VERTICAL DISTRIBUTION OF ATMOSPHERIC OZONE IN LOW LATITUDES

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§1. Introduction

The first rough estimates of the height of atmospheric ozone were obtained in 1925–27 from photometric measurements[1] of the spectrum of direct sunlight at different altitudes of the sun, and these gave a mean height of about 40-50 km. In 1929, F.W.P. Götz[2] observed that the light scattered from the zenith sky was relatively richer in ultraviolet light in the region of ozone absorption when the sun was on the horizon than when it was a few degrees higher up in the sky. He called this the 'Umkehr Effect' and suggested that it could be used to deduce the vertical distribution of ozone in the atmosphere by taking observations of the light scattered from the blue zenith sky. Using the photo-electric spectrophotometer developed by Dobson,[3] Götz, Meetham and Dobson[4] made reliable measurements of the Umkehr Effect in 1934 at Arosa (Lat. 47° N.) in Switzerland and developed methods for calculating the vertical distribution of ozone. From 46 days' observations of the Umkehr curves in different seasons of the year and with different total amounts of ozone, they found that the average height of ozone at Arosa was about 22 km. above sea-level, that the ozone was distributed mainly between the ground and 35 km., and that the nature of the vertical distribution changed more or less systematically with the total amount of ozone, higher ozone amounts in general lowering the centre of gravity. The average height of ozone deduced from observations of zenith sky intensities was confirmed by Regener[5] from his independent studies of the ultraviolet end of the solar spectrum with spectrographs carried in sounding balloons.

The vertical distribution of atmospheric ozone in high latitudes was investigated by Meetham and Dobson[6] from observations made at Tromsø (Lat. 69° 40′ N.) in Norway in the summer of 1934. They could get only 13 days' observations. The average height of ozone was found to be slightly lower (20·8 km.) at the higher latitude, the maximum concentration of ozone also being in a region centred at 21 km.

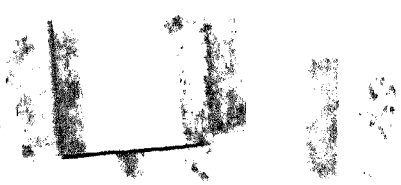
Recently, Tønsberg and Langlo[7] have published a detailed account of their investigations on atmospheric ozone at Nordlysobservatoriet, Tromsø. These include measurements of the total quantity of ozone by sunlight,

starlight, and moonlight with different types of instruments during the years 1935–42. The zenith sky measurements for the vertical distribution of ozone were made with Dobson's photo-electric spectrophotometer during 1939–42. The measurements were more numerous than the observations made by Meetham and Dobson in 1934. The new Tromsø results show a markedly different type of distribution from the earlier results of Meetham and Dobson, the centre of gravity of ozone showing a variation from 26·7 km. for 0·160 cm. of ozone to 20·8 km. for 0·400 cm. in the new series as compared with a more or less fixed height of 20·8 km. in the old one. The new distributions show that, when the total amount of ozone varies, the most marked changes in the ozone content occur between 5 and 20 km.

§2. Observations in India

Little information has been available so far about the vertical distribution of atmospheric ozone in low latitudes. Observations with one of Dobson's photo-electric spectrophotometers were started in India at Poona (Lat. 18° 31′ N.) in February 1940 by Dr. Ramanathan and Umkehr curves for about six clear days were obtained during the months of February and March of that year. The fact that in low latitudes the height of the sun changes rapidly when it is near the horizon makes it rather difficult to take accurate and numerous observations at sunset or sunrise; still, the observations were good enough to indicate the existence of the 'Umkehr Effect'. The same instrument was later taken to Delhi (Lat. 28° 35′ N.) and systematic observations were made during the period November 1945 to March 1947. The calibration of the optical wedges in the instrument was in doubt and many clear days were spent in recalibrating the wedges. The new calibration[8] brought out some significant differences and these were taken into account in working out the results. Observations on many cloudless days in summer had to be excluded because of the peculiar white haze characteristic of the hot season in north-west India. About 35 clear days' Umkehr curves were obtained at Delhi. In April 1947, the same instrument was taken to Simla (31° 06′ N., 2·45 km. above sea-level) to clarify some points raised by the Delhi observations on the effect of dust and haze on the intensities of direct sunlight and zenith sky light. At Simla, 15 Umkehr curves were obtained in April and May 1947 and 9 curves in November 1947. The instrument was again taken to Poona and used during the months of February and March 1948, and Umkehr curves were obtained on eight clear days.

The present paper gives the results of the analysis of the zenith sky observations at Delhi and Poona. It was found that for the same quantity



of ozone (0·220 cm.), the average height of ozone at the latitude of Delhi is higher (25·1 km.) than the height 22·5 km. at Arosa.[4] At Tromsø, Meetham and Dobson's[6] analysis indicated a mean height of about 20·8 km. for this amount of ozone, while Tønsberg and Langlo[7] found it to be 25·7 km. The Umkehr curves and the average heights deduced from observations at Simla are more or less similar to those obtained at Delhi. At Poona, zenith sky observations are not available for the ozone amount 0·220 cm., but on a number of days when the ozone amount was between 0·164 and 0·177 cm., the average height was found to be about 28 km. Further work is required at Poona and still lower latitudes.

§3. Methods of Calculating the Vertical Distribution of Ozone

Two methods (A and B) for calculating the vertical distribution of ozone, which differ from each other only in matters of detail, have been described by Götz, Meetham and Dobson in their Arosa paper.[4] Observations are made on the light scattered from the clear zenith sky at different zenith distances Z of the sun. If I, I′, I″ be the intensities of the zenith-scattered light at the three wavelengths λ 3110 A, λ' 3300 A and λ'' 4450 A, the instrument directly gives log I/I′ + C and log I″/I′ + C′, where C and C′ are instrumental constants which are eliminated in the final calculations. When log I/I′ (C being dropped hereafter for convenience) is plotted against Z^4 (the fourth power being chosen to open out the scale at low altitudes of the sun), it is seen that log I/I′ continuously decreases with increasing values of Z, reaches a minimum when Z is 85° to 87° and again increases with further increase of Z. The shape of this curve, called 'Umkehr curve' by Götz, and the position of the inversion depend upon the height distribution of atmospheric ozone.

Considering the scattering by an element at height h above the earth's surface, the intensity I of light of wavelength λ reaching the instrument from unit angle of the zenith sky can be shown to be given by

$$I = K(1+\cos^2 Z)\, I_0 \int_0^\infty \rho_h \left[10^{-\alpha \int_h^\infty x_h \sec \xi_h\, dh - \alpha \int_0^h x_h dh} \times 10^{-\int_h^\infty \beta_h \sec \xi_h dh - \int_0^h \beta_h dh}\right] dh$$

$$= K(1+\cos^2 Z)\, I_0 \int_0^\infty \rho_h \cdot 10^{-\alpha Y} \cdot 10^{-\beta F}\, dh.$$

Here,

$K = \frac{3}{16\pi} \cdot \frac{\beta}{H\rho_0}$ and is a constant proportional to the scattering per unit solid angle by unit volume of air, β being the scattering for the whole of the

atmosphere of homogeneous height H, and ρ_0 the density of air at the earth's surface,

Z = the zenith angle of the sun as seen from the earth's surface, *i.e.*, the angle between the incident sunlight and the scattered vertical ray,

ξ_h = the zenith angle of the sun as seen from a point in the atmosphere at height h from the earth's surface, *i.e.*, the angle between the incident sunlight and the normal to the shell of the atmosphere at height h,

I_0 = the intensity of the incident solar radiation of wavelength λ outside the earth's atmosphere,

ρ_h = density of the air at height h,

$\beta_h = \frac{\beta}{H\rho_0}\rho_h$ and refers to the scattering by air at height h,

α = the decimal absorption coefficient per cm. at N.T.P. of ozone at the wavelength λ,

x_h = the ozone amount per unit length at height h.

Y thus denotes the total integrated thickness of ozone traversed by sunlight from outside the atmosphere to the scattering element and afterwards by the scattered light from the latter on its way to the observing instrument. Y will therefore depend on the vertical distribution of ozone in the atmosphere. Similarly F denotes the integrated 'airmass' traversed, the integration being taken in a way similar to that for Y.

An expression similar to I can be written for the intensity I′ of the light of wavelength λ'. Hence Log I/I′ can be calculated and equated to the observed value. A strict mathematical solution for a given 'Umkehr curve' is not practicable and two different approximate methods have been given by Götz, Meetham and Dobson.

(*a*) *Method A.*—In this method, the atmosphere is divided into 5 sections, *viz.*, 0–5 km., 5–20 km., 20–35 km., 35–50 km. and above 50 km. The atmosphere above 50 km. is assumed to contain no ozone. In the lowest layer, the ozone amount is assumed to be what is given by spectroscopic or chemical measurements made at ground level. Let this be u cm. and let the unknown ozone amounts in the sections 35–50 and 20–35 km. be x_1 and x_2 respectively; then the ozone amount in the layer 5–20 km. is $x-(x_1+x_2+u)$, where x is the total ozone obtained from direct sun observations. The ozone in each section is assumed to be distributed uniformly. The two unknowns x_1 and x_2 can be determined by taking two suitable values of log I/I′ corresponding to two values of the zenith distance Z from an

observed mean Umkehr curve and writing down two numerical equations. Generally, log I/I′ corresponding to a third value of Z is used as a check. This method has been used by Tønsberg and Langlo in working out the ozone distribution at Tromsø from the observations during 1939–42.

(*b*) *Method B.*—Here, the whole atmosphere is divided into 8 sections and arbitrary amounts of ozone are assumed to be present in each, the sum of the amounts in all the sections together being equal to the total ozone amount. By calculating the scattering and absorption of light at all heights under these conditions, a theoretical 'Umkehr curve' can be calculated. This will, in general, differ from the observed curve and the assumed distribution of ozone in the various sections can be varied by trial and error until a reasonably good agreement is obtained between the calculated and observed curves. In general, more than one such solution can be found for a given Umkehr curve, but it is found that the solutions are not substantially different and the average height of ozone for all these is found to be almost identical. This method has been used by Götz, Meetham and Dobson in working out the ozone distributions from observations at Arosa and from the earlier series at Tromsø.

Method A was used for analysing the Indian data preliminarily in an exploratory manner so as to give an approximate idea of the ozone distributions. Method B was then applied on the basis of the results of method A, and the necessary variations in the assumed ozone quantities made so as to get a good fit with the observed Umkehr curves. Details of method B only are given below.

§4. Details of Method B used in India

In this method, Dobson divided the atmosphere into a number of horizontal sections such that the mass of air in any section was $1/\sqrt{10}$ of that in the section next below it. The whole of the air in any section is then supposed to be concentrated at such a height that half the air in the section is above that level and half below it. The ozone in each section is also supposed to be distributed in the same way as the air, which means that, within each layer, ozone is not uniformly distributed but decreases nearly exponentially with height.

Dividing the atmosphere in geometrical progression with a factor of $1/\sqrt{10}$ simplifies some numerical calculations. The method used in this paper is slightly different. The atmosphere is divided into layers each of 9 km. thickness from the sea-level upward. For simplicity in calculations, it was assumed that the centre of mass of each layer was situated at 3 km. above the base of that layer. This is usually correct to within $\frac{1}{2}$ km., and

the approximation is good enough. For pressures, temperatures and densities upto 25 km. in the atmosphere, the average values given by Dr. Ramanathan[9] for Agra have been used; for 30 km. and upward, values recently given by Penndorf[10] are used. Table I below summarises the assumed values of temperatures, pressures and densities at different heights. Table II gives the heights of the different sections and the masses of air in the sub-sections.

TABLE I

Height a.s.l. km.	Temp. °A	Pressure mb.	Density gm./m^3	Height a.s.l. km.	Temp. °A	Pressure mb.	Density gm./m^3
0	300	1013·3	1176·7	30	227·5	11·7	17·9
2	288	799	966·6	35	233	5·56	8·31
5	270	554	714·9	40	263	2·79	3·70
10	239	284	414·0	45	293	1·55	1·84
12	225	210	325·2	50	323	0·86	0·93
15	206	130	219·9	60	283	0·28	0·35
17	199	93	162·8	70	243	0·076	0·11
20	208	56	93·8	80	203	0·017	0·029
25	217	26	41·1	90	275·5	0·0039	0·005
				100	348	0·0013	0·0013

TABLE II

Section No.	Boundaries of section: km.	Assumed C.G. of section:km.	Sub-section	Boundaries of sub-section:km.	Fraction of atmosphere in the sub-section
1	0–9	3	1*a*	0–3	·3022
			1*b*	3–9	·3776
2	9–18	12	2*a*	9–12	·1130
			2*b*	12–18	·1298
3	18–27	21	3*a*	18–21	·0302
			3*b*	21–27	·0288
4	27–36	30	4*a*	27–30	·00693
			4*b*	30–36	·00677
5	36–45	39	5*a*	36–39	·00162
			5*b*	39–45	·00163
6	45–54	48	6*a*	45–48	·000455
			6*b*	48–54	·000532
7	54–63	57	7*a*	54–57	·000155
			7*b*	57–63	·000200
8	63–72	66	8*a*	63–66	·000061
			8*b*	66–72	·000071

Scattering from all significant layers was taken into account when the sun was very near the horizon; with higher altitudes of the sun, the effect of the higher layers became less and less important.

All the ozone was assumed to be present only in the first six sections, *i.e.*, up to 54 km. The ozone in each section was further assumed to be uniformly distributed within each section, so that in considering the absorption due to ozone, two-thirds of the quantity in the section came in the slant path of the sunlight and only one-third in the lower vertical path.

To get the integrated 'airmass' F traversed by the sunlight along the slant path and by the scattered ray along the vertical path, F can be conveniently expressed in the form

$$F = \frac{\rho_h}{\rho_0} [f(Z) - 1] + 1$$

where $f(Z)$ is a function of Z. $f(Z)$ tends to sec Z for high altitudes of the sun; but owing to the curvature of the earth, $f(Z)$ differs increasingly from sec Z as Z approaches 90°. Götz[11] has given tables of slant length in different 2 km. steps above the point of observation for values of Z= 60°·75, 80°, 86°·5 and 90°. Similar tables were prepared for a few more angles and these were used in the calculations.

The following Table III gives the values of the scattering and absorption coefficients used in the calculations.

TABLE III

Wavelength	Decimal absorption coefficient per cm. of ozone at N.T.P.	Decimal scattering coefficient for the air in the whole atmosphere
λ 3110 A	α 1·275	β 0·457
λ' 3300 A	α' 0·074	β' 0·361
λ'' 4450 A	α'' 0	β'' 0·109

The scattering coefficients in the last column correspond to pure molecular scattering including anisotropic scattering and refer to the whole atmosphere above mean sea-level. The actual height of Delhi is 218 m. above sea-level and that of Poona is 563 m. and the assumption of pure molecular scattering is also not quite true even on apparently clear days. But considering the uncertainty of the amount of dust in the atmosphere above Delhi and Poona even on clear days and the fact that the errors caused by the above two discrepancies are of opposite signs, it was considered that the values adopted were good enough.

§5. Observational Data

Plotting log I/I′ against Z^4, Dobson found that for any group of days on which the total ozone content was nearly identical, the points lay practically on the same Umkehr curve. There was a largish scatter of points when Z was large and this was attributed to the larger errors of observation with weaker light. He concluded that the shape of the Umkehr curve and hence the vertical distribution of ozone was a function mainly of the total ozone content.

As regards the observational data at Delhi, the ozone amounts for which Umkehr curves were obtained during the period November 1945 to March 1947 varied only between 0·155 cm. and 0·217 cm., 35 good days' curves being obtained in all. Out of these, 27 curves were obtained during the period November to June. Dust and haze during the latter part of the hot season and cloudiness during the monsoon season make it difficult to obtain good observations during these seasons. The following table gives the number of Umkehr curves obtained for various amounts of ozone at Delhi.

Ozone amount	No. of Umkehr curves
<0·160 cm.	4
0·160—0·170 cm.	12
0·170—0·190 cm.	12
0·190—0·200 cm.	4
>0·200 cm.	3

For the purposes of calculations in this paper, a few representative curves relating to clear days will be taken and these are shown in Fig. 1. They relate to ozone amounts 0·155 cm. (lowest quantity observed on 6–1–46 at Delhi), 0·217 cm. (highest quantity observed on 20–1–47), 0·175 cm. (mean ozone amount for a group of 3 similar curves) and 0·200 cm. (the amount on another selected clear day). All these curves happen to be from the winter season and have a more or less uniform spread of ozone amounts and consistent changes in positions of inversion.

As regards the observational data at Poona, the curves relate to the period February and March 1948 only,* 8 good curves being obtained in

* There are a few days' observations taken by Dr. Ramanathan in 1940 when the instrument was first set up at Poona. The calibration of the optical wedges in the instrument was, however, not checked in 1940, and on doing this later in 1945 at Delhi, the new calibration showed some significant differences from the one supplied by the manufacturers. The calibration was therefore checked regularly on different occasions during the periods of observation at Delhi and Poona and fortunately it has been found to remain the same. Moreover, in 1940, zenith sky observations for values of the zenith distance Z of the

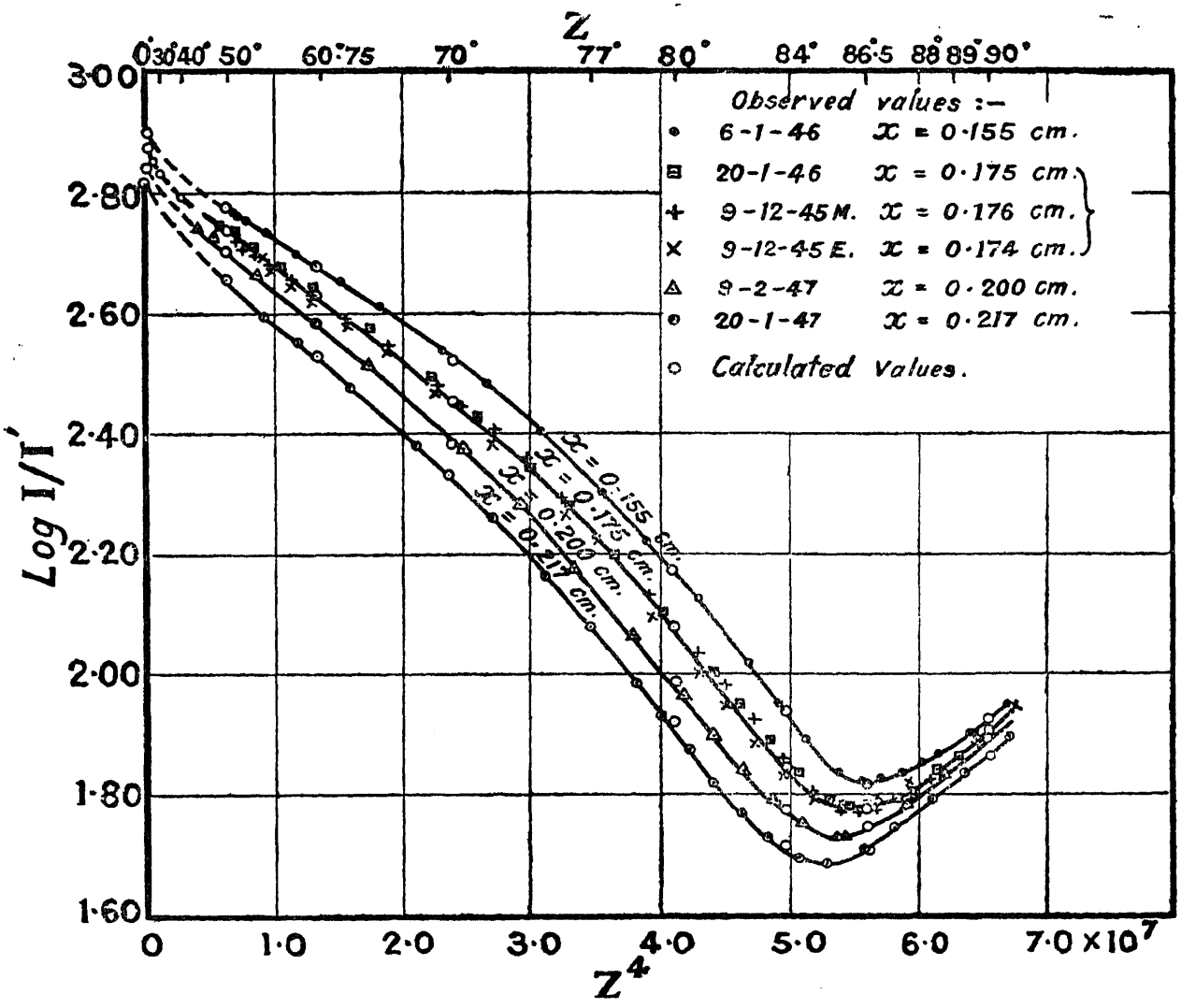


FIG. 1. Intensity of zenith sky light with different ozone amounts at Delhi

all for ozone amounts varying between 0·164 cm. and 0·177 cm. Fig. 2 gives two representative curves for Poona with ozone amounts 0·164 cm. and 0·174 cm.

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sun larger than 87° or 88° could never be obtained. The observations made in 1948 were quite satisfactory even upto Z = 90° or more, due to the increased sensitivity of the instrument resulting from the replacement of the old valves in the amplifier by new ones and also due to the use of higher voltages (within the limits allowed) for the amplifier and photo-cell when the incident light was weak at the time of sunrise or sunset. More weight has therefore to be given to the observations obtained in 1948.

Assuming the new calibration to hold good for the observations obtained in 1940, calculations were also made for an Umkehr curve with an average quantity 0·183 cm. of ozone and this gave about 30 km, as the average height of ozone over Poona. This may be compared with the average height 28·0 km. obtained in 1948 for an ozone amount 0·174 cm.

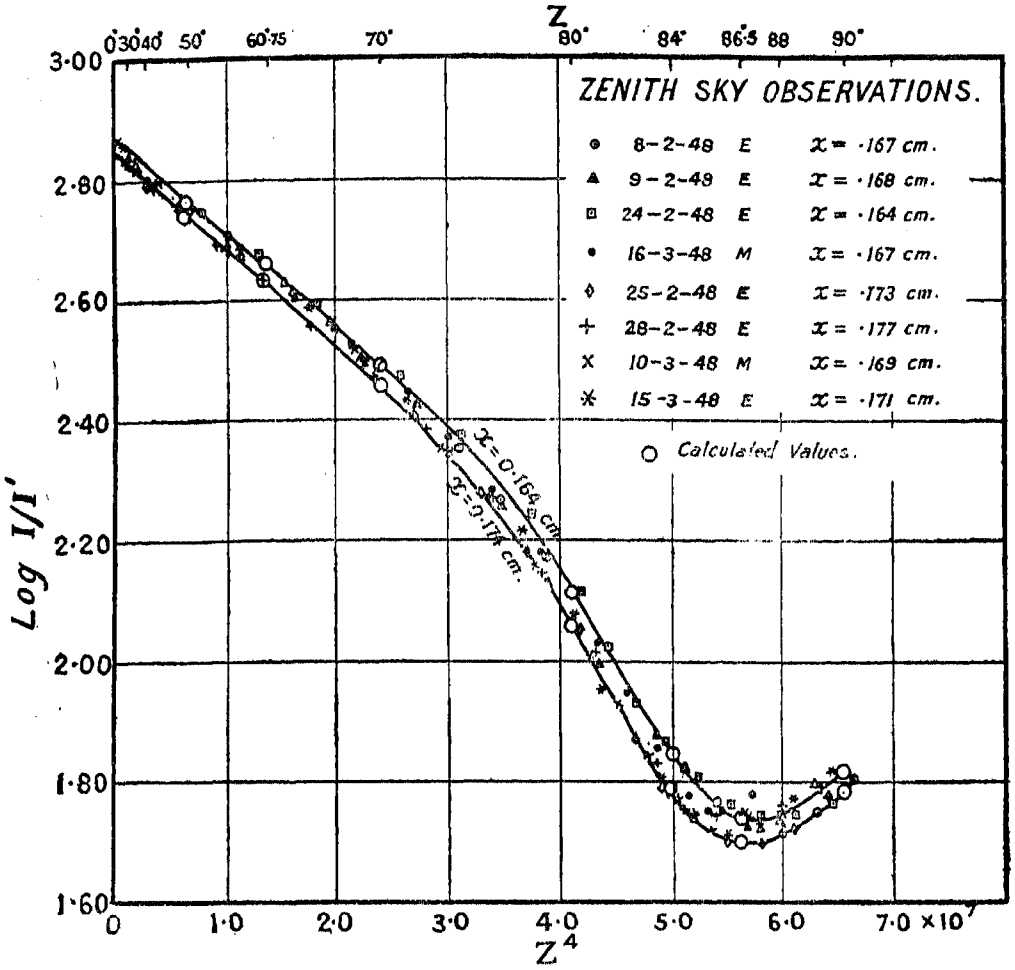

FIG. 2. Intensity of zenith sky light with different ozone amounts at Poona

§6. CALCULATION OF THE HEIGHT DISTRIBUTION AND RESULTS

Table IV shows the values of log I/I' for the four curves relating to Delhi and the two curves relating to Poona for different zenith distances Z of the sun.

TABLE IV

Observed values of log I/I' for different values of Z

Z	$Z^4 \times 10^{-7}$	Total ozone content in cm. at N.T.P.					
		Delhi				Poona	
		0·155	0·175	0·200	0·217	0·164	0·174
50°	0·625	2·773	2·738	2·703	2·652	2·774	2·738
60°·75	1·36	2·678	2·627	2·581	2·523	2·660	2·632
70°	2·40	2·528	2·456	2·397	2·324	2·495	2·457
80°	4·10	2·173	2·068	1·978	1·907	2·116	2·060
84°	4·98	1·933	1·840	1·770	1·704	1·845	1·790
86°·5	5·60	1·821	1·782	1·742	1·713	1·740	1·703
90°	6·56	1·928	1·910	1·893	1·873	1·812	1·785

Calculations were made assuming different ozone amounts in the different sections and adjusting them by trial and error till satisfactory agreement was reached between the observed and calculated values. Since the observed values also include a constant C which depends on instrumental factors, this constant has to be eliminated by making the observed and calculated values equal at some angle. The observed values extended only upto $Z = 50°$ for the Delhi curves except in the case of the curve for 0·175 cm. for which they extended upto 43°. For the Poona curves, observations are available even upto 20°. $Z = 50°$ would be a sufficiently good point to secure agreement between the observed and calculated values, since at such an angle, the value of log I/I′ depends very little on the height distribution of ozone but only on its total amount. Thinking that $Z = 0°$ might be an even better point to choose, the values of log I/I′ at $Z = 0°$ were determined by extrapolation from the observed curves. It was, however, found that when there was agreement at 0° and at values of Z equal to 80° and higher, it was not possible to obtain agreement at the intermediate points 50°, 60°, 70° whatever changes were made in the assumed distributions. The plot of the calculated values in the region 0°–50° also showed considerable differences from the observed or extrapolated curves.

From later systematic observations at Simla,[12] the trouble was traced to the effect of large particle scattering. Although the sky might be apparently clear and this effect negligible for *large* values of Z, it would assume considerable proportions as the sun approached the zenith. The result was that there was an increasingly greater proportion of longer wavelengths in the zenith-scattered light at small zenith distances of the sun than pure molecular scattering would give. This effect is more pronounced for the longer wavelengths 4450 and 3300 A (due to their greater separation and smaller ozone-absorption) than for the shorter wavelengths 3300 and 3110 A, but affects the shorter wavelengths also to some extent. As a result, at small zenith distances of the sun, there is a marked difference between the observed values of log I/I′ and the values calculated on the assumption of molecular scattering. This can be seen from Figs. 1 and 2.

Dobson took $Z = 37°{\cdot}5$ as the point where the calculated and observed curves were made to coincide and whatever difference he found at this point between the slopes of the lines drawn through the observed and calculated points, he attributed to secondary scattering. Secondary scattering has undoubtedly some effect and would make the observed curve slightly less steep than the calculated one. But since secondary scattering affects both the wavelengths more or less to the same extent, the effect on the ratio log I/I′ may be expected to be small. An inspection of Figs. 1 and 2 giving the

curves for Delhi and Poona suggests that the discrepancies observed at these places are more pronounced than can be attributed to neglect of secondary scattering alone. Large particle scattering due to the presence of dust and haze in the atmosphere appears to be mainly responsible for the difference between the observed and calculated curves for small zenith angles of the sun.

It was decided to adopt $Z = 50°$, for which observations are available in all seasons, as the point where the observed and calculated curves should be made to coincide, and adjust the distribution of ozone so as to secure agreement at higher values of Z. Since the effect of large particle scattering becomes less important for values of Z higher than about 40°–45°, this procedure was considered satisfactory. The calculated and observed points are shown in Figs. 1 and 2 and it will be noted that the agreement is satisfactory in the region 50°–90°. This region alone is important for determining the height distribution of ozone.

Table V gives the amounts of ozone in cm. per km. height in the different sections obtained from the final calculated distributions corresponding to the different total ozone amounts. Since we have assumed uniform distribution of ozone within each layer, the centre of gravity of each layer is at its midpoint and the centre of gravity of the total atmospheric ozone can also be found easily by taking moments about the earth's surface. These are given at the bottom of Table V.

TABLE V

Amounts of ozone in cm. per km. height in different layers of the atmosphere over Delhi and Poona

Layer No.	Boundaries of layer in km.	Total ozone content in cm.					
		Delhi				Poona	
		0·155	0·175	0·200	0·217	0·164	0·174
6	45—54	0·0004	0·0004	0·0005	0·0005	0·0004	0·0004
5	36—45	0·0010	0·0010	0·0010	0·0012	0·0023	0·0024
4	27—36	0·0077	0·0080	0·0080	0·0080	0·0070	0·0075
3	18—27	0·0055	0·0070	0·0091	0·0104	0·0070	0·0075
2	9—18	0·0016	0·0020	0·0026	0·0030	0·0014	0·0014
1	0— 9	0·0010	0·0010	0·0010	0·0010	0·0001	0·0001
Average height of C. G. of ozone above sea-level in km.		26·3	25·9	25·3	25·1	28·1	28·0

Fig. 3 gives block diagrams of the vertical distributions of ozone at Delhi and Poona. Assuming uniform distribution within each layer, smooth curves of distribution can be drawn, care being taken to see that the areas under the smooth curve and the block diagram for each section are equal. Fig. 4 shows the smooth distribution curves so obtained for Delhi and Poona. The same figure also gives for comparison the distribution curves obtained at Arosa and Tromsø. The ratio of ozone to air by volume at different levels in the atmosphere was also calculated and the results are summarised in Table VI which gives the height distributions both of ozone amount per km. and of the ratio of ozone to air for fixed levels.

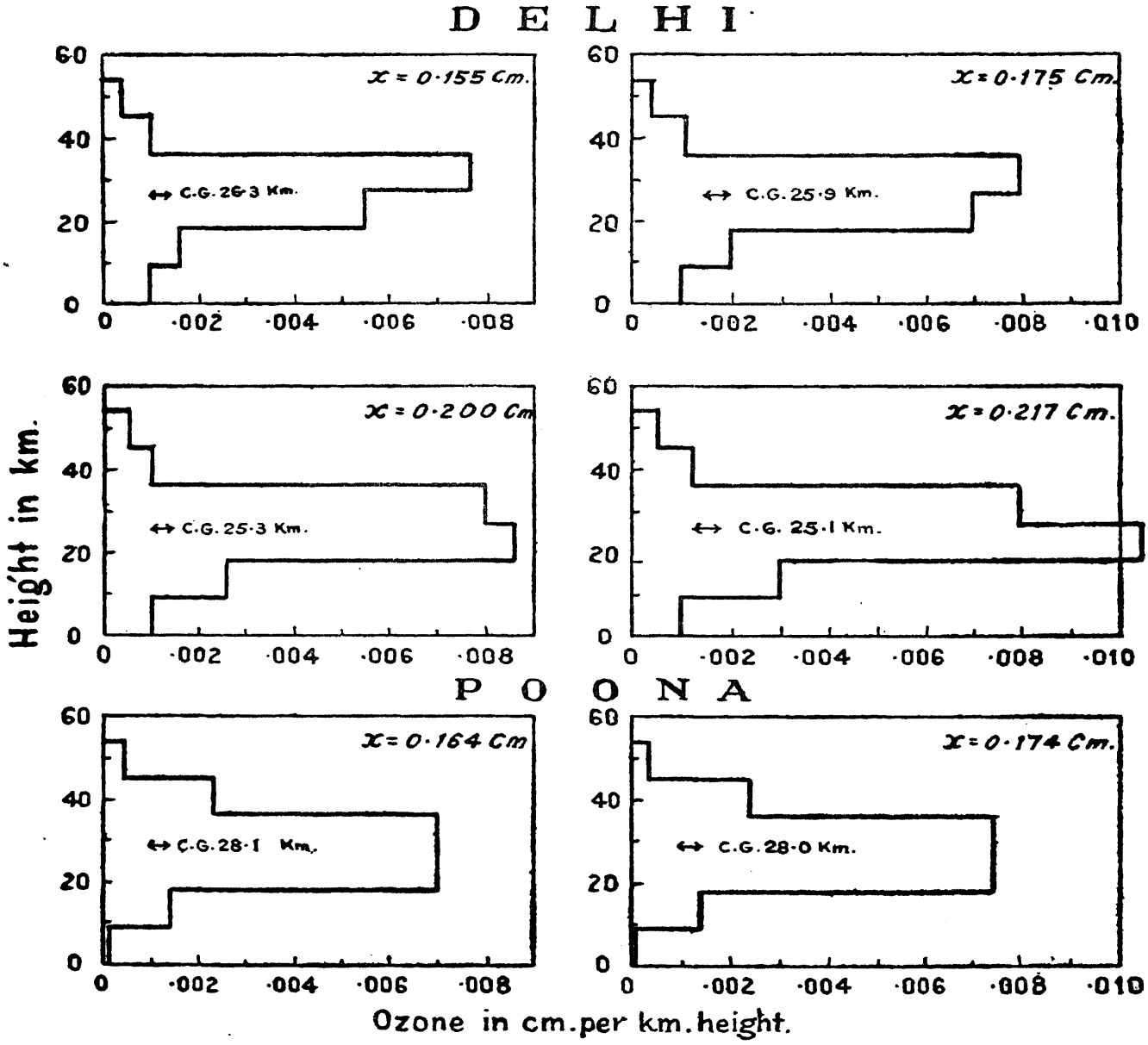

FIG. 3. Calculated vertical distributions of ozone over Delhi and Poona corresponding to different total ozone amounts x

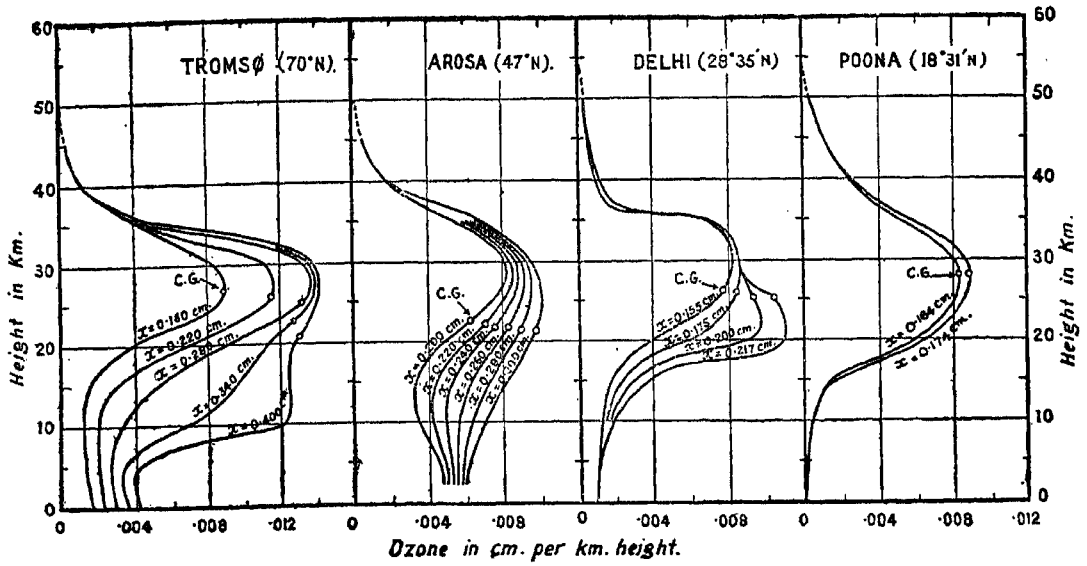

FIG. 4. Height distributions of atmoshperic ozone in different latitudes

TABLE VI

Height distribution of ozone over Delhi and Poona as cm. of ozone per km. height and as ratio R of ozone to air by volume

Height above M.S.L.	Delhi								Poona			
	0·155 cm.		0·175 cm.		0·200 cm.		0·217 cm.		0·164 cm.		0·174 cm.	
	O_3/km. $\times 10^3$	R $\times 10^6$	O_3/km. $\times 10^3$	R $\times 10^6$	O_3/km. $\times 10^3$	R $\times 10^6$	O_3/km. $\times 10^3$	R $\times 10^6$	O_3/km. $\times 10^3$	R $\times 10^6$	O_3/km. $\times 10^3$	R $\times 10^6$
50	0·30	3·8	0·33	4·2	0·36	4·6	0·38	4·8	0·30	3·8	0·30	3·8
45	0·52	3·3	0·55	3·5	0·58	3·7	0·60	3·8	1·00	6·4	1·00	6·4
40	0·93	3·0	0·99	3·1	1·05	3·3	1·10	3·5	2·35	7·5	2·40	7·6
35	6·6	9·3	6·6	9·3	6·6	9·3	6·6	9·3	5·15	7·3	5·55	7·9
30	8·15	5·36	8·4	5·52	8·4	5·52	8·4	5·52	7·95	5·23	8·60	5·65
25	7·1	2·03	8·05	2·30	9·25	2·65	10·25	2·93	8·00	2·29	8·55	2·45
20	3·85	0·48	5·9	0·74	9·1	1·14	10·7	1·34	6·05	0·76	6·50	0·81
15	1·65	0·09	2·15	0·11	2·95	0·16	3·55	0·19	1·45	0·08	1·50	0·08
10	1·15	0·03	1·35	0·04	1·55	0·04	1·70	0·05	0·45	0·01	0·45	0·01
5	0·98	0·02	0·98	0·02	0·98	0·02	0·98	0·02	0·10	0·002	0·10	0·002
0	0·90	0·01	0·90	0·01	0·90	0·01	0·90	0·01	0·10	0·001	0·10	0·001

§7. DISCUSSION OF RESULTS

In a recent paper[8] on the day-to-day variations of ozone amount over Delhi, it was pointed out (i) that during the monsoon months, there was very little day-to-day variation of ozone in spite of the varying character

of the surface weather, and (ii) that during the season of western disturbances, there were marked fluctuations in ozone amount, deep cold waves of dry air being generally associated with increase in its quantity. In general, advent of air of northerly origin in the upper part of the troposphere is accompanied by increase in ozone amount and advent of southerly air (south-westerly or south-easterly or easterly) by a decrease. During the monsoon when the upper air movement is persistently from the east or south-east, there is very little day-to-day fluctuation. In Europe also, July-August is the season of minimum day-to-day variation of ozone.

Considering the vertical distribution over Delhi, it will be seen from Table V that the maximum ozone content lies either in the 18–27 km. layer or the 27–36 km. layer. The smooth curves for Delhi in Fig. 4 show that the height of maximum ozone content increases from about 22 km. for 0·217 cm. to 30 km. for 0·155 cm. The smooth curves for Poona show the corresponding height of maximum ozone content to be about 28–30 km. for 0·170 cm. of ozone.

In general, during winter and early hot season, any increase in ozone occurs mainly in the layer 18–27 km. and to a smaller extent in 9–18 km. It is interesting to compare these results with those obtained in higher latitudes at Arosa (47° N.) and Tromsø (70° N.). For the latter place, there are two sets of curves, one determined from the earlier short-term observations of Meetham and Dobson[6] using method B and the other from the later long-term observations of Tønsberg and Langlo[7] using method A. The later Tromsø curves show better agreement with the Arosa and Delhi curves and will be used for discussion here. Both at Arosa and Tromsø, a very important feature is that, while a layer of comparatively high ozone content lies between 25 and 30 km. for different total ozone amounts, the increases of ozone content for the higher ozone amounts occur mainly between 10 and 25 km. and to a less extent between 5 and 10 km.

Götz[11, 13] has made the suggestion that, at least for larger amounts of ozone, there are probably two maxima in the ozone distribution curves, one of which is between 25 and 30 km. and the other at a lower level. Recently, Durand and co-workers[14] have given a preliminary estimate of the vertical distribution of ozone in the atmosphere from measurements of the solar ultraviolet spectra obtained upto an altitude of 88 km. during a V-2 rocket flight over White Sands, New Mexico, when the total amount of ozone was 0·27 cm. Their curve shows two peaks in ozone concentration at about 17 and 25 km. The distribution curves obtained at Tromsø and Delhi also show the possibility of a similar feature of two maxima in the

case of higher ozone amounts, one at about 30 km. at both the places and the second between 10 and 15 km. at Tromsø and between 20 and 25 km. at Delhi. This point, however, requires further finer analysis and will no doubt be cleared up in due course.

As it stands, it appears to be a world-wide feature that there is a primary maximum of ozone content at 25–30 km. and that variations in ozone amount occur mainly between 10 and 25 km. and to a smaller extent between 5 and 10 km.

§8. Concluding Remarks

It will be useful to conclude with a very brief survey of the existing knowledge regarding the distribution of ozone in the earth's atmosphere. The following are the major features of the horizontal distribution:

(*a*) On the mean of the year, the ozone amount is least over equatorial regions, the average amount being about 0·18 cm. There is little variation over the tropics, but betwen 20° and 60°, it increases with latitude, the annual average being about 0·25 cm. at 60° and 70° N. Very low values of ozone seem to be common within the Arctic Circle during polar nights and the annual average may be expected to decrease on the poleward side of latitude 70°.

(*b*) In the northern hemisphere, the ozone amount is a maximum in March-April with a value of about 0·33 cm. at 70° N. In latitudes up to 60° N., the minimum occurs in October-November, but at Tromsø (70° N.), the month of minimum is delayed till December. In the region of Indian and Chinese monsoons, there is a tendency for the occurrence of a secondary minimum in July-August.

(*c*) The day-to-day variations are smallest throughout the northern hemisphere in July-August. They are in general a maximum in December-March when the horizontal gradients of ozone amount are a maximum. Near the Arctic Circle, violent fluctuations occur in December-January, changes of 0·10 to 0·15 cm. in one day being not uncommon.

Our knowledge regarding the vertical distribution has already been summarised. In the tropics, most of ozone is in the stratosphere and its amount is largely controlled by the photo-chemical actions causing its formation and decomposition.[15] These do not vary much during the year.* The tropospheric convective processes which carry water vapour and other

* Observations at Delhi and Poona show, however, that there is a regular daily variation in the amount of ozone in the tropics with a minimum at about midday. The average daily amplitude is 0·003 to 0·005 cm. of ozone.

particles into the upper part of the troposphere apparently tend to destroy any ozone that might come down from the stratosphere. Laboratory experiments support this. For example, A. W. Ewell[16] found that photochemical formation of ozone is decreased and photochemical decomposition increased, each by a factor 3, when dry air at room temperature was replaced by moist air.

The total amount of ozone over any place at a definite time is the sum of (i) the daily equilibrium amount produced by the photochemical action of sunlight and the recombination of ozone by collision processes with atomic oxygen and air molecules, and (ii) the accumulated ozone below the region of photochemical ozone formation which is largely screened from the decomposing radiation from the sun and which, owing to low temperature, undergoes only very slow thermal decomposition. The vertical distribution curve cannot be expected to be identical with that worked out on the basis of purely photo-chemical processes; there will always be more ozone content on the lower side of maximum owing to accumulation. The lower the tropopause and the greater the thermal stability of the troposphere, the larger will be the accumulation of ozone below the level of ozone formation. As is well known, Meetham[17] found a positive correlation of $+0{\cdot}8$ between ozone amount over Oxford and potential temperature at 18 km., and Dobson and Meetham[18] found a negative correlation of $-0{\cdot}7$ between ozone amount and height of tropopause. Meteorological factors mainly affect (ii) and it is mainly changes in accumulated ozone that show themselves when western depressions and cyclones cause changes in air-mass over a place.

Where, as in the tropics, or also in temperate latitudes in July and August, lapse-rates are high in the upper half of the troposphere and water vapour has the greatest chance of being systematically carried upward, the amount of accumulated ozone in the troposphere and the day-to-day changes in ozone amount remain persistently small. The most violent fluctuations occur where, as in the polar regions in December and January, there is a high gradient of photochemically formed ozone and also frequent changes of air-mass and accumulated ozone due to movement of depressions and storms.

The study of the vertical distribution of ozone in equatorial regions and of the daily variation of ozone on meteorologically undisturbed days in all parts of the world may be expected to throw further light on the causes of formation, accumulation and transport of ozone in the earth's atmosphere.

§9. Acknowledgment

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Summary

Observations of the light scattered from the clear blue zenith sky were made with Dobson's photo-electric spectrophotometer at Delhi (28° 35′ N.) and Poona (18° 31′ N.) during the periods November 1945 to March 1947 and February-March 1948, and these have been used to determine the height distributions of atmospheric ozone at these places. After using Dobson's method A in an exploratory way, the more detailed method B was used to calculate the vertical distributions from the observed Umkehr curves. Agreement between the observed and calculated points was obtained by trial and error at various zenith angles of the sun in the range 50°–90° where the effect of large particle scattering is negligible.

Distributions of ozone are given for total ozone amounts varying from 0·155 cm. to 0·217 cm. at Delhi, the average heights of ozone for these being from 26·3 km. to 25·1 km. A decrease in the total ozone amount is found to cause a rise in the centre of gravity. At Poona, distributions for ozone amounts 0·164 cm. and 0·174 cm. give a more or less fixed height of 28·0 km. for the centre of gravity.

The paper concludes with a brief survey of the distribution of ozone in the earth's atmosphere both in the horizontal and the vertical and shows that it is easier to understand the regional, seasonal and day-to-day variations of ozone if we separately consider the contributions to total ozone content over any place from the photo-chemical action of sunlight and from transport in the horizontal and vertical directions of the accumulated ozone below the level of primary ozone formation.

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