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New features of haze scattering in India as deduced from measurements of atmospheric turbidity

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ABSTRACT. Aerosols and dust which lead to the turbidity of the atmosphere are known to play an important role in the radiation budget of the earth's atmosphere. For the quantitative formulation of any generalised turbidity coefficient, the law governing the wavelength dependance of aerosol or haze scattering as embodied in the factor α of the well known Angstrom formula has to be known precisely. A study based on measurements of solar radiation using standard cut-off filters at two representative stations in India reveals that for most part of the year, α values are much less than the usual value of $1 \cdot 3$ reported in literature. It approaches zero for a good part of the year and even turns negative during some months. Therefore, it is apparent that a single value of α for universal applicability would lead to erroneous results in the evaluation of the Angstrom turbidity coefficient. Both α and β will have to be determined for each location and each season. The lower values of α at the two Indian stations would imply a lower value of ν in the Junge power law for the size distribution of aerosols and consequently a higher proportion of large particles in the general aerosol spectrum.

1. Introduction

Atmospheric turbidity, defined in a broad sense as the lack of transparency of the atmosphere to visible light is caused by the presence of aerosols and dust particles. Quantitative evaluation of the turbidity can yield information on two different aspects. In the first place, turbidity values, together with data on water vapour content enable fairly exact computations of the sun's energy that becomes actually available at the earth's surface for heating the lower atmosphere. Secondly, the magnitude of the extinction of the direct solar radiation by the aerosols and dust, as embodied in the concept of a turbidity coefficient or a turbidity parameter, could give useful information on the total concentration of particles in a vertical column and their probable size distribution. Despite its importance, there does not appear to be any universally adopted system for the measurement and publication of the turbidity values on a routine climatological basis. In this paper, the results of an investigation on the turbidity values at two representative stations in India for two different regions of the solar spectrum are presented. The implications of the results on the size distribution of aerosols are discussed.

In its passage from outer space into the earth's atmosphere, the sun's radiation undergoes attenuation due to (1) direct selective absorption by the permanent gases as well as by water vapour, (2) Rayleigh scattering and (3) scattering, (and some absorption too) by haze particles which are mostly confined to the lowest 2 to 6 km from the ground. If due allowance is made for the effects of the first two, the contribution due to dust and aerosols can be determined from ground-based measurements of direct solar radiation falling on unit area normal to the beam. At present, there are two turbidity coefficients in actual use, namely, the Angstrom's turbidity coefficient β and the Schuepp's coefficient B. Full details of the evaluation of these are described in the *IGY Instruction Manual No. 6* (1956). The coefficient B represents what may be called a monochromatic turbidity factor and as such does not depend on any assumed law for haze scattering. Since the sun's energy

TABLE 1

$\alpha_\circ$ values corresponding to different ratios of β_{rr} / β_g

β_{rr}/β_g	$\alpha_\circ$	β_{rr}/β_g	$\alpha_\circ$
0·52	3·0	1·47	0·3
0·63	2·5	1·52	0·2
0·77	2·0	1·58	0·1
0·80	1·9	1·64	0
0·83	1·8	1·71	—0·1
0·86	1·7	1·78	—0·2
0·89	1·6	1·85	—0·3
0·92	1·5	1·92	—0·4
0·96	1·4	1·99	—0·5
1·00	1·3	2·07	—0·6
1·04	1·2	2·15	—0·7
1·08	1·1	2·24	—0·8
1·12	1·0	2·32	—0·9
1·16	0·9	2·42	– 1·0
1·21	0·8	2·61	– 1·2
1·26	0·7	2·82	– 1·4
1·31	0·6	3·04	– 1·6
1·36	0·5	3·29	—1·8
1·41	0·4	3·55	—2·0

TABLE 2

$\beta_\circ/\beta_{rr}$ for different values of $\alpha_\circ$

$\alpha_\circ$	$\beta_\circ/\beta_{rr}$	$\alpha_\circ$	β_o/β_{rr}
3·0	0·5	0·3	1·50
2·5	0·61	0·2	1·56
2·0	0·75	0·1	1·62
1·9	0·78	0	1·69
1·8	0·82	—0·1	1·76
1·7	0·86	—0·2	1·83
1·6	0·89	—0·3	1·90
1·5	0·92	—0·4	1·98
1·4	0·98	—0·5	2·06
1·3	1·00	—0·6	2·15
1·2	1·04	—0·7	2·24
1·1	1·08	—0·8	2·33
1·0	1·13	—0·9	2·43
0·9	1·18	-1·0	2·53
0·8	1·22	—1·2	2·74
0·7	1·28	—1·4	2·97
0 6	1·33	—1·6	3·22
0·5	1·38	—1·8	3·49
0·4	1·44	– 2·0	3·78

in the visible spectrum is largely centred around 0·5 micron, B becomes a convenient measure of the total dust and aerosol scattering.

The use of a single parameter embodied in the Angstrom turbidity coefficient β suffers from the drawback that it is derived from energy measurements covering a wide wavelength band. The wavelength exponent α of the haze or aerosol scattering has to be known fairly accurately if β is to have any quantitative significance. Deviation of the prevailing α from the assumed standard value of 1.3 could lead to serious errors in the value of β as would be evident from the discussions that are to follow. Angstrom(1961)outlined a simple technique for the evaluation of both α and β from measurements of solar radiation using the Schott filters OG_1, RG_2, and RG_8 which have cut-off wavelengths at 0.530, 0.630 and 0·710 microns. Using Angstrom's method an attempt has been made to evaluate both α and β for conditions prevailing in India, in order to examine how far the assumption $\alpha = 1.3$ is justified and also to see to what extent errors in β could arise on account of such assumptions.

It may be mentioned that few determinations of the parameter α has so far been made in the tropical areas.

2. Principle of the method and evaluation procedure

Following Angstrom (1961), the transmission of radiation through aerosols alone at any two wavelengths λ_1 and λ_2 may be designated as, $p\lambda_1$, and $p\lambda_2$. These are related to the turbidity parameters α and β in accordance with,

$$p\lambda_1 = \exp\left(-\frac{m\,\beta_1}{\lambda_1^{1\cdot 3}}\right) = \exp\left(-\frac{m\,\beta_\circ}{\lambda_1^{\alpha_\circ}}\right) \tag{1}$$

$$p\lambda_2 = \exp\left(-\frac{m\,\beta_2}{\lambda_2^{1\cdot 3}}\right) = \exp\left(-\frac{m\,\beta_0}{\lambda_2^{\alpha_\circ}}\right) \tag{2}$$

Here β_1 and β_2 are turbidity coefficients at λ_1 and λ_2 calculated under the assumption $\alpha = 1\cdot 3$, $\alpha_\circ$ the true wave length exponent for haze scattering at the time of observation and $\beta_\circ$ the true turbidity coefficient. From (1) and (2) we have,

$$\alpha_\circ = 1.3 - 5\cdot 94 \log_{10} (\beta_2/\beta_1) \tag{3}$$

$$\text{and} \quad \log_{10} (\beta_2/\beta_\circ) = (1.3 - \alpha_\circ) \log_{10} \lambda_2 \tag{4}$$

In the measurement technique using the cut off filters and the Angstrom compensation pyrheliometer, λ_1 is taken as $\cdot 454\mu$ corresponding to the green region of the spectrum and λ_2 as $\cdot 669\mu$ corresponding to the red region of the spectrum. For easy identification β_1 and β_2 will henceforth be designated as β_g and β_{rr}. From a knowledge of both β_g and β_{rr}, it is possible to evaluate β_0 and $\alpha_\circ$ appropriate to the time of observation

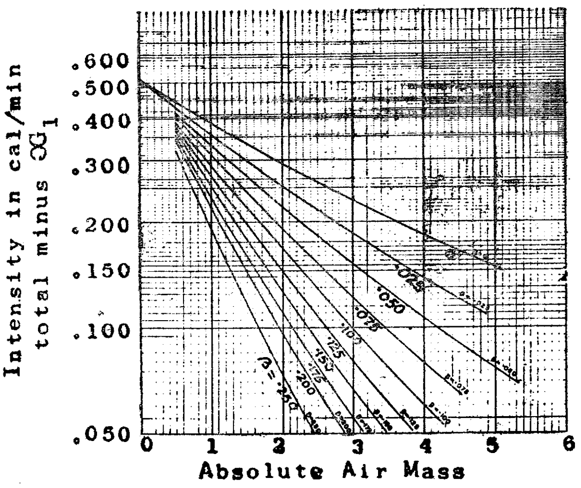


Fig. 1. Nomogram for evaluation of β_g

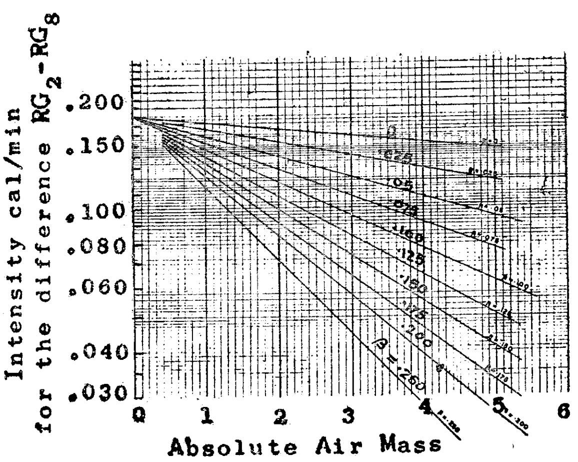


Fig. 2. Nomogram for evaluation of β_{rr}

From equation (4) it may be seen that so long as β_{rr} (or β_2) is greater than β_g (or β_1), the correct value of α_0 would be less than the standard value of 1·3. Table 1 shows the values of α_0 for different ratios of β_{rr}/β_g and Table 2 shows the ratios β_0/β_{rr} for different α_0 values. When β_{rr}/β_g exceeds about 1·6, α_0 turns out to be negative.

For the rapid evaluation of the coefficients β_g and β_{rr} nomograms were prepared as follows. From the *Handbook of Geophysics* (1960) the extra-terrestrial values of solar radiation in the different wavelengths were obtained. These were grouped into intervals of 10 millimicrons. For each of these intervals the attenuation of the direct solar beam due to Rayleigh scattering and ozone absorption were calculated assuming a mean value of 0·25 cm of ozone for the tropics. The Rayleigh scattering coefficients were taken from the tables published by Penndorf (1957) and those for ozone absorption from the data of Vigroux (1953). The total intensity of solar radiation contained in the interval 0·300 to 0·530 micron that would be received at sea level for each of the air masses, 1, 2, 3 and 4 was calculated. A semilogarithmic grid was chosen for the construction of the nomogram which is shown in Fig. 1. The solar intensities were accurately marked on the logarithmic absessae and the air masses on the linear ordinates. The calculated intensities at sea level for a dust free atmosphere were plotted on the grid and joined by a smooth line and labelled as $\beta = 0$. By multiplying the intensities for $\beta = 0$ by the exponential factor exp $(-m\beta/\lambda_1{}^{1\cdot3})$ with β having different values at intervals of 0·025 and $m = 1, 2, 3$ and 4 successively, it was possible to mark out lines corresponding to different values of the turbidity β under the assumption of $\alpha = 1\cdot3$. λ_1 was taken as the weighted mean of the band represented by —

$$\int_{300}^{530} F(\lambda)\, d\lambda$$

and numerically equated to 0·454 micron after Angstrom (1961). Thus a set of smooth lines were obtained each representing a unique value of β, all lines converging at a single point at $m = 0$ which represents the extra-terrestrial energy in the band considered. Using this nomogram it is possible to evaluate β_g rapidly by simple interpolation knowing the air mass and the intensity of solar radiation, total *minus* that received behind the OG_1 filter, corrected for the mean earth-sun distance. In similar manner, another nomogram (Fig. 2) was constructed for the evaluation of β_{rr} from the measured values of solar radiation in the band 0·630 to 0·710 microns (the difference between the radiations received behind filters RG_2 and RG_8). Using large scale drawings of the nomograms, it was possible to evaluate β_g and β_{rr} to an accuracy of 0·002.

As part of the routine observational programme, the radiation stations at New Delhi and Poona measure the solar intensities behind the OG_1 RG_2 and RG_8 filters in addition to the total radiation. These raw data formed the basic observational material used in this study. The times of routine observations were approximately 08, 11, 14 and 17 hours local time on all days when the sun could be seen unobscured by clouds. The data for 08 and 17 hours were not utilised as there

TABLE 3

Monthly mean values of β_g, β_{rr}, β_o and α_o

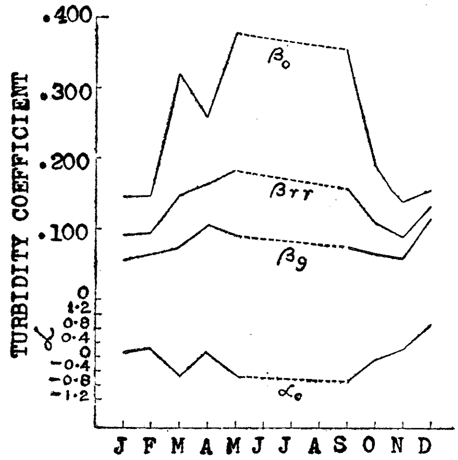
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(a) New Delhi during 1963												
n	29	36	22	14	16				11	35	19	26
β_g	·084	·082	·084	·070	·075				·108	·092	·067	·072
β_{rr}	·104	·111	·120	·142	·139				·164	·147	·108	·100
β_{rr}/β_g	1·24	1·35	1·43	2·03	1·85				1·52	1·60	1·61	1·39
β_o	·131	·153	·173	·298	·264				·256	·238	·178	·141
α_o	0·75	0·5	0·4	—0·55	—0·3				0·2	0·1	0·05	0·45
(b) New Delhi during 1964												
n	26	12	31	13	27				10	41	27	22
β_g	·057	·062	·071	·105	·090				·073	·064	·058	·113
β_{rr}	.090	.093	·149	·163	·182				·158	·108	·088	·130
β_{rr}/β_g	1·58	1·50	2·10	1·55	2·00				2·16	1·69	1·52	1·15
β_o	·146	·145	·320	·259	·375				·353	·190	·137	·153
α_o	0·1	0·2	—0·6	0·15	—0·5				—0·7	—0·1	0·2	0·9
(c) Poona during 1965												
n	15	24	18	27	36					24	13	17
β_g	·060	·060	·062	·057	·074					·049	·043	·040
β_{rr}	·076	·077	·133	·147	·195					·083	·065	·086
β_{rr}/β_g	1·27	1·28	2·14	2·58	2·63					1·69	1·51	2·15
β_o	·097	·098	·298	·403	·534					·146	·101	·192
α_o	0·7	0·7	—0·7	—1·2	—1·2					—0·1	0·2	—0·7

was evidence of higher turbidities occurring in the mornings arising from condensation of water vapour on hygroscopic aerosols. Further it appeared that observations made with air masses of the order of 4 could be subject to more errors than those made with air masses near 1 or 1·5. For New Delhi, a total of about 400 observations were available covering the year 1964 and 1965 and for Poona, a total of about 140 covering the year 1965. From each set of observations, β_g and β_{rr} were determined using the nomograms of Figs. 1 and 2. From the monthly mean β_g and β_{rr}, the values of the monthly mean β_o and α_o were determined using Tables 1 and 2. The results are presented in Tables 3(a), (b) and (c).

As an illustration, the annual variation of the turbidity parameters at New Delhi for 1964 is depicted in Fig. 3. The frequency distribution of α_o at New Delhi and Poona are illustrated in Fig. 4. For comparison, the frequency distribution of α at Potsdam as found by Angstrom (1964) is also shown.

3. Discussion of results

One striking fact emerging out of this investigation is that on most occasions, β_{rr} is appreciably higher than β_g implying after Eq. (3) that the α_o values applicable to the conditions prevailing in India (as would most probably be represented by the stations considered) are considerably smaller than the standard value of 1·3 assumed in the preparation of standard tables for the calculation of the Angstrom turbidity coefficient β. This will be evident from the tables as well as figures. The true turbidity values β_o become quite high during the period March to June, when the ratio β_{rr}/β_g also becomes higher and the α_o values approach zero or even turn negative. During the winter season November to February the α_o values tend to be about 0·1 to 0·8. At Poona even during the month of December negative values of α_o occur, but confirmation of this may have to be made from future observations. When the wavelength exponent α attains a value of zero or nearly zero, it means that the scattering of light by the aerosol particles is independant of wavelength. In other words,



NEW DELHI 1964

Fig. 3. Annual variation of β_g, β_{rr}, β_o and α_o at New Delhi during the year 1964

the haze extinction becomes practically neutral at the two stations for a good part of the year. At Potsdam (Lat. 52°N) in Germany, Angstrom (1964) found a frequency distribution for α in such a manner that a wide range of values occur with a rather flat maximum near 0·9 to 1·6. At Davos (Lat. 46°N) in Switzerland, a more or less similar distribution was found with a sharper maximum near 1·3–1·4. The difference in the frequency distribution of α at the two places was attributed by Angstrom to the difference in the altitudes of the places. The two Indian stations provide a marked contrast as would be evident from Fig. 4. Further, the annual variation of the parameter α at European stations is characterised by a *maximum* during the summer season. In marked contrast, the α at the two Indian stations reveal a *minimum* during summer. The low values of α are indicative of an increase in the relatively larger ærosols. The origin of the large sized ærosols could be (1) fine dry dust raised from ground through convection and thermal instability and (2) the condensation of water vapour on the hygroscopic nuclei which could lead to an increase in the number of the larger particles.

As a consequence of the low values of the prevailing α_0, the true values of the Angstrom turbidity coefficient β_0 turn out to be appreciably higher than what are calculated on the basis of a standard value of $\alpha = 1\cdot3$. This would be evident from Fig. 3. These higher values of β_0 could explain why the intensity of total solar radiation as received at the ground and measured by pyrheliometers is appreciably lower at the Indian stations when compared with other stations (Mani and Chacko 1963).

The occurrence of negative values of the exponent α_0 at New Delhi has been reported earlier by Ramanathan and Karandikar (1949) who made a careful study of the haze correction factor (δ–δ') that is used in the measurement of total ozone by the Dobson spectrophotometer. This factor is a measure of the differential scattering due to haze particles at the two wavelengths 3300 and 4450 A. On days with the normal type of haze in winter they found that (δ–δ') is positive and increases with increasing haziness of the day, similar to what was observed earlier by different investigators in Europe. However, on most days during the premonsoon period, in North India (δ–δ') was found to be negative implying that the extinction of the solar radiation at the wavelength of 3300 A was less than that at 4450 A. This anomalous scattering is naturally associated with a negative value of the wavelength exponent in the Angstrom formula for haze scattering. Ramanathan and Karandikar (1949) further observed that "the fact that

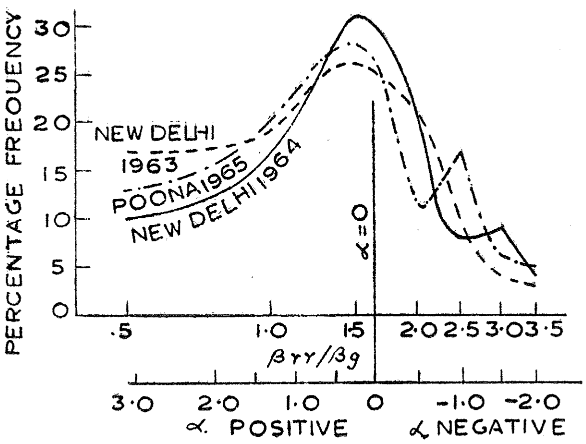


Fig. 4 (a). Frequency distribution of α_0 (whole year) at New Delhi and Poona

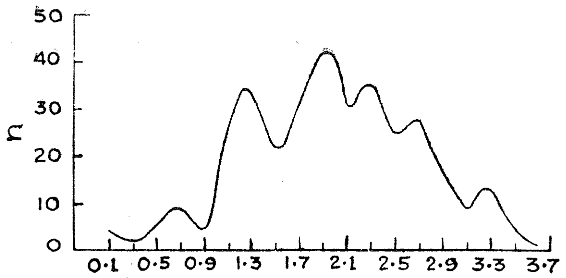


Fig. 4(b). Frequency distribution of α at Potsdam (1932-1936) (after Angstrom 1964)

the magnitude of ($\delta - \delta'$) does not become enormously large even with the haziest of skies and that it changes sign with the season show that scattering by haze is, for the most part, independant of wavelength". This is also corroborated by the visual appearance of the Indian sky in the hot weather season. The haze is mostly whitish in colour and the real blue of the sky gets replaced by a milky canopy.

4. Application of the Mie theory of scattering

The Mie theory of scattering of light by particles having sizes comparable to that of the wavelength of light has been dealt with in detail by Van de Hulst (1957) and applied to scattering of natural ærosols by Bullrich (1964). If there are n particles per cm³ all of radius r, the scattering coefficient per unit volume $\sigma_D{}'$ is given by,

$$\sigma_D{}' = n.\ \pi\, r^2.\ k\,(r,\ \lambda,\ m) \qquad (5)$$

where $k\ (r, \lambda, m)$ is a function related to the size of the haze particle, its refractive index m, and the wavelength of the light λ. In the actual atmosphere, the aerosols have a wide range of sizes and the number in each size range between r and $(r + dr)$ is given by the power law of Junge (1955),

$$\frac{d\,n\,(r)}{d.\,\log r} = c.\ r^{-\nu}\ (\mathrm{cm})^{-3} \qquad (6)$$

where, c is a constant dependant on the total number of particles per unit volume and ν the exponent ranging in value between 2 and 4 depending on the nature of size distribution. The above power law was found to hold good for the ærosol size range .04 to 10 microns by Junge (1955). This has also been verified experimentally by Clarke and Whitby (1967). By making reasonable assumptions about the upper and lower limit to the size of ærosols normally found in the atmosphere, it was shown by Junge (1963) and Bullrich (1964) that the power law index ν is related to the exponent α of the Angstrom formula by the equation,

$$\alpha = (\nu - 2) \qquad (7)$$

Thus the wavelength exponent of the Angstrom formula which can be determined from solar radiation measurements gives a clue to the value of ν. The validity of the equation (7) is open to doubt when α approaches zero. Junge (1963) found that for the case $\alpha = 0$, the upper limit to the giant size particles cannot be ignored and that α tends to be near 0·2. Taking into account the experimental errors involved in the determination of α by the above method, we may assume that for all values of $\alpha \nless 0$ as determined by turbidity measurements, the value of ν could be between 2 and 2.5. The results in respect of New Delhi and Poona indicate that α values are generally close to zero. This would seem to indicate

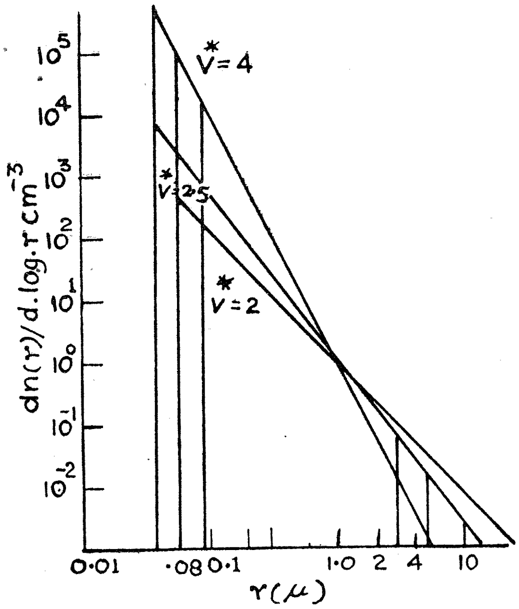


Fig. 5. Relative aerosol size distribution when $\nu=4, 2\cdot5$ and $2\cdot0$

that for the atmospheric conditions generally prevailing at these two stations the exponent of the Junge power law should be between 2·0 and 2·5. These values being appreciably lower than those found for the European latitudes would suggest an ærosol size distribution in which the larger ærosols are more numerous. Fig. 5 illustrates how with different values of ν the relative size distributions of aerosols undergo changes.

5. Suggestions for future work

The above investigation brings out the need for collecting more observational data on the parameters of atmospheric turbidity. While the technique using pyrheliometric measurements with cut-off filters might be adequate for studying synoptic or climatological aspects of atmospheric turbidity, it is not suitable for the precise evaluation of the Angstrom wavelength exponent α. For better precision, it is necessary to conduct careful measurements on the intensity of solar radiation over narrow wavelength bands with the aid of interference filters and photoelectric sensors. Such measurements at any combination of three wavelengths, say at 0·4, 0·5 and 0·6 microns could yield valuable information on the law governing the haze scattering at different locations and in different seasons.

6. Conclusions

The main conclusions may be summarised as follows—

(1) The turbidity coefficients for the two representative stations in India in the green region of the solar spectrum turn out to be appreciably less than those in the red region, if the standard value of $\alpha = 1\cdot3$ is assumed in the Angstrom formula for haze scattering.

(2) The real wavelength exponent applicable to the two Indian stations studied is appreciably less than 1·3. It is close to zero for a good part of the year suggesting that haze scattering is mostly neutral.

(3) Because of the low values of the prevailing α the true turbidity coefficients β should be appreciably higher than that what is determined using the standard value of $\alpha = 1\cdot3$.

(4) The low values of α imply a correspondingly lower value of the exponent ν in the Junge power law for the size distribution of aerosols, thus suggesting an increased concentration of the larger particles.

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