. '85	30	0.219	0.179	0.172	1.6	0.205	0.212	0.189	0.197	1.035
JAN. '86	9	0.234	0.190	0.185	1.6	0.219	0.227	0.202	0.211	1.027
FEB. '86	3	0.224	0.182	0.187	1.6	0.209	0.217	0.193	0.202	0.973
	4	0.244	0.199	0.200	1.5	0.228	0.236	0.218	0.224	0.995
	7	0.224	0.192	0.187	1.6	0.209	0.217	0.193	0.202	0.973
MAR. '86	24	0.219	0.178	0.170	1.6	0.204	0.212	0.188	0.197	1.047
APR. '86	9	0.223	0.192	0.173	1.5	0.208	0.215	0.199	0.204	1.052
	13	0.239	0.195	0.191	1.6	0.223	0.231	0.206	0.215	1.021
	14	0.196	0.160	0.154	1.6	0.183	0.190	0.169	0.177	1.039
	16	0.194	0.158	0.152	1.6	0.191	0.188	0.167	0.175	1.039
JAN. '87	19	0.200	0.163	0.180	1.6	0.187	0.194	0.172	0.180	0.906
APR. '87	4	0.220	0.179	0.171	1.6	0.206	0.213	0.190	0.198	1.047
	13	0.125	0.102	0.097	1.6	0.117	0.122	0.108	0.113	1.052

TABLE 2

MONTHLY MEAN VALUES OF TURBIDITY PARAMETERS C(KASTROV) AND T (LINKE) THE NUMBER OF OBSERVATIONS (N) HAVE ALSO BEEN INDICATED

		NOVEMBER			DECEMBER			JANUARY			FEBRUARY			MARCH			APRIL		
		C	N	T	C	N	T	C	N	T	C	N	T	C	N	T	C	N	T
1984 /85	$\bar{X}$	-		-	-		-	2.871	11	14.10	2.990	10	15.43	2.628	5	14.45	-		-
	σ	-		-	-		-	0.890		2.22	0.788		2.56	0.387		1.06	-		-
	CI	-		-	-		-	2.871 ±0.598		14.10 ±1.49	2.990 ±0.605		15.43 ±1.83	2.628 ±0.481		14.45 ±1.31	-		-
	$\bar{X}_{UL}$	-		-			-	3.469		15.59	3.596		17.26	3.109		15.76	-		-
	$\bar{X}_{LL}$	-		-	-		-	2.273		12.61	2.385		13.60	2.147		13.14	-		-
1985 /86	$\bar{X}$	1.349	2	8.69	3.104	10	13.68	2.793	21	14.01	1.040	7	8.54	1.787	10	10.82	0.938	7	7.95
	σ	0.652		1.87	1.281		2.91	1.213		3.42	0.244		1.207	1.340		3.79	0.211		1.09
	CI	1.349 ±5.853		8.69 ±16.80	3.104 ±0.916		13.68 ±2.08	2.793 ±0.568		14.01 ±1.56	1.040 ±0.226		8.54 ±1.12	1.787 ±0.958		10.82 ±2.71	0.938 ±0.195		7.95 ±1.01
	$\bar{X}_{UL}$	7.202		25.49	4.020		15.76	3.361		15.57	1.266		9.66	2.745		13.53	1.133		8.96
	$\bar{X}_{LL}$	-		-	2.188		11.60	2.225		12.45	0.814		7.42	0.829		8.11	0.743		6.94
1986 /87	$\bar{X}$	1.325	3	9.30	1.512	9	9.87	2.385	18	12.68	2.342	17	12.91	2.270	7	12.31	1.567	21	10.38
	σ	0.384		1.45	0.627		2.24	0.657		1.75	0.799		2.30	1.191		3.31	0.680		2.31
	CI	1.325 ±0.953		9.30 ±3.61	1.512 ±0.482		9.87 ±1.72	2.385 ±0.327		12.68 ±0.87	2.342 ±0.411		12.91 ±1.18	2.270 ±1.102		12.31 ±3.06	1.567 ±0.310		10.38 ±1.05
	$\bar{X}_{UL}$	2.279		12.91	1.994		11.59	3.042		13.55	2.753		14.09	3.372		15.37	1.877		11.43
	$\bar{X}_{LL}$	0.372		5.69	1.030		8.15	1.728		11.81	1.931		11.73	1.168		9.25	1.257		9.33

KEY: $\bar{X}$ is the monthly mean for each turbidity parameter;
σ is the standard deviation of the sampling distribution;
CI indicates the "confidence intervals" while
$\bar{X}_{UL}$ and $\bar{X}_{LL}$ indicates the upper and the lower limits of the confidence interval for a 95% confidence level.

TABLE 3

MONTHLY MEAN VALUES OF UNSWORTH'S TURBIDITY COEFFICIENT τ_a AND ENERGY ABSORBED BY THE ATMOSPHERIC WATER VAPOUR (A) FOR THREE HARMATTAN SEASONS

		NOVEMBER			DECEMBER			JANUARY			FEBRUARY			MARCH			APRIL		
		τ_a	N	A (Wm^{-2})	τ_a	N	A (Wm^{-2})	τ_a	N	A (Wm^{-2})	τ_a	N	A (Wm^{-2})	τ_a	N	A (Wm^{-2})	τ_a	N	A (Wm^{-2})
1984/85	$\bar{X}$	-		-	-		-	1.115	11	166.5	1.259	10	153.2	1.153	5	159.8	-		-
	σ	-		-	-		-	0.220		3.323	0.255		13.4	0.105		6.7	-		-
	CI	-		-	-		-	1.115 ±0.148		166.5 ±2.233	1.258 ±0.182		153.2 ±9.6	1.153 ±0.130		159.8 ±8.3	-		-
	$\bar{X}_{UL}$	-		-	-		-	1.263		168.7	1.440		162.8	1.283		168.1	-		-
	$\bar{X}_{LL}$	-		-	-		-	0.967		164.3	1.076		143.6	1.023		151.5	-		-
1985/86	$\bar{X}$	0.604	2	174.2	1.121	10	161.2	1.125	21	156.0	0.572	10	166.8	0.789	7	161.4	0.501	7	160.5
	σ	0.198		9.0	0.303		11.2	0.333		10.3	0.116		4.0	0.375		1.9	0.108		0.0
	CI	0.604 ±1.774		174.2 ±80.9	1.121 ±0.217		161.2 ±8.0	1.125 ±0.151		156.0 ±4.7	0.572 ±0.109		166.8 ±3.7	0.789 ±0.268		161.4 ±1.345	0.501 ±0.100		160.5 ±0.0
	$\bar{X}_{UL}$	2.378		255.1	1.338		169.2	1.276		160.7	0.681		170.5	1.057		162.7	0.601		160.5
	$\bar{X}_{LL}$	-		93.3	0.904		153.2	0.974		151.3	0.463		163.1	0.521		160.1	0.401		160.5
1986/87	$\bar{X}$	0.661	3	168.0	0.726	9	156.4	0.996	18	168.0	1.001	17	165.9	0.932	7	162.1	0.728	21	169.0
	σ	0.141		0.0	0.222		12.2	0.172		0.0	0.224		2.7	0.325		3.9	0.231		4.8
	CI	0.661 ±0.349		168.0 ±0.0	0.726 ±0.171		156.4 ±9.4	0.996 ±0.088		168.0 ±0.0	1.001 ±0.115		165.9 ±1.4	0.932 ±0.301		162.1 ±3.6	0.728 ±0.105		169.0 ±2.2
	$\bar{X}_{UL}$	1.010		168.0	0.897		165.8	1.084		168.0	1.116		167.3	1.233		165.7	0.833		171.2
	$\bar{X}_{LL}$	0.312		168.0	0.555		147.0	0.908		168.0	0.886		164.5	0.631		158.5	0.623		166.8

TABLE 4

MONTHLY MEAN VALUES OF TURBIDITY PARAMETERS α_o, B AND β FOR THREEE HARMATTAN SEASONS.
THE QUANTITY IN BRACKETS SPECIFIES THE NUMBER OF OBSERVATIONS

		NOVEMBER			DECEMBER			JANUARY			FEBRUARY			MARCH			APRIL		
		α_o	B	β	α_o	B	β	α_o	B	β	α_o	B	β	α_o	B	β	α_o	B	β
1984/85	$\bar{X}$	-	-	-	-	-	-	-	0.553	0.450	-	0.558	0.454	-	0.519	0.423	-	-	-
	σ	-	-	-	-	-	-		0.121	0.099		0.065	0.053		0.036	0.029	-	-	-
	CI	-	-	-	-	-	-		0.553 ±0.127	0.450 ±0.104		0.558 ±0.044	0.454 ±0.036		0.519 ±0.057	0.423 ±0.047	- -	- -	- -
	$\bar{X}_{UL}$	-	-	-	-	-	-		0.680	0.554		0.602	0.490		0.576	0.470	-	-	-
	$\bar{X}_{LL}$	-	-	-	-	-	-	(6)	0.426	0.346	(8)	0.514	0.418	(4)	0.462	0.376	-	-	-
1985/86	$\bar{X}$	1.6	0.386	0.314	-	0.587	0.477	1.6	0.399	0.325 (0.185)	1.6	0.304	0.247	1.6	0.390	0.309	1.6	0.287	0.234
	σ		0.167	0.136		0.059	0.048		0.165	0.135		0.080	0.065		0.086	0.070		0.146	0.119
	CI		0.386 ±1.500	0.314 ±1.221		0.587 ±0.062	0.477 ±0.050		0.399 ±2.096	0.325 ±1.709		0.304 ±0.084	0.247 ±0.069		0.380 ±0.072	0.309 ±0.059		0.287 ±0.135	0.234 ±0.110
	$\bar{X}_{UL}$		1.886	1.535		0.649	0.527		2.495	2.034		0.388	0.316		0.452	0.368		0.422	0.344
	$\bar{X}_{LL}$	(2)	-	-	(6)	0.525	0.427	(2)	-	-	(6)	0.220	0.178	(8)	0.308	0.250	(7)	0.152	0.124
1986/87	$\bar{X}$	-	0.379	0.309	-	0.294	0.240	1.6	0.336	0.273	-	0.354	0.288	-	0.370	0.301	1.6	0.173	0.140
	σ		0.106	0.086		0.016	0.013		0.106	0.086		0.081	0.066		0.080	0.065		0.048	0.039
	CI		0.379 ±1.347	0.325 ±1.096		0.294 ±0.026	0.240 ±0.021		0.336 ±0.169	0.273 ±0.137		0.354 ±0.129	0.288 ±0.105		0.370 ±0.198	0.301 ±0.161		0.173 ±0.603	0.140 ±0.491
	$\bar{X}_{UL}$		1.726	1.405	(4	0.320	0.261		0.505	0.410		0.483	0.393		0.568	0.462		0.776	0.631
	$\bar{X}_{LL}$	(2)	-	-	(4)	0.268	0.219	(4)	0.167	0.136	(4)	0.225	0.183	(3)	0.172	0.140	(2)	-	-

Legends To Figures

Fig.1: Graph of daily variation of Linke's turbidity coefficient T for 1986/87 season.

Fig.2: As for fig 1 but for Kastrov's turbidity coefficient C.

Fig.3: As for fig1 but for Unsworth turbidity coefficient τ_a.

fig.4: A frequency Distribution map of Schuepp coefficient B and Angstrom coefficient β for the three seasons. The means, extreme values and standard deviations are as indicated.

Fig.5: A plot of Unsworth turbidity coefficient τ_a against Kastrov turbidity coefficient, C for the 1984/85 season. The correlation coefficient r between the two and the regression parameters for the two are as shown .

Fig.6: As in Fig 5 but for τ_a against T.

Fig.7: As in fig 5 but for C against T.

Fig.8: As in Fig 5 but for τ_a against C for 1985/86 harmattan season.

Fig.9: As in Fig.5 but for τ_a against T for 1985/86 harmattan season.

Fig.10: As in Fig 5 but for C against T for 1985/86 harmattan season.

Fig.11: As in Fig 5 but for τ_a against C for the 1986/87 harmattan season.

Fig.12: As in Fig 5 but for τ_a against T for the 1986/87 harmattan season.

Fig.13: As in Fig 5 but for C against T for the 1986/87 harmattan season.

Fig.14: The graph of the daily variation in T and the horizontal visibility for the 1985/86 harmattan season. A negative correlation is found to exist between them ($r = -0.80$).

Fig.15: As in Fig 14 but for the 1986/87 harmattan season. Here also, a negative correlation ($r = -0.76$) has been found between T and visibility.

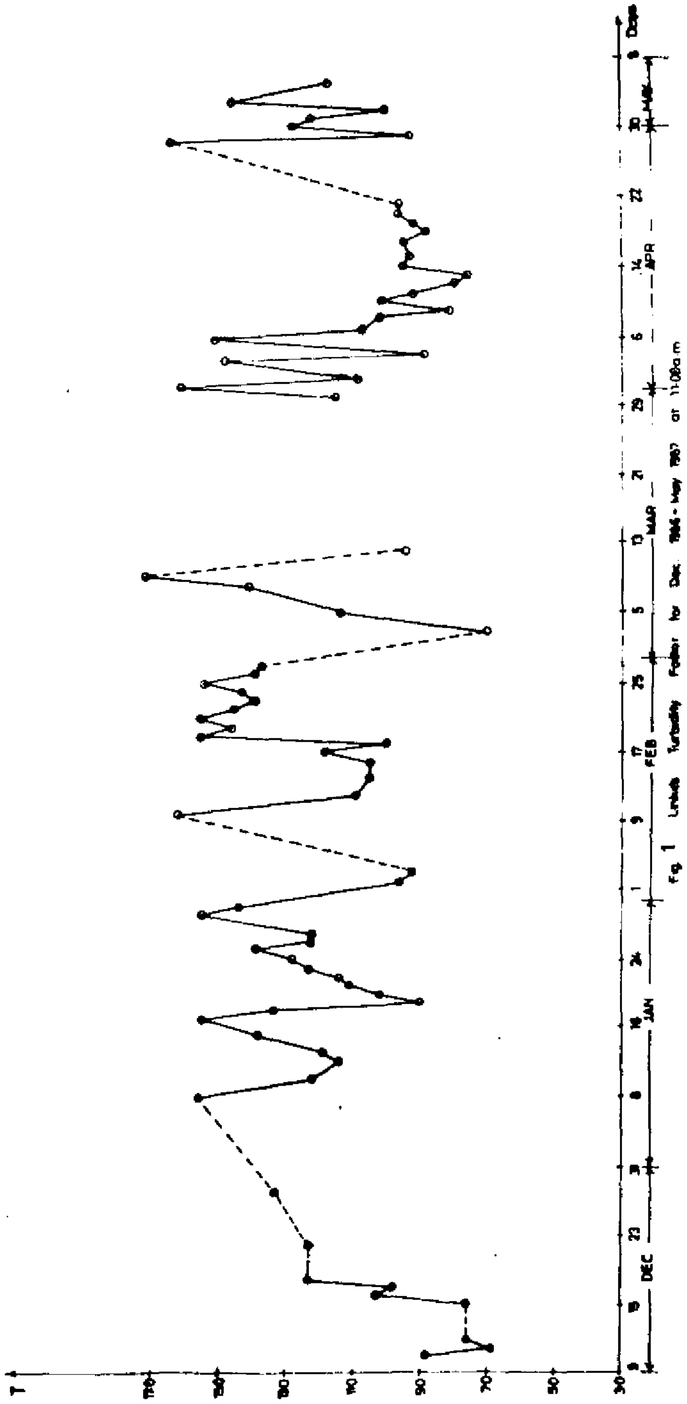

Fig 1 Linke's Turbidity Factor for Dec. 1986 - May 1987 at 11:08a.m

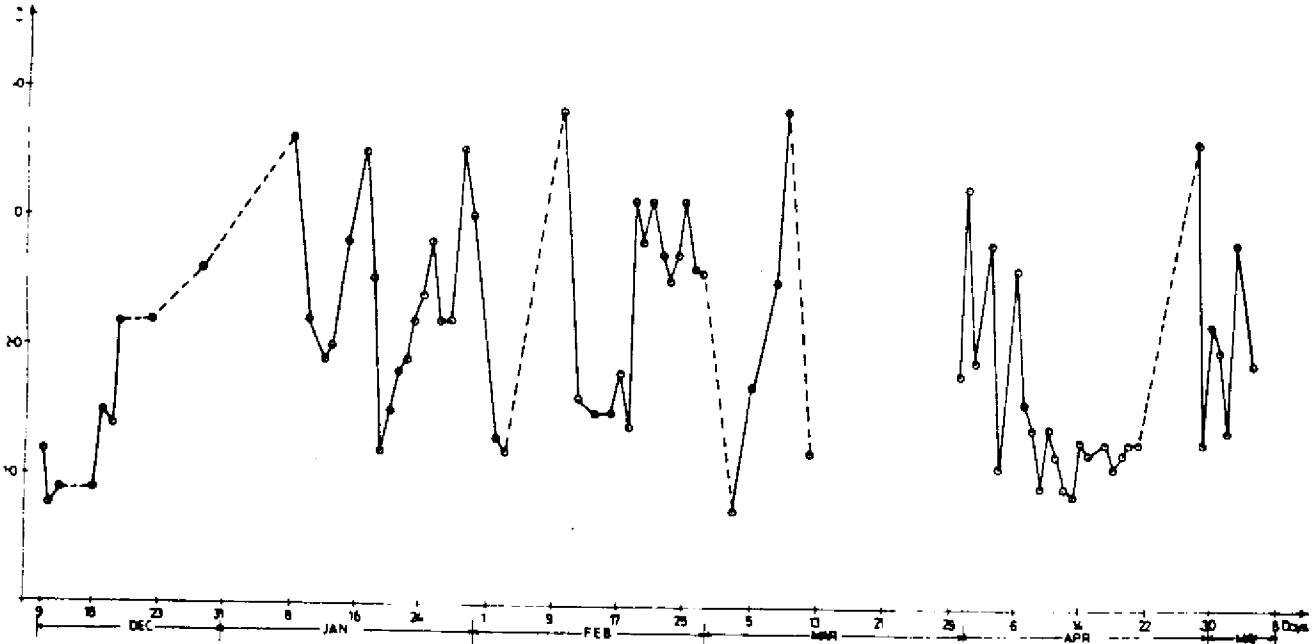

Fig. 2 Kastrov's Turbidity Formula, C for Dec 1986 - May 1987 at 11:00 a.m

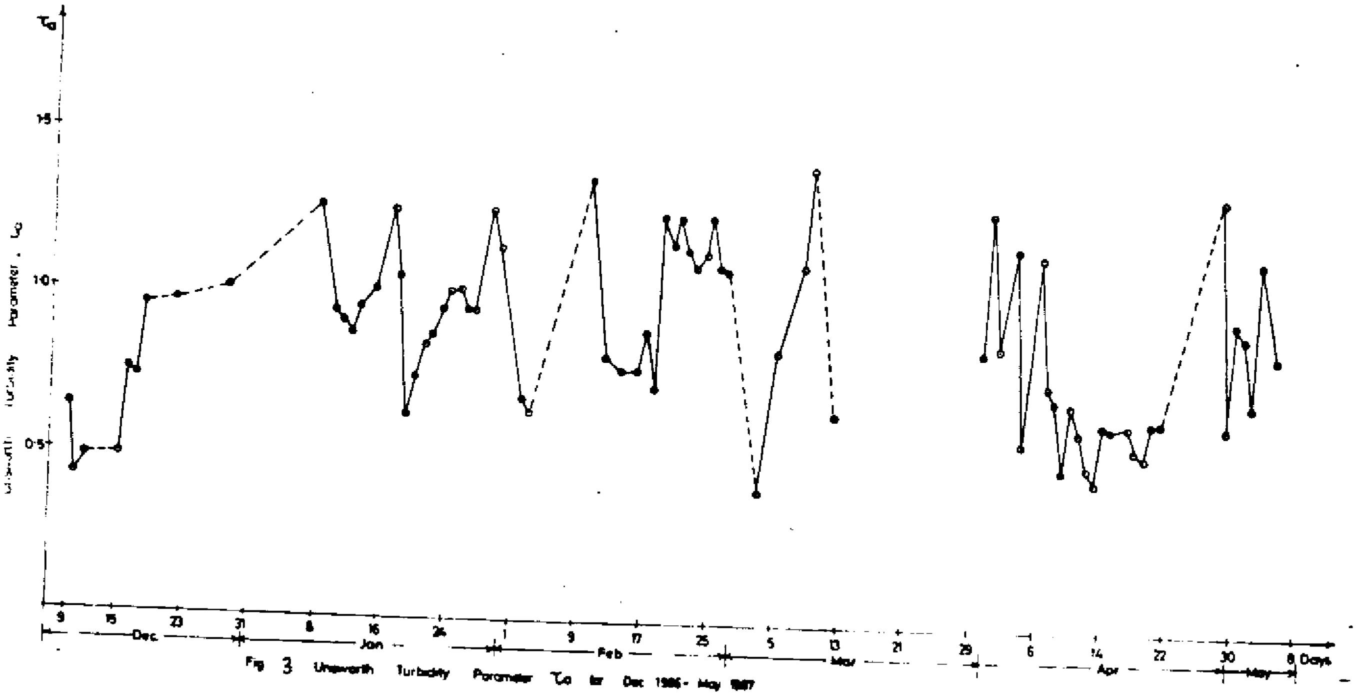

Fig 3 Unsworth Turbidity Parameter τa for Dec 1986 - May 1987

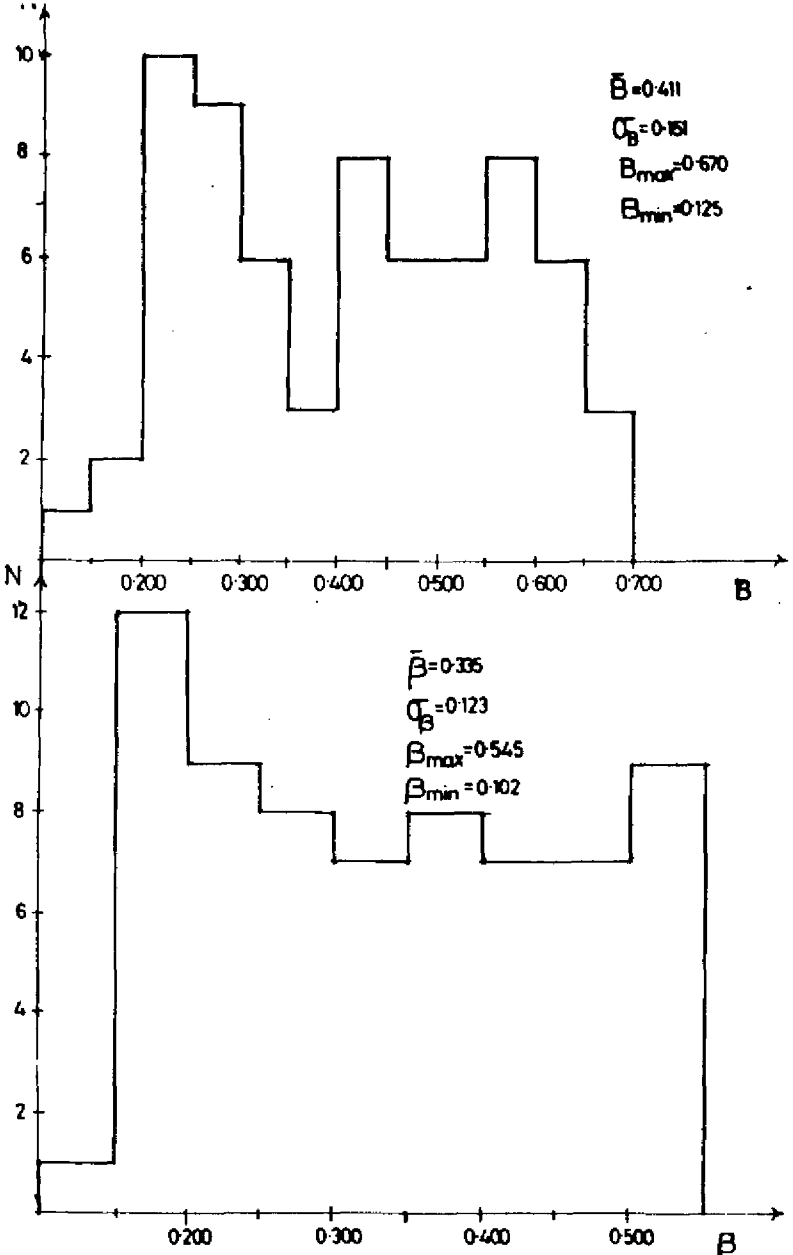

Fig 4 Frequency Distribution of Schüepp and Angström turbidity coefficients. The mean, extreme values and standard deviation for each parameter are shown.

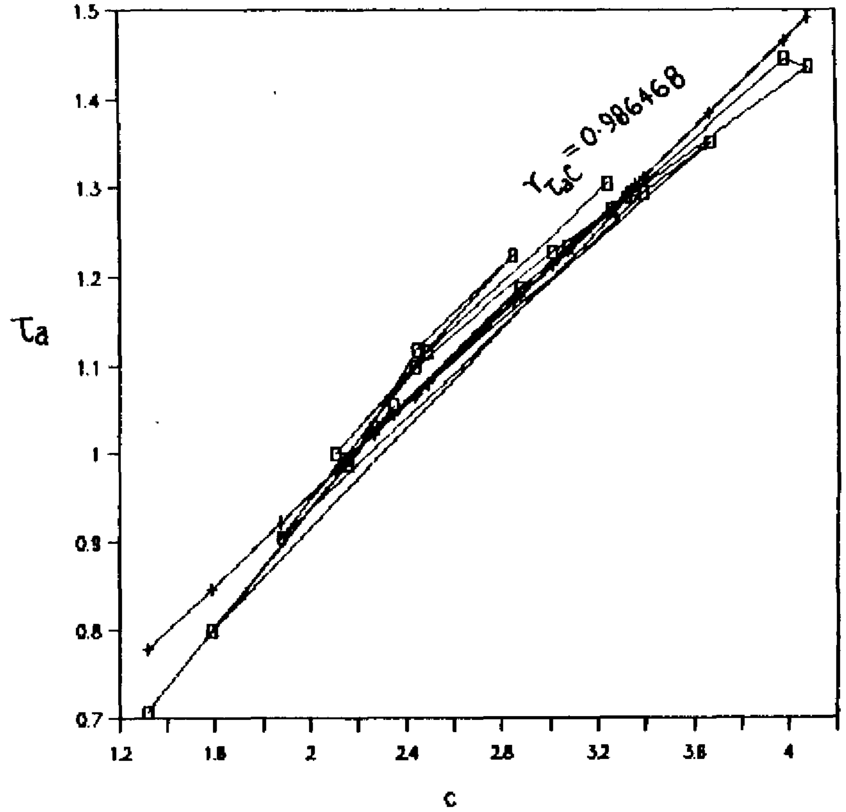

Fig. 5 : Graph of ta versus C
(1984/85 Harmattan Season)

```
             Regression Output:
Constant                           0.437011
Std Err of Y Est                   0.032326
R Squared                          0.973119
No. of Observations                      23
Degrees of Freedom                       21

X Coefficient(s)  0.257816
Std Err of Coef.  0.009350
```

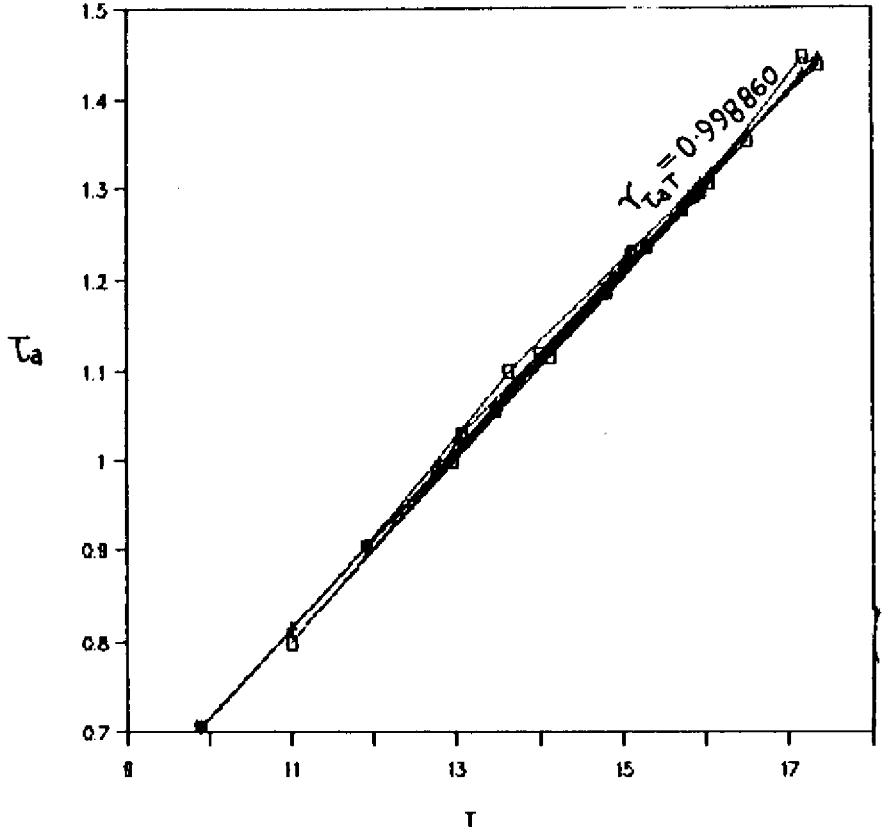

Fig. 6 : Graph of ta versus T
(1984/85 Harmattan Season)

```
        Regression Output:
Constant                        -0.27567
Std Err of Y Est                0.009411
R Squared                       0.997721
No. of Observations                   23
Degrees of Freedom                    21

X Coefficient(s)  0.099009
Std Err of Coef.  0.001032
```

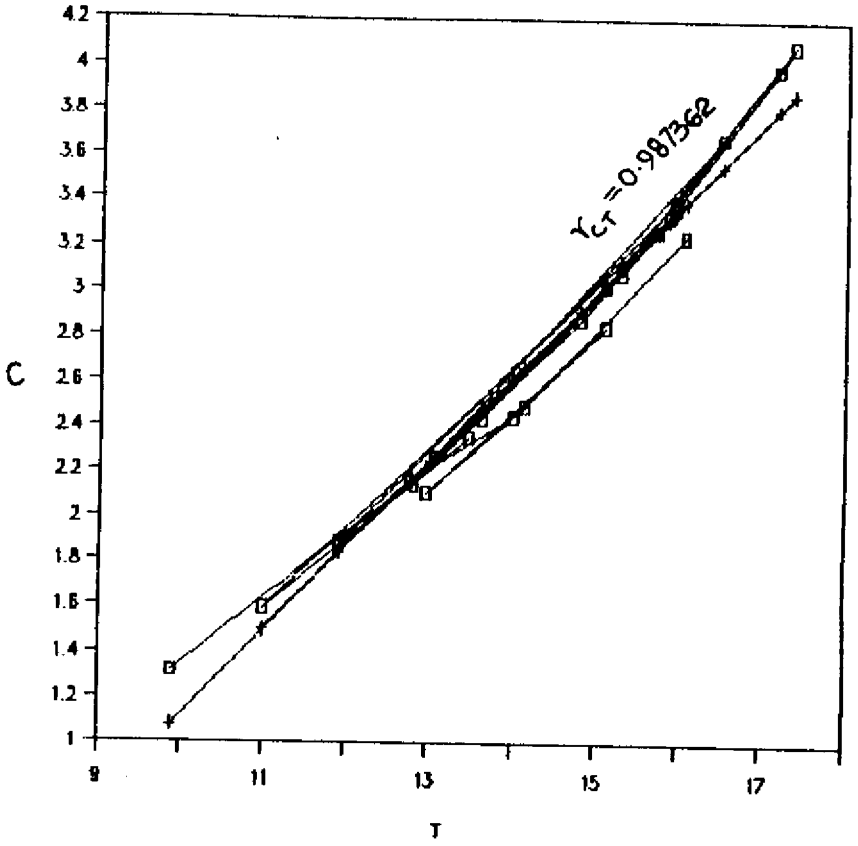

Fig.7 : Graph of C versus T
(1984/85 Harmattan Season)

```
        Regression Output:
Constant                        -2.62696
Std Err of Y Est                0.119556
R Squared                       0.974884
No. of Observations                   23
Degrees of Freedom                    21

X Coefficient(s)  0.374471
Std Err of Coef.  0.013116
```

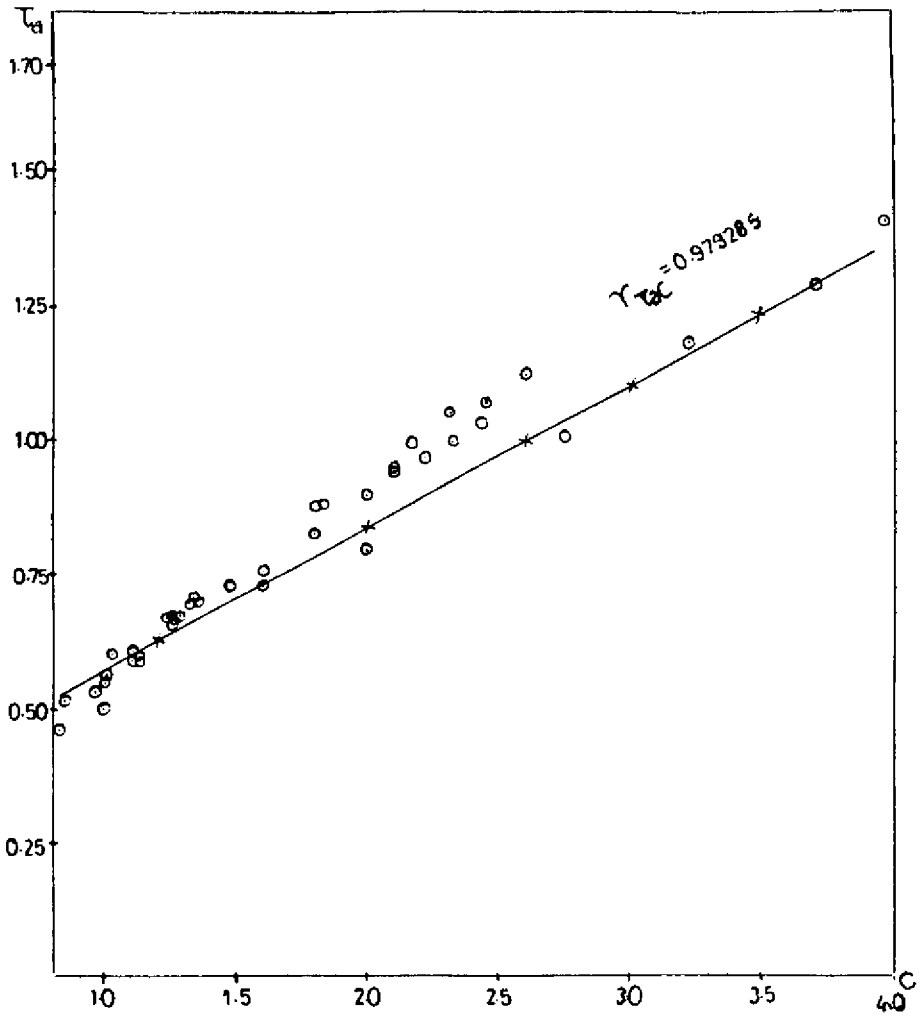

Fig. 8 : Graph of τ_a versus C
(1985/86 Harmattan season)

```
              Regression Output:
Constant                              0.311183
Std Err of Y Est                      0.076237
R Squared                             0.958993
No. of Observations                         55
Degrees of Freedom                          53

X Coefficient(s)    0.265155
Std Err of Coef.    0.007531
```

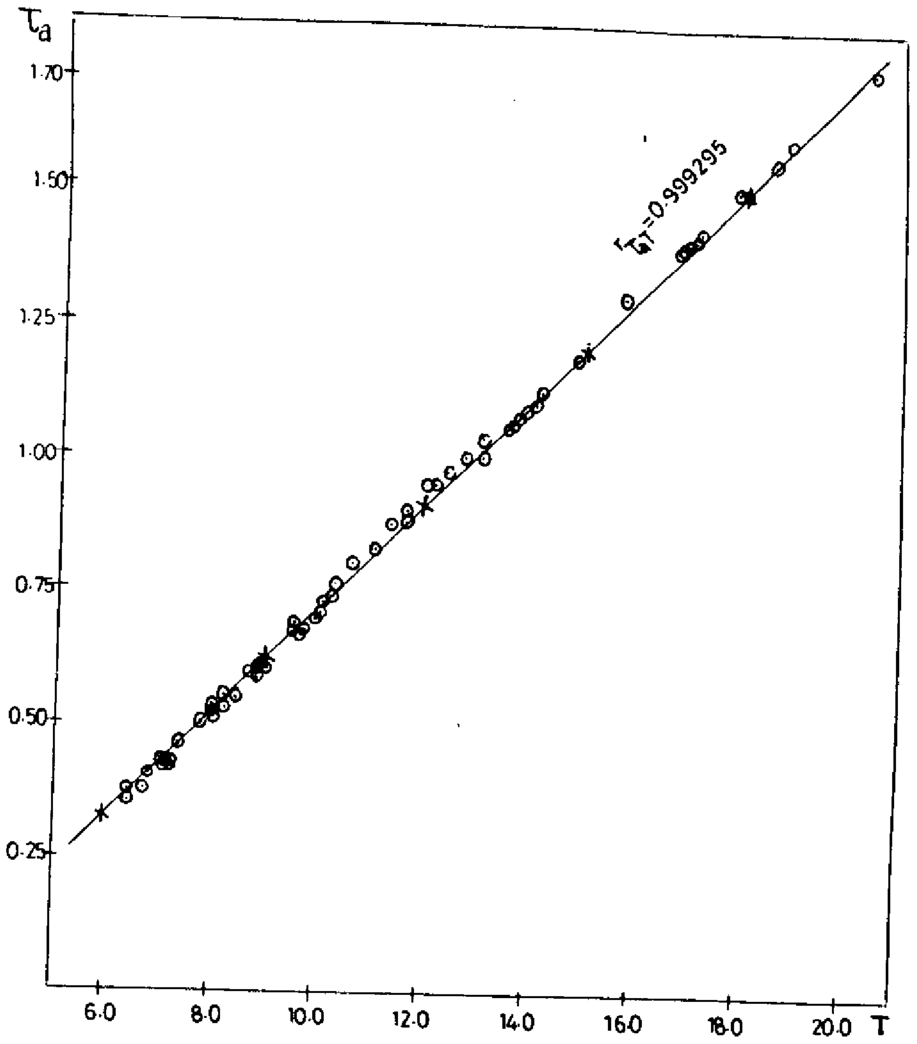

Fig. 9 : Graph of τ_a versus T
(1985/86 Harmattan season)

```
              Regression Output:
Constant                             -0.27583
Std Err of Y Est                      0.014133
R Squared                             0.998590
No. of Observations                         55
Degrees of Freedom                          53

X Coefficient(s)    0.099461
Std Err of Coef.    0.000513
```

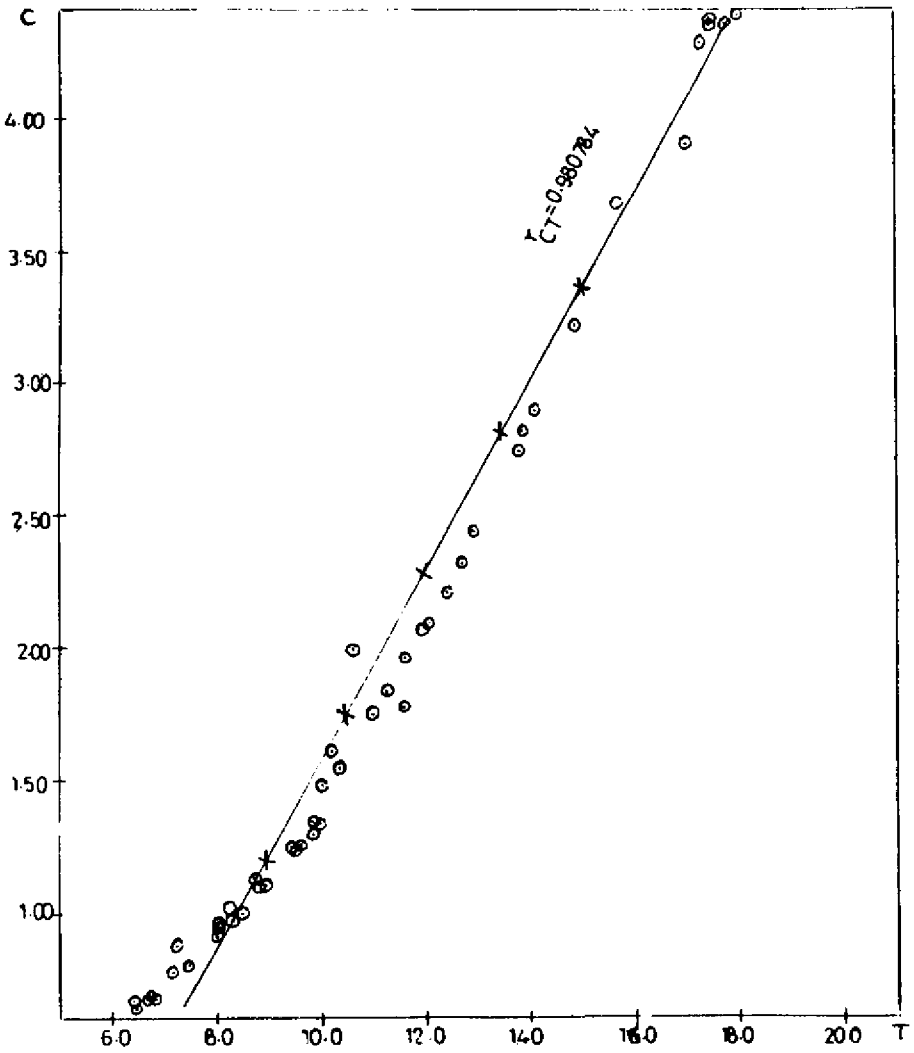

Fig. 10 :Graph of C versus T
(1985/86 Harmattan season)

```
                 Regression Output:
Constant                                 -2.04498
Std Err of Y Est                          0.271279
R Squared                                 0.961938
No. of Observations                             55
Degrees of Freedom                              53

X Coefficient(s)    0.360526
Std Err of Coef.    0.009850
```

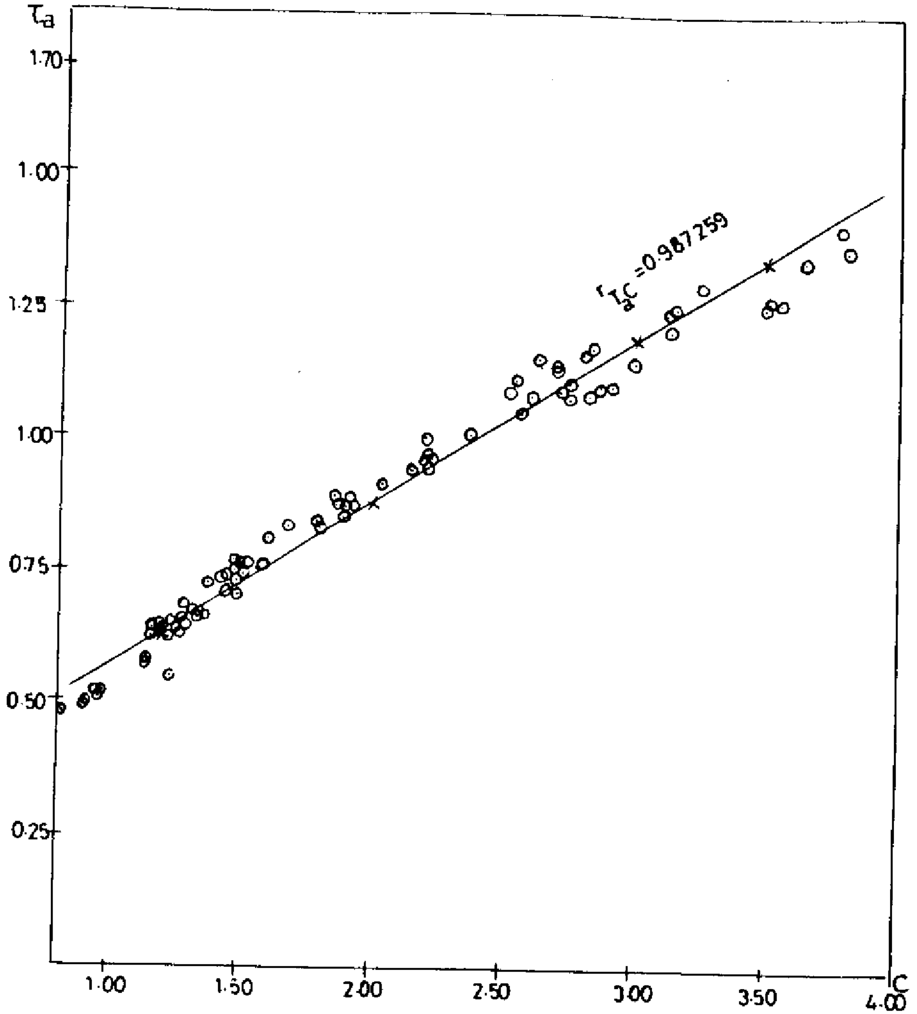

Fig. 11 Graph of τ_a versus C
(1986/87 Harmattan season)

```
            Regression Output:
Constant                    0.261902
Std Err of Y Est            0.042068
R Squared                   0.974680
No. of Observations             72
Degrees of Freedom              70
X Coeffcient(s)   0.307671
Std Err of Coef.  0.005926
```

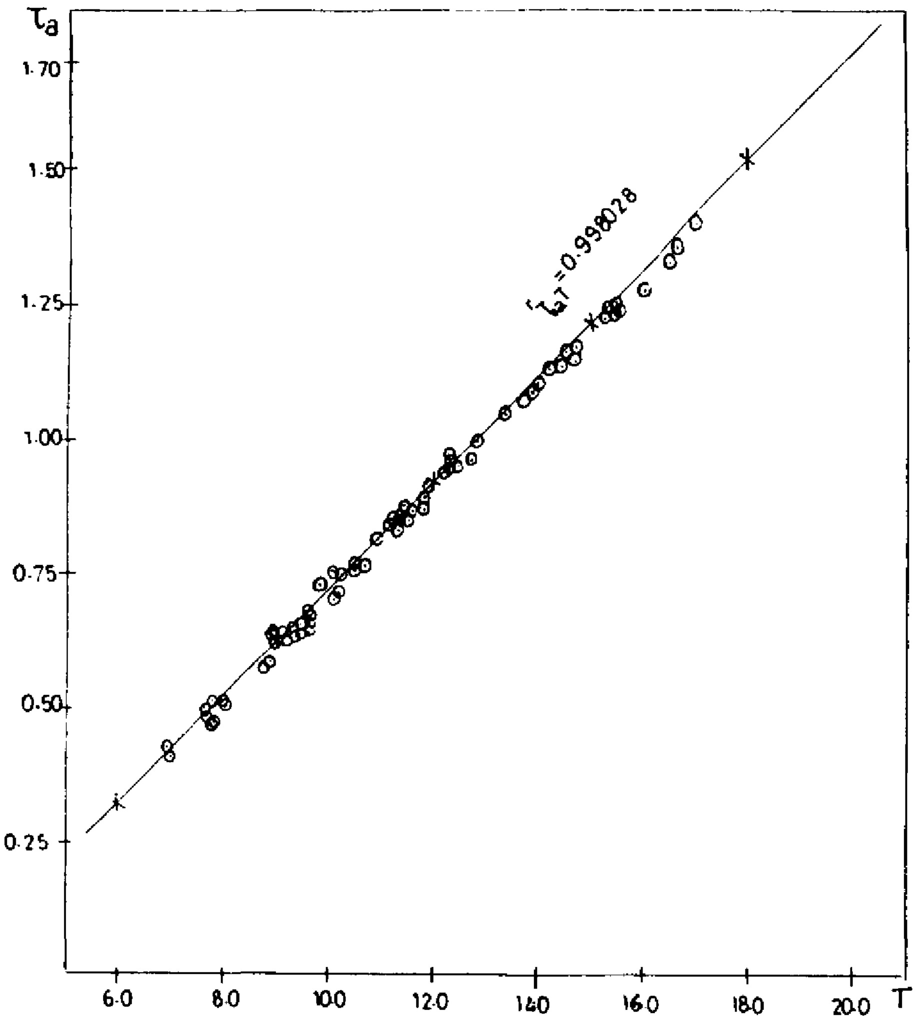

Fig 12 : Graph of τ_a versus T
(1986/87 Harmattan season)

```
    Regression Output:
Co.stant                   -0.27003
Std Err of Y Est           0.016596
R Squared                  0.996059
No. o. Observations              72
Degrees of Freedom               70

X Coefficient(s)  0.098402
Std Err of Coef.  0.000739
```

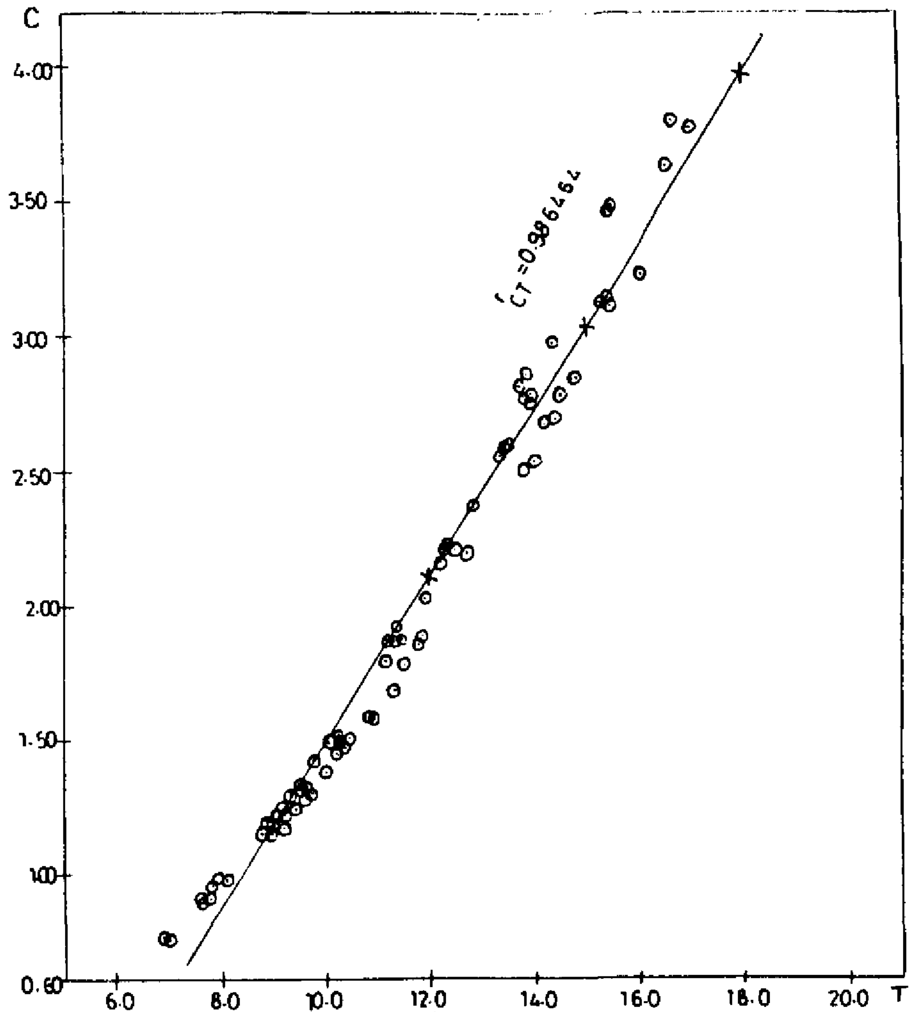

Fig. 13 : Graph of C versus T
(1986/87 Harmattan season)

```
    Regression Output:
Constant                  -1.65959
Std Err of Y Est          0.139107
R Squared                 0.973112
No. of Observations             72
Degrees of Freedom              70

X Coefficient(s)  0.312095
Std Err of Coef.  0.006200
```

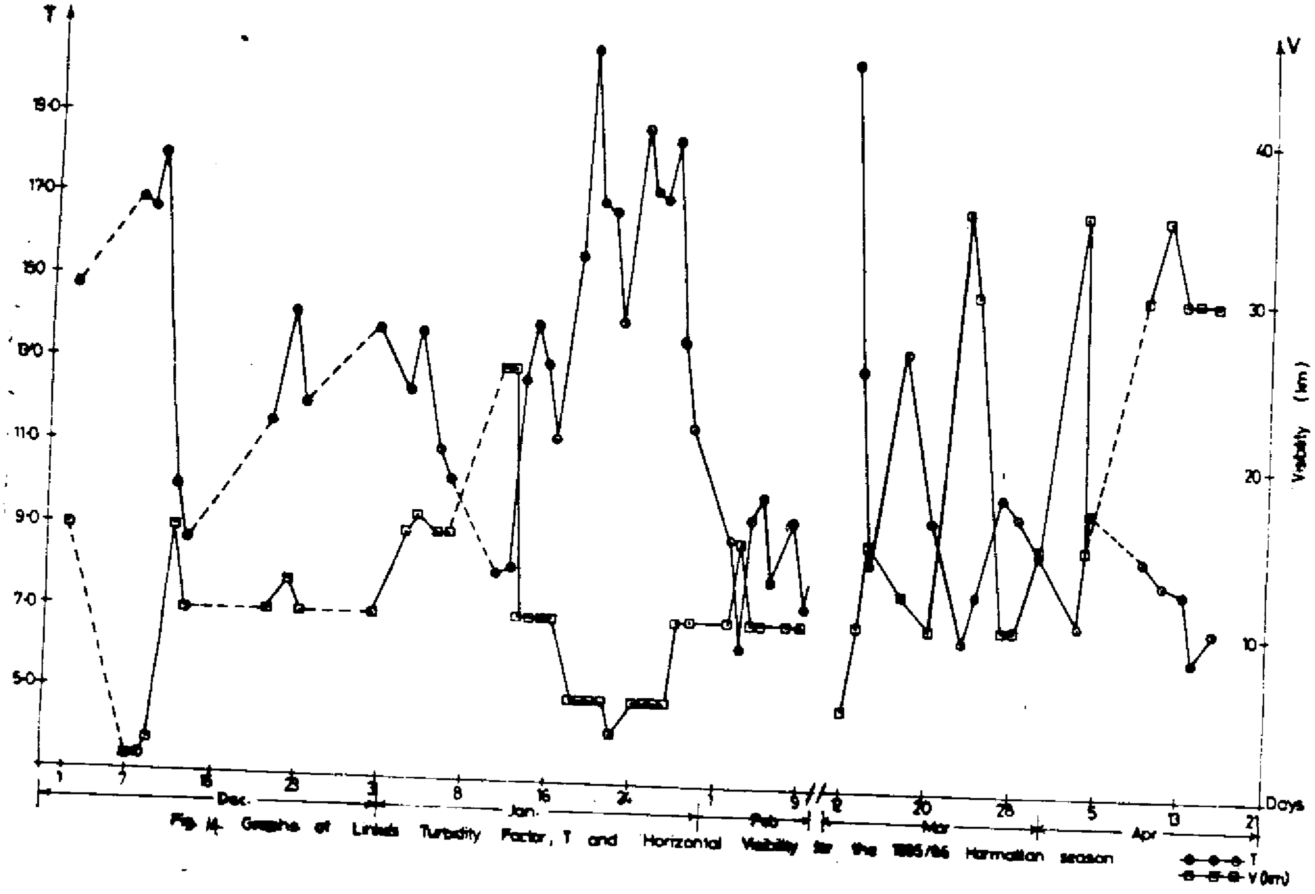

Fig 14 Graphs of Linke's Turbidity Factor, T and Horizontal Visibility for the 1985/86 Harmattan season

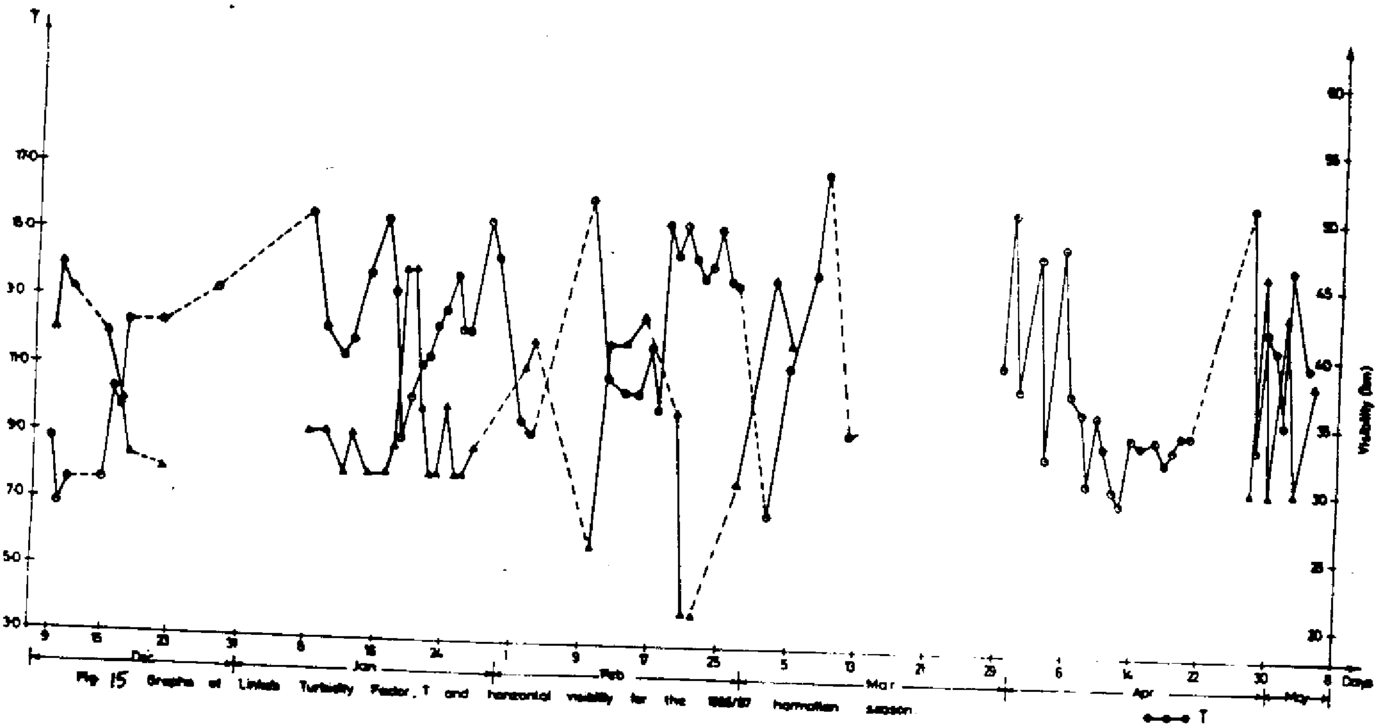

Fig 15 Graphs of Linke's Turbidity Factor, T and horizontal visibility for the 1986/87 harmattan season