HEIGHT DISTRIBUTION OF ATMOSPHERIC OZONE

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Received January 27, 1953

In extra-tropical latitudes, fluctuations in ozone amount occur from day to day.[1] These are most marked in late winter and early spring and least marked in late summer. In low latitudes, the inter-diurnal variability is generally small; in N. India, during the months December to April, when active western disturbances pass across the country, fluctuations of a similar character occur, but are less frequent and of smaller amplitude. This can be seen from Fig. 1 which shows the daily values of ozone over Mount Abu (Lat. 24° 26′ N., Long 72° 43′ E., 3,900 ft. above sea level) in the period November 1951 to June 1952.

DAILY OZONE AMOUNTS
Mount Abu — Nov. 1958 to June 1952

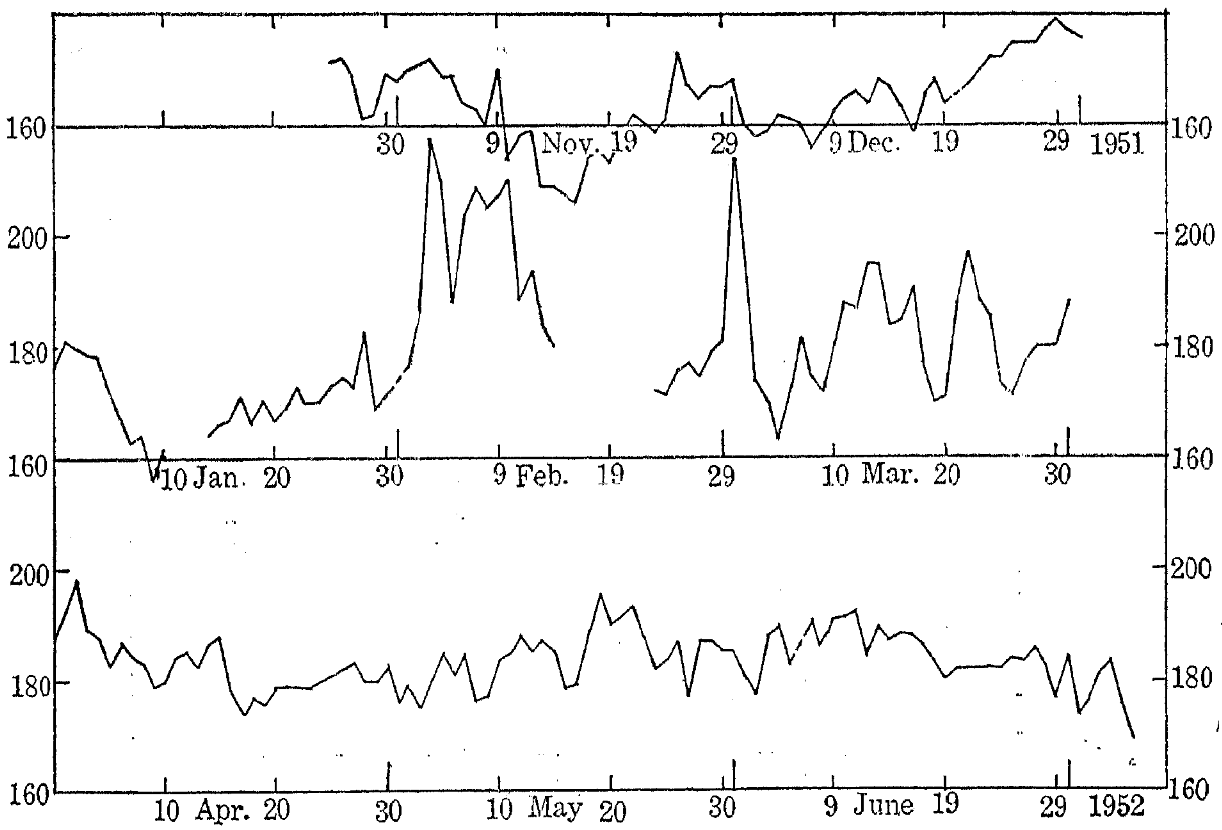

Fig. 1. Daily ozone amounts at Mount Abu 1951 to June 1952

The inter-diurnal variation of ozone at a station in Europe is known to be closely related to meteorological conditions, the closest correlation perhaps being between the ozone amount and the height of the tropopause, the ozone amount increasing with a lowering of the tropopause.[2, 3] In India, with the limited high-level upper air data available, it appears that even during winter, the correlation between the height of the tropopause and the pressure field at ground level is much less close than in temperate latitudes; so also is the association between ozone and surface pressure.[4] Still, it was felt that some insight would be obtained into the connection between ozone and weather if in the period of western disturbances, not only the changes

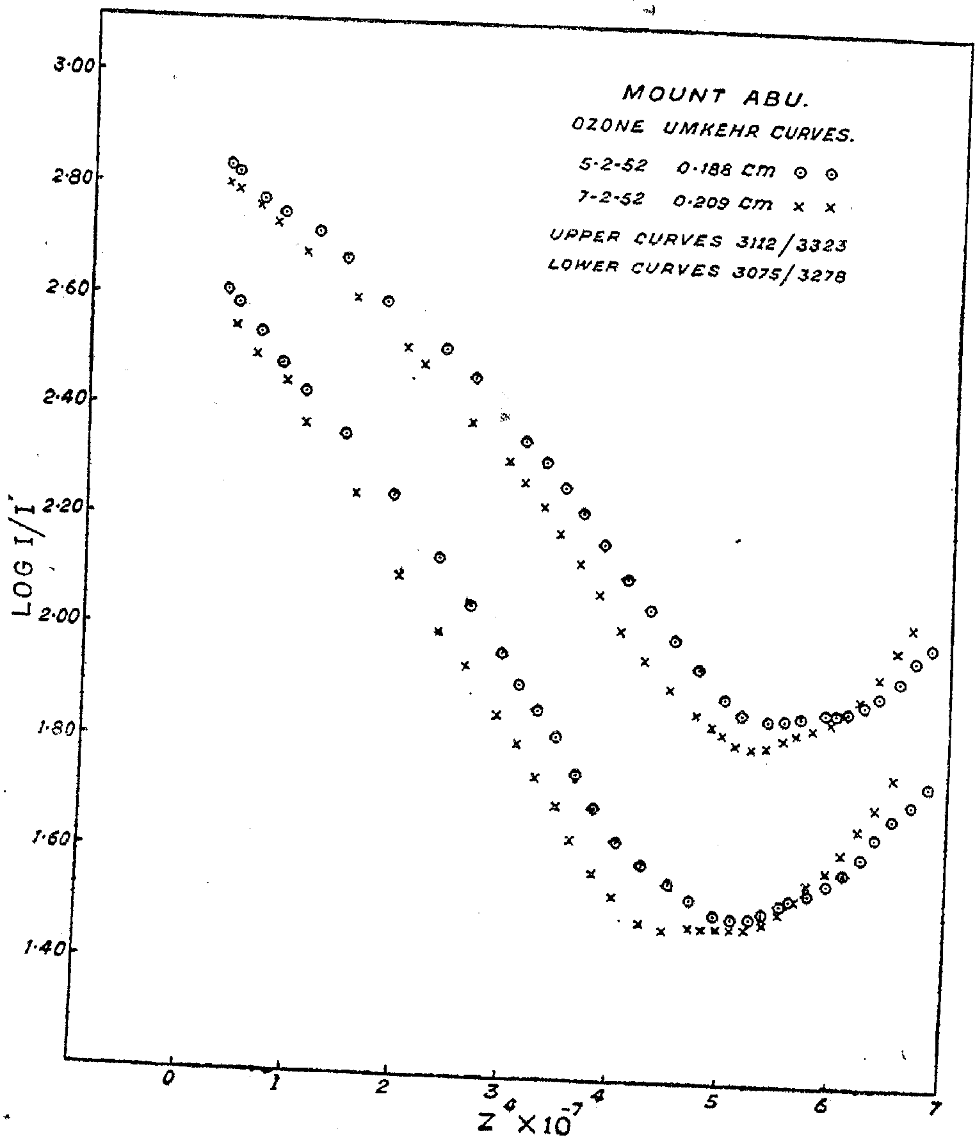

FIG. 2

TABLE I

Height Distribution of Ozone at Mount Abu

Date		Pressure at 1730 hrs. I.S.T. (mb.)	Ozone Amount 10^{-3} cm.	Amount in successive 9 km. layers in 10^{-3} cm./km. (1)	(2)	(3)	(4)	(5)	(6)
1951—Oct.	21 ..	901·9	153	0	1·0	6·9	7·5	1·3	0·3
	31 ..	901·3	164	0	1·0	8·4	7·2	1·3	0·3
Nov.	2 ..	903·4	173	0	1·0	8·1	8·2	1·6	0·3
	3 ..	903·2	172	0	1·0	8·0	8·2	1·6	0·3
	4 ..	904·2	169	0	1·0	7·8	8·0	1·6	0·4
	6 ..	..	164	0	1·0	7·3	8·0	1·6	0·3
	8 ..	903·9	160	0	1·0	7·3	7·6	1·6	0·3
	10 ..	904·2	154	0	1·0	6·7	7·6	1·5	0·3
	11 ..	902·1	158	0	1·0	7·2	7·6	1·5	0·3
	13 ..	902·8	149	0	1·0	6·4	7·6	1·4	0·2
	19 ..	902·2	154	0	1·0	6·7	7·6	1·4	0·4
	21 ..	901·7	173	0	2·0	8·0	7·2	1·7	0·3
Dec.	16 ..	903·0	159	0	1·0	7·5	7·4	1·4	0·4
	23 ..	905·5	172	0	1·3	8·5	7·2	1·6	0·5
	25 ..	904·8	175	0	1·0	8·3	8·0	1·6	0·5
	31 ..	899·5	176	0	1·0	8·4	8·1	1·6	0·6
1952—Jan.	4 ..	902·6	177	0	1·6	8·4	7·6	1·6	0·5
	9 ..	900·7	156	0	1·0	8·0	6·5	1·4	0·4
Feb.	5 ..	901·8	188	0	2·0	11·0	5·9	1·6	0·4
	7 ..	901·3	209	1·0	1·5	12·3	7·1	1·2	0·1
Mar.	14 ..	898·6	195	0	1·0	12·2	6·4	1·6	0·5
	18 ..	901·4	177	0	1·0	9·5	7·3	1·4	0·5
	19 ..	900·4	170	0	1·0	9·1	7·0	1·5	0·3
	22 ..	898·0	198	0	1·0	12·5	6·5	1·5	0·5
	25 ..	900·8	173	0	1·0	9·1	7·2	1·5	0·4
	28 ..	900·2	180	0	1·0	9·9	7·2	1·5	0·4
Apr.	2 ..	900·7	198	0	1·0	12·6	6·5	1·4	0·5
	7 ..	901·1	185	0	1·0	10·3	7·2	1·5	0·5
	13 ..	902·3	183	0	1·0	10·3	7·2	1·5	0·2
Sept.	9 ..	896·3	162	0	1·0	7·8	7·4	1·4	0·2
Oct.	10 ..	898·2	164	0	1·0	8·0	7·5	1·5	0·3
Nov.	11 ..	901·4	158	0	1·0	7·7	7·2	1·4	0·3

Weather Remarks :—

Nov. 13–17—Arabian Sea storm appeared near 12° N., 65° E. on 13th, moved north and disappeared off Kathiawar on 17th.

Feb. 5—Following W. disturbance which was active in Punjab, U.P.

Feb. 7—Disturbance from south affecting Madhya Pradesh.

Mar. 14—W. disturbance centred between Bikaner and Gwalior,

Mar. 22—W. disturbance located N.-E. of Abu.

Apr. 2—W. disturbance over N. Rajasthan, U.P, of ozone amount but also the changes in vertical distribution could be studied. This is a difficult problem, because, close to a centre of low pressure, clouding prevents the collection of a connected series of clear zenith sky observations which are necessary for determining the height distribution of ozone. Mount Abu is however well situated for attempting such observations, and it has been possible to collect umkehr observations of the zenith sky on 112 days during the period October 1951 to November 1952. Some of the observations were on consecutive days. The present paper contains a summary of the results so far analysed, followed by a discussion of the variations in the height distribution of ozone corresponding to different ozone amounts, first over Mount Abu, and then over other places on earth for which data are available. The consideration of the Indian data in relation to weather will be taken up on a later occasion.

2. The zenith sky intensity observations were taken on two pairs of wavelengths, the usual pair $\lambda\, 3112/\lambda\, 3323$ and another pair $\lambda\, 3075/\lambda\, 3278$.* The method of calculating the height distribution is the same as that explained in a previous paper.[5] It was found that practically identical results were obtained from observations on either pair of wavelengths made on the same day (Sample umkehr curves on the two pairs of wavelengths are given in Fig. 2 (5–2–1952 and 7–2–1952).

3. Table I gives the height distribution of ozone on 34 days in the period October 1951 to November 1952 for which the data have been calculated. Of these, 29 days fall in the months November to April. The ozone amounts and the evening pressures at Mount Abu at 1730 hours I.S.T. have also been given.

The following points are noteworthy.

(1) Most of the changes in ozone take place in the layer 18 to 27 km., the amount in that layer increasing with increasing total amount. The largest increases have occurred shortly before, or shortly after, the passage of centres of western depressions across the longitude of Abu.

(2) There is no detectable ozone in the layer 0–9 km., and only a very small quantity in 9–18 km. The latter shows a slight increase when the ozone amount is high.

* The usual method of computing the height distribution of ozone from umkehr observations with the assumption that the vertically scattered skylight is entirely made up of primarily scattered light is open to objection and probably leads to too low a value of ozone in the first, second and third layers. This question is under investigation (*Q. J. Roy. Met. Soc.*, 1952, 78, 625). It is however believed that the general nature of the discussion followed in this paper will not be invalidated.—K. R. R.

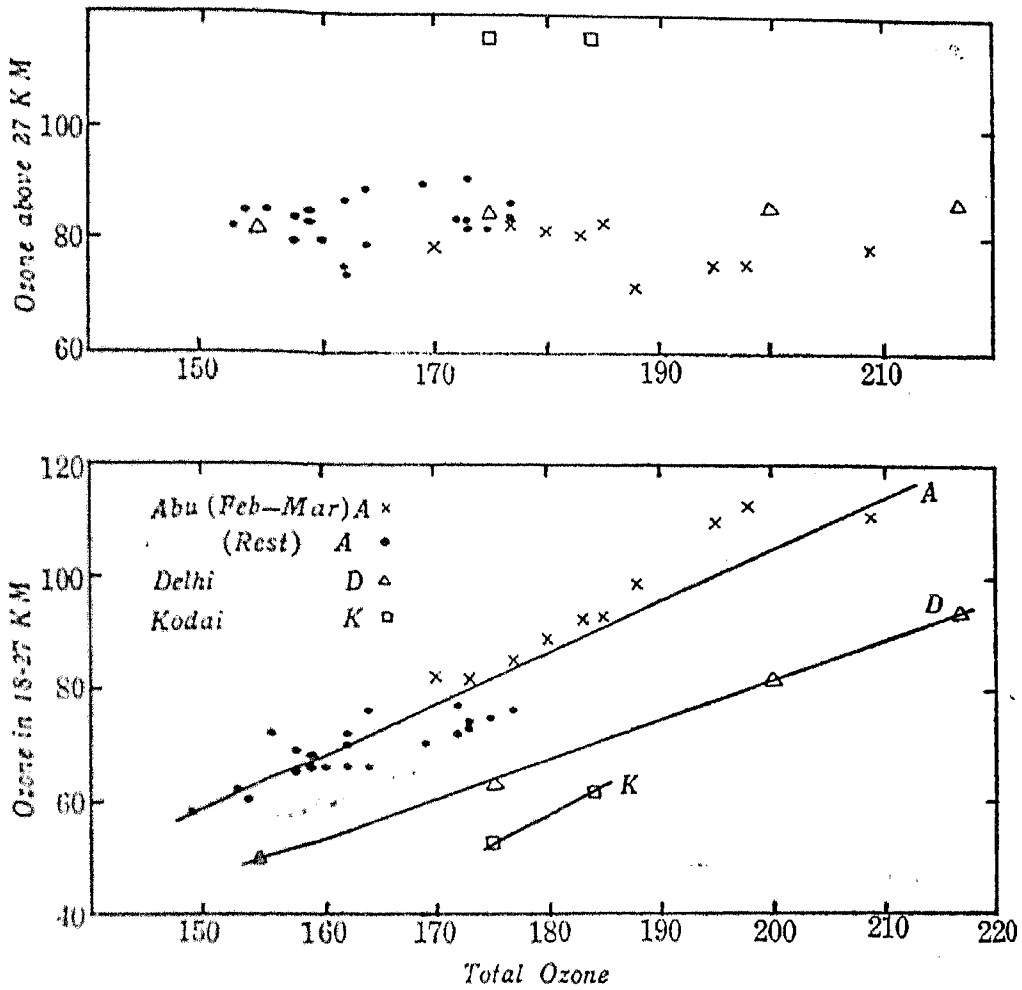

FIG. 3. Ozone amount in 18–27 km. and above 27 km. for different total amounts at Mount Abu.

(3) When the ozone amount is abnormally high as on 5–2–1952 and 7–2–1952, there is a tendency for the amount above 27 km. to be slightly smaller than usual.

Fig. 3 is a dot diagram showing the ozone amounts in 18–27 km. and above 27 km. plotted against the total ozone amount on individual days. The mean data relating to Delhi and Kodaikanal are also plotted in the same figure. The high correlation of the amount in 18–27 km. with the total amount is obvious. This suggests that air-movement and convergence associated with low pressure centres of western depressions sometimes extend well into the stratosphere.

In Table II, the data have been grouped according to the total ozone amount, and the corresponding mean distributions are given.

TABLE II

Mean Height Distributions for Different Ozone Amounts (Grouped Means) at Abu, Delhi, Poona and Kodaikanal

Station	Ozone Amount 10^{-3} cm.	(Height distribution 10^{-3} cm.) 0–9	9–18	18–27	27–36	36–54 km.
Abu ..	153 (4)	0	9	60	68	15
	159 (11)	0	9	68	68	15
	172 (8)	0	11	76	70	18
	180 (6)	0	10	86	60	19
	195 (4)	0	11	106	57	18
	209 (1)	9	14	111	64	12
Delhi ..	155 (1)	9	15	49	69	13
	175 (3)	9	18	63	72	13
	200 (1)	9	23	91	73	13
	217 (1)	9	27	94	62	15
Poona ..	169 (8)	1	13	65	65	25
Kodaikanal ..	175 (4)	0	6	53	99	17

It may be remarked that the ozone distributions in September, October and November do not show any appreciable difference from those in the months December to April, when they relate to the same ozone amount.

4. Comparing the ozone distributions over Mount Abu with those over Delhi and Kodaikanal (Table III), the main features are similar. A small amount of ozone seems to get down to the lowest layer 0–9 km. at Delhi during winter. While the amount above 27 km. is practically the same as at Delhi and Abu, it is nearly independent of the total amount. Over Kodaikanal in South India for which umkehr curves are available for only 5 days in March,[6] a larger amount of ozone is situated between 27 and 36 km. The abnormally high figure for the ozone amount above 36 km. for Poona is not understood.

5. The highest ozone amount for which we have height distribution data in India is 0·217 cm. It is interesting to extend the range by considering the data of Arosa and Tromsø and see how they compare. For this purpose, it is convenient to estimate the amounts of ozone over these places for the same height intervals 0–9 km., 9–18 km., etc. This has been done from the data given in the following two papers.

(i) Ozone height distribution data for Arosa. By Götz, Meethan and Dobson[7] (Method B).

(ii) The same for Tromsø. By Tønsberg and Olsen[8] (Method A).

Knowing the uncertainties associated with the determination of the height distribution of ozone from the zenith sky measurements, not much accuracy can be attached to the figures but they are good enough for a

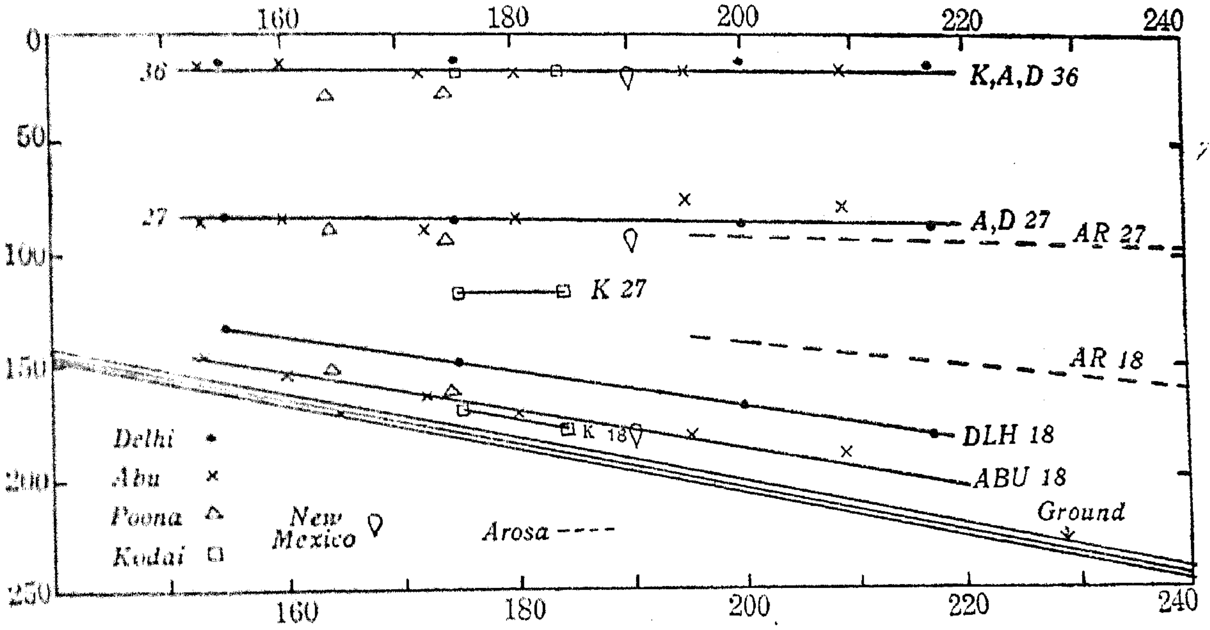

FIG. 4*a*. Height Distribution of ozone for different ozone amounts at Indian Stations

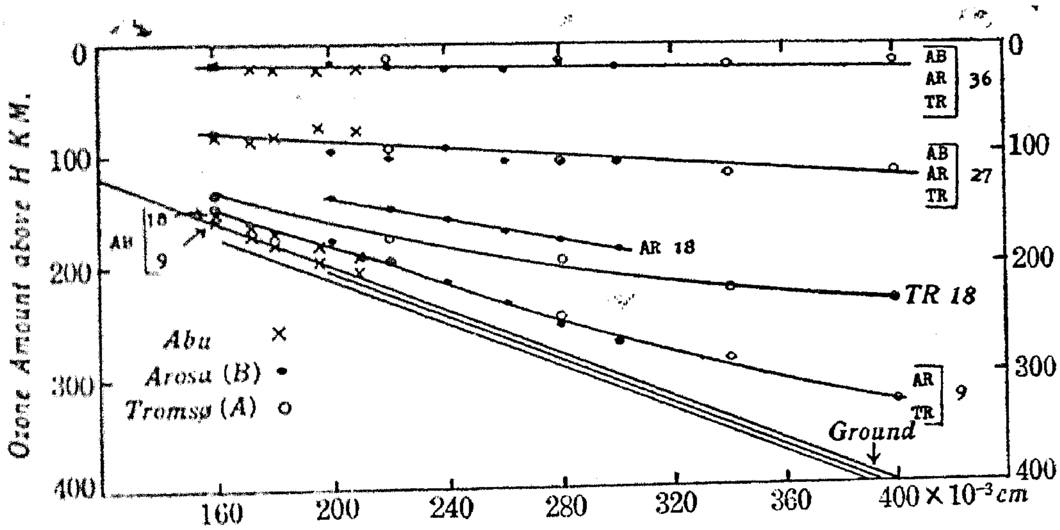

FIG. 4*b*. Height Distribution of ozone for different ozone amounts, from Abu (24°·4 N.) to Troms (69°·7 N.)

* In Fig. 4 (*a*), the results obtained from a V_2 rocket ascent have been added (F. S. Johnson, *et al.*, *Jour. Geophys. Res.*, 1952, **57**, 154).

general survey and at any rate, nothing better is available. The data have been plotted in two composite diagrams [Figs. 4 (*a*)* and 4 (*b*)] with total ozone amounts as abscissæ and the amounts above the levels 36 km., 27 km., 18 km. and 9 km. as ordinates. These diagrams enable us to make a few general statements:—

(1) The ozone amount above 30 km. or thereabouts remains nearly the same irrespective of the total amount of ozone.[9]

(2) In low latitudes, more than half the ozone is concentrated between 18 and 27 km. This amount increases with increasing ozone amount, and the increase continues for the still larger amounts that occur over Arosa and Tromsø, tending to become constant for the highest value of ozone.

There are substantially larger amounts of ozone over N. India in winter between 18 and 27 km. than over Arosa between the same levels for the same ozone amount. This may be partly due to the fact that low ozone values over Arosa refer to summer conditions and the data are therefore not strictly comparable. Fig. 4 (*b*) also suggests that as we go from north Indian latitudes to the latitude of Arosa, part of the ozone in the layer 18–27 km. descends to lower levels and is distributed in a greater thickness of the atmosphere.

(3) Below 18 km., the ozone is present only in small quantities in low latitudes and probably has a maximum in the cold season. It increases with latitude from Kodaikanal (10° N.) to Delhi (28½° N.).

(4) In middle and high latitudes, there are substantial amounts of ozone below 18 km., and the larger the total amount, the larger is the proportion in the lowest levels below 9 km. For the largest ozone amounts, that occur in high latitudes (0·350 cm.), nearly half the quantity may be below 20 km.

DISCUSSION

6. One of the most remarkable features of the distribution of ozone which came out from the world survey organised by Dobson was the general increase of ozone from the Equator towards high latitudes and its strong annual variation in middle and high latitudes with maximum in spring and minimum in autumn. Ozone is a product of the photo-chemical action of ultra-violet solar radiation on the oxygen of the upper atmosphere, and if the atmosphere were stagnant, the rate of formation of ozone by light of wavelengths shorter than 2420 A° would balance the rate of its destruction by light of wavelengths < 11400 A° and an equilibrium amount with an appropriate vertical distribution would be established depending on the latitude and the season. The height of maximum ozone amount will rise

with increasing zenith distances of the sun. Such a photo-chemical theory first suggested by Chapman and worked out in greater detail by Wulf and Deming and others, explains generally the observed vertical distribution in the tropics, but does not explain either the actual ozone amounts or the dependence on latitude and season.

K. Langlo in his recent memoir[9] "On the Amount of Atmospheric Ozone and its Relation to Meteorological Conditions" has given a comprehensive survey of the variations of ozone in the atmosphere. We can supplement it by the following remarks:

(1) Fig. 4 (*b*) shows that approximately 0·100 cm. of ozone is contained in the atmosphere above 27 km. in all places where there is sunshine. Within the Arctic Circle during the polar night, this amount seems to disappear. Langlo has compared the five-day mean ozone values at Dombas (62° N.) and Tromsø (70° N.) in the period December 1945 to January 1946. Tromsø values are lower by about this amount, providing evidence for the view that the ozone above 27 km. or thereabouts is in photo-chemical equilibrium with sunshine and if the sunshine is removed for a few days, the ozone above this height disappears. It is interesting to note that if this view is accepted, the annual ozone variations at Tromsø will fall into line with those at Oslo and Arosa and not show any anomaly. The ozone observations now being taken at Spitzbergen under International auspices will show whether this view is correct or not.

(2) *Most* of the ozone which is situated below 27 km. is accumulated ozone and is in the stratosphere. Where the tropopause is permanently high as in the tropics (16–17 km.), the amount is permanently low. The high negative correlation between the height of the tropopause and the ozone amount in temperate and polar latitudes, which seems to apply even to the region of tropopause funnels elucidated by Palmen,[10] shows that in general the lower the tropopause and the greater the accommodation available in the stratosphere, the larger is the ozone amount. The stratosphere below 27 km. seems to be a safe place for ozone. The extreme dryness of the stratosphere may have something to do with this.[11]

(3) The almost complete absence of ozone in the tropical troposphere is a fact of great significance. It would appear that water vapour and other material, oxidisable or catalytic, which are carried up into the upper atmosphere from the lower layers by convective currents are responsible for destroying the ozone in the upper layers of the tropical troposphere. The destructive action may be aided by light filtered through ozone. This view is supported by the rapid disappearance of the occasional incursions of

ozone to the sub-tropical troposphere and the steady decline in ozone amount in late spring and summer in the atmospheres of middle and high latitudes.

(4) Over " cold sinks ", on earth such as the polar regions and large continental areas in winter where the tropopause is already low, some of the stratospheric air can sink into the troposphere and ride over inversions, retaining its ozone content for fairly long periods. Ehmert's observations made on aircraft bring this out clearly.[12] The ozone will quickly disappear when it gets into regions of convective activity.

(5) Langlo has noted that on the mean of the year, the ozone amount is nearly constant from Tromsø to Arosa with a mean value of about 0·235 cm. and that it drops steeply to 0·190 cm. at 25° N. This rapid change runs parallel to the change in the average height of the tropopause. It is only in the season of western disturbances in N. India when composite tropopauses are frequent that marked day-to-day fluctuations in ozone occur.

(6) The average tropopause has a height varying from 17 km. to 9 km. with a rather steep drop or break between 16 and 12 km. and yet other breaks near polar fronts. Although the air between 9 and 16 km. is highly stratified, it is subject to large-scale movements, both vertical and horizontal, particularly between 20° N. and 60° N. associated with extra-tropical weather.

A mechanism is thus available for a large-scale but slow stirring up of the air between 8 and 25 km. bringing down the ozone from higher levels and destroying it in the lower levels by mixing it with water-vapour and dust (perhaps also methane) contained in the tropospheric air of lower latitudes.

The problem of atmospheric ozone and its variations thus becomes a problem of the large-scale turbulence and circulation of the upper troposphere and lower stratosphere.

SUMMARY

The paper contains a summary of the results of the height distribution of ozone in the atmosphere obtained at Mount. Abu with a Dobson Spectrophotometer during the period October 1951 to April 1952, when western disturbances affect North Indian weather. The observations show that there is very little ozone in the atmosphere below 18 km., that the ozone amount above 27 km. show very little systematic change with total amount, and that most of the changes take place in the layer 18 to 27 km. These results are compared with those obtained at Delhi, Kodaikanal, New Mexico (with V_2 rockets), Arosa (in Switzerland) and Tromsø (Norway). In middle and high latitudes, there are substantial amounts of ozone below 18 km.,

and the larger the total amount, the larger is the proportion in the lower levels. For high ozone amounts in high latitudes, nearly half the total amount may be below 20 km.

These results are discussed in relation to the variations of ozone with latitude and season, connecting them with the photo-chemical formation of ozone in the atmosphere above 27 km., the existence of a shelter-region for ozone between 27 km. and the tropopause and the destruction of ozone by mixing it with water-vapour and oxidisable matter carried up in the troposphere by convective activity.

It is concluded that the problem of variations of atmospheric ozone is one of large-scale turbulence and circulation in the upper troposphere and lower stratosphere.

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Yours truly
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28.2.1953