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Depletion of Solar Radiation by particulate matter in the atmosphere — A study with special reference to New Delhi

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ABSTRACT. The depletion of solar radiation in the wave length range $0 \cdot 31\ \mu$ to $0 \cdot 63\ \mu$ by particulate matter in the atmosphere, appears to be a useful measure of particulate content. A method of computing this depletion from pyrheliometer observations of direct solar radiation, separating attenuation due to scattering by atmospheric gases and water vapour, has been described. Values of this dust depletion factor d have been computed for New Delhi for the hot dry season (April-June) for five years 1961 to 1965, and compared with values of Angstrom turbidity coefficient for the same station.

1. Introduction

Estimation of amounts of particulate matter in the lower and middle troposphere is a matter of great practical interest especially during the hot dry summer over north India. While there is no simple method of direct estimation of dust concentration and its variation from day to day, it is generally accepted that depletion of solar radiation by particulate matter can be taken as a useful measure of dust concentration. This depletion of radiation can be computed from routine measurements of direct solar radiation made over the whole spectrum and in selected spectral regions at stations using pyrheliometers. However, dust particles in the atmosphere have a wide size spectrum and are large in comparison with the wavelength of solar radiation. Hence the extinction of radiation by dust varies with wavelength in a complicated manner. Various 'turbidity coefficients' or 'turbidity factors' (Linke 1922, 1942; Angström 1929, 1930; Schüepp 1949, 1953) have been defined in the literature as measures of turbidity, *i.e.*, extinction by water vapour, haze and dust.

A new quantity which may be defined as "the total fraction of incoming solar radiation in the wavelength range $0 \cdot 31\,\mu$ to $0 \cdot 63\ \mu$ which is scattered, diffusely reflected or absorbed by all solid or liquid particles suspended in a cloudless atmosphere" is introduced in this paper. For brevity we shall call this quantity "dust depletion factor for shortwaves (Kurzstrahlung)" and represent it by the symbol d. Values of this quantity for New Delhi in the hot dry season have been worked out and compared with values of Angström turbidity coefficient β which are also available for this station.

2. Atmospheric transmission

The Angström pyrheliometer measures the intensity of direct solar radiation received at the ground after absorption and scattering by atmospheric gases, water vapour and particulate matter. The ratio a of this intensity I to the intensity of solar radiation outside the atmosphere I_0 may be called the atmospheric transmission factor. The transmission factor for a cloud-free, dust-free atmosphere, *i.e.*, for an atmosphere where only the absorption and scattering by atmospheric gases and water vapour is taken into account, represented by the symbol $a_{m,w}$ (m representing optical air mass and w the precipitable water content) can be computed from data available on scattering and absorption by these gases. Kimball (1927, 1928, 1931) introduced a quantity $d_d = a_{m,w} - a$ which gives the fraction of solar radiation depleted by dust. Kimball prepared a chart giving $a_{m,w}$ for various values of m and w. Knowing a (as the ratio I/I_0) and $a_{m,w}$, d_d could be computed as the difference between the two quantities. Such computations have been made by Kimball (1927, 1931) and by Klein (1948) for various stations.

The most important of the other measures of turbidity referred to earlier is the Angström turbidity coefficient β (Angström 1929, 1930) which is a measure of the depletion by dust and by scattering due to water vapour. The determination of this coefficient is generally recommended and is being made at many radiation stations including New Delhi (Mani and Chacko 1963).

β may be defined by the relation —

$$m_h.\ a_{D_\lambda} = m_h.\ \beta \lambda^{-\alpha}$$

where a_{D_λ} is the extinction coefficient for atmospheric haze corresponding to wavelength λ, m_h is the relative air mass and α is an index which is less than 4. It may be mentioned that a_{D_λ} includes the effect of scattering (but not absorption) by water vapour in addition to extinction by dust. According to Angström the scattering by water vapour and by dust cannot be completely separated. The exponent should be 4 for very small particles for which Rayleigh scattering applies, but for dust particles for which the Mie theory has to be applied, the value of α is somewhere between 0·5 and 2. Indeed no unique value of α can be postulated as the particulate matter extends over a considerable size spectrum. Angström assumes an average value of $\alpha = 1 \cdot 3$ and in practice values of β are computed on this assumption. While the relation between $a_{D\lambda}$ and β is theoretically sound, the assumption of the value of α as 1·3, reduces to some extent the practical validity of β as a measure of the depletion by dust. Indeed α varies considerably with latitude and the assumption of the value of 1·3 is perhaps representative of temperate latitudes. In a tropical regime especially for a region like northern India in summer where particles of large size (which are raised to great heights by convection currents) are numerous, it may not be safe to assume this value of α. The value may be considerably lower. The work of Ramanathan and Karandikar (1949) shows that in India α may be anywhere between 0 and 1·3 in the Chappuis band. In the absence of actual determinations of α which were advocated by Schuepp (1949, 1953, 1956) it appears desirable to use a factor such as Kimball's for the estimate of depletion of radiation by dust.

Kimball's d_d takes account of solar radiation at all wavelengths reaching the ground. Hence in preparing his chart Kimball had to take into account not only scattering by air molecules and water vapour but selective absorption by the various gases. However by considering only the radiation in the range of wavelengths below 0·63 μ (*i.e.*, Linke's shortwave) all the principal absorption bands of water vapour as well as the permanent gases can be excluded (except for a slight ozone absorption in the Chappuis band). Radiation intensity at the ground at wavelengths below 0·31 μ can also be neglected because of the heavy absorption by ozone in the Hartley band coupled with the fact that even the extra-terrestrial intensity ($I_{0\lambda}$) at these wavelengths is relatively low. The wavelength range below 0·63 μ is also the region of the spectrum where the extinction by particulate matter is greatest. Hence a dust depletion factor similar to that of Kimball has been evaluated in this paper, by considering only the wavelength range 0·31 μ to 0·63 μ.

3. Computation of molecular and water vapour scattering in the shortwave region

The transmission factor of solar radiation in this spectral region after depletion by molecular and water vapour scattering corresponding to any values of air mass and precipitable water content is determined by a method to be described presently. Let us represent this transmission factor by $(a_{m,w})_k$. The actual transmission factor a_k for this spectral region is given by the ratio —

$$I_{\lambda = 0\cdot31}^{\lambda = 0\cdot63} \Big/ I_{0\lambda\,=\,0\cdot31}^{\lambda = 0\cdot63}$$

where, the numerator represents the radiation intensity at the ground in this spectral range measured by a pyrheliometer and the denominator the extra-terrestrial intensity in the same range of wavelengths. The depletion factor d due to dust for this spectral band is then given by —

$$d = (a_{m,w})_k - a_k$$

Here it must be noted that the absorption by ozone in the Chappius band is neglected. It will be seen from the data plotted in Figs. 2(a) to 2(e) that d is of the same order as $(a_{m,w})$ and a_k. Hence errors in d are not likely to be greater than errors in the other quantities.

The extra-terrestrial intensity $I_{0\lambda}$ corresponding to various wavelengths based on Moon's (1940) values is given by List (1951a). These refer to the mean distance of the earth from the sun. The transmission coefficent $a_{a\lambda}$ for vertical transmission in a dry dust free atmosphere (*i.e.*, according to Rayleigh scattering by air molecules only) for various wavelengths is also given by List (1951b) and by Linke (1933). For any air mass m the radiation of wavelength λ received after transmission through dry clean air will, therefore, be $I_{0_\lambda} \; a_{a_\lambda}^{m}$

The transmission coefficient a_{w_λ} for vertical transmission through one centimetre of precipitable water vapour based on Fowle's (1913) work are also given by List (1951c). These values of a_{w_λ} are available only for wave lengths greater than 0·342 μ but could be extrapolated upto 0·31 μ without much error. For any value of precipitable water content w the radiation intensity at the ground after scattering by air molecules and water vapour will be —

$$I_{0_\lambda} \; a_{a_\lambda}^{m} \; a_{w_\lambda}^{mw} = I_\lambda \text{ (say)}$$

This expression has been computed for each wavelength interval of 0·01 μ from 0·31 μ to 0·63 μ, for various values of m ranging from 1 to 5 and values of w from 0 to 5 cm. For any given m and w the summation of the above expression over the range of wave lengths, *i.e.*,

$$\sum_{\lambda = 0.31}^{\lambda = 0.63} I_{0_\lambda} \; a_{a_\lambda}^{m} \; a_{w_\lambda}^{mw} = \sum_{\lambda = 0.31}^{\lambda = 0.63} I_\lambda$$

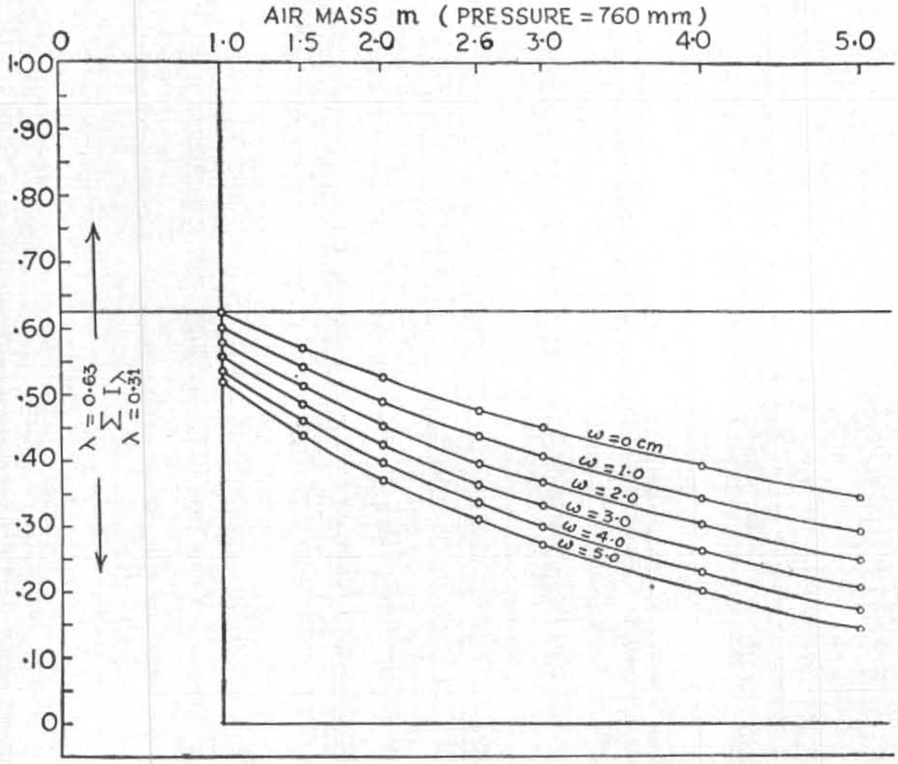

Fig. 1. Variation of $\sum_{\lambda=0\cdot31}^{\lambda=0\cdot63} I_\lambda$ with air mass (m) and precipitable water content (w)

was carried out. The variation of ΣI_λ with m and w is shown in Fig. 1. A set of curves on a larger scale were used for the computations in this paper to ensure greater accuracy in making interpolations. These curves can be extended to air mass values less than 1, if evaluations at high level stations are needed.

4. Computation of the factor d

Values of actual solar radiation intensity at the ground are readily available from Angström pyrheliometer observations with an RG2 filter (CSAGI 1958a) and without the filter. Since $0\cdot63\mu$ is the lower cut-off wavelength for the RG2 filter, the difference between the measurements with and without the filter, gives the radiation intensity I_k corresponding to the wavelengths below $0\cdot63$ μ. Radiation of wavelengths below $0\cdot31$ μ has been considered negligible for reasons already stated. Values of this intensity multiplied by a correction factor S for variation of solar distance from the mean (CSAGI 1958 b) are available for New Delhi for several years now. The intensities measured with the filter have also been corrected to take into account the transmittance of the filter. This quantity $S \times I_k$ divided by $\sum_{0\cdot31}^{0\cdot63} I_{o\lambda}$ gives the total transmission a_k corresponding to any pyrheliometric observation. Observations are made at New Delhi at approximately 0830, 1130, 1430 and 1730 IST subject to conditions being favourable for observations (CSAGI 1958 c). Corresponding to any observation, the value of a_k could be readily computed. To find the corresponding value of ΣI_λ from the curves of Fig. 1, it is of course necessary to know the value of w. The 0830, 1430 and 1730 IST observations are fairly close to routine radiosonde observations made at 0530 and 1730 IST. The 0530 ascent was taken to represent w values for the 0830 radiation observation. The 1730 ascent was taken to represent w values corresponding to the 1430 and 1730 radiation observations. The radiation intensity values obtained at 1130 IST were not, however, made use of in most cases as they were far removed in time from the radiosonde observations. From the known values of dew point temperatures at various levels, the mixing ratios and hence the precipitable water content upto the level at which dew point data are available could be computed. As the radiosonde in use measures wet bulb temperature, humidity data are available only upto to the freezing level. The contributions to the precipitable water content by higher levels though quite small, were obtained from

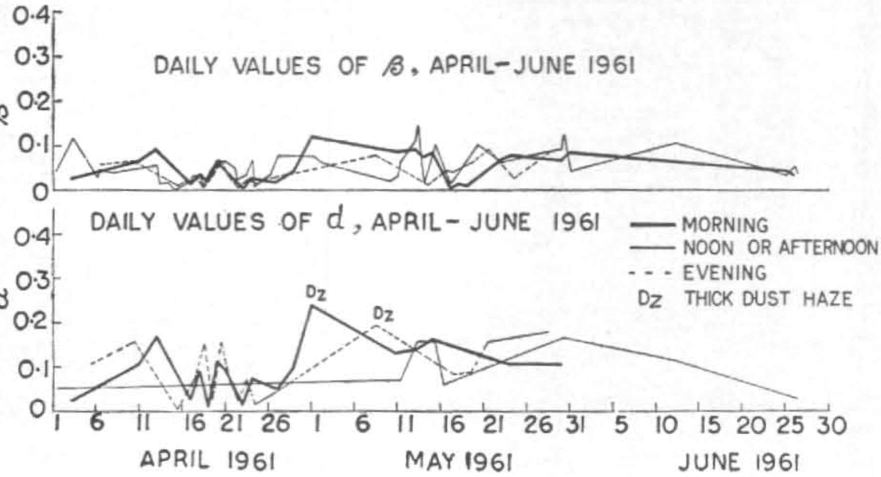

Fig. 2 (a)

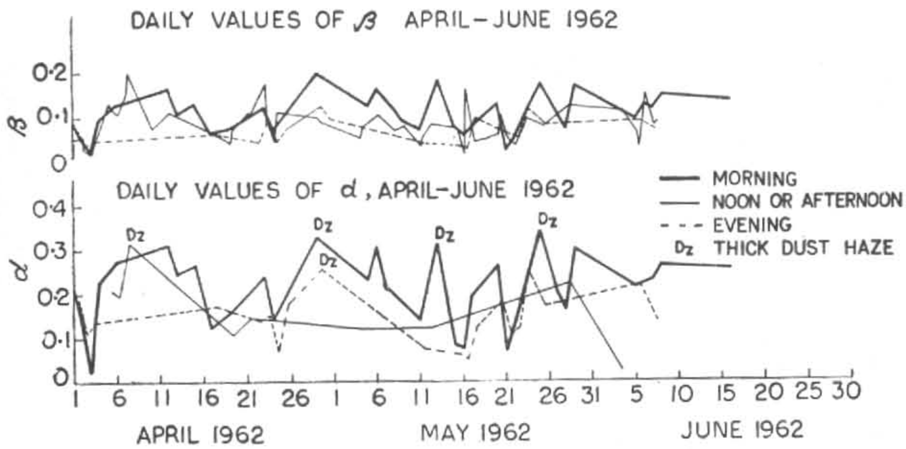

Fig. 2 (b)

monthly mean extrapolated values computed by Ananthakrishnan *et al.* (1964) and added to the w values computed from the radiosonde data. Knowing w and m corresponding to any pyrheliometer observation, ΣI_λ can be picked up from the curves in Fig. 1.

Then $(a_{m,w})_k$ is given by $= \Sigma I_\lambda \;/\; \sum_{\lambda=0.31}^{\lambda=0.63} I_{0_\lambda}$

Hence $d = (a_{m,w})_k - a_k = (\Sigma I_\lambda - S \times I_k)/\Sigma I_{0\lambda}$

In this way d has been computed for all pyrheliometer observations in the season April to June for five years from 1961 to 1965.

5. Discussion of the data

In this paper, only the dust depletion for the hot dry season April to June in New Delhi has been considered (on the basis of five years' data) as this is the season of duststorms and high particulate concentration in the atmosphere in this part of the country. Dust particles have been observed over extensive areas in this season even at heights of 4 to 5 km. This quantity is not of as much interest over New Delhi in other months of the year.

The daily values of d corresponding to the morning (0830), afternoon (1430) and evening (1730) observations for the five years 1961-65 are plotted separately in Figs. 2 (a) to 2 (e). Values of the Angström turbidity coefficient β are also plotted in the same figures on the same scale for comparison. Details of the method of computation of β are given by Mani and Chacko (1963). In the case of β, values are available for the 1130 hrs observations also and these have been given with the 1430 hrs data as the airmass values at these two observation times are not very different. Since pyrheliometer observations cannot be attempted when there is

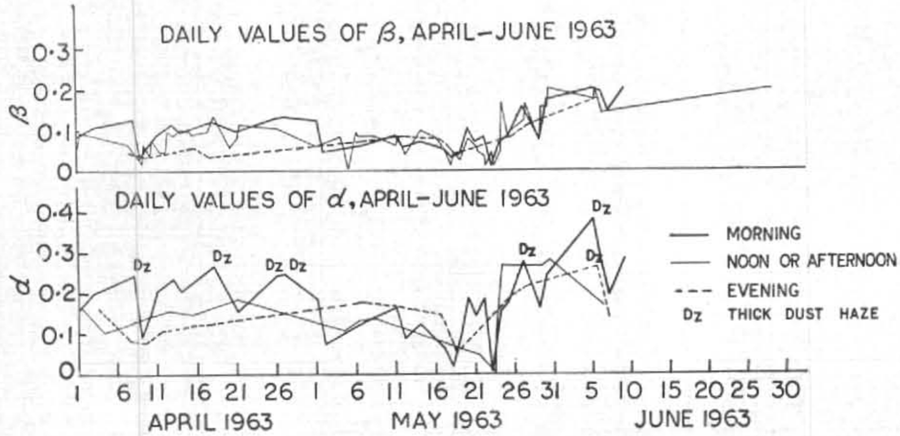

Fig. 2(c)

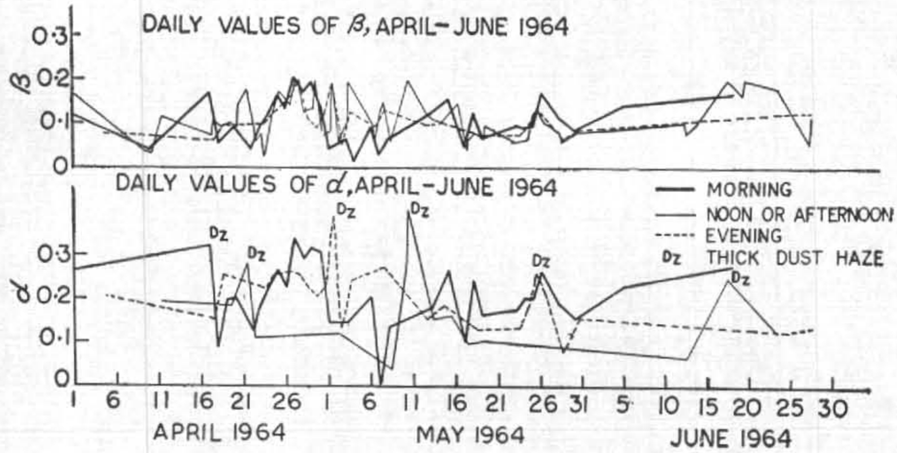

Fig. 2(d)

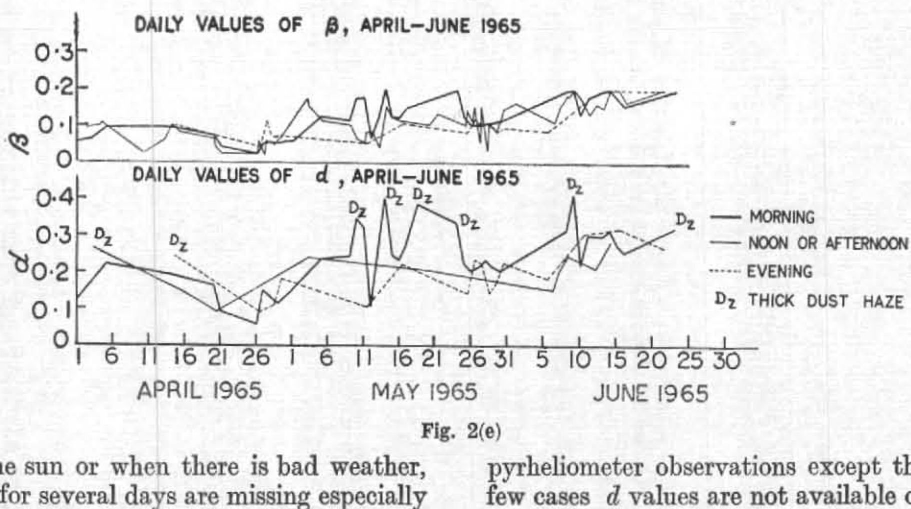

Fig. 2(e)

cloud near the sun or when there is bad weather, observations for several days are missing especially in June when cloudiness increases. Therefore the lines in the figures join available points successively and do not necessarily represent depletion on intervening days.

The β and d curves for the morning observations are comparable as they are derived from the same pyrheliometer observations except that in a very few cases d values are not available owing to non-availability or doubtful nature of radiosonde data. The same is true of the evening observations. However, the noon and afternoon curves in Figs. 2 (a) to 2 (e) for β and d are not quite comparable, as there are no d values corresponding to most of the 1130 hrs observations. While there is a general agreement between variations of β and

TABLE 1

Mean d values for April to June

Year	Morning	Afternoon	Evening
1961	·109	·101	·095
1962	·209	·162	·149
1963	·176	·156	·141
1964	·208	·199	·204
1965	·267	·207	·208
Total	·969	·825	·797
Mean	·194	·165	·159

of d which is evident from the figures, it must be remembered that β includes the effect of water vapour scattering while d does not. Considering also that d is numerically larger, it appears to be more sensitive than β to variations of particulate content. There is a qualitative agreement between the haziness as noted down at the times of observation and the values of β and d though there is no means of independently estimating the haziness quantitatively. Observation times at which thick dust haze was observed are marked in Figs. 2 (a) to 2 (e). It will be seen that these coincide in most cases with high values of β and of d.

The seasonal mean values of d for each year and for all the five years 1961-65, for the morning, evening and afternoon observations are shown in Table 1.

The table shows that mean d value assumes a decreasing trend from morning towards evening. The mean values appreciably differ from year to year; for instance the year 1961 has the minimum and 1965 the maximum mean depletion in the morning, afternoon and also evening hours. It should be interesting to compare these values with those for other stations in the region, but at present no observations are available at any other station in the neighbourhood.

6. Conclusions

The dust depletion factor in the shortwaves (Kurzstrahlung) is a quantity which has some promise of representing the variations of particulate content in the atmosphere excluding all other media of extinction of solar radiation. This quantity can be computed wherever pyrheliometer observations with filters and radiosonde observations are made. A dust climatology of a region could be prepared if radiation data are available at more stations.

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