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Mean meridional distributions of ozone in different seasons calculated from *umkehr* observations and probable vertical transport mechanisms*

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(Manuscript received 21 September 1959; in revised form 22 December 1959)

SUMMARY

The paper contains a study of the mean meridional distributions of ozone in different seasons. The vertical distributions of ozone at a number of stations at different latitudes in the Northern Hemisphere were worked out from the intensities of light scattered from the zenith sky on individual clear days using method B, i.e., the method of curve fitting, with suitable correction for secondary scattering. Diagrams of vertical distribution corresponding (1) to high ozone amounts (frequent in winter and spring) and (2) to low ozone amounts (frequent in summer and autumn) are shown. Mean distribution diagrams are also given for the months of March, July and November. An important feature of the distribution is the strong increase in ozone amount in March below 18 km when the latitude increases beyond 30°. The results are discussed in relation to the idea of a poleward flow of air from the lower stratosphere and the neighbourhood of the equatorial tropopause, as suggested by Dobson and Brewer from frost-point measurements over the United Kingdom. The existence of a stratospheric warm air pool over the middle latitude in winter and spring as revealed by sounding-balloon ascents is confirmatory evidence of this. The influence of the pool of cold air which exists in winter above 20 km in the stratosphere of the dark polar night is also considered. It is suggested that in winter and spring there is an ozone-regenerating cycle due to meridional circulation in the stratosphere of tropical and middle latitudes, which carries air from the lower equatorial stratosphere to lower levels in the stratosphere of middle latitudes and puts back some of this accumulated air to higher levels in the equatorial stratosphere above 25 km. The more vigorous this circulation, the greater will be the rate of ozone storage in the lower stratosphere of extra-tropical latitudes.

1. INTRODUCTION

In a paper by Kulkarni, Angreji and Ramanathan (1959) on measurements of atmospheric ozone in Kashmir, the data of vertical distributions calculated from observations on the *umkehr* effect, dividing the atmosphere into 6 km layers and allowing for secondary scattering, have been given. In this paper, the study is extended to higher latitudes, using *umkehr* data of individual days with varying amounts of ozone, from Tateno in Japan, from Arosa and Tromsö in Europe, and Alaska in North America. The data of all these stations together with those of Indian stations are integrated to give pictures of the mean vertical meridional distributions of ozone in March, July and November. March and November are the months when the total ozone amount is maximum and minimum respectively in the Northern Hemisphere. In the light of these distributions, a stratospheric circulation which can lead to the annual regeneration of ozone in the stratosphere and its destruction in the troposphere is suggested.

NOTE : All ozone amounts in this paper are expressed in terms of Nye and Choong's values of ozone absorption coefficients. To express them in terms of Vigroux's coefficients of absorption, they should by multiplied by 1·33.

2. VERTICAL OZONE DISTRIBUTION DATA FROM INDIAN STATIONS

Vertical distributions of ozone by the *umkehr* method are available from observations over Kodaikanal, Poona, Abu and Delhi (Karandikar 1952; Ramanathan and Kulkarni 1953; Degaonkar 1955). In particular, a large number of observations have been made over Abu, many of them on a series of consecutive days. The analysis of these observations has shown that as the ozone amount increases, most of the increase takes place in the 18-27 km layer, a conclusion arrived at many years ago by Karandikar and Ramanathan (1949).

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* Presented at the International Ozone Symposium held at Oxford in July 1959.

In his address on atmospheric ozone at the Rome Assembly of the International Association of Meteorology (1956), Ramanathan drew attention to the sharp increase in atmospheric ozone at about 30°N as one moved poleward from tropical to middle latitudes and suggested that the increase might be connected with the tropopause break associated with the sub-tropical jet stream.

The starting of an ozone station in Kashmir at about 34°N in 1955, gave an opportunity for the study of the vertical distributions associated with changes of ozone in that region. Vertical distributions have been calculated from *umkehr* observations at Gulmarg or Srinagar on days with ozone amounts varying from 0·160 cm to 0·230 cm, dividing the atmosphere into 6 km layers and allowing for secondary scattering as described by Ramanathan and Dave (1957). The following table shows the percentages of ozone amounts in successive 6 km layers for typical small and large ozone amounts.

TABLE 1. PERCENTAGES OF OZONE AMOUNTS IN SUCCESSIVE 6 KM LAYERS OVER KASHMIR FOR TYPICAL SMALL AND LARGE OZONE AMOUNTS

		0-6	6-12	12-18	18-24	24-30	30-36	above 36 km
Small amount O_3	0·160 cm	4	4	13	14	35	20	9 per cent
Large amount O_3	0·230 cm	5	**12**	11	**22**	34	**10**	7 per cent

The Kashmir distributions show :

(1). Above 36 km, there is no significant change in ozone content.

(2). With increase in total ozone amount, there is in general an increase in ozone in the 6-12 and 18-24 km layers and a decrease in the 30-36 km layer. When the ozone amount exceeds 0·190 cm, the increase in ozone content in the 6-12 km layer becomes very pronounced. The amount in the 6-12 km layer is sometimes even larger than in 12-18 km.

The occasional appearance of more ozone in the 6-12 km layer than in the 12-18 km layer over Srinagar is significant. Srinagar being situated in a region where the occurrence of double tropopause is frequent in winter and spring, it may be expected that occasionally the cold air adjacent to the equatorial tropopause will spread out into the stratosphere of middle latitudes, and the ozone-rich air of the lower stratosphere of middle latitudes be drawn into the troposphere of the lower latitudes, roughly following the isentropes.

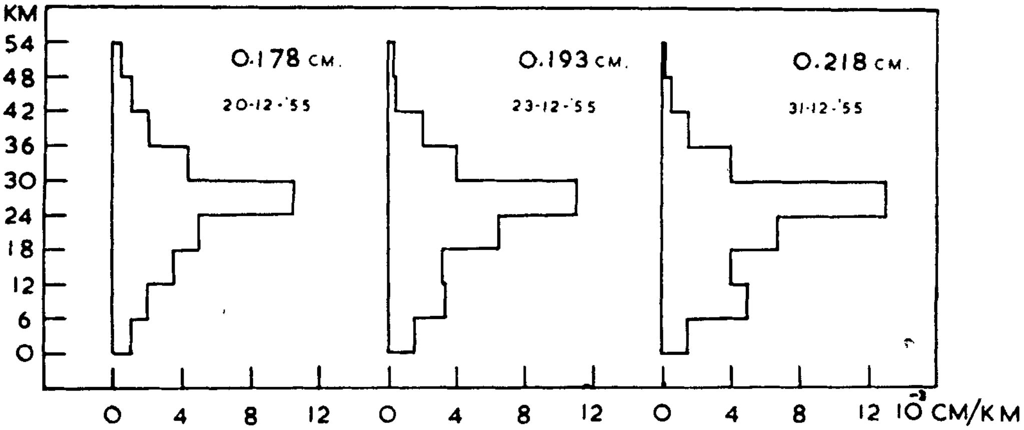

Figure 1. Srinagar – vertical distribution of ozone, using Nye and Choong's values of absorption coefficients of O_3.

3. Vertical distributions of ozone over Tateno (35°·7 N, 139°·7 E)

Owing to the kindness of the Japan Meteorological Agency (1958/9) we have been receiving their upper-air and ozone data, and have calculated from their *umkehr* observations the vertical distributions over Tateno on a number of days in 1958. The latitude of Tateno near Tokyo is only 2° higher than that of Srinagar, yet the ozone amounts over Tateno vary over a much larger range of values, from about 0·180 cm to over 0·360 cm. When the ozone amounts exceed those usually found in India, we have used the following corrections ΔN to the values of N to allow for multiple scattering.

TABLE 2. Correction for multiple scattering to observed values of N on C wavelengths

	Zenith angle of sun							
Total ozone amount	60°	70°	75°	80°	84°	86·5°	88°	90°
0·230 cm	0	1·0	2·0	4·0	6·0	6·0	6·0	6·0
0·230-0·310 cm	0	3·0	4·5	6·0	6·0	6·0	6·0	6·0
0·310 cm	0	3·5	5·0	7·0	6·5	6·0	6·0	6·0

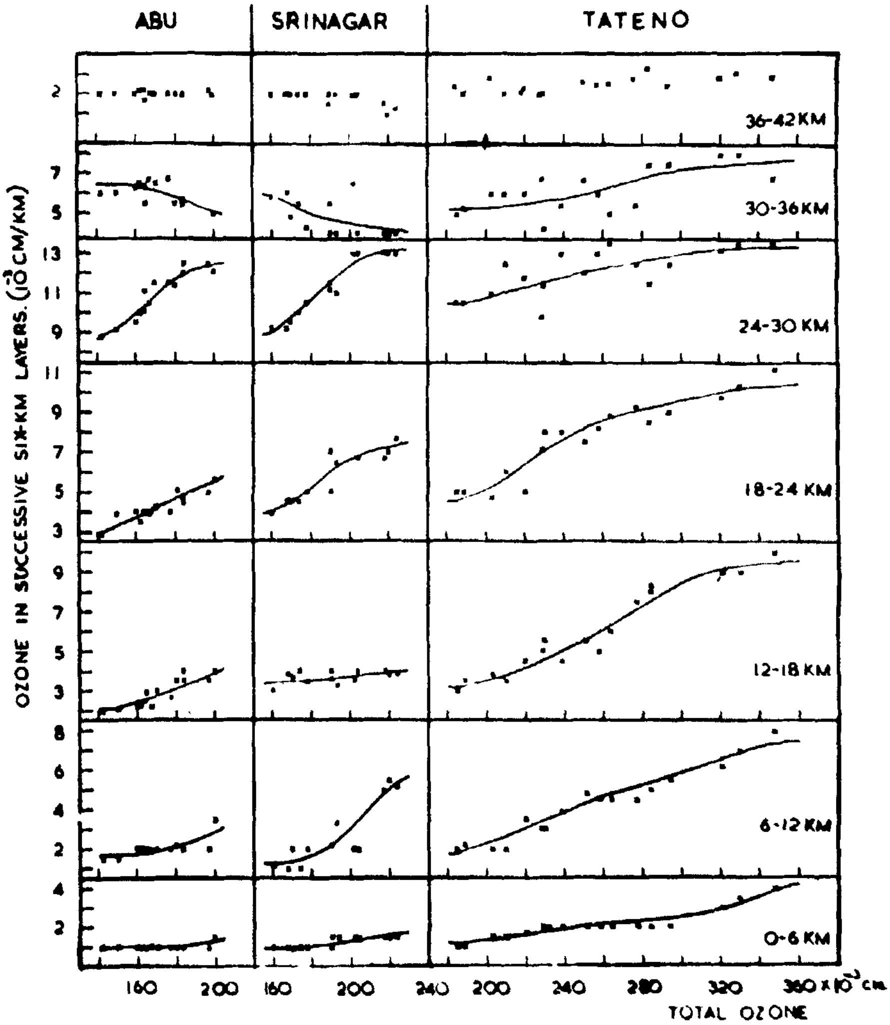

Figure 2. Vertical distribution of ozone for different ozone amounts at Abu, Srinagar and Tateno (with Choong's α).

The corrections were estimated from Dr. Walton's calculations (1953) of secondary scattering and empirical values based on *umkehr* observations on different wave-lengths made in India. Compared with the vertical distributions found over India, the distributions found over Tateno show the following features :

(1). In all layers up to 36 km, there is, in general, an increase of ozone with increasing ozone amount. This may be compared with observations over Srinagar where, with increase of ozone amount, there is a decrease of ozone in the 30-36 km layer and only a small change in 0-6 and 12-18 km layers. There is very little variation above 36 km.

(2). The ozone amount in 12-18 km increases rapidly when the total ozone increases from 0·220 cm to about 0·300 cm.

(3). When the total ozone exceeds 0·300 cm, the amounts at levels above 12 km tend to reach saturation, but the increase continues at lower levels.

(4). At Tateno in winter and spring, double and multiple tropopauses are frequent. On occasions when the ozone amount is high, the vertical distributions over Tateno correspond to those of higher latitudes with the same high ozone amount. Perhaps owing to its location to the south-east of the Siberian high-level low-pressure area in winter, the winter character of a higher latitude is sometimes imported to as low a latitude as 36°N.

A further study of the variations in the 30-36 km layer by analysing the observational data of other stations is desirable in order to elucidate the reason for the difference between Tateno and the Indian stations.

4. MERIDIONAL DISTRIBUTION OF OZONE IN SPRING AND AUTUMN

For the understanding of the transport mechanism of ozone, one would like to study the varying distributions of ozone from day to day. If synoptic distributions could be obtained, even over limited areas, from the I.G.Y. observations, they would be of great value. In anticipation of such analysis, it was felt desirable to compute vertical distributions from the available *umkehr* observations made at different places, but following an identical procedure for computation. Vertical distributions have thus been calculated from observations on individual days at the following places :

Kodaikanal (10°·2 N, 77°·5 E), Poona (18°·5 N, 73°·9 E), Mt. Abu (24°·6 N, 72°·7 E),
Delhi (28°·5 N, 77°·2 E), Srinagar (34°·1 N, 74°·9 E), Tateno (35°·7 N, 139°·7 E),
Arosa (46°·8 N, 9°·7 E), Tromsö (69°·7 N, 18°·9 E), Alaska (64°·8 N, 147°·9 W).

In computing the vertical distributions, the tables given in the *I.G.Y. Instruction Manual* have been used. When the ozone amounts were higher than 0·230 cm, two different corrections for multiple scattering were used for ozone amounts 0·230 to 0·310 cm and for amounts greater than 0·310 cm respectively.

Dr. Dütsch in a paper on 'Vertical distributions from *umkehr* observations' (*Arch. Met. Geophys. und Biokl.*, **11**, p. 240, 1959) has given the distributions of ozone calculated by him on a large number of days from the Arosa *umkehr* data. Two of these days, 9 August 1956 and 13 February 1956, are common to our Tables. Dr. Dütsch's results differ from ours on 13 February 1956 with significantly larger ozone amounts in the layers 6-24 km. The difference is less marked on 9 August 1956. The differences arise from two causes :

(1) Dr. Dütsch has not used the observed value of total ozone but has obtained it by integrating the amounts in different layers as calculated from the *umkehr* observations. There is a difference between the observed total ozone (0·278 cm) and the integrated total ozone (0·298 cm). We have, on the other hand, used in our calculations the observed total ozone with the *umkehr* curve.

(2) The corrections for multiple scattering used by Dr. Dütsch are smaller than the corrections used by us.

The differences between the results of our calculations and those of Dr. Dütsch do not affect the main conclusions of the present paper. A further examination of the effect of multiple scattering on the *umkehr* curve is in progress.

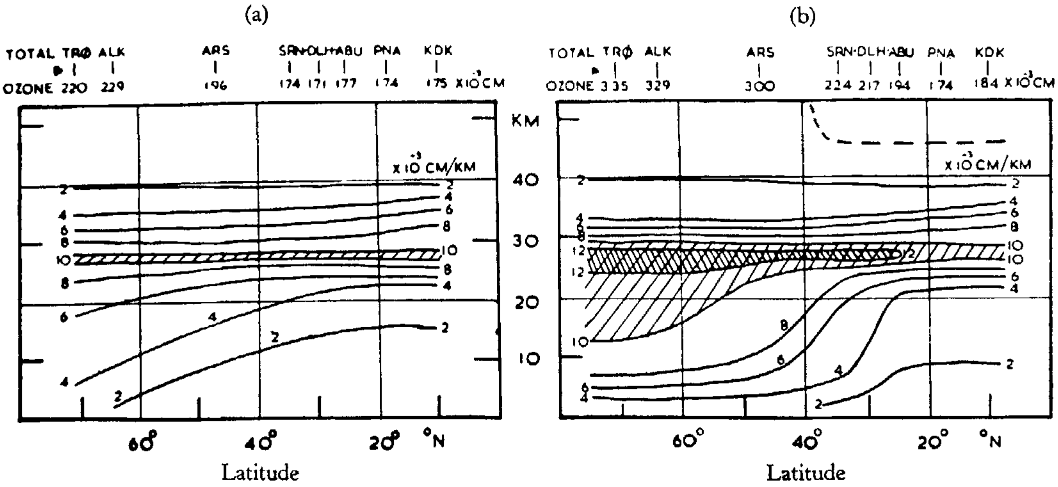

Figure 3. Vertical distribution of ozone (with Nye and Choong's α). (a) when ozone amounts are low, (b) when ozone amounts are high.

Although the same value for the total ozone amount does not mean that the vertical distribution is the same, it is found that there are certain general changes in the vertical distribution which go with changes in the total ozone. Taking into consideration the fact that in middle and high latitudes the ozone amount is generally high in January to April, and low in September to November, mean meridional distributions of ozone were prepared (a) when the ozone amounts are low and (b) when ozone amounts are high.

Figure 3 shows vertical distributions corresponding to winter-spring and late-summer and autumn and the following points are of interest.

(1) Throughout the year, there is more ozone in the lower layers in latitudes higher than 30°N than in lower latitudes.

(2) The increase of ozone in the lower levels with increase in latitude is gradual in summer, whereas in winter, the rise is steep at 30°N. This amplifies Ramanathan's picture (1956) of the latitudinal distribution of total ozone with its steep rise north of 30°N.

(3) There is a tendency for the ozone in the 30-36 km layer to decrease with latitude, and more rapidly when the ozone amounts are high. At 40 km, there is little change in ozone content with latitude or season. There is also a general tendency for the ozone amounts above 42 km in middle and high latitudes to be larger than in India. We are not sure whether this is real or due to the inaccuracy of the multiple scattering corrections for high values of ozone. These corrections for higher values of ozone amount require further examination.

Mean meridional distributions of ozone have also been calculated for each of the months March, July and November (Fig. 4), using the appropriate ozone amounts from the diagram of annual variation published by Normand (1956). Two steps of ozone variation with latitude are seen in the March diagram; presumably they correspond to the tropopause breaks associated with the sub-tropical and polar jet streams.

As the ozone amount increases from November to March, the increase takes place mainly at levels below 30 km. In March at 15 km, the ozone content changes from 4×10^{-3} cm km^{-1} at the Equator to 10×10^{-3} cm km^{-1} at 70°. At 27 km, the change from the Equator (10×10^{-3} cm km^{-1}) to 70° (12×10^{-3} cm km^{-1}) is small in all the three months. At 30-36 km in March, the ozone content decreases from the Equator (7×10^{-3} cm km^{-1}) to higher latitudes (4×10^{-3} cm km^{-1}). (See Table 3).

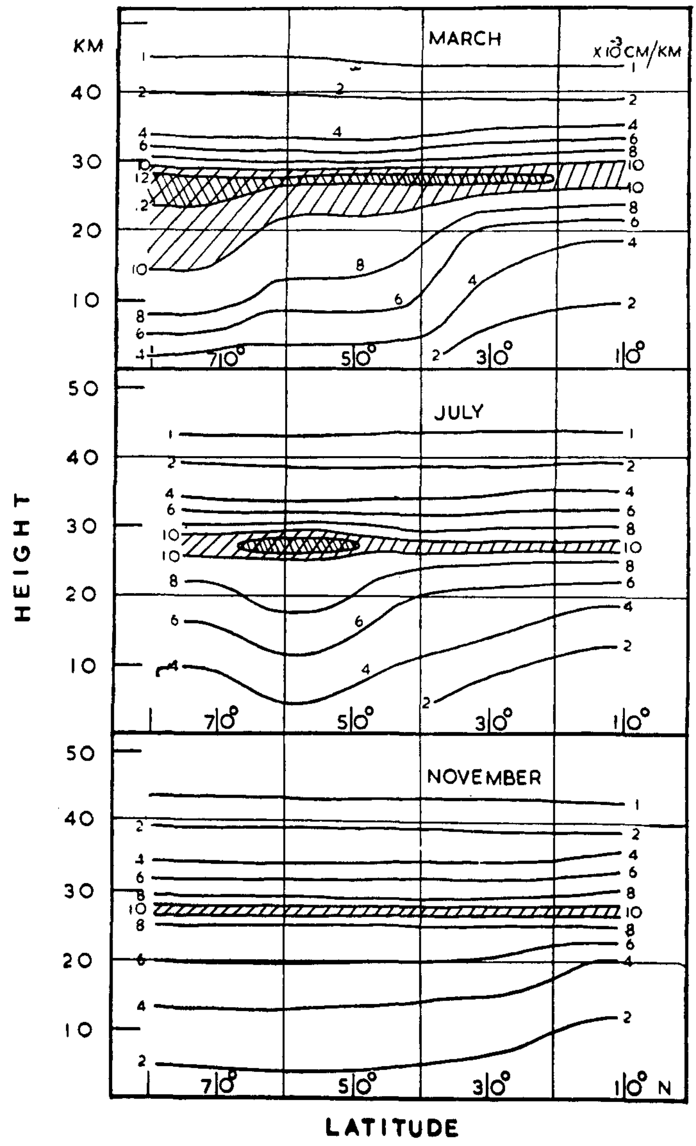

Figure 4. Mean vertical distribution of ozone in March, July and November (10^3 cm km^{-1} with Nye and Choong's α).

A mean meridional distribution is a greatly simplified picture. Not only does the distribution change from month to month; there is evidence that, in the same month, there are significant differences of distribution over different meridians. Still, even the simplified picture adds to our understanding.

5. Discussion

How is the large increase in ozone in the lower stratosphere from November to March brought about? The rate of production of ozone by photo-chemical processes is, according to Dütsch (1956), at maximum at about 25 km for vertical incidence of sunlight, and the ozone mixing ratio increases with height up to 30-35 km and decreases thereafter.

TABLE 3. Vertical distributions of atmospheric ozone

(Amounts calculated with Nye and Choons's values of α)

Date	Total ozone	Mean ozone amount (10^{-3} cm km^{-1})								
	(cm)	0-6	6-12	12-18	18-24	24-30	30-36	36-42	42-48	48-54
Kodaikanal (10°N)										
15 February 1958	0·167	1·0	1·5	2·0	3·0	9·9	7·5	2·0	0·5	0·4
10 March 1949	0·175	1·0	1·5	2·0	3·3	10·5	8·0	2·0	0·5	0·3
16 March 1949	0·184	1·0	2·0	2·0	4·0	11 2	7·7	2·0	0·5	0·3
18 April 1958	0·187	1·0	2·0	2·0	4·2	11·5	7·5	2·0	0·6	0·4
Poona (18½°N)										
15 March 1948	0·174	1·0	2·0	2 0	3·5	10·2	7·0	2·0	0·8	0·4
Mt. Abu (24½°N)										
27 November 1957	0·152	1·0	1·5	2·0	2·9	8·8	6·0	2·0	0·7	0·5
25 November 1953	0·160	1·0	1·5	2·1	3·9	9·2	6·0	2·0	0·5	0·4
23 November 1953	0·170	1·0	2·0	2·2	4·0	9·5	6·3	2·0	0·6	0·2
8 January 1958	0·172	1·0	2·0	2·2	3·5	10·0	6·5	2·2	0·8	0·4
21 March 1954	0·174	1·0	2·0	2·5	4·0	10·1	6·4	2·2	0·5	0·4
6 March 1955	0·175	1·0	2·0	2·9	4·0	11·1	5·5	1·7	0·5	0·4
3 July 1957	0·177	1·0	2·0	2·2	4·0	10·5	6·7	2·0	0·6	0·5
18 June 1957	0·180	1·0	2·0	3·0	4·2	11·5	6·5	2·0	0·6	0·6
26 January 1958	0·187	1·0	2·0	2·7	4·0	11·5	6·8	2·0	0·8	0·4
12 March 1958	0·190	1·0	2·2	3·5	5·1	11·4	5·5	2·1	0·5	0·4
26 February 1954	0·194	1·0	2·0	3·5	4·5	12·5	5·7	2·0	0·6	0·5
31 March 1955	0·194	1·0	2·0	4·0	4·7	12·0	5·5	2·0	0·6	0·5
1 April 1955	0·207	1·0	2·0	3·5	5·0	12·5	7·0	2·2	0·5	0·3
2 March 1955	0·210	1·5	3·5	4·0	5·6	12·1	5·0	2·0	0·7	0·5
New Delhi (28½°N)										
10 March 1955	0·170	1·0	2·0	2·9	5·0	9·0	5·7	1·8	0·5	0·4
18 March 1955	0·171	1·0	2·0	3·0	5·0	9·1	5·7	1·8	0·5	0·4
17 March 1955	0·190	1·5	2·0	3·7	5·1	10·6	5·5	2·0	0·8	0·5
4 March 1955	0·209	1·5	2·0	4·0	5·5	12·5	6·0	2·0	0·8	0·6
20 January 1947	0·217	1·5	3·0	4·5	5·5	13·0	6·0	2·0	0·5	0·2
Srinagar (S) or Gulmarg (G) (34°N)										
G. 23 October 1955	0·160	1·0	1·2	3·0	3·9	9·2	5·8	2·0	0·3	0·2
G. 20 October 1955	0·168	1·0	1·0	3·8	4·5	9·2	6·0	2·0	0·3	0·2
S. 11 December 1955	0·170	1·0	2·0	3·7	4·5	9·5	4·8	2·0	0·6	0·2
G. 25 October 1955	0·174	1·0	1·0	4·0	4·5	10·0	5·5	2·0	0·6	0·4
S. 20 December 1955	0·178	1·0	2·0	3·5	5·0	10·5	4·3	2·0	1·0	0·4
G. 29 October 1955	0·190	1·0	2·2	4·0	5·0	11·5	5·5	2·0	0·3	0·2
S. 23 December 1955	0·193	1·5	3·3	3·2	6·5	11·0	4·0	2·0	0·3	0·2
S. 7 February 1956	0·195	1·5	3·3	3·6	7·0	11·2	4·0	1·5	0·6	0·3
S. 5 August 1957	0·202	1·5	2·0	3·5	4·2	13·0	6·5	2·0	0·5	0·4
S. 26 December 1955	0·204	1·5	2·0	4·0	6·7	13·0	4·0	2·0	0·5	0·2
S. 31 December 1955	0·218	1·5	5·0	4·0	6·7	13·0	4·0	1·5	0·5	0·2
S. 5 February 1956	0·220	1·5	5·5	3·8	7·0	13·0	4·0	1·0	0·5	0·4
S. 16 February 1956	0·224	1·5	5·2	3·8	7·7	13·0	4·0	1·3	0·5	0·4
Tateno (36°N)										
4 November 1958	0·185	1·0	2·0	3·0	5·0	10·5	5·0	2·4	1·0	0·9
26 November 1958	0·189	1·0	2·0	3·5	5·0	10·5	5·0	2·0	1·1	0·9
29 October 1958	0·203	1·5	2·0	3·8	4·7	11·0	6·0	2·8	1·0	0·9
10 January 1958	0·210	1·5	2·0	3·5	6·0	12·5	6·0	2·0	0·8	0·6
8 October 1958	0·220	1·7	3·5	4·5	5·0	11·8	6·0	2·3	1·0	0·9
11 August 1958	0·229	2·0	3·0	5·0	7·2	9·8	6·8	2·0	1·4	1·0
19 November 1958	0·230	2·0	3·0	5·5	8·0	11·4	4·2	2·0	1·4	1·0
6 January 1958	0·239	2·0	3·9	4·5	8·0	13·0	5·4	2·1	1·0	0·8

TABLE 3 (continued)

Date	Total ozone (cm)	Mean ozone amount (10^{-3} cm km^{-1})								
		0-6	6-12	12-18	18-24	24-30	30-36	36-42	42-48	48-54
		TATENO (36°N)								
21 June 1958	0·251	2·0	4·8	5·5	6·5	12·0	6·7	2·6	1·0	0·9
19 March 1958	0·258	2·0	4·5	5·0	8·2	13·0	6·0	2·5	1·0	0·9
4 January 1958	0·264	2·0	4·5	6·0	8·8	13·5	5·0	2·5	1·0	0·8
18 January 1958	0·277	2·0	4·5	7·5	9·3	12·5	5·5	2·8	1·1	0·9
31 March 1958	0·284	2·0	5·0	8·0	8·5	11·5	7·5	3·3	0·8	0·7
31 January 1959	0·294	2·0	5·5	8·3	9·0	12·3	7·5	2·4	1·0	0·9
3 March 1958	0·321	3·0	6·2	9·0	9·8	13·2	7·0	2·8	0·8	0·6
4 March 1958	0·330	3·5	7·0	9·0	10·3	13·5	7·0	3·0	0·9	0·8
30 March 1958	0·348	4·0	8·0	10·0	11·2	13·5	6·8	2·8	0·8	0·7
		AROSA (47°N)								
9 August 1956	0·196	1·5	2·5	3·6	6·0	10·5	5·0	2·0	0·8	0·8
1933 (average)	0·240	2·0	4·0	5·5	8·0	13·2	4·0	2·0	0·8	0·6
14 February 1933	0·253	2·0	4·5	5·4	8·3	13·5	5·0	2·0	0·8	0·7
3 June 1933	0·263	2·0	4·5	5·5	8·8	13·5	5·5	2·5	1·0	0·9
13 February 1956	0·278	3·0	6·0	6·1	8·5	13·3	5·0	2·5	1·0	0·9
1933 (average)	0·300	3·5	7·0	9·0	9·0	12·0	5·5	2·3	1·0	0·9
		ALASKA (65°N)								
25 October 1953	0·229	2·0	4·5	4·7	7·2	11·5	4·5	2·0	1·0	0·8
24 March 1954	0·329	4·5	8·6	9·5	11·5	12·5	4·2	2·3	0·9	0·8
		TROMSÖ (69·5°N)								
25 March 1941	0·335	3·0	9·1	11·5	11·5	12·5	4·5	2·5	0·9	0·8

The mixing of air from different levels below 30 km will, in general, increase the ozone content in the lower levels and decrease it in the higher. In the lower levels of the stratosphere of middle and high latitudes, ozone can be effectively conserved for a period of many months as the air is cold, dry, and stably stratified and most of the ozone-destroying radiation from the sun has been filtered-out by the higher layers. Dobson, Brewer and Cwilong (1946) and Brewer (1949), from measurements of frost-points in the stratosphere over England, produced evidence for a large-scale flux of dry air into the stratosphere over the United Kingdom. It was suggested that this came from near the equatorial tropopause. The large amount of data collected by Murgatroyd, Goldsmith and Hollings (1955); Helliwell, Mackenzie and Kerley (1956) show that the dryness at 14-15 km is not occasional but general. The occurrence of a warm-air pool in the stratosphere over middle latitudes, its extreme dryness corresponding to equatorial tropopause temperatures, and accumulating ozone amount during winter, all support a poleward transport of subsiding air from near the equatorial tropopause. How is the circulation completed ? For the present, we can only make reasonable guesses at the character of the circulation. It will take many years before we shall have enough wind data in the stratosphere to calculate the magnitude of the meridional mass fluxes there.

Fig. 5 shows diagrams of distribution of temperature (T°C) and potential temperature (θ°K) over a sample meridian in the months of January, April, July and October. These have been put together from the work of Kochanski (1955) and Murgatroyd (1957). The January diagram shows a pool of warm air (— 50 to — 55°C) in the stratosphere lying between 45° and 65° and extending from the tropopause to a height of over 24 km. Considering its position and the trend of the lines of potential temperature, it appears likely that this warm pool is formed mainly by the subsidence of originally cold air from near the equatorial tropopause, and to a smaller extent from the upper cold pool in the Arctic stratosphere which is located at 25-30 km. There is much more volume of relatively cold air near the tropopause over equatorial regions.

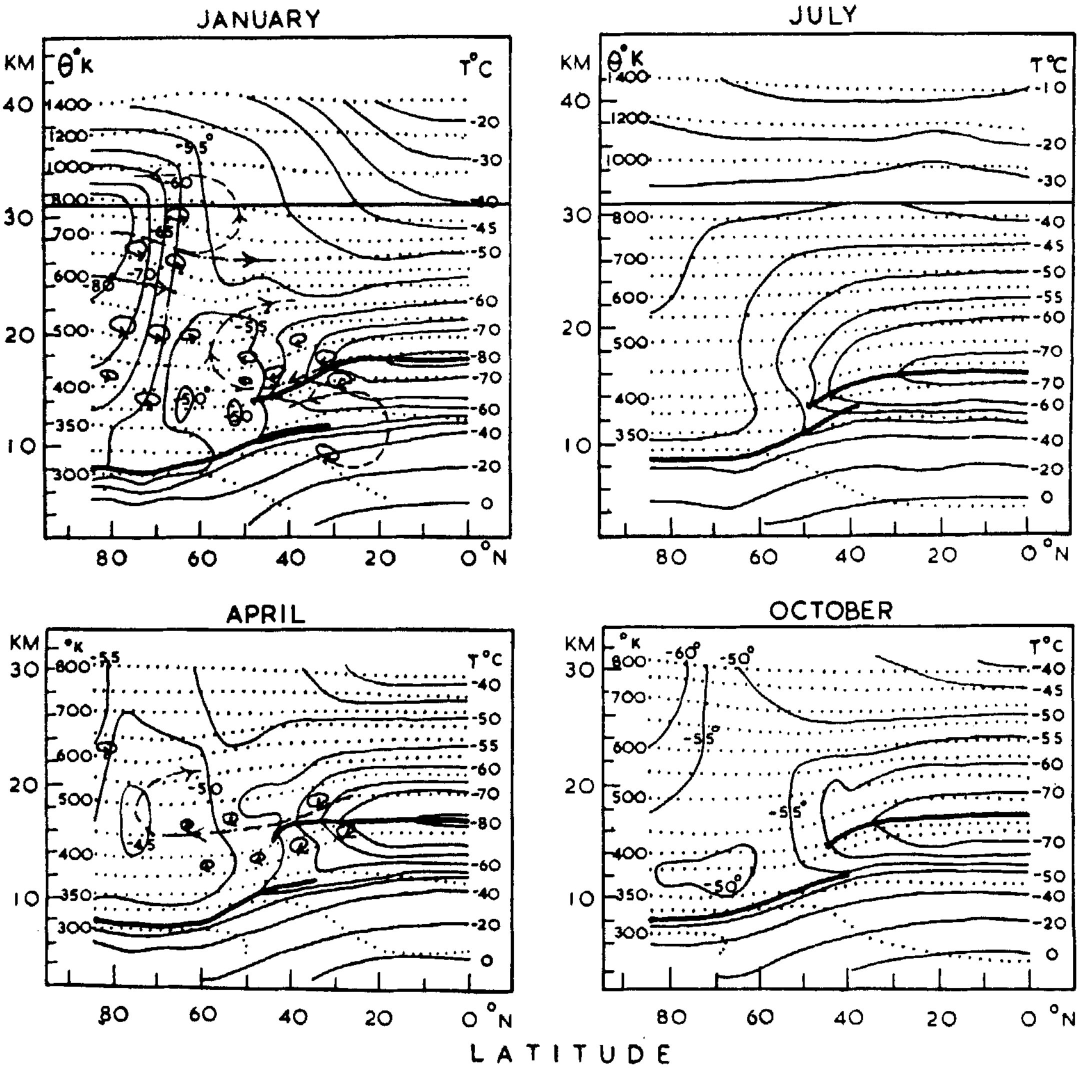

Figure 5. Meridional cross-sections of temperatures and potential temperatures θ°K (after Kochanski and and Murgatroyd).

The air collected in the mid-latitude stratosphere could be removed (a) by a return circulation at higher levels in the stratosphere towards the Equator; (b) by a similar circulation towards the pole, and (c) by entry into the troposphere at favourable places and times. Of these, the circulation involving the return of air towards the Equator may be expected to produce in its upper arm an increase in the ozone content, because it would be travelling towards a region where ozone-producing radiation is more abundant. During its subsidence and travel towards the Pole, the ozone will be conserved and stored in the lower stratosphere. Part of the stored ozone will periodically leak into the troposphere, particularly in the region of sub-tropical jets, and get lost by chemical decomposition or wash-out by rain. Whenever this circulation accelerates, there will be an increase of ozone in the lower stratosphere and whenever it weakens, the ozone will decrease or remain steady depending on its rate of leakage into the troposphere. It is unlikely that the exchange of air is purely meridional. It is more likely that the contemplated circulation is associated with zonal waves in the upper baroclinic region at levels below and above the equatorial tropopause between latitudes 20° and 40°. As is well known, the mid-latitude tropopause reaches its lowest level in March-April.

The formation of the upper cold pool in the stratosphere of the Arctic during winter is an important contributory cause for intensifying the warm pool in the stratosphere of middle latitudes and pushing it towards the Equator. The increased gradient of temperature between the tropics and middle latitudes at, and near, the level of the equatorial tropopause will strengthen the stratospheric circulation between the middle and equatorial latitudes, and increase the rate of storage of ozone in the stratospheric reservoir. The mixing associated with the upper cold pool over the Arctic at 50-25 mb can only lead to a small overall averaging of ozone. The distributions of temperature and potential temperature in the stratosphere in January, April and July make it clear that the ozone-regenerating circulation will be weaker in April than in January and weakest in July. It again begins to be active in October. It may thus be expected that the period January to April will be the period of maximum ozone storage in the Northern Hemisphere.

Entry of ozone from the stratosphere into the troposphere can take place by small-scale turbulence associated with wind shears. Perhaps this is the only mechanism by which ozone passes through the tropopause over the tropics. Large-scale entry can occur through (1) the sub-tropical tropopause breaks and the associated jet streams and (2) polar front breaks and jet streams. The sub-tropical breaks extend over a greater depth of the atmosphere and are longer and are therefore of greater significance for the seasonal variations of ozone. The strength and number of jet streams associated with the breaks vary with the season. Occasionally, and over certain areas such as Korea and Japan, the sub-tropical and polar jet streams approach each other in winter and spring, permitting the entry of large masses of stratospheric air into the troposphere and vice versa.

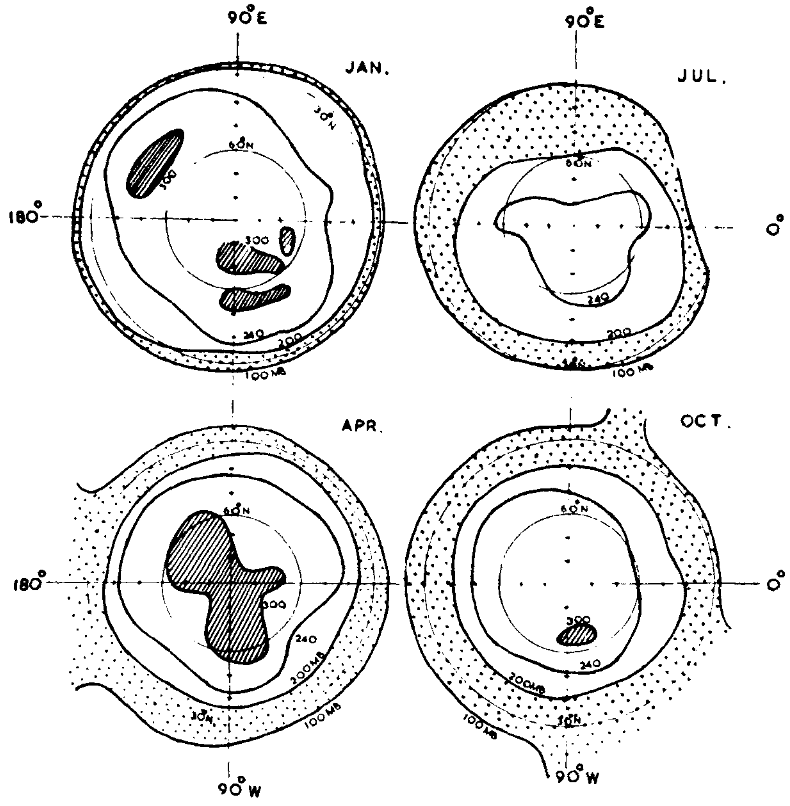

Figure 6. Average isopleths of tropopause pressure levels in January, April, July and October (100, 200, 240 and 300 mb); (after Goldie, Moore and Austin).

6. Conclusions

The following significant facts regarding ozone variations have been established. Over equatorial regions, the day-to-day variations are small, but there is a seasonal variation of ozone with maximum in June-August and minimum in December-January. In middle and high latitudes, the maximum occurs in March-April and the minimum in October-November. There is high correlation between ozone amount and tropopause pressure in winter and spring, and when increase of ozone takes place, it is mainly in the atmosphere below 18 km.

In view of these facts, it is relevant to link up the study of ozone problems with the study of the time and space variations of tropopause levels, of the discontinuities occurring in them and of the causes leading to such discontinuities.

Fig. 6 gives the isopleths of average tropopause pressure levels (100, 200, 240 and 300 mb) over the Northern Hemisphere in January, April, July and October according to Goldie, Moore and Austin (1958).

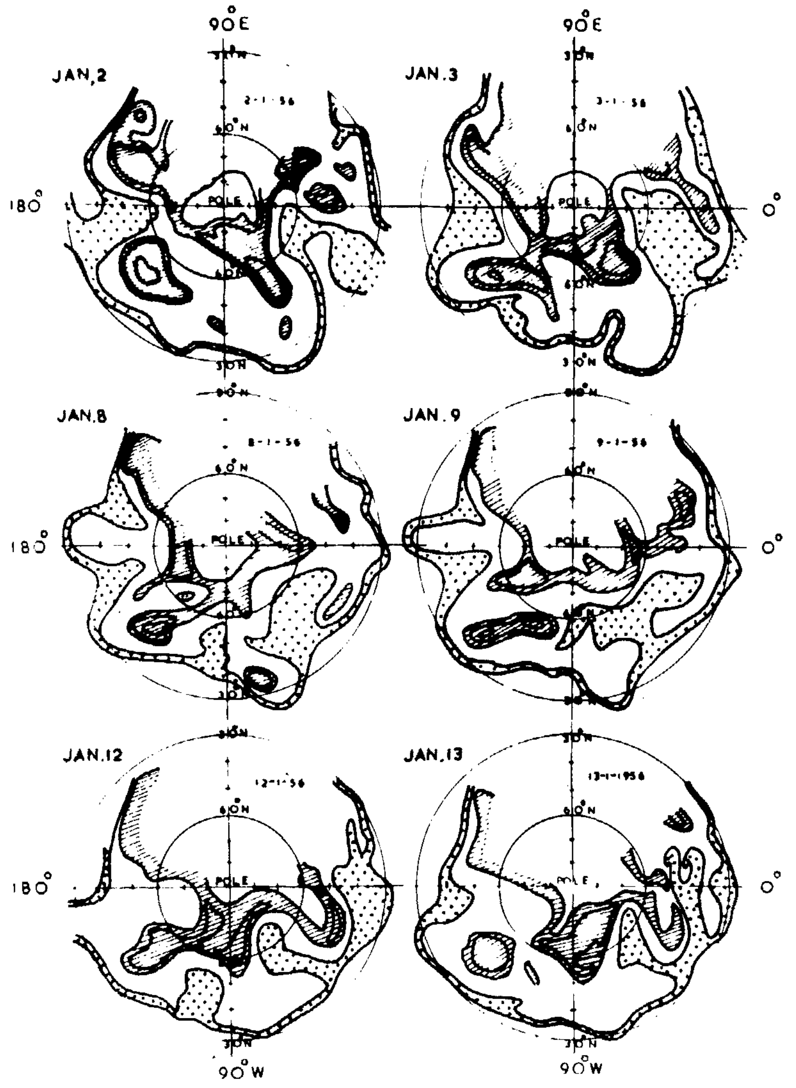

Figure 7. Isopleths of tropopause levels (100, 200, 300 and 350 mb) on individual days in January 1956 (after Fr. Defant and H. Taba and printed by courtesy of *Tellus*).

The closeness of the 100 and 200 mb-level tropopauses and the occurrence of the lowest tropopauses, not close to, but some distance away from the Pole are noteworthy features of the January diagram. In April, low-level tropopauses at pressures higher than 300 mb occur over a wide area round the Pole. The separation between the 100 mb and 200 mb-level tropopauses is widest in October and they are nearly symmetrical round the Pole. October-November are the months when the ozone amounts are smallest in extra-tropical latitudes. The day-to-day variations of ozone are largest in January to March and are least in June to October.

The January diagram of average tropopause levels may be compared with the day-to-day tropopause isopleths of the first half of January 1956 recently published by Defant and Taba (1958) (see Fig. 7). While the 100 mb level remains near 30°, the 200 mb isopleth takes deep excursions towards the Pole. Similarly, tropopauses at 300 or 350 mb move down to lower latitudes. There seem to be preferred regions for such excursions. Occasionally the 200, 300 and even 350 mb-level isopleths come close to each other. The pattern changes from day to day with a general slow W-E movement. We should expect corresponding complex changes in ozone amounts with regional preferences for high or low ozone amounts. We look forward to corresponding isopleth diagrams of ozone amounts.

Acknowledgments

The authors wish to express their thanks to the Director of the Aerological Observatory, Tateno, and the Director-General of the Japan Meteorological Agency, Tokyo, for sending their ozone and upper-air data of Tateno. Thanks are also due to the Council of Scientific and Industrial Research, India, and the Director-General, India Meteorological Department, who have for many years supported ozone studies in India.

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