Wavelength exponent for haze scattering in the tropics as determined by photoelectric photometers

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ABSTRACT

Sun photometers using narrow-band interference filters, photoelectric sensors and solid-state operational amplifiers were constructed and intensive measurements of the haze extinction co-efficients at 0.40 and 0.60 μm wavelengths made at Poona (Lat. 18° N) over a one-year period. The most significant result obtained is that the wavelength exponent for the haze scattering as calculated from 520 pairs of simultaneous observations shows a median value of 0.5 and a mode of about 0.8. These are substantially lower than corresponding values found in the case of middle latitude stations. In general, the exponent is correlated positively with the turbidity itself in the case of wet haze, and under conditions of very clear and dry air it assumes near zero values. A marked diurnal variation in the value of the exponent occurs during the regimes of tropical continental air. The consequences of the prevailing lower values of α in relation to determination of the Ångström turbidity coefficient β in the tropics are briefly discussed.

1. Introduction

In many problems relating to the transmission of solar radiation through the atmosphere, we come across two types of extinction besides selective absorption, viz. extinction due to Rayleigh scattering by air molecules and that due to aerosol scattering. The physical laws relating to the first type of extinction are more precisely known than the latter. Especially in regard to the variation of aerosol extinction with the wavelength of light, reliable experimental information available in literature is very meagre. All that is probably known with a fair amount of certainty, is that on most occasions, the aerosol scattering is a continuous function of wavelength. Ångström's empirical formula for haze extinction for a vertical sun is given by the well-known equation

$$p_\lambda = \exp\left(-\beta/\lambda^\alpha\right) \qquad (1)$$

where p_λ is the transmission at wavelength λ, β the overall turbidity coefficient that is to be assigned to the entire solar spectrum and α the wavelength exponent the magnitude of which is generally taken in scientific literature as about 1.3. Historically, the first determinations of α were made on the European continent and they indicated wide variations with a probable mean value of 1.3. In this context the papers of Ångström (1964) and Herovanu (1959) are relevant. Recently, Ahlquist & Charlson (1969) determined α at the University of Washington Campus and found a modal value of about 1.8 which is even higher than the European values. But it may be pointed out that since they used horizontal optical paths, the higher α values pertain to the surface conditions only. Few determinations of α have been made in the tropical areas with sufficiently accurate experimental set up. Volz (1970) using photoelectric photometers found near neutral haze scattering in the dry tropical air mass that once invaded the Caribbean region; but he (Volz, 1971) did not find such neutral scattering in the few observations made over Thailand.

Commencing from the I.G.Y. period 1957–58, observations of the Ångström turbidity coefficient are being made at a few stations in India. Using the tables of the International Radiation Commission which took into account a standard value of 1.3 for α, it was found that the calculated β values were unrealistically low on a number of occasions. On some clear days, even negative values of β were obtained. On examining into the causes for the anomaly, it became apparent that the abnormally low values of β arose, because the spectral correction for haze scattering was overdone by using $\alpha = 1.3$. It will be evident from Eq. (1) that for the same observed shortwave transmission p_λ, the β values will tend to become too low if the value of α adopted is too high. Since only pyrheliometric observations were made in India for determining turbidity, an attempt had been made in 1965 following the method of Ångström (1961) to determine α approximately from these observations. Rangarajan (1966) analysed the pyrheliometric data of Poona (Lat. 18° N), and N. Delhi (Lat. 28½° N) and found a frequency distribution of α such that the modal value was about 0.6. However, it was evident to the author that the individual observations lacked accuracy and self consistency and hence the scatter of α values was large. The limited accuracy of the thermoelectric sensors used in the pyrheliometers is the main reason for the inaccuracies and the observations made with the OG_1, RG_2 and RG_8 filters are not suitable for the reliable determination of α. In the absence of a reliable mean value of α, the concept of an integrated turbidity coefficient β serves no useful purpose and would yield misleading values of turbidity. With a view to improving the accuracy in the determination of α for the Indian region, a beginning was made recently by constructing photoelectric photometers for the measurements of aerosol extinction coefficients at 0.4 and 0.6 μm wavelengths and for calculating the α values therefrom. Although a larger wavelength interval would normally yield more reliable values of α, the choice of these two wavelengths was made from the following considerations. Below 0.4 μm the Rayleigh extinction becomes much more than the haze extinction and the corrections to be given to the total extinction coefficient to yield the haze extinction becomes abnormally large. Furthermore, the effects of variable ozone absorption becomes significant at 0.35 μm. Above 0.65 μm on the other hand, the variable water vapour absorption proves to be a serious hindrance. Suitable narrow-band interference filters to coincide with the windows in the water vapour absorption bands in the near infrared were also not available. Since the solar energy between the 0.40–0.60 μm limits constitute nearly 60 % of the total energy in the visible spectrum, α values determined by using extinction coefficients at the two wavelengths would be fairly representative of the entire visible solar spectrum. In this paper, the results of the measurements of α made at Poona over a one-year period January 1970 to January 1971 are presented.

2. Description and performance of the instruments

The apparatus built consists of (*a*) the photometer boxes and (*b*) solid state operational amplifier with built-in meter. The photometer boxes are similar to the lensless type of Volz photometer described by Flowers et al. (1969). As shown in Fig. 1 they consist of rectangular light-tight boxes made of wood and painted black inside, with three parallel partitions fitted inside. Circular holes of 2 mm diameter are properly aligned in position on the partitions to enable a narrow pencil of sunlight to be directed through the interference filter F to the photocell P. The filter for the blue light has a peak transmission at 0.4010 μm with a half width of 30 A.U. and that for the red light at 0.6005 μ with a half width of 20 A.U. It was verified that the blue filter did not have any second order transmission band in the near infrared. The photocell is a selenium barrier cell, type A5PL made by International Rectifier Inc. U.S.A. having an impedance of 9 000 ohms. The electrical leads of the photocells are terminated at a pair of sockets to which the input leads of the operational amplifier can be connected at will. Partial attenuation of the intensity of the Sun's rays was done to the required extent by neutral density filters so as to

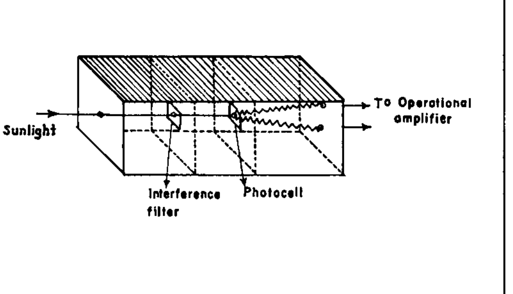

Fig. 1. Sketch of the photometer boxes.

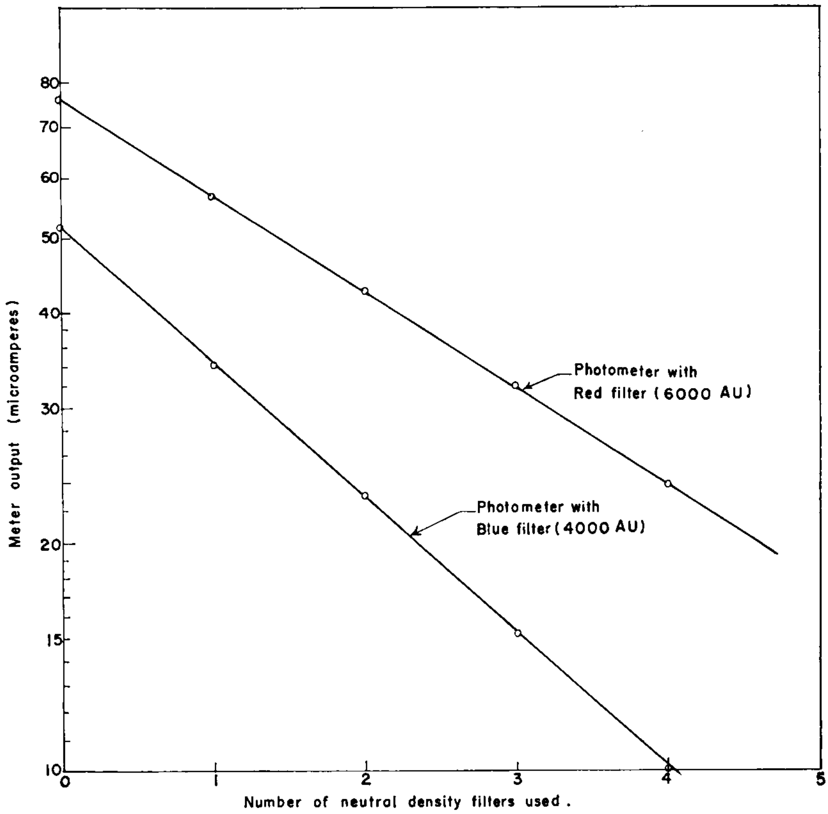

Fig. 2. Linearity test results for the two photometers.

obtain convenient readings within the range of the output meter.

The operational amplifier used is a Philbrick NEXUS L-201 solid state module fed by ± 2.7 volts power supplies from dry cells. The components were enclosed in wooden box of 19 cm × 11 cm × 8 cm. The advantage in keeping the amplifier in a separate housing is that the output meter can always be kept in a constant position even though the photometer may be turned at any angle towards the Sun. In the conventional Volz photometer, the microammeter is built into the box itself so that the pivot of the meter needle has necessarily to change position with the varying angle of the Sun. Such an arrangement, even with meters of good quality, was found to be unsatisfactory, the meter readings sometimes differing by more than 2 microamperes for the same light intensity but different orientations of the meter. The same amplifier was used for the two photometers.

The overall linearity of the apparatus was tested as follows. At noontime on days of constant turbidity the photometer opening was covered with different layers of neutral density filters cut from the same sheet. A plot of the logarithm of the intensities of sunlight as recorded by the meter versus the number of filters used gave a straight line as shown in the Fig. 2. The extra-terrestrial constants of the two photometers were determined by the usual Langley method viz. by obtaining a plot of the logarithm of intensities against the air mass on days of nearly constant turbidity and extrapolating the intensity to zero air mass. Such determinations were made for both the photometers on as many occasions as possible during the year; but owing to the diurnal changes in turbidity, not all determinations of the constants were found equally reliable. Those cases wherein the graphical plot of log intensity versus air mass took a reasonably linear shape

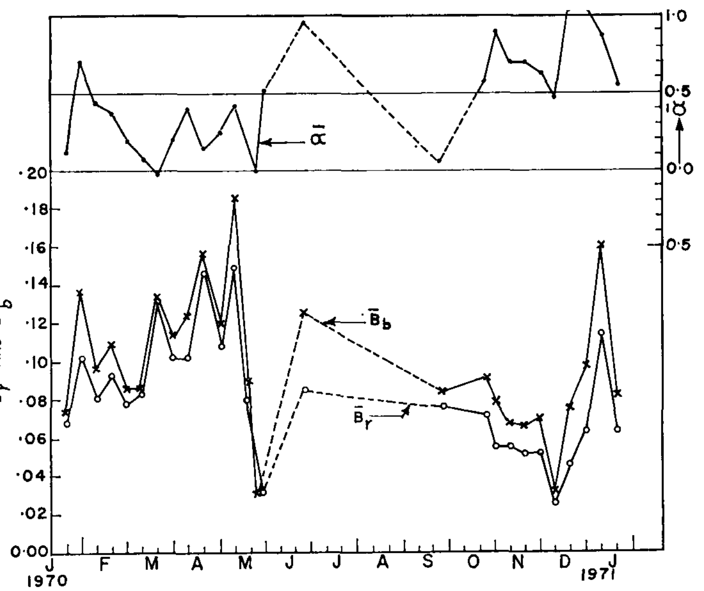

Fig. 3. Variation of $\bar{B}_b$, $\bar{B}_r$ and $\bar{\alpha}$ during the period Jan. 1970 to Jan. 1971 (10-day means).

were alone chosen. Such cases were available on six occasions during the year and it was found that the constants were maintaining fairly steady values. On very clear days of low turbidity, the inevitable diurnal variation of turbidity was responsible for the non-determination of extra terrestrial constants.

3. Method of evaluation

If $J_0(\lambda)$ is the extra-terrestrial constant of the instrument corrected for the varying earth–sun distance and $J(\lambda)$ the actual reading of the instrument when the air mass traversed by the solar beam is m (relative to the vertical sun),

We have $\log J(\lambda) = \log J_0(\lambda) - m(A_\lambda + B_\lambda)$ (2) for values of m, not exceeding about 6;

where A_λ is the combined decadic attenuation coefficient for Rayleigh scattering and ozone absorption at wavelength λ and B_λ is the decadic turbidity coefficient for haze extinction at wavelength λ. From observed values of $J_0(\lambda)$, $J(\lambda)$ and m, the total extinction $(A_\lambda + B_\lambda)$ is calculated and by subtracting A_λ, appropriate to the wavelength, B_λ is obtained.

If B_r and B_b are the extinction coefficients in the red and blue regions of the spectrum (0.60 μm and 0.40 μm respectively) the wavelength exponent α for variation of B_λ with λ is given by

$$\alpha = -\frac{\log \Delta B_\lambda}{\log \Delta \lambda}$$

$$= -\frac{\log (B_r/B_b)}{\log 3/2} \quad (3)$$

This relation is made use of for obtaining α. During the one-year period extending from January 1970 to January 1971 it became possible to make simultaneous observations of B_r and B_b on 127 days yielding a total of 520 pairs. On many days it was possible to record about six observations at intervals of about one hour, while on some days the daily number had to be restricted to two or three only on account of clouding. All the observations were made during the period 10 a.m. to about 5 p.m. Indian Standard Time, when the value of the air mass (m) remained in the range 1.0 to 3.5 only. For calibration purposes m was extended up to 5.0 on some days. For each of the pairs of observation made, the turbidity coefficient in the green region was also measured, with a conventional Volz photometer. It was found that in practically all cases the turbidity coefficient in the green region had a value somewhat intermediate between those of the B_r and B_b. During the period June to September 1970, very few observations were possible on account of persistent clouding. For each of the days with observations, mean values of B_r, B_b and α were also determined.

As the turbidity was found to undergo changes over periods of one week to 10 days, consecutive ten-day-means of $B_r B_b$ and α were worked out. The 10-day mean α was worked out using the individual α values obtained during the period. Fig. 3 depicts the seasonal variation of B_r, B_b and α. Epochs of high and low turbidities are clearly noticeable. In general, high values of turbidity are observed in April–May, but there was a spell of high turbidity in January 1971 also. The ten-day means of α indicate low values during the first half of the year with a mean less than 0.5. From Oct. 1970 to Jan. 1971, however, slightly increased values are noticeable with a mean of about 0.75.

The frequency distribution of occurrence of α using all the individual pairs of observations is shown in Fig. 4 which in a nutshell presents the salient finding of this investigation. In the same figure is also shown the frequency of occurrence of daily mean value of α for the 127 days, these being derived from the individual values of α recorded during each day. The median value of α comes out to be about 0.5 in both the frequency distributions, this value being considerably less than the values of α reported for the middle latitude stations. The distribution of α is not Gaussian but exhibits negative skewness, the mode being greater than the median. Although the mode is about 0.8 in the continuous curve (based on all the individual observations) an appreciable number of cases occur with near zero values of α; whereas on the high side even the extreme value hardly exceeds 1.5. The dashed curve based on daily averages reveals the same features. Here two maxima appear, one at 0.5 and the other at 0.9, the former appears to be more representative as this coincides with the median.

According to the Ångström formula for aerosol extinction given by eq. (1) the physical processes governing extinction are determined by the arbitrary constants α and β. It is easy to see that β is proportional to the total number of particles contained in unit volume of air and α is determined by the size distribution of the particles, *vide* eq. (6). These two constants

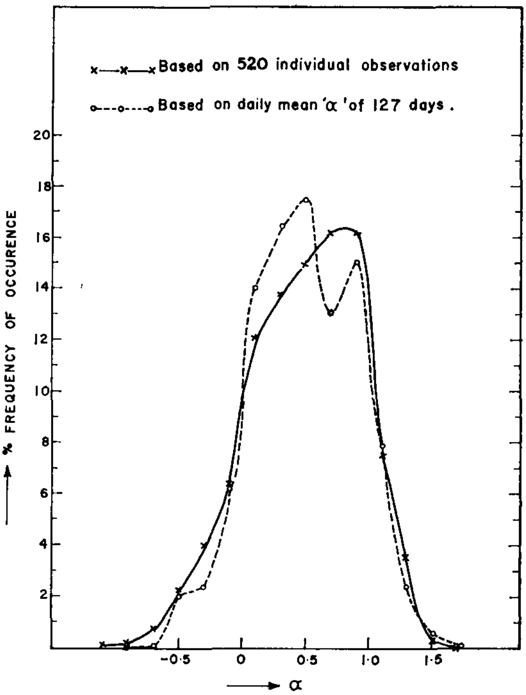

Fig. 4. Frequency distribution of α during the one-year period.

may not be really independent of each other. To see whether any relationship exists between α and B, a plot was made of the 520 individual values of α and the corresponding values of B_b. The result is shown in Fig. 5 which brings out the fact that generally very low or near-zero values of α are associated with low turbidities. Further B_b and α are correlated positively, higher values of α occurring, in general with higher values of turbidity. Most of the values of B_b greater than 0.100 were associated with morning haze which forms with relative humidity higher than about 60 %. Thus one might conclude that for wet haze the higher values of α are associated with higher turbidity. Another feature revealed by the diagram is that whereas for turbidity less than about 0.10, the values have a larger scatter, the larger turbidities are associated with a much smaller range in α values. These findings, though based on data of one station seem to show that the haze extinction exponent α tends to be affected by the total concentration of aerosols per unit volume of air.

A marked diurnal variation in the turbidity

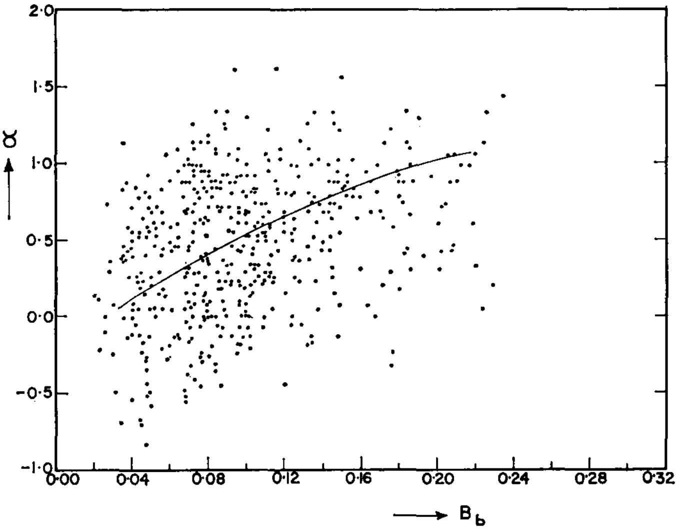

Fig. 5. Dot diagram showing dependence of α on B_b (based on all individual observations).

parameters is found to occur during the dry season characterised by the tropical continental air mass. A typical example of this is illustrated in Fig. 6 wherein the daily variation of B_r, B_b and α for 9th March 1970 have been plotted. The relatively higher values of turbidity at about 10 a.m. is due to the remnant of the wet haze that occurs in the morning due to partial condensation of water vapour on aerosols, under the higher relative humidity conditions prevailing. With the progress of the day, relative humidity falls with the increasing temperature and evaporation of the condensed water takes place. The wet haze becomes converted into dry haze. By evening, there is a tendency for the more moist coastal sea breeze to blow into the Poona area from the west, this being accompanied by an increase in turbidity presumably due to partial condensation under higher relative humidities. It is interesting that the values are minimum in the afternoon hours when the turbidity also is a minimum. Such diurnal changes in turbidity and α are not always accompanied by significant changes in the records of autographic meteorological instruments like thermograph or anemograph. Nevertheless the turbidity measurements afford a sensitive means for studying changes in the aerosol characteristics in the air over the location.

4. Discussion of the results

The main results of this investigation mentioned in the preceding section are (1) The frequency distribution of α with a median around 0.5 and with an extreme value of not more than 1.5. (2) A marked diurnal variation of α leading to a minimum in the afternoon hours and (3) near zero values of α occurring occasionally in the dry season with low turbidities.

These results appear to be of considerable importance in the problem of transmission of solar radiation in the tropical continental atmosphere as well as the nature and origin of the aerosols in the continental tropics. Though the discussion is based on intensive and careful observations made at a single station, climatological considerations lead us to conclude that vast areas of the continental tropics around India would reveal more or less the same features. During the course of one year, the air mass over Poona undergoes changes from tropical continental to Tropical maritime and then to Equatorial maritime. The first two air masses are known to prevail over the greater part of the country also for nearly eight months of the year. The equatorial maritime air mass pervades over the country from June to September. Because of the heavy clouding and precipitation, turbidity observations are generally very rare

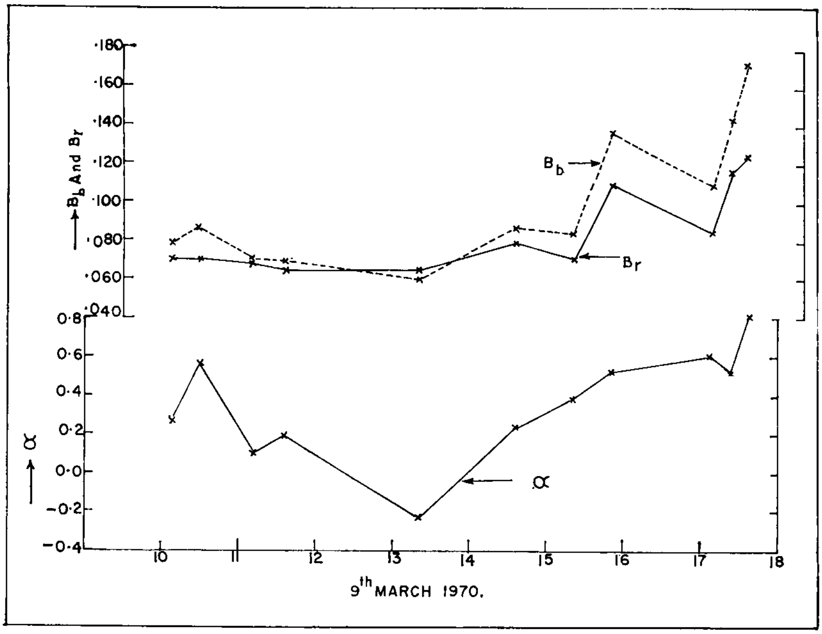

Fig. 6. Typical diurnal variation of B_b, B_r and α in tropical continental air mass (9th March 1970).

when this air is present. During 1970, the monsoon air advanced over Poona quite early by the third week of May. In all 9 observations of α are available during the period 19th May to end of September, when monsoon air prevailed over the location. These have been given in Table 1 and show about the same values of α when compared to the dry season, their median value being 0.4. It is therefore reasonable to conclude that the frequency distributions shown in Fig. 4 is generally representative of all the seasons and locations of India.

In many numerical models for the transmission of solar radiation through the earth's atmosphere a suitable mean value of α for aerosol attenuation will have to be assumed. It has been customary in meteorological literature to assign a value of 1.3 for worldwide conditions. In the light of the results obtained now, it would appear more reasonable to assign a smaller value of 0.5 or 0.6 to the tropics which cover nearly half the earth. Secondly, the assignment of a standard value for α is of direct consequence to the derivation of the Ångström turbidity coefficient as already mentioned earlier. Unlike the Schuepp's coefficient B, the former is essentially a polychromatic entity and serves a meaningful purpose only if the correct values of the prevailing α is incorporated in the formula for haze scattering. Wherever the exact values of α cannot be determined, for example in radiation station networks in the tropics, it is more correct to adopt a value of 0.6 rather than 1.3. To substantiate this, the Ångström turbidity coefficients determined at the radiation station at Poona for two different periods May 1970 and November 1970 have been tabulated in Table 2 along with the turbidity parameters B_r, B_b, B and α derived by

Table 1. *Turbidity parameters measured during the Monsoon season of 1970 at Poona*

Date	Time	B_b	B_r	α
19.5.70	1020	.068	.064	+0.15
19.5.70	1115	.079	.078	+0.03
19.5.70	1430	.078	.066	+0.40
19.5.70	1635	.121	.087	+0.81
20.5.70	1045	.089	.088	+0.05
30.5.70	1210	.036	.036	+0.00
1.6.70	1200	.047	.038	+0.52
26.6.70	1510	.126	.085	+0.99
28.9.70	1515	.092	.076	+0.46

Table 2. *A comparison of B and β during two different epochs at Poona when α values were contrasting*

Date	Air-mass 'm'	B_r	B_b	α	B	β
First epoch						
4.5.70	1.00	.117	.128	0.23	.121	.081
8.5.70	1.02	.098	.099	0.03	.100	.033
12.5.70	1.02	.156	.201	0.61	.181	.142
13.5.70	1.02	.091	.098	0.18	.096	.039
15.5.70	1.41	.171	.218	0.78	.195	.122
18.5.70	1.25	.092	.106	0.34	.101	.051
19.5.70	1.02	.078	.079	0.03	.081	.043
20.5.70	1.05	.088	.088	0.00	.090	.041
Second epoch						
6.11.70	1.66	.055	.084	1.06	.068	.051
7.11.70	1.32	.053	.078	0.95	.069	.073
9.11.70	1.49	.052	.076	0.95	.060	.041
10.11.70	1.57	.062	.090	0.92	.076	.070
12.11.70	1.42	.050	.074	0.99	.066	.065
17.11.70	1.63	.064	.091	0.88	.082	.085

the author. The two epochs provide a contrasting study. During the May 1970 epoch, the α values were very low being mostly below 0.6. The disparity in the values of B and β is very striking. On the other hand, during the November 1970 epoch the α values were appreciably higher being 0.9 to 1.0. The disparity in the values of B and β is much less during this epoch. It will thus be seen that the Ångström turbidity coefficient β takes realistic values only under conditions when $\alpha \geqslant 1.0$; if the present method of determining β with an assumed $\alpha = 1.3$ is employed. If a smaller value of $\alpha = 0.6$ is adopted for the tropics, the same intensities of solar radiation (as measured by the Ångström Pyrheliometer) would yield higher values of β which would relate better with B in accordance with the generalised equation:

$$B = \beta 2^{\alpha} \log_{10} e \tag{4}$$

The smaller values of α found at Poona have a direct bearing on the aerosol size distribution. For a Junge type of aerosol size distribution,

$$dN/d \log r = cr^{-\nu} \tag{5}$$

where dN is the number of particles in the radius interval r and $(r + dr)$, c is a constant and ν the size distribution constant. Under the actual aerosol distributions prevailing in the atmosphere, an approximate relation of the type

$$\nu = (\alpha + 2) \tag{6}$$

can be deduced (Junge, 1963). The smaller values of α found at Poona would seem to indicate a smaller value of 2.5 to 2.8 for the size distribution exponent, ν. This implies a relative preponderance of large sized particles in the tropics when compared with conditions in the middle latitudes.

The negative values of α found on some occasions of very clear weather need a comment. It seems rather unlikely that such cases can occur in the real atmosphere. These values appear to have arisen at least in part on account of some of the J_0 values for the 0.4 μm photometer being too low. As already mentioned the determination of J_0 by the Langley method could not be made on the very clear days because of the nonconstancy of turbidity. This unfortunate limitation could not be rectified. It is hoped to carry out further series of observations with calibration carried out at suitable locations where diurnal variation in the turbidity is smaller.

Conclusions

The main findings of this investigation could be summed up as follows:

(1) The frequency of occurrence of the wavelength exponent of haze extinction α at Poona shows a median value of 0.5 and a mode of 0.8 in an analysis of 520 pairs of simultaneous observations by photoelectric sun photometers at the wavelengths 0.40 μm and 0.60 μm. The maximum value of α ever found is only 1.5.

(2) Near zero values of α tend to occur on many occasions with clear dry air prevailing over the location. In general, the higher the turbidity, the higher the wavelength exponent in the case of wet haze.

(3) A marked diurnal variation of α is observed during regimes of tropical continental air, the lowest values occurring during noon and afternoon hours.

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ПОКАЗАТЕЛЬ СТЕПЕНИ В ЗАВИСИМОСТИ ОТ ДЛИНЫ ВОЛНЫ КОЭФФИЦИЕНТА РАССЕЯНИЯ ДЫМКИ, ОПРЕДЕЛЕННЫЙ ПРИ ПОМОЩИ ФОТОЭЛЕКТРИЧЕСКИХ ФОТОМЕТРОВ

Построены солнечные фотометры с использованием узкополосных интерференционных светофильтров, фотоэлектрических приемников и полупроводниковых усилителей, с помощью которых в течение года в Пуне (18° с. ш.) были проведены измерения коэффициента экстинкции дымки для длин волн 0,40 и 0,60 мкм. Наиболее значительным из полученных результатов является то, что показатель степени в зависимости коэффициента рассеяния дымки от длины волны, вычисленный из 520 пар одновременных наблюдений, дает среднее значение 0,5 и моду около 0,8. Эти величины существенно меньше, чем соответствующие значения, полученные на станциях в средних широтах. В целом, величина показателя степени хорошо коррелирует с величиной мутности в случае влажной дымки, а при условии очень прозрачного и сухого воздуха она близка к нулю. Заметные суточные вариации в величине показателя степени наблюдаются при режимах тропического континентального воздуха. Кратко обсуждается влияние преобладания в тропиках более низких значений α на определение коэффициента мутности Ангстрёма β.