STUDY OF AEROSOLS IN THE ATMOSPHERE BY TWILIGHT SCATTERING

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Abstract

Photometric measurements of the light scattered from the twilight sky in the direction of the sun's vertical at an angle of 70° from the zenith, were made during IGY-IGC (1957-59) at Mt. Abu with a photometer the telescope of which covered a circular field of about 1 degree.

Observations showed that there were changes in the slopes of the curves of intensity against the depression θ of the sun below the horizon, when θ was 5-6°. This could be explained by assuming the existence of an aerosol layer at 20-25 km. The height of the layer could however vary from 15 to 30 km.

The lowest heights of the stratospheric aerosol layer at Abu were found to occur in June and the highest in November-December.

A second feebler maximum corresponding to a scattering layer at a height of 45-50 km. was also found on a number of occasions.

Introduction

Part of the sky illumination during the day and during the twilight is due to the scattering of sunlight by large particles of condensed water and/or dust. There is a more or less permanent but variable haze layer in the lower layers of the troposphere, whose intensity normally decreases upward, and there is evidence that there are also other layers at higher levels.

Particles of linear dimensions larger than the wavelength of light, scatter light more in the forward than in the backward direction and it may be expected that the intensity of the twilight glow will depend largely on the size, nature and distribution of dust and water particles present in the atmosphere. The dust will also have the effect of reducing the intensity of the incident primary light illuminating the atmosphere below the dust layer.

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Changes in the intensity of sky light at a fixed angle above the horizon where the earth's shadow traverses different levels of the atmosphere, can give information about the vertical distribution of larger particles (aerosols) in the atmosphere.

Many observers have measured the intensity of twilight at various zenith angles and wavelengths. A comprehensive work is that of Ljunghall (1949) who also summarised the earlier work. One of the aims of the earlier work was to determine the air density as a function of height; in recent years experiments have been made specifically to study the aerosols.

E. K. Bigg (1956) in Australia constructed a photoelectric photometer with a small aperture to detect the variation in the brightness of a small part of the sky during twilight. He carried out measurements at an angular distance of 70° from the zenith in the sun's meridian plane for solar elevations 0–14° below the horizon and in the spectral region 6000–8000 Å. He plotted the values of $1/I \times dI/dt$ against h where h is the lowest height in the atmosphere which the direct sun's rays would illuminate when the sky is observed in the particular direction and I is the intensity of the light (in arbitrary units). Bigg assumed that the lowest height corresponded to rays grazing the earth's surface tangentially. Refraction through the earth's atmosphere was allowed for.

Bigg (1959) concluded from the study of his twilight curves that there was dust accumulation at 15–20 km. height and also at 80 km. He also tried to correlate low level temperature inversions shown by radiosonde data with maximum in the twilight intensity curves of $1/I \times dI/dt$ against h and concluded that inversions were detectable, though he could not decide whether the discontinuities represented boundaries between regions of different dust content or signified rapid changes in atmospheric density.

In U.S.S.R., Megrelishvili (1958) made intensity measurements of twilight in the direction of 70° from the zenith in the sun's meridian plane in the spectral region 5270–9400 Å. He plotted curves of $1/I \times dI/dh_{eff}$ against h_{eff}, where h_{eff} is the effective height of the earth's shadow. He assumed that due to the extinction of the grazing rays during sunset, the least height accessible for investigation would be about 20 km., hence the effective height of the scattering layer would be $(h + 20)$ km., where h is the earth's geometrical shadow height (with no allowance for atmospheric refraction). Megrelishvili found from his twilight curves that the first maximum occurred at 45–50 km. and a second at about 100 km.

Volz and Goody (1962) in a comprehensive study, describe the twilight observations made by them at the Blue Hill Observatory, Mass., at 20° above the horizon towards the sun, using a photometer and filters in three different spectral ranges in the neighbourhood of 5,000 Å, 6600 Å and 8000 Å. In their plot of $1/I \times dI/d\theta)$ against θ they found the maximum value to occur (where θ is the sun's depression below the horizon at the place of observation) when the sun's centre was 5–6° below the horizon. A correction for atmospheric refraction of 1·3° was made for a ray passing through the whole of the earth's atmosphere tangentially at sea-level.

With the idea of detecting the presence and levels of dust layers, and their day-to-day changes by the method of twilight scattering, twilight intensity measurements were started at Mt. Abu (24° N), in India which is 4,000 ft. above sea-level, in 1957 and continued from 1957 to 1959. A twilight photometer in conjunction with a telescope of small aperture and a colour filter transmitting in the spectral range 6,400–7,000 Å was used. These observations were resumed in Ahmedabad when it was noticed in September 1963 that there was an enhanced twilight glow, presumably due to volcanic eruptions in Bali (Indonesia).

Experimental technique used in India (Abu).—For obtaining good resolution of the different dust layers, one should use (*a*) the longest convenient wavelength in order to reduce the scattering contribution by air molecules and *b*) the smallest possible beamwidth in the light-gathering equipment in order that the position of the discontinuity may be clearly defined. Hence a telescope was designed which covered a circular field of sky of about 1° diameter and a Chance filter OR-1 which, when used in conjunction with the photomultiplier RCA 1P22 as a light detector, covered wavelengths in the effective range 6400–7000 Å.

The output of the photomultiplier was fed to a stable, sensitive D.C. amplifier and the current was measured with an Avometer. The amplified current varied linearly with the incident illumination. The meter readings I were recorded every 30 seconds from the time of sunset to the time when the centre of the sun was 14° below the horizon.

Direction of observations.—Bearing in mind that there will be a preponderance of light in the forward direction in the light scattered by particles whose linear dimensions are large in comparison with λ, and there will also be an increasing attenuation of light with approach to the horizon, a compromise had to be made in deciding the direction of observation. The telescope of the photometer was directed towards the sun at an angle of 70° from the zenith.

Height of the earth's shadow.—The earth's geometrical shadow height h is defined as the vertical height from the surface of the earth, of a point Q_1 where the solar ray grazing the surface of the earth, meets the line of sight, which is 70° from the zenith in the sun's meridian plane, after allowing for atmospheric refraction (*see* Fig. 1).

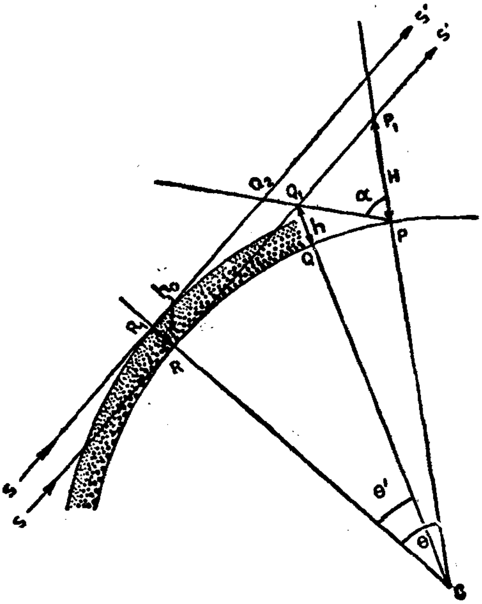


FIG. 1. Diagram showing grazing solar rays illuminating the twilight atmosphere.

Figure 1 presents a schematic diagram of solar grazing rays illuminating the twilight sky. SS' are the sun's grazing rays, and QQ_1 the height h of the earth's geometrical shadow at the point where the direction of vision from P cuts the tangential ray from the sun, θ the depression of the centre of the sun below the horizon of the observer at P, and θ' the depression of the sun at the point Q_1. a denotes the earth's radius, and α the angle between the zenith and the direction of observation from P.

Due to the long air path traversed by the grazing rays, the incident light will suffer attenuation in passing through the atmosphere owing to molecular scattering, and the attenuation will depend on the wavelength. Moreover, the particles of dust and of condensed water which exist in varying quantities in the troposphere will add further attenuation. So, some portion of the earth's atmosphere will be almost opaque to the grazing rays and a correction has to be applied to the geometrical earth's shadow-height in order to get the effective height of the earth's shadow. This screening height h_0 will raise the base of the effective scattering layer. It can be shown that the effective height h' of the earth's geometrical shadow at the point where the direction of vision from P cuts the tangential ray from the sun at a height h_0 from the solid earth is

$$h' = (a + h_0) \sec. \theta' - a$$

where h_0 is the screening height at the tangential point, and

$$\tan \theta' = \frac{\sin \alpha - \sin (\alpha - \theta)}{\cos (\alpha - \theta)} = \frac{2 \sin \frac{\theta}{2} \cos \left(\alpha - \frac{\theta}{2} \right)}{\cos (\alpha - \theta)} .$$

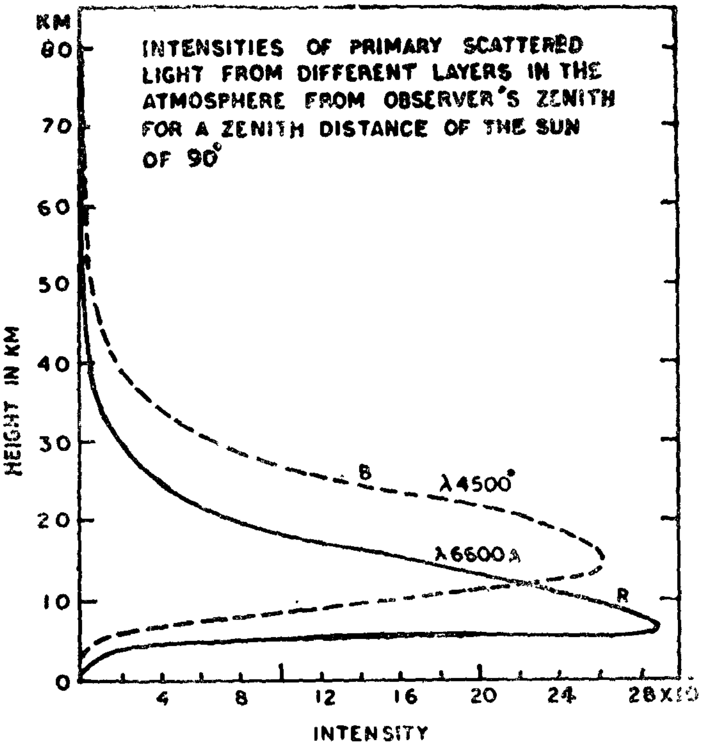
Van de Hulst has taken 3 km. as the screening height to compute the height of the scattering layer at the observer's zenith for different depressions of the sun. Bigg assumed that if longer wavelengths are used, the earth's shadow height will correspond to the geometrical height of the lowest grazing ray. Volz and Goody have given arguments to show that in a normal turbid atmosphere, we may take that the twilight comes from above 10 km. The author has also made calculations of the intensity of primary scattered light from the zenith using extinction coefficients due to molecular scattering and assuming that the decimal extinction coefficient due to dust to be the same as that found by Ljunghall (1949) from his observations at Helwan, Curve-R in Fig. 2 is the height-intensity curve for red light of wavelength 6600 Å and curve-B for blue light (4500 Å).

It is seen from the curves that the maximum scattered light in blue comes from a height of about 15 km. and falls off rapidly at lower heights.

In red, the maximum primary scattered light comes from a height of about 6 km. above the surface of the earth and very little light comes from below 4 km. Remembering that there will always be some dust in the lowest layers of the atmosphere, the screening height for red light has been assumed to be 6 km.

Table I gives the heights of the directly illuminated region in the atmosphere for different depressions of the sun, for a screening height of 6 km. allowing for refraction, when observations are made in a direction 70° from the zenith in the sun's meridian plane.

Analysis.—In a pure dust-free atmosphere, if the intensity of sky light is assumed to be due mainly to the primary scattered light, the intensity I will be proportional to the pressure p at the level of the effective shadow. But, as a matter of fact there is a certain amount of secondary and multiply scattered light added to the primary scattered radiation and moreover the atmosphere contains some particles of haze and condensed water-vapour which cause additional brightness in certain directions and also attenuate the direct radiation.



NO ALLOWANCE HAS BEEN MADE FOR REFRACTION IN CALCULATING THE HEIGHTS OF THE SCATTERING LAYERS -

ATTENUATION DUE TO HAZE

h KM	δ
1 - 2	0·085
2 - 4	0·052
4 - 6	0·021
>6	0·000

FIG. 2. Intensity of primary scattered light (6600 Å and 4500 Å) from different levels in the zenith sky when $Z = 90°$. δ is the attenuation coefficient per km. due to haze.

Now $dI/I = dp/p$ for a dust-free Rayleigh atmosphere and the change of pressure with height in the atmosphere is given by the equation

$$dp = -g\rho dh$$

where dp is the fall of pressure corresponding to an increase in height of dh.

TABLE I

h′ *has been calculated assuming a screening height of* 6 *km. and allowing* 0·6° *for refraction at that height*

θ	θ'	h'
(Deg.)	(Deg.)	km.
0	0·0	..
1	1·0	6·5
2	2·0	8·0
3	2·8	10·5
4	3·6	15·0
5	4·5	21·5
6	5·3	28·5
7	6·1	36·5
8	6·9	46·0
9	7·7	56·0
10	8·4	67·5
11	9·1	79·5
12	9·8	93·5
13	10·5	107·5
14	11·2	121·5
15	11·9	135·5

Since

$$p = \frac{\mathrm{RT}\rho}{\mathrm{M}}$$

we get

$$\frac{-dp}{p} = \frac{\mathrm{M}g\,dh}{\mathrm{RT}}$$

(assuming T to be constant within *dh*) the value of h' in Fig. 1 is

$$h' = (a + h_0)\sec\theta' - a$$

$$= a\frac{\theta'^2}{2} + h_0 \text{ when } \theta' \text{ is small,}$$

$$\therefore dh = a\,\theta' d\theta'$$

and

$$\frac{d\mathrm{I}/\mathrm{I}}{dp/p} = \frac{d\log\mathrm{I}}{d\log p}$$

$$= \frac{d\mathrm{I}}{\mathrm{I}dh}\cdot\frac{\mathrm{RT}}{\mathrm{Mg}}$$

or

$$\frac{d\log\mathrm{I}}{d\log p} = \frac{d\mathrm{I}}{\mathrm{I}\theta' d\theta'}\times\frac{\mathrm{R}}{a\mathrm{Mg}}$$

(θ' measured in radians) where R is universal gas constant.

If a curve of $(d\log 1)/(d\log \mathrm{I})$ is plotted against θ, it is found that it shows significant rapid changes at some values of θ, and these are attributed to changes in the structure of the atmosphere, either of density or of changes in the dust content of atmosphere.

Since there is a certain amount of uncertainty in defining the effective height of the earth-shadow, we considered it desirable to plot different sample functions of $d\mathrm{I}/\mathrm{I}$ or $d\log\mathrm{I}$ against θ. Figure 3 shows the plots of $\log\mathrm{I}$, $\log p$ and of

$$\frac{d\log\mathrm{I}}{d\log p}\left(= \frac{d\mathrm{I}}{\mathrm{I}}\cdot\frac{\mathrm{RT}}{a\mathrm{Mg}\theta' d\theta'}\right)$$

against θ on two days. p and T are the atmospheric pressure and temperature at the point Q_2 corresponding to θ' in Fig. 1.

The temperature at the heights of the geometrical earth's shadow h', corresponding to θ', are also plotted on the extreme right.

Among the other functions that were tried were

$$\frac{1}{\mathrm{I}}\frac{d\mathrm{I}}{dt}$$

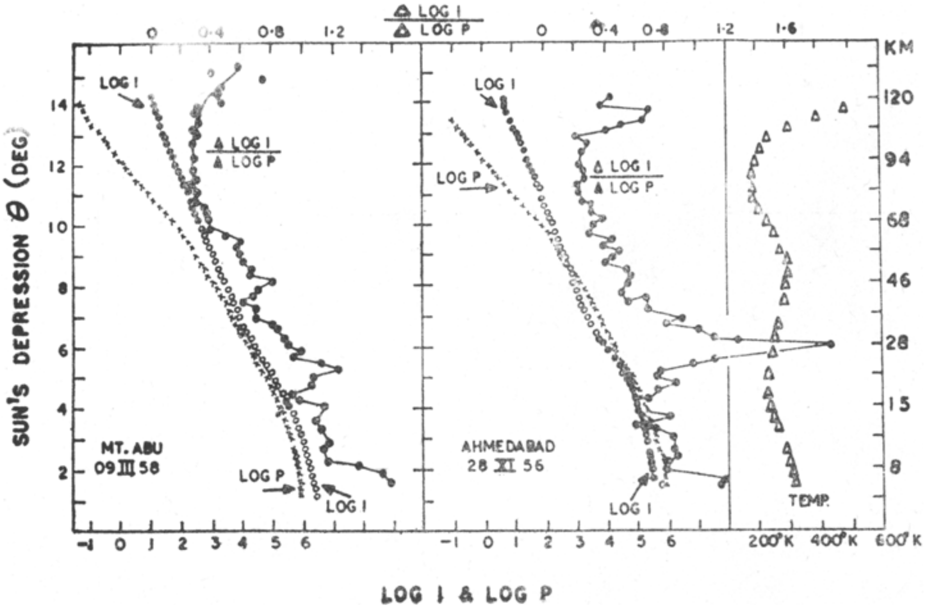


FIG. 3. Plots of log I, log p and of Δ (log I)/Δ (log p) against solar depression θ on 28-11-1956 and 9-3-1958.

and

$$\frac{d\log \mathrm{I}}{\mathrm{T}d\log p} = \left\{\frac{d\mathrm{I}}{\mathrm{I}\theta' d\theta'} \times \frac{\mathrm{R}}{a\,\mathrm{Mg}}\right\}.$$

Figure 4 shows these three curves relating to the observations in the dawn of 27-1-1958. Figure 5 represents the plots of (d log I/d log p) and (d log I/Td log p) against θ on 28-11-1956.

On the right side of Figs. 4 and 5 the effective shadow heights of the directly illuminated region in the direction of 70° from zenith, corresponding to different depressions of the sun's centre θ, are given, calculated on the assumption that the screening height is 6 km. and allowance for refraction is as given by Van de Hulst.

From Figs. 4 and 5 it will be seen that in the curve of (d log I/d log p) against θ, the temperature structure of the earth's atmosphere is reflected, while in the curves of (d log I/Td log p) and 1/I . dI/dt against θ it is practically absent. The plot of

$$\frac{d\log \mathrm{I}}{\mathrm{T}d\log p} = \frac{d\log \mathrm{I}}{\theta' d\theta'}\left(\frac{\mathrm{R}}{a\,\mathrm{Mg}}\right)$$

against θ does not depend on the screening height. A change of screening height bodily shifts the curve up or down but the trend of the curve will remain unaffected. The geometrical height of the peak will however change.

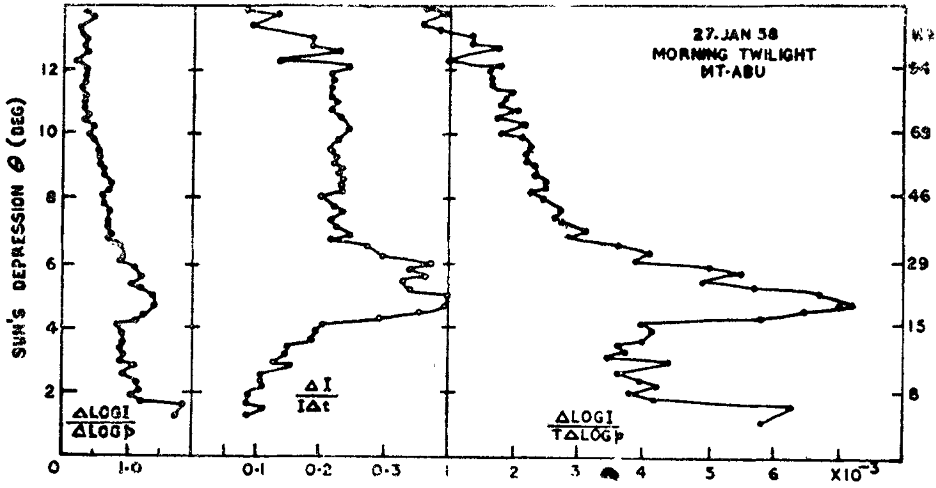


FIG. 4. Plots of (log I)/(log p), $d\text{I}/\text{I}dt$ and Δ (log I)/TΔ (log p) against θ on 27–1–1958.

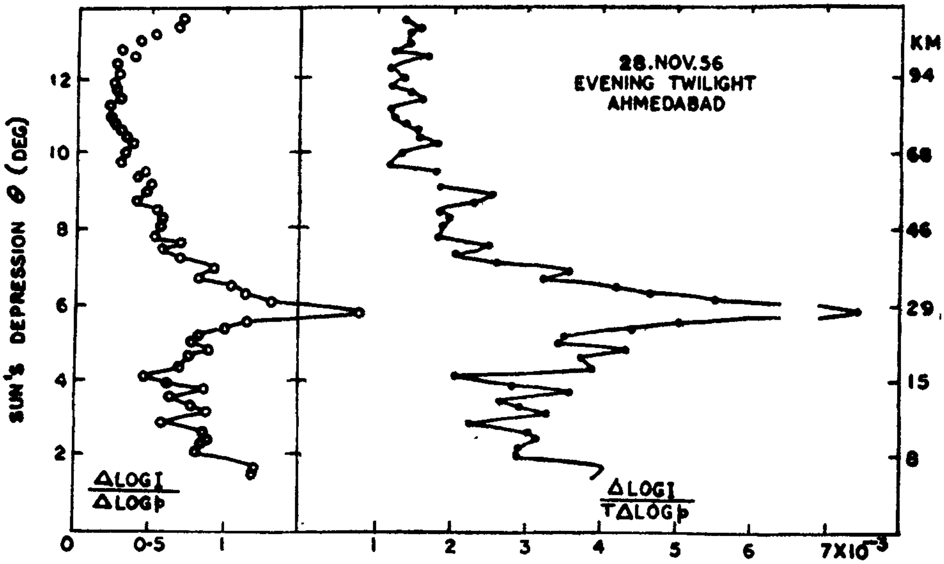


FIG. 5. Plot of Δ (log I)/Δ (log p) and Δ (log I)/T Δ (log p) against θ on 28–11–1956 at Ahmedabad.

Presentation of results.—Figures 6–9 show the plots of values of (d log I/d log p) against θ, the sun's depression below the geometrical horizon in different months of January, June, November and December 1958. The temperature at the heights of the geometrical earth's shadow h' corresponding to θ' are also plotted.

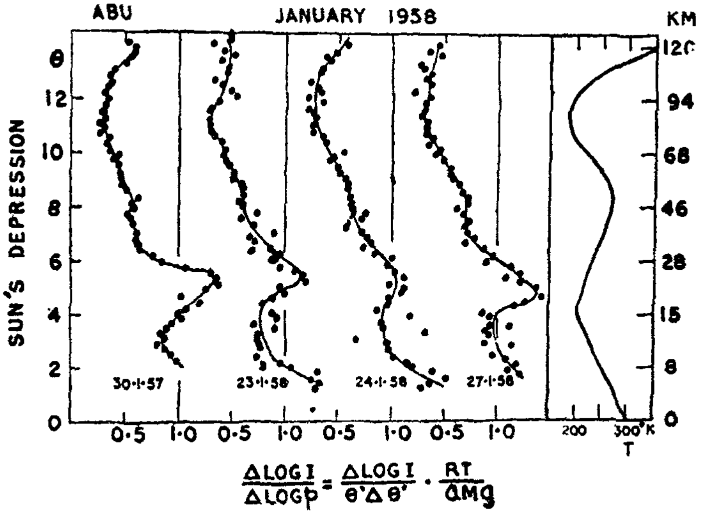


FIG. 6. Day-to-day variation of Δ (log I)/Δ (log p) against θ in January 1957 and 1958.

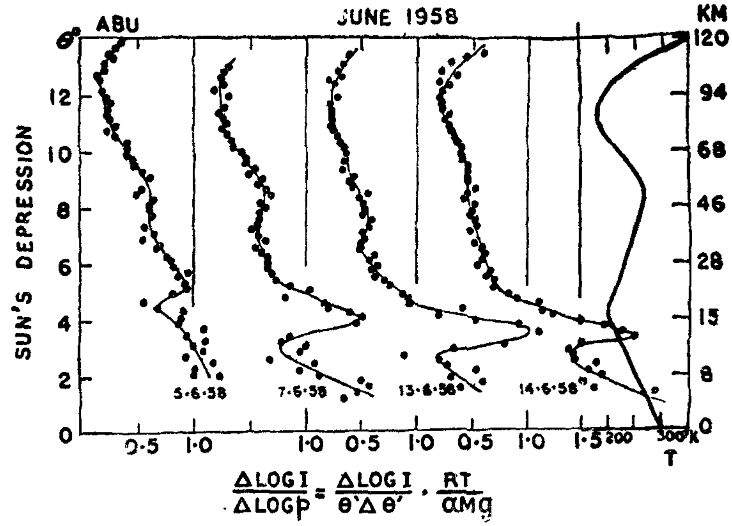


FIG. 7. Day-to-day variation of Δ (log I)/Δ (log p) against θ in June 1958.

The curves show a first maximum at 5–6° sun's depression which is equivalent to an effective height of 20–30 km. of the layer illuminated by the grazing rays. The occurrence of this maximum is more or less a regular feature of the curves. A second feebler maximum is found at about 8·5° sun's depression ($h_{eff} = 50$ km.). The minimum occurs at 11–11·5° sun's depression ($h_{eff} = 80$–90 km.).

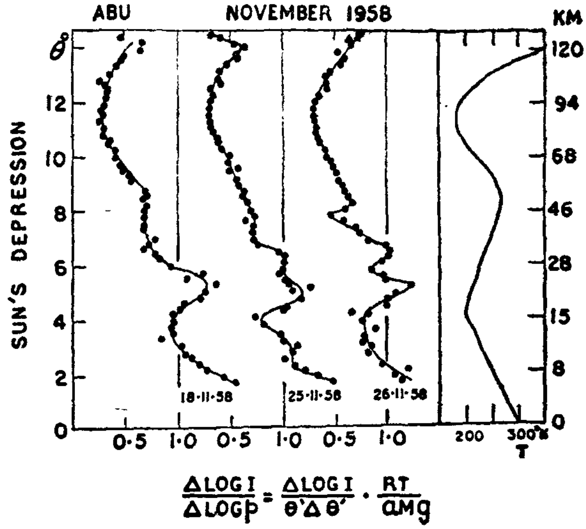


Fig. 8. Day-to-day variation of Δ (log I)/Δ (log p) against θ in November 1958.

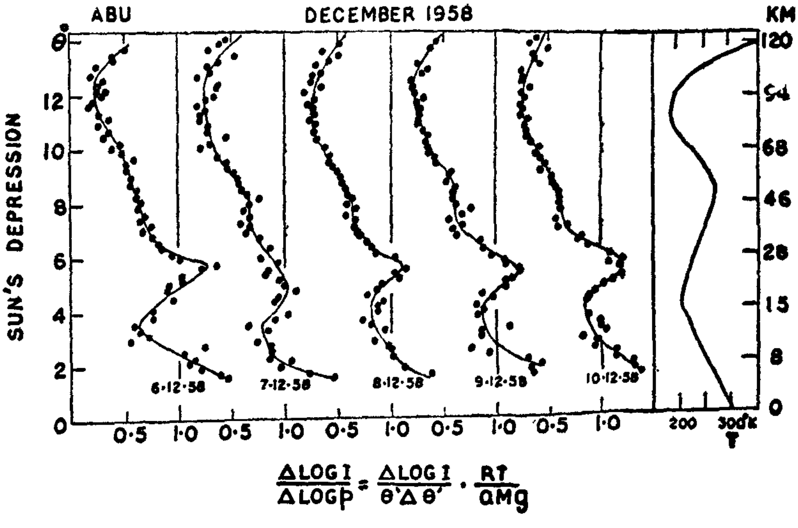


Fig. 9. Day-to-day variation of Δ (log I)/Δ (log p) against θ in December 1958.

The maximum sometimes occurs at a lower height (near 15 km.) as on 13 and 14 June 1958.

DISCUSSION

Junge *et al.* (1961) in their study of stratospheric aerosols by direct observation of the particles collected by means of balloon-borne inertial impactors at Bismarck, N.D., Omaha and Hyderabad, found that the vertical distribution of stratospheric particles within a range of radius of $0{\cdot}1\,\mu$ to $1{\cdot}0\,\mu$, consistently showed a maximum in the stratosphere with a broad maximum between 15 and 23 km. They suggested that these aerosol layers were identical with the layers responsible for the purple glow of twilight and the haze layers observed by fliers in the stratosphere. They also showed that on the upper side of the stratospheric aerosol layer there is very pronounced stratification. These twilight phenomena had been observed and studied for many years in Switzerland by Gruner (1958). The characteristics of the purple glow, especially the time of its appearance as a function of the sun's depression below the horizon, allow an estimation of the height of the scattering layer to be made. Gruner estimated it to be at about 25 km. From our observations it is found that the first maximum occurs at 5–6° sun's depression which is equivalent to a layer at a height of 20–25 km. Sometimes, these maxima are found to be at 4°–5° sun's depression which corresponds to 15–20 km. This means that the layer of dust descends to a lower level in the atmosphere. Sometimes, thin layers of dust occur which are revealed by two or three maxima on the ($\log I/\log p$) curves. The first scattering layer seems to vary from 15 to 30 km. At Abu, the lowest heights are found to occur in June and the highest in November to December.

A second layer is found at about 50 km. in all the curves, irrespective of season. Sometimes it is sharp, and sometimes it is less pronounced. A minimum occurs at a height of about 80 km.

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