STUDIES IN ATMOSPHERIC OZONE AND AIRGLOW

A Thesis submitted

by

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PREFACE

The studies on atmospheric ozone and night airglow incorporated in the thesis are grouped into two sections, one on atmospheric ozone (Chapters 1-8) and the other on night airglow (OI) 5577 Å (Chapters 9-11).

Section I - STUDIES ON ATMOSPHERIC OZONE

The results of ozone measurements, surface and total ozone and the distribution of ozone in the vertical, made at Srinagar/Gulmarg (34°N) during June 1955-December 1960 are given in Chapter 1. The ozone measurements made at Hyderabad (17°N) in March-April 1961 are reported in Chapter 2 (reprint). Chapter 3 consists of two notes (reprints), in which our work on a possible ozone increase at night are reported. Observations were made simultaneously on three pairs of wavelengths and the attenuation due to large particle scattering was considered. Observations made at Ahmedabad during 1962-64 on second and third umkehrs occurring during the twilight period, are reported in Chapter 4. The second hump in the curve of N_λ against Z^4 is accentuated when the twilight glow due to atmospheric aerosols is enhanced.

Chapters 5-8 are devoted to the study of biennial and larger-period variations in atmospheric ozone. The latitudinal extent of the biennial oscillations in ozone data, and regularity in occurrence of phase-shifts are considered in Chapters 5, 6 and 7. Correlation between the biennial variations in ozone and stratospheric zonal winds, stratospheric warmings are discussed in Chapter 7. Ozone variations in relation to geomagnetic activity are discussed in Chapter 8. 11-year cycles in ozone variations are found to be correlated with solar cycle changes in geomagnetic activity.

Section II - STUDIES ON NIGHT AIRGLOW (OI) 5577 Å

Results of night airglow measurements made at Srinagar during March 1958-November 1960 are presented in Chapter 9 (reprint). Mean nocturnal variations of (OI) 5577 Å intensity (I_{5577}) observed at Srinagar are compared with those observed at other stations situated along 75°E meridian in Chapter 10. The results suggest meridional movements of bright airglow patch between equator and about 30°N latitude in course of a night. This however requires further observations.

Some observational results on time-variation and latitudinal distribution of I_{5577} suggesting influence of magnetic activity are reported in Chapter 11. Significant positive correlation is found to exist between year-to-year variations of I_{5577} and 11-year cycle in magnetic activity. The observational material used in Chapter XI is very inhomogeneous and the results obtained should therefore be regarded as exploratory and tentative.

R. Mukherjee

ACKNOWLEDGEMENTS

The ozone observations were started at Gulmarg/Srinagar by Dr.R.N.Kulkarni. The ozone and night airglow measurements at Srinagar after 1957, and the ozone measurements made at Ahmedabad during 1961-64 are made by the author. I am thankful to Dr.G.M.Shah for providing his unpublished surface ozone measurements made during 1959 at Mt.Abu, and collaborating in the moon observations reported in Chapter 3. My colleagues, Dr.G.M.Shah and Dr.R.N. Kulkarni have helped me in the initial stages of the work, and Dr.R.V.Bhonsle and Dr.B.S.Dandekar in the construction and calibration of the airglow photometer used at Srinagar (Chapter 9).

I am thankful to Prof.M.W.Chiplonkar for providing the tabulated mean hourly values of (OI) 5577 Å intensity observed during 1957-62 at Poona, and to Dr.S.D.Sinhval for the Naini Tal observations used in Chapter 10.

Most of the computations and analyses reported here were made by me. I acknowledge assistance received from Mr.Mahesh Shukla and Mr.N.C.Shah in this connection. Mr.S.R.Thakore and others of the I.B.M. center at the Physical Research Laboratory have helped in the computations of results reported in Chapters 6 and 7.

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C O N T E N T S

SECTION I - STUDIES ON ATMOSPHERIC OZONE

LIST OF ILLUSTRATIONS

Chapter VIII

Chapter IX

Chapter X

Chapter XI

List of Tables

Ch.V.

Ch.VI.

Ch.VII.

Ch.VIII.

CHAPTER I

RESULTS OF OZONE MEASUREMENTS AT SRINAGAR/GULMARG (34°N) DURING 1955-60

1. Introduction

The latitudinal variation of atmospheric ozone has attracted the attention of many investigators (Dobson and Harrison, 1930; Tonsberg and Langlo, 1944; Langlo, 1952; Ramanathan, 1956; Ramanathan and Kulkarni, 1960; London, 1963). Ramanathan pointed out in 1954, from the ozone data available then, that the latitudinal distribution of ozone (in all seasons) showed a rapid change at about 30°N latitude. At that time, Delhi (28°.6N, 77°E) and Mt.Abu (24°.6N, 73°E) were the only two stations in India. In view of the latitudinal profile at about 30°N latitude, it was decided to set up an ozone observing station at Gulmarg (34°.1N, 74°E) in the Kashmir valley, N.India. Routine observations with a Dobson ozone spectrophotometer were made at Gulmarg from June to October 1955 by Dr.R.N.Kulkarni. As Srinagar (34°.1N, 75°E), 40 km east of Gulmarg, was more easily accessible, the ozone spectrophotometer was shifted there, first for the period November 1955 to May 1956 and then on a permanent basis in November 1956.

Towards the end of 1956, an Ehmert's chemical ozonometer for the measurement of ground-level ozone was also set up at Srinagar. Umkehr observations, from which the vertical distribution of atmospheric ozone could be evaluated, were also made whenever sky-conditions were favourable.

The ozone measurements in the pre-IGY period were made by Dr.R.N.Kulkarni, and those from July 1957 to December 1960 (IGY-IGC period) were made by the author. The said Dobson ozone-spectrophotometer was handed over to the India Meteorological Department in December 1960 for continuing the ozone measurements at Srinagar.

In the present chapter, we shall review the observational results obtained during the five and half years of operation, June 1955-December 1960. The methods of observation and salient features of ozone variation observed at Srinagar are given. These features are then compared with similar features seen at other station.

2. Observational material

During the observational programme 1955-60, the total ozone data based on the direct-sun observations (or the sun observed through cloud) are available on an average for about 80 per cent of the total number of days. The percentage is lowest in January (45 per cent) and highest in summer and autumn (~ 90 per cent).

Umkehr observations were obtained on 166 days, of which 51 were in the first two years of the programme while 115 were during the IGY-IGC period. The observations were secured in all the 12 months; the data coverage, naturally, is poor in the late winter and early summer months. During the months January, February, April and May the total number of observations in each calendar month is less than 10 (the average is 5) while in rest of the year the total number of observations is about 15.

Surface ozone measurements were made at Srinagar all the year round. In the 3½ years' period, December 1956-August 1960, a total of 1350 observations of the surface ozone concentration were made; of these 350 observations were made at 0800 hr, about 100 at 1000 hr, 830 determinations refer to 1400 hr, and 60 to 1800 hr. On 417 days two observations were made, one at noon and another either at the morning or in the evening.

3. Ozone in ground-level air

3.1 Method of measurement used at Srinagar

Surface ozone measurements were carried out using the simple method developed by Ehmert (1949, 1952 and 1959). The method consists of

(i) Reaction - A definite volume of air is bubbled through potassium iodide solution in a reaction vessel, where the ozone in the air reacts with the solution; and the iodine liberated reacts with sodium thiosulphate also present there.

(ii) Titration - The residual sodium thiosulphate in the 'exposed' solution is measured coulometrically and compared with a blank, unexposed solution.

The chemical reaction is the well known oxidation of potassium iodide by ozone in neutral solution.

$$2\ KI + O_3 + H_2O \longrightarrow O_2 + 2\ KOH + I_2 \qquad (1)$$

Addition of a small quantity of sodium thiosulphate to the potassium iodide solution (Regener, 1938) brings the free iodine into the nonactive ionic form according to the secondary reaction.

$$2\ Na_2S_2O_3 + I_2 \longrightarrow 2\ NaI + Na_2S_4O_6 \qquad (2)$$

The reaction vessel (Fig.1.1) consists of an outer tube with an air intake, a solution bottle, a bubbling-column with sintered-glass filter at the bottom, and a bent outlet to be connected to a pump or an aspirator.

A measured quantity of a neutral 2 per cent KI solution containing a few micrograms* of sodium thiosulphate is pipetted in the small bottle, it is then attached to the bubbling-column and the aspirator is started. The inflowing air forces the solution through the sintered-glass filter and the air stream

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* 1 ml of 0.01 N sodium thiosulphate is added to 750 ml of the 2 per cent potassium iodide solution.

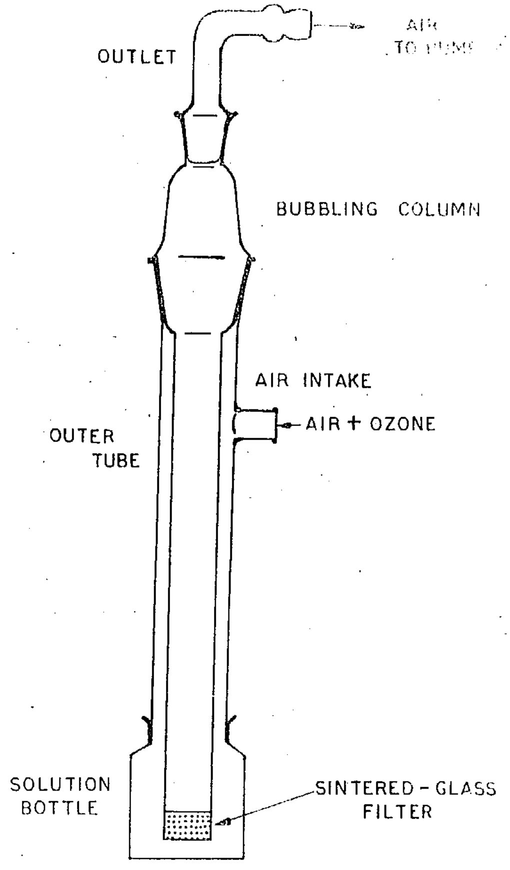

Fig.1.1 Reaction vessel of Ehmert's apparatus used for measurements of ozone in the ground-level air.

bubbles through the solution in the central column. The ozone in the air reacts with the KI solution and liberates iodine (Eq.1) which reacts with the sodium thiosulphate in the solution (Eq.2). After the desired volume of air (about 20 liters) has been aspirated at the rate of 1 liter/minute through the solution, the solution is blown back into the bottle. Traces of the solution which might still be adhering to the side-walls of the bubbling-column and in the crevices in the sintered-glass filter are recovered by rinsing the reaction vessel with a small quantity of distilled water.

The coulometric measurements of the sodium thiosulphate in the exposed solution (or in the 'blank') is rendered simple and rapid by the use of an iodinemeter (Fig.1.2). Two pairs of platinum electrodes (one pair for electrolysing and another to serve as collecting electrodes) are placed in the solution in a small bottle, which is mounted on a turn-table and rotated. If a small potential, about 0.15 V, is applied to the collecting electrodes, no current will flow unless free iodine is present. If now, a small current, is passed through the electrolysing electrodes; it follows from coulomb's law that an electrolysing current of 38 μamp would liberate 1 microgram of iodine from the KI solution in 20 seconds. This iodine reacts with the sodium thiosulphate in the solution and its strength will steadily decrease with time. As electrolysis proceeds, a stage is reached when no more sodium thiosulphate is found in the solution. The free iodine would then depolarize the cathode and the following reactions take place (Brewer and Milford, 1960).

At the cathode the free iodine is reduced to iodide,

$$I_2 + 2e \longrightarrow 2I^- \qquad (3)$$

with time. From the plot of this current against time, the exact time when the end-point of reaction (2) is reached can be obtained and hence the amount of sodium thiosulphate in the solution. The difference between the quantities of sodium thiosulphate present in the blank (unexposed solution) and the 'bubbled' solution (exposed one) gives the measure of the reduction of sodium thiosulphate in the reaction vessel due to atmospheric ozone in the air aspirated.

3.2 Surface-Ozone measurements made at Srinagar - Day-to-day, diurnal and seasonal variations

Junge (1962) has noted 'the daily maximum values of surface ozone usually occurs around noon, when vertical mixing is the strongest and the influence of the ground is widely eliminated. It can be expected that these (noon) values are approximately representative for ozone in the troposphere in areas which are free from pollution.' Hence for the purpose of studying the day-to-day and seasonal variations in the surface-ozone at Srinagar we have used only the noon observations - since the daily maximum occurs here at this hour of the day.

In Fig.1.3 the daily values of surface-ozone concentrations observed at 1400 hr are shown for the period July 1957-June 1958. In the same diagram, the daily values of total ozone amount, station-level pressure and relative humidity (both measured at 1700 hr local time) are also shown. Compared to the changes in total ozone amount the variations in the

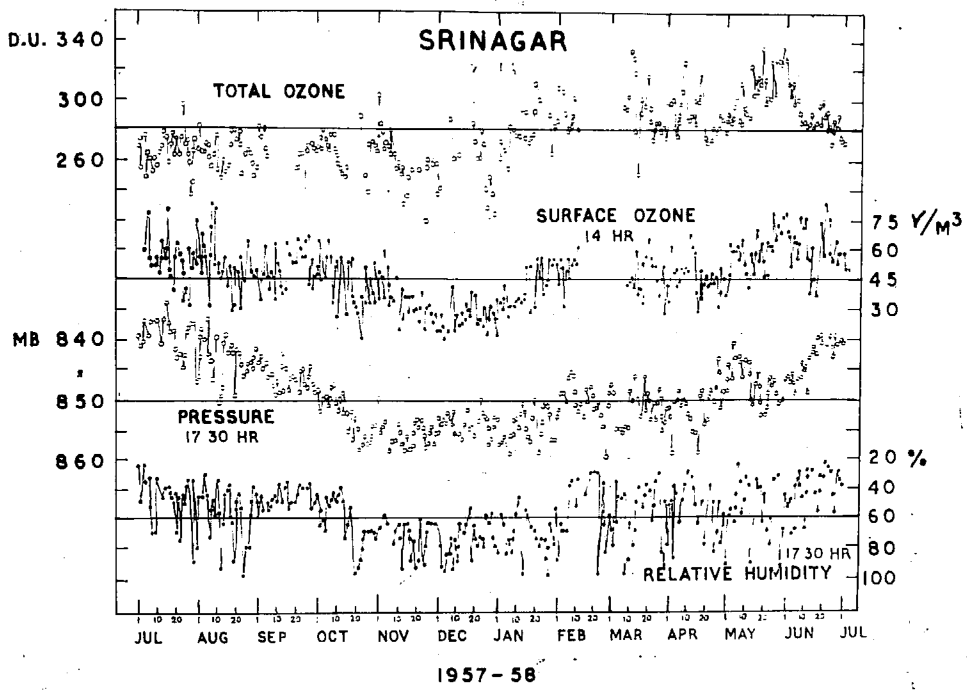

Fig.1.3 Daily values of total ozone amount, surface ozone concentrations (1400 hr), station level pressure and relative humidity (both 1730 hr values) observed at Srinagar.

surface ozone concentrations lag behind by about a month; the negative correlations between the surface ozone variations and (i) the station-level pressure and (ii) relative humidity may also be noted.

The day-to-day variations in surface ozone concentration are large in summer and less in winter; while the annual cycle also shows maximum in summer and minimum in winter. Fig.1.4 shows the daily values of surface ozone measured at Srinagar at 0800 and 1400 hr during May and June 1958 (seasonal maximum) and November and December 1957 (seasonal minimum). It is seen that day-to-day variations are larger (in the 0800 and 1400 hr series both) in summer than in winter. Another point to be noted here is that the seasonal variation in the 0800 and in the 1400 hr series are identical.

Surface ozone measurements made at Srinagar (1956-60) are summarized in Table 1.1. It gives the monthly ozone values (γ); mean monthly values based on the 1400 and 1500 hr observations ($\overline{\gamma}$); interdiurnal variability ($\delta\gamma$) — defined as the difference between the values on two successive days; and the average difference between the 0800 and 1400 hr values and the 1400 and 1800 hr values (along with the number of observations on which these differences are based). The monthly mean values (γ) of 1400 hr values for the period July 1957-August 1960 are plotted in Fig.1.5.

Following inferences regarding the diurnal, day-to-day and seasonal variations observed at Srinagar, can be drawn from these data :

1. The surface ozone values recorded at noon (1400 hr, say) are the highest observed during the sunlit hours.

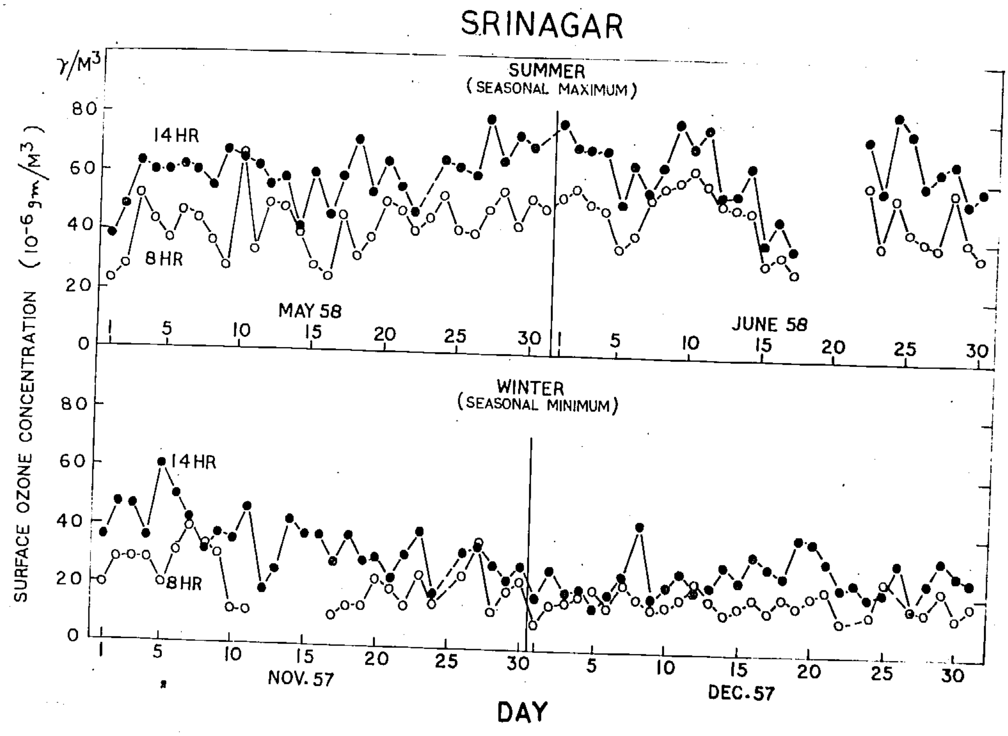

Fig.1.4 Surface ozone concentrations recorded at 0800 and 1400 hr at Srinagar during summer and winter months.

2. The amplitude of diurnal variation as can be judged from the mean differences between the 1400 hr values and the morning and evening ones is larger in summer than in winter.

Table 1.1

Surface ozone measurements made at Srinagar 1956-60 (Tabulated ozone values are in $\mu gm/m^3$; $21.4\ \mu g/m^3 \equiv 1$ D.U./km).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
γ_{1956}												31*
γ_{1957}	33*	41*	33@	32@	35@	33@	55	54	50	45	36	26
γ_{1958}	40	50	48	49	58	62	53	51	49	41		
γ_{1959}			45	47		52	54	49	39	41	49	36
γ_{1960}	41	44	48	55	62		49	55				
γ mean (noon)	38	45	47	51	60	57	53	52	46	42	43	31
$\delta\gamma$ **	8	7	9	9	10	10	11	11	10	10	10	9
γ-range 1400-0800	10	12	14	12	17	16	17	18	17	18	13	9
(No.of obs.)	(27)	(12)	(19)	(27)	(29)	(26)	(37)	(55)	(34)	(36)	(24)	(30)
γ-range 1400-1800			12	12			18	12	14	11	15	
(No.of obs.)			(20)	(11)			(5)	(13)	(2)	(3)	(7)	

* 1500 hr observations } rest all are 1400 hr observations.
@ 1000 hr observations }

** $\delta\gamma$ = interdiurnal variability.

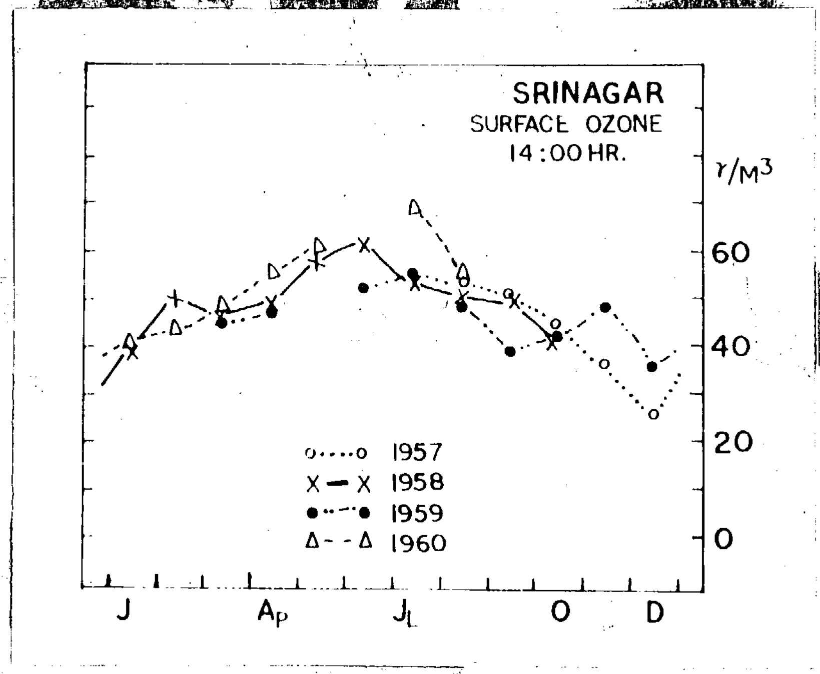

Fig.1.5 Annual variation in surface-ozone concentrations, Srinagar (1957-60).

3. The mean monthly ozone concentration (noon value) is the highest (60 gamma, 1 gamma $\equiv 10^{-6}$gm. m^{-3}) in May and the lowest (31 gamma) in December. The summer-mean value is 55 gamma. The annual mean is 48 gamma.

4.4. The annual oscillations have the same phase and amplitude year after year.

5. Day-to-day variations (in 1400 hr values) are about 20 per cent of the mean monthly ozone values, 19 per cent in summer and 23 per cent in winter.

3.3 Comparison with the surface ozone measurements made elsewhere

The day-to-day variations observed at Srinagar are of the same magnitude as observed at other stations. The standard deviations of the daily maximum surface ozone concentrations at Arosa (47°N, 10°E) in the Swiss Alps, according to Junge (1962), have mean value of 23 per cent, the same as that observed at Mauna Loa (20°N, 156°W), a mountain station in Hawaii.

In Table 1.2, we have compared the diurnal variations in the surface ozone observed at Srinagar, Mt.Abu (24.5° N) and Ahmedabad (23°N), both in W.India (Ahmedabad is 180 km south of Mt.Abu), and at Mauna Loa. At Srinagar (which is situated in a high valley measuring some 200 km in length and 50-80 km in breadth and surrounded by mountain ranges scaling some 6,000 ft more), and also at Ahmedabad (which is situated in a flat terrain) the diurnal maximum is recorded at noon.

On the other hand, at Mt.Abu during the sunlit hours very little change is observed; while at Mauna Loa a diurnal oscillation with small amplitude and characteristic maximum at about 0200 hr and minimum at noon is in evidence. The Mauna Loa observatory is situated near the peak of a mountain a little more than 3 km high in the central Pacific region, and Mt.Abu station is located on a rather exposed ridge at an elevation of 3,800 ft and some 3,000 ft above the flat lands. The difference in behaviour between Mt.Abu and Ahmedabad is similar to that between Capillo Peak and Acomita (a valley station) noted by

Table 1.2

Diurnal variation in Surface Ozone concentrations observed at Srinagar and other low latitude stations.

Month	Srinagar (34°N)* 1957-60 γ_N				Ahmedabad (23°N)** 1954-55 γ_N				Mt.Abu (24½°N)*** 1959 γ_N				Mauna Loa (20°N), Hawaii**** 1958 γ_N				
(Hrs)	0800	1400	1800	$\gamma_{14}-\gamma_{08}$	0800@	1400	1800	$\gamma_{14}-\gamma_{08}$	0900	1300	1700	$\gamma_{13}-\gamma_{09}$	0200@@	0900	1300	1700	$\gamma_{13}-\gamma_{09}$
Jan.	29	39		10	31	48	42	17					45	41	36	35	-5
Feb.	32	44		12	34	51	49	17					56	50	46	48	-4
Mar.	33	47	35	14	28	50	44	22					56	53	48	47	-5
Apr.	39	51	39	12	28	45	44	17					*@74	71	59	63	-12
May.	42	59		17	22	39	33	17					62	58	47	47	-11
Jun.	41	57		16	21	29	26	8	22	27	23	5	62	54	45	45	- 9
Jul.	41	58		17	23	30	29	7	25	25	26	0					
Aug.	34	52	40	18	16	25	24	9	17	14	14	-3	41	38	35	34	- 3
Sep.	30	47	33	17	16	24	19	8	20	14	18	-6	41	40	32	34	- 8
Oct.	25	43	32	18	22	43	30	21	20	22	20	2	34	34	30	31	- 4
Nov.	29	42	27	13	18	43	29	25	22	24	20	2	42	42	37	35	- 5
Dec.	22	31		9	27	47	38	20	25	20	21	-5	45	42	40	38	- 2

* Observations by the author at Srinagar, N.India (1586 m) situated in center of a high valley in the Hindukush.

** Observations by Dr.J.V.Dave (1957) at Ahmedabad, W.India (49 m) situated in a flat terrain.

*** Observations by Dr.G.M.Shah (unpublished) at Mt.Abu, W.India (1200 m) situated on a 3000 ft peak.

**** Mauna Loa, Hawaii (3400 m) station is situated near peak of the 13680 ft mountain in the Central Pacific. (Data, courtsey of U.S.Weather Bureau).

@ Morning observations at Ahmedabad were made at 0600 hr; and 1000 hr; the averages shown here are derived from the γ_{0600} and γ_{1000} values.

@@ Flat maximum at this station is noted to extend from about 2200 hr to 0800 hr.

*@ Based on the data for 1-10 April 1958.

Bowen and Regener (1951): at Ahmedabad and Acomita a significantly large diurnal variation with maximum occurring at noon is observed, while at Capillo Peak and at Mt.Abu the diurnal variation is very small during sunlit hours.

A reference to Fig.1.2 and Table 1.2 shows that the ranges of diurnal variations at these stations are larger at time of the seasonal maxima than at time of the minima.

A comparison of seasonal variations in the daily maximum values of surface ozone observed at different stations shows that the annual oscillation recorded at Srinagar is similar in amplitude and phase to those noted to exist at Arosa, Mauna Loa and Fichtelberg (in Germany); while that observed at Ahmedabad stands in a class apart (Junge, 1962). The seasonal variation seen in the surface ozone measurements made in 1959 at Mt.Abu by Dr.G.M.Shah (shown in Table 1.2) agrees with that observed at Ahmedabad. In the observations for Mt.Abu, since they refer to the period June-December only, the seasonal maximum cannot be decided but the minimum is seen occurring (at both the places) in August-September, while at Ahmedabad a flat maximum is observed during December-March. It may be noted here that during July-September both Mt.Abu and Ahmedabad are in the realm of the monsoon; at Srinagar rainfalls are rare in these months while thick fog etc. are prevalent there in December.

3.4 Annual variation in surface ozone versus meteorological parameters measured at the station level

In connection with Fig.1.3 we have mentioned about the negative correlation seen existing between the surface ozone values observed at Srinagar and (i) the station level pressure and (ii) relative humidity. In Fig.1.6 we have plotted mean monthly values of total ozone amount (in D.U.), noon values of surface ozone concentrations (in gamma) the range of diurnal variation in the surface temperatures ($T_x - T_N$, in ^{o}C) and the relative humidity. The stations included here are Mt.Abu, Ahmedabad and Srinagar. The meteorological data are the normals (mean monthly averages) taken from the Indian monthly weather summaries published by the India Meteorological Department.

It is seen that like the difference in the annual variation in the surface ozone values observed at Srinagar and the other two stations, the meteorological data (normals) observed at these stations show striking contrasts. The phase and amplitude of the annual oscillations because of the differences in latitude and environs, are different at different stations; and they also show that the annual variation in surface ozone at a given station is positively correlated with the changes in diurnal range of temperature and negatively with the changes in relative humidity. It may be concluded therefore that the differences are mainly due to the different annual variations in relative humidity etc.

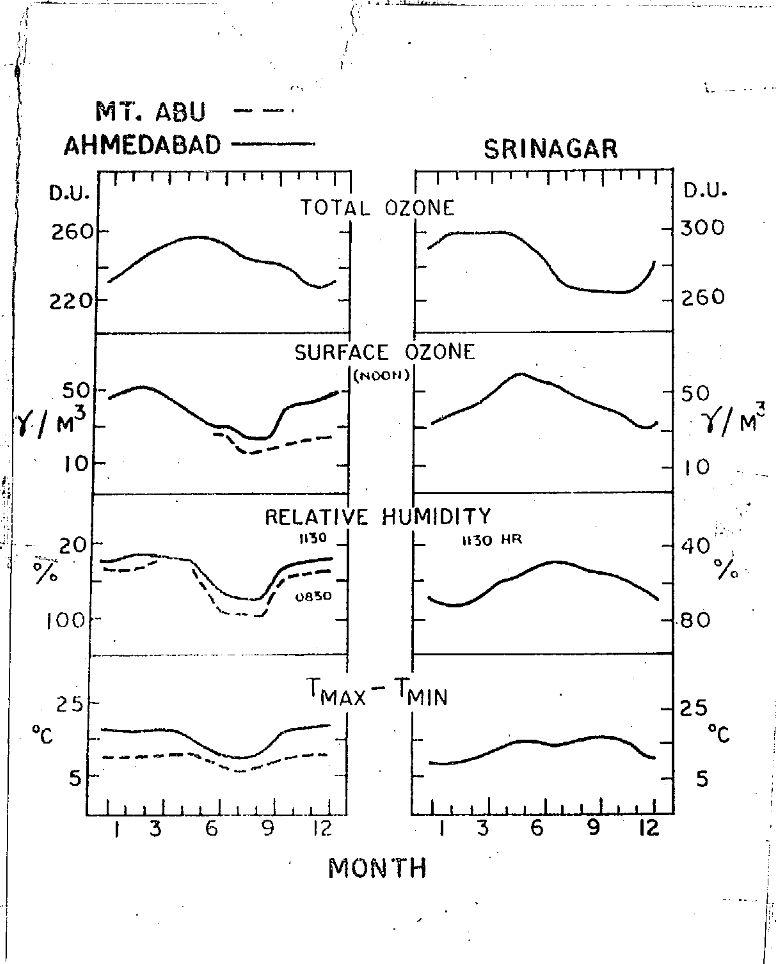

Fig.1.6 Annual variations in surface-ozone concentrations at Mt.Abu, Ahmedabad and Srinagar compared with those in (i) total ozone amount, (ii) difference in maximum temperature (T_x) and minimum temperature (T_N), and (iii) relative humidity.

4. Total ozone in the atmosphere and vertical distribution of ozone

4.1 Instrument and observation

Dobson ozone spectrophotometer (Dobson, 1957) made by

Messrs R. & J. Beck Ltd., London, is the standard instrument used for the total ozone measurements. Instrument No.10 duly checked for wavelength-setting and wedge calibrations was used for the regular measurement of total ozone and its vertical distribution over Srinagar/Gulmarg.

The amount of ozone contained in a vertical column of air extending from the ground to the top of atmosphere is deduced from the measured reduction in the intensity of sunlight of certain suitable wavelength in passage through the atmosphere. Since it is much easier to measure the relative absorption of two wavelengths than the absolute absorption of the wavelength, two wavelengths are used having very different absorption coefficients.

A. Wavelengths used

In the region of Huggins band(between λ 3000 Å and 3400 Å) the ozone absorption changes very greatly so that it is easy to select pairs of wavelengths about 200 Å apart which are suitable for this purpose. The wavelengths are chosen so that the difference between the ozone absorption coefficients at these wavelengths ($\alpha - \alpha'$) is kept as large as possible while keeping the differential scattering in the atmosphere as small as possible. The wavelength must also be selected such that the ground spectrum is relatively flat in intensity over a small range of wavelengths on either side of the selected wavelength. On the otherhand the wavelengths used to estimate the corrections for scattering due to dust or haze in the lower atmosphere, are chosen so that the difference in atmospheric scattering is large but not so in case of the ozone absorptions.

Table 1.3 lists the standard wavelength pairs which satisfy these conditions and are used for observations with the Dobson spectrophotometer. Also included in the table are the decimal absorption coefficients of ozone (per cm of ozone at S.T.P.) and the decimal scattering coefficients due to the air molecules in the atmosphere. These values of α , α' are based on the measurements by Vigroux (1953) and suggested by the International Ozone Commission for use from 1 July 1957 [Dobson (1963) and Ramanathan et al (1965a) have discussed the appropriateness of these values of $(\alpha - \alpha')_B$ and $(\alpha - \alpha')_C$].

B. Determination of the intensity ratio

The ratio of the intensity of light in two narrow bands of wavelengths from the sun or the zenith sky is measured as follows :

In the latest design of the instrument (Fig.1.7) three wavelengths bands in the Huggins ultra-violet bands of the solar spectrum are isolated by slits S_2, S_3 and S_4 situated at the focal plane of a double monochromator having quartz optics. An accurately cut sector-wheel passes light from two of the bands one after another to a photomultiplier behind the exit slit S_5. So long as the responses of the photomultiplier to the two

Table 1.3

Wavelengths and other constants used in connection with the ozone measurements made with a Dobson Spectrophotometer.

Designation of Wavelength pair		Mean wave-length Å	Ozone absorption coefficients α	α'	$\alpha - \alpha'$	Atmospheric scattering coefficients β	β'	$\beta - \beta'$
A	Short	3055	1.882		1.762	0.491		0.116
	Long	3254		0.120			0.375	
B	Short	3088	1.287		1.223	0.470		0.113
	Long	3291		0.064			0.357	
C	Short	3114.5	0.912		0.865	0.453		0.110
	Long	3324		0.047			0.343	
D	Short	3176	0.391		0.374	0.416		0.104
	Long	3398		0.017			0.312	
C'	Short	3324	0.047		0.045	0.343		
	Long	4536		0.002				

Taken from "Observers' Handbook for the Ozone Spectrophotometer" prepared by Prof.G.M.B.Dobson (1957).

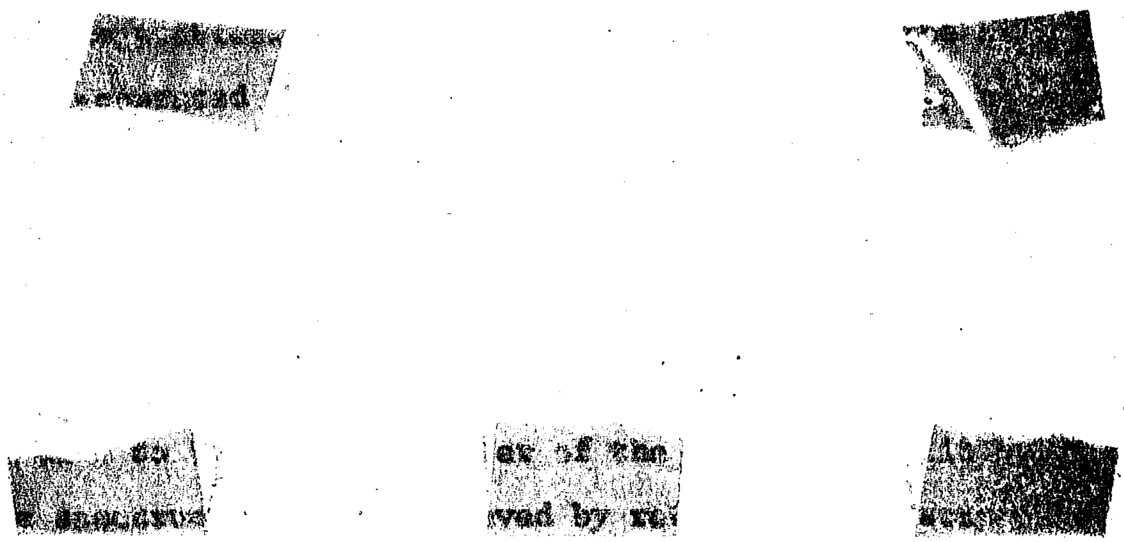

Fig.1.7 Optical system of Dobson spectrophotometer (after Normand & Kay, 1952).

wavelengths differ, the output fluctuates and is amplified in an a.c.amplifier. The amplified signal is rectified by a synchronous mechanical commutator mounted on the shaft driving the sector-wheel and is observed on a d.c.microammeter. The intensity of the wave-band passing through the slit S_3 is diminished by optical wedges situated in front of it until the output of the photomultiplier is the same for each wave-band. The micro-ammeter reading then becomes zero. This position of the calibrated wedge measures the intensity ratio of the two wave-bands in the incident beam.

C. Wavelength settings

The wave-band 3000-3200 Å enters the second monochromator through the slit S_2, band 3200-3450 Å through the slit S_3 and the wavelengths 4300-4800 Å (used to estimate the corrections for the scattering due to dust or haze) through the slit S_4. Lever-operated shutters block either S_2 or S_4, keeping open S_2 and S_3, or S_3 and S_4 at a time. Primary wavelength setting is made with the help of this lever.

The slit-widths of S_2, S_3 and S_4 are approximately 10, 30 and 30 Å respectively. Desired wavelength in a given band is made to fall on the center of the respective slit by displacing the spectrum. This is achieved by rotating the quartz plates Q_1 and Q_2 mounted in front of the entrance slit S_1 and exit slit S_5 and thereby changing the angle of incidence.

4.2 Calculation of the total amount of ozone

The total ozone amount is customarily expressed as 'x' cm - the height that the ozone in a vertical column above the station would occupy if it were all brought to standard temperature and pressure. Now-a-days the total ozone amount is expressed in milli atmo-centimeters (m atm-cm). This is also known as Dobson Units (D.U.) the accepted symbol is Ω .

Observations for total ozone are usually made on direct sunlight during day time. Focussed image of the sun, if the sunlight is dim, (or the moon, if observations are scheduled at night) can also serve the purpose. In absence of either of these, the light scattered from the zenith sky (clear as well as cloudy) might be used to evaluate the total ozone amount, provided such observations have been 'calibrated' against observations made on direct sun (Dobson, 1957; see also, Shah, 1961 and Sanyal, 1965).

If L and L_o are the intensity ratios for wavelength pair $\lambda\lambda'$ as observed at the surface of the earth and outside the earth's atmosphere, the change in intensity ratio $L_o - L$ can be connected with "x" or Ω by equation of the type

$$\Omega \times 10^{-3} = x = \frac{L_o - L}{\mu(\alpha - \alpha')} - \text{a correction term for scattering by air molecules} - \text{correction term for scattering due to the dust or haze.}$$

where 'μ' is relative path length of the sunlight through the ozone gas (the unit being the path length for the vertical incidence). Let 'm' be the path length of the sunlight through the entire atmosphere, called the Air-Mass (the unit is the Air-Mass for vertical incidence); then Ω is given by

$$\Omega \times 10^{-3} = x = \frac{(L_o - L) - m(\beta - \beta')}{\mu . (\alpha - \alpha')} - \frac{K'}{(\alpha - \alpha')}(\delta' - \delta'') \qquad (5)$$

the last term is a correction term for large-particle scattering. This term can be evaluated either as suggested by Ramanathan and Karandikar (1949) the additional information required is the measurement of the ratio for wavelengths λ' and λ'' ($\lambda\lambda$C', say); or by the Difference Method (Dobson, 1957) in which the observations are made on $\lambda\lambda$ A and C or $\lambda\lambda$ A and D.

If L_o' and L' are the intensity ratios for wavelengths λ' and λ'' outside the atmosphere and as measured at the earth's surface, Ramanathan and Karandikar have shown that Eq.(5) can be rewritten as

$$\Omega \times 10^{-3} = x = \frac{(L_o - L) - m(\beta - \beta')}{\mu . (\alpha - \alpha')} - \frac{K'}{\alpha - \alpha'}\left[\frac{L' - L_o'}{m} - (\beta' - \beta'') - \alpha' . x\right]$$

which upon substituting the numerical values of α, α' and β, β', β'' from Table 1.1 for $\lambda\lambda$ CC', we get

$$\Omega \times 10^{-3} = x = \frac{(L_o - L)_c}{0.865\,\mu} - 0.127\,\frac{m}{\mu} - 0.239\left[\frac{(L' - L_o')_{c'}}{m} - 0.273\right] \qquad (6)$$

with $N - N_o \cong 100\,(L_o - L)$, (7)

the right hand side of Eq.(6) becomes

$$= \frac{(N - N_o)_c}{\mu\; 86.5} - 0.127\,\frac{m}{\mu} - 0.239\left[-\frac{(N' - N_o')_{c'}}{m} - 0.273\right]$$

The extra-terrestrial constants N_o and N_o' (or L_o and L_o') are determined by linear extrapolation for $\mu = 0$ from a set of the direct-sun observations of N and N' made on days of settled weather when the value of μ changes from 1 to 3(or 4).

Since the contributions due to large particles for both the wavelength pairs are practically the same, the correction term is eliminated by considering the differences (and hence the name Difference Method). If the observations are made on $\lambda\lambda$ A and D, Eq.(5) is modified as

$$\Omega \times 10^{-3} = x = \frac{(N-N_o)_A - (N-N_o)_D}{\mu \cdot 100\{(\alpha-\alpha')_A - (\alpha-\alpha')_D\}} - \frac{m\{(\beta-\beta')_A - (\beta-\beta')_D\}}{\mu\{(\alpha-\alpha')_A - (\alpha-\alpha')_D\}}$$

$$= \frac{(N-N_o)_A - (N-N_o)_D}{138.8\ \mu} - 0.009 \qquad (8)$$

Calculating μ and m from the time of observation, observing $(N-N_o)_\lambda$ for λ = C and C' and using Eq.(7), or observing $(N-N_o)_\lambda$ for λ = A and D and then using Eq.(8) the total ozone amount can be evaluated. Both these methods were employed at Srinagar to estimate the total ozone amount.

4.3 Vertical distribution of ozone by Gotz-Umkehr Effect

With the increase of solar zenith distance, because of rise in the effective height of scattering for the shorter wavelength λ, the ratio L decreases. Once the effective height goes above the region of maximum ozone, its intensity I_λ decreases at a rate smaller than that of the longer wavelength λ' $(I_{\lambda'})$. This leads to an inversion in the curve of L versus Z^4 (Z is in degrees).

Gotz, working in Spitzbergen, first observed the Umkehr Effect in 1929 and also noted its significance (Gotz, 1931). Since then this effect has been extensively used for determining the vertical distribution of ozone. To study the day-to-day changes in ozone at various levels associated with the weather changes, this method is widely used, as the observations do not require any special equipment, Dobson Ozone spectrophotometer is sufficient for the purpose.

The measurements consist of knowing the intensity ratios of $\lambda\lambda$ A, B, C or D from the zenith sky for the solar zenith distances varying from 40-60° to 90°.

Götz, Meetham and Dobson (1934) developed two different methods of determining vertical distribution of ozone from the observed umkehr curve. In the analytical method (referred to as Method A), the equation of L is obtained on the basis of primary scattering for Z = 0°, 80° and 90° in terms of x_1 and x_2 (the ozone amounts in the 35-50 and 20-35 km layers respectively). Knowing the total ozone amount x obtained from the direct sun measurement and the surface ozone u taken as fixed percentage of x.

The synthetic method (or the Method B) consists of starting with an assumed vertical ozone distribution and varying it till the calculated and measured umkehr curves are in tolerably good agreement at several points. The method B was modified by Karandikar and Ramanathan (1949) by considering 9 km thick layers; and later by Ramanathan and Dave (1957), the region 0-54 km was divided now into 6 km layers and agreement was sought at 6-8 zenith distances of the sun including the inversion-point also. Dütsch (1959) and Mateer (1960) considered the departures of the measured intensity ratios from the standard umkehr curves; and in recent years Mateer ([illegible]) and [illegible]

Dütsch (1964) have developed computor methods for rapid and objective evaluations. Dütsch and Mateer (1964, 1965) have worked out vertical distributions of ozone from umkehr observations at all the stations in the world ozone network. The vertical distribution of ozone for Srinagar/Gulmarg (1955-59) and other stations used in this chapter are taken from their reports.

5. Results (total ozone amount and vertical distribution of ozone)

5.1 Total ozone amount

A. Day-to-day variations

Relative magnitudes of the day-to-day fluctuations in the total ozone amounts are shown in Table 1.4. The standard deviation of daily values from the respective monthly means and the interdiurnal variability defined as the difference between the values on two successive days, are given in this table. Average number of observations in the month are also shown here to given an idea of the weight that can be attached to these values. It is seen from these data that the day-to-day variations are large ($\sim$ 15 D.U.) in winter and spring when the total ozone amounts are also large and small (7-10 D.U.) in summer and autumn.

B. Seasonal variations

In Table 1.5 are given the individual monthly values ($\bar{\Omega}$), their standard deviations ($\sigma_{\bar{\Omega}}$), and the number of

Table 1.4

Day-to-day variations in total ozone amounts SRINAGAR/GULMARG, 1955-60

(ozone values tabulated here are in m atm-cm)

	J	F	M	A	M	J	J	A	S	O	N	D
Mean monthly total ozone amount (Ω_N)	299	299	299	300	295	288	276	267	266	265	266	276
Mean interdiurnal variability	15	15	14	10	12	7	7	7	7	7	10	16
Standard deviation of daily values (σ_Ω)	17	18	14	13	15	10	9	8	10	10	14	17
Average number of observations	14	19	23	25	25	28	28	28	27	26	26	20

observations in each month. Also included here are the mean monthly ozone values, the Normals (Ω_N), the annual means and the range of variation of $\bar{\Omega}$ in the year (defined as the maximum minus the minimum). The range of Ω_N is 35 D.U., whereas in individual years the range is found to very from 52 D.U. (1958 and 1960) to 27 D.U. (1957) giving an average range equal to 45 D.U. (16 per cent of the total ozone amount, 282 D.U.). Since the variation of individual $\sigma_{\bar{\Omega}}$'s hardly exceeds 3-4 D.U. (about 1½ per cent or less), the seasonal variation stands out conspicuously. It can be seen that the seasonal variation conforms to the normal variation appropriate to middle latitudes with maxima occurring in late winter and spring, and minima in autumn.

Table 1.5

Total ozone amounts Srinagar/Gulmarg* (1955-60)

$\bar{\Omega}$ - monthly mean; $\sigma_{\bar{\Omega}}$ - standard deviation of $\bar{\Omega}$; Ω_N - mean monthly ozone amount;

n - number of observations in a month (ozone values are given in m atm-cm).

Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean	Range of $\bar{\Omega}$ (Max-Min)
1955				$\bar{\Omega} \pm \sigma_{\bar{\Omega}}$ (n)		282±2 (17)	268±2 (21)	253±1 (26)	255±1 (28)	259±3 (26)	259±1 (28)	273±5 (24)		
1956	306±5 (16)	304±5 (27)	296±3 (24)	290±3 (26)	280±1 (30)	279±1 (24)	272±2 (25)	258±2 (22)	255±1 (25)		266±5 (6)	261±2 (25)	277	51
1957	293±5 (16)	283±5 (22)	285±3 (22)	293±3 (21)	294±4 (21)	290±2 (30)	272±1 (31)	271±2 (28)	275±3 (16)	273±4 (22)	267±4 (23)	268±5 (17)	280	27
1958	289±3 (20)	300±4 (10)	301±5 (21)	300±3 (28)	314±3 (30)	301±3 (30)	281±2 (22)	282±2 (31)	270±2 (27)	268±1 (29)	261±3 (28)	262±4 (9)	286	52
1959	301±5 (10)	302±5 (19)	307±3 (27)	298±2 (29)	287±4 (16)	285±1 (30)	284±2 (28)	270±1 (30)	271±2 (25)	262±2 (28)	272±2 (29)	292±4 (31)	282	45
1960	305±4 (21)	305±5 (17)	307±6 (21)	318±3 (21)	301±2 (29)	291±2 (26)	275±2 (29)	267±2 (23)	268±2 (30)	266±2 (29)	272±2 (29)	283±5 (18)	288	52
Ω_N	299	299	299	300	295	288	276	267	266	265	266	273	282	

* Observations made during Jun-Oct.1955 and Jun-Sep.1956 are from Gulmarg, 40 km in the west of Srinagar.

C. Large period variations

The existence of other systematic large-period variations can also be seen from these data. The spring values in alternate years are found to differ by significant amounts from those in the intermediate years. The means for February-April in the even years 1958 and 1960 are higher than those in the odd years 1957 and 1959, the difference is about 10 D.U. (4 per cent of the total amount). It is also noted that eventhough the trend (as indicated by comparison of the annual means) is towards an increase, the spring values in 1956 were higher than those in 1957. This biennial modulation of the spring maxima is seen in the annual means and in the values of the range also.

In these data, 1955-60, an increasing trend is identified. The annual mean which was 277 D.U. in 1955-56 was found to increase steadily, becoming 288 D.U. in 1959-60.

D. Comparison with data from other stations

That these features are also present in the concurrent ozone data from other stations situated between 25°-45° latitudes in Europe, Asia and Australia, can be seen from Fig.1.8. The monthly means of the total ozone amounts observed in the years 1954-63 are shown here. The mean annual oscillations at all stations (shown in the left hand blocks in this diagram) are smooth and show annual maxima in spring and minima in autumn.

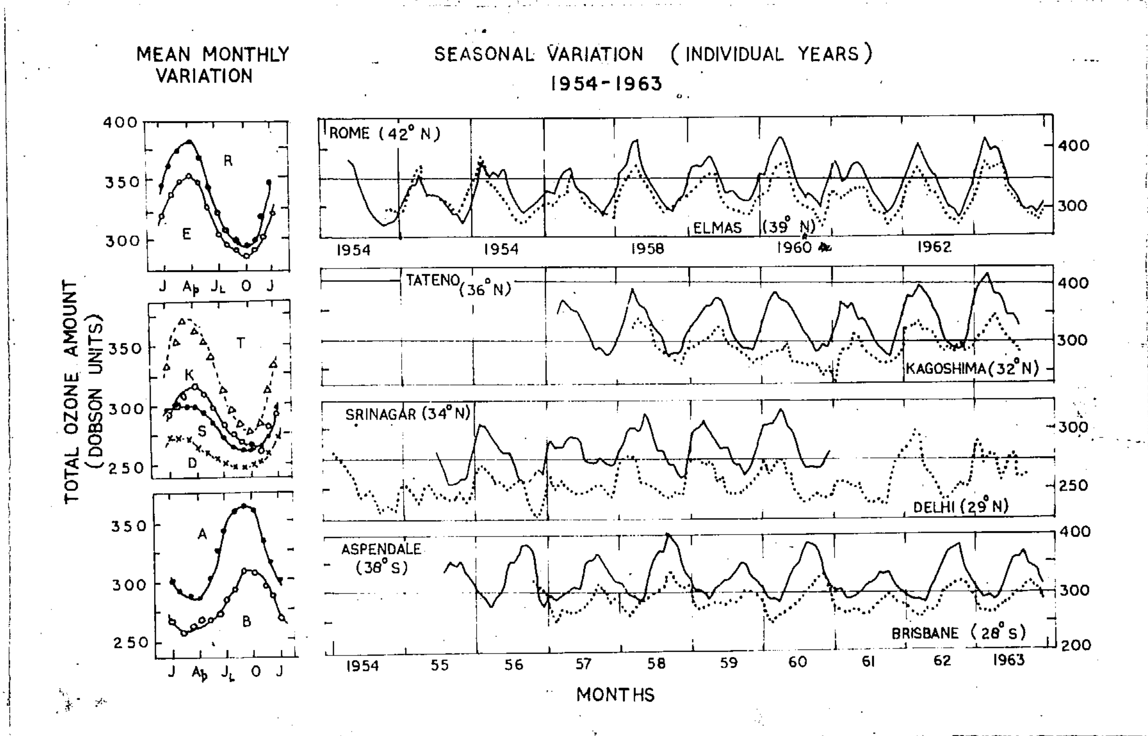

Fig.1.8 Mean monthly ozone variations and plots of monthly mean ozone amounts observed at stations (latitude 25°-45°) in Europe, Asia and Australia during 1954-63.

The deviations from the sinusoidal normal seasonal variations seen in individual years are significant and indicate the existence of the biennial oscillations in the total ozone amount at these latitudes (see chapter 5-7); and identical large-period variations (trends) are noticeable in the case of Rome, Elmas and Delhi also where the data cover the entire decade.

As a result of comparison of the day-to-day and seasonal variations of ozone amounts measured in 1957-58 over Tateno with those over Srinagar and Delhi, shows clearly that the distribution of ozone is affected by geographical factors. The Indian observations show that the monsoon region is one of small ozone amounts. It was suggested that the cold Siberian anti-cyclones with their periodic cold waves tended to increase the ozone amounts over Tateno (36°N) in Japan, and the Indian summer monsoon and the Himalayas likewise exerted a strong depressing influence on the ozone amounts south of the Himalayas (Kulkarni, Angreji and Ramanathan, 1959; abstract is given in Appendix I).

E. Annual variation seen in 1957

The departure of the annual curve in 1957 at Srinagar from the mean annual curve is quite large and deserves a special mention here. This abnormality was noted earlier also by Kulkarni et al (1959). The ozone amounts observed in February 1957 at Mt.Abu (24°.6N), Delhi (28°.6 N) and Srinagar (34°.1 N) in India, are the lowest ever observed in February, the ozone data for Mt.Abu/Ahmedabad and Delhi cover today 15 and 14 years respectively. The ozone values observed at Srinagar in March 1957 also did not reach the high values usually observed there in this part of the year.

The ozone deficiency in February and March and high ozone amounts in June-October have reduced the range of annual variation to 27 D.U. as compared to about 50 D.U. in the other years.

5.2 Vertical distribution of ozone

The data of vertical distribution of ozone for Srinagar/Gulmarg and other stations used for this study were obtained from the data published by Mateer and Dutsch (1964) from their analysis of umkehr observations.

In his recent study, Dutsch (1965) has taken into consideration the primary and secondary scattering as well as higher order scatterings by incorporating the recent results of Dave (1965). He has shown that the numerical values of the corrections to be applied to the observed umkehr curve now become double of what he had been using when only the primary and secondary scatterings were considered. This change when adopted would change the ozone distribution-profile slightly; with a tendancy to put more ozone into layer 2 at the expense of layers 3 and 4 (Dutsch, 1965). Table 1.6 gives particulars of the layers into which the first 50 km of the atmosphere is divided, for depicting the vertical distribution of ozone.

Table 1.6

Particulars regarding the layers in which the 0-50 km region of the atmosphere is divided while describing the distribution of ozone in the vertical.

Layer	1	2	3	4	5	6	7	8	9
Pressure (mb)	500 to 250	250 to 125	125 to 62.5	62.5 to 31.2	31.2 to 15.6	15.6 to 7.8	7.8 to 3.9	3.9 to 1.95	1.95 to 0.98
Approx. ht.(km)	5-10	10-15	15-19	19-24	24-28	28-33	33-38	38-43	43-48

The absolute values of ozone concentrations at different levels reported here may not be quite correct, but the relative variations with time and location would be reliable, since the same method has been used for the analysis.

A. Changes in vertical distribution with changes in the total ozone amount

The vertical distribution of ozone on individual days are shown in Appendix II; the grouping is done according to the calendar months. Pictorial comparison of changes in ozone concentration in various layers observed at different stations with changes in total ozone is shown in Fig.1.9. These data refer to the IGY-IGC period. The reference levels for various layers are marked individually and the ordinate scales are marked at the extreme left. The abscissae show total ozone amounts (in m atm-cm) and the heights of the layer-boundaries are shown at the right. Table 1.7 shows the average vertical distributions averaged over 10 D.U. intervals for Srinagar for the IGY-IGC period. For the pictorial comparison the distributions were grouped according to the total ozone amounts (group interval was 5 D.U.) and mean curves were drawn from the plots of layer-mean ozone partial pressures against total ozone amounts. The ozone variations at three Japanese stations Marcus Is. (24.°3 N, 154°E), Kagoshima (31.°6 N, 131°E) and Tateno (36.°1 N, 140°E) are shown by broken lines and are compared with those observed at Mt.Abu (24.°6 N, 73°E), Srinagar (34.°1 N, 75°E) and Aspendale (38.°0 S, 145°E) respectively.

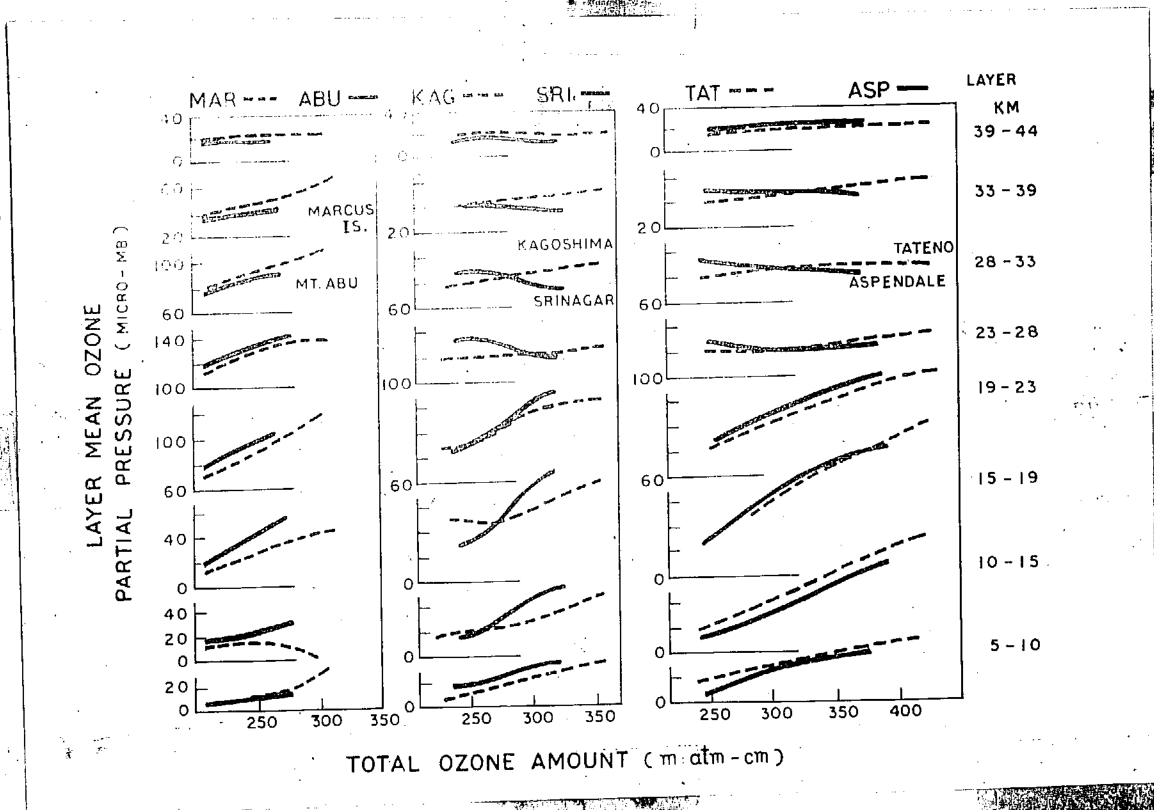

Fig.1.9 Changes in ozone concentration at various levels with changes in total ozone amount.

The following points may be noted :-

1. Compared to the ozone amounts in 5-23 km over the Indian stations Mt.Abu and Srinagar, those for the same ozone amount, at the Japanese stations Marcus Is. and Kagoshima are markedly lower. Above the main ozone peak, the situation is opposite. Except for a slight

Table 1.7

Changes in ozone amounts in various layers with change in total ozone amount
SRINAGAR (1957-59)

Total ozone amount (D.U.) Range	Mean	No. of obs.	Layer-mean ozone partial pressure-p_3 (in μ mb), in the Layer 1	2	3	4	5	6	7	8	9
236-245	240	9	16	15	29	86	129	89	43	16	4
246-255	251	20	21	20	32	89	132	90	42	15	4
256-265	259	22	18	22	39	97	137	91	41	15	4
266-275	269	12	22	21	43	102	135	91	42	15	4
276-285	280	10	25	42	62	104	116	78	40	16	5
286-295	290	14	28	36	64	116	121	83	39	14	4
296-310	304	8	26	50	87	130	122	77	34	14	4

difference in the layers 5 to 8 (23-44 km) in case of Tateno and Aspendale there are no serious differences.

2. The downward change in ozone centre of gravity, for an equal change in the total ozone amount, is more over Mt.Abu, Srinagar and Aspendale than over the Japanese group of stations.

3. The main increase in ozone is recorded at 15-24 km over Mt.Abu, in layers 10-24 km over Srinagar, and Aspendale, while at the Japanese stations the increase continues upto the main ozone peak and even higher.

4. At Srinagar, and to some extent at Aspendale, the ozone concentrations in the middle stratosphere are markedly higher in summer and autumn than in winter and spring. The trends at Kagoshima and Tateno indicate higher values in late winter and spring than in summer and fall.

5. It is interesting to note that the ozone concentration in the 10-15 km layer over Marcus Is. reduces to small values at the time of the seasonal maximum in the total ozone amount. The annual maximum in total ozone is observed there in summer months.

B. Day-to-day changes at various levels

Pairs of nearly consecutive days on which umkehr observations were available were considered. In about two-thirds of the cases distribution profiles were available either on the next day or on the third day. Some such pairs are shown in Fig.1.10. It will be seen that noteworthy ozone changes are observed at 200- and 100-mb levels in spring and summer, while in autumn and winter the seat of the day-to-day ozone changes seem to be at 400- and 200-100 mb levels.

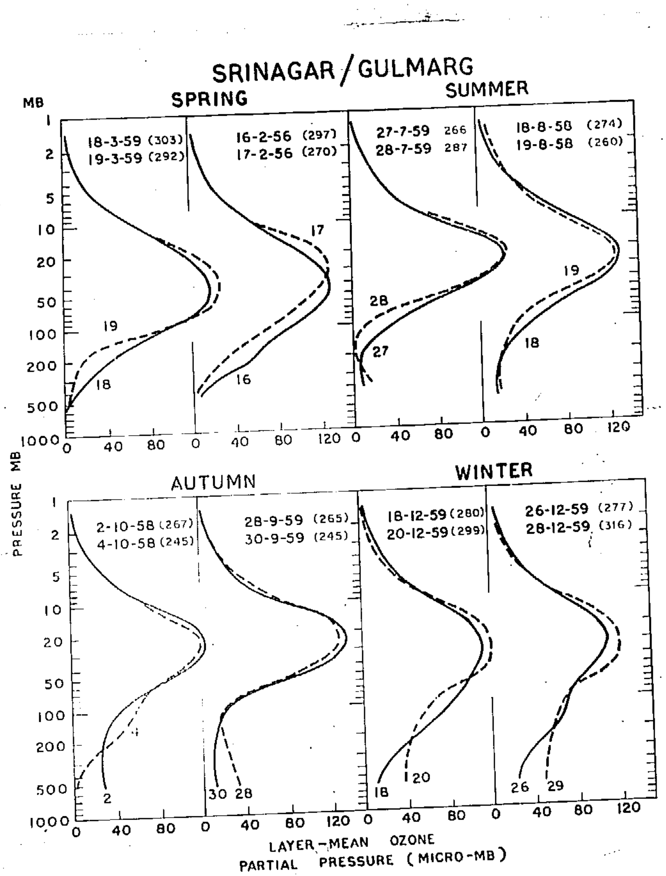

Fig.1.10 Day-to-day changes in the vertical distribution of ozone in different seasons.

Table 1.8

Srinagar/Gulmarg, 1955-59

Changes in ozone concentrations at various levels when the total ozone amount (Ω) changes by 20 m atm-cm.

(A) Seasonal averages

Period	No. of obs.	Layer c.g. at								
		400 mb	200	100	50	25	12	6	3	1.5
				p_3 (micro mb)						
Feb, Mar.	5	5	22	12	5	-11	-4	3	0.5	0.5
Jun-Aug.	7	8	16	12	4	- 7	-1	1	-1	-1
Sep-Nov.	12	18	7	0.5	-0.5	- 5	-5	-3	0.5	0.5
Dec.	5	20	1	-8	2	2	2	-2.5	-2	0

(B) Grouped according to ozone changes (all seasons combined)

Ozone increment	No. of obs.									
+ 20 D.U.	12	17	6.5	2	3.5	- 2	-3	-3	-0.5	0.5
- 20 D.U.	22	- 9.5	-10.5	-7	-5.5	4	1.5	-1	0	0

Table 1.8(a) provides the same information in figures worked out from all the pairs. To give equal weight to all the entries the ozone changes in all observations were normalized to increase of 20 D.U. since a majority of pairs showed ozone changes of this magnitude. The changes in layer-mean ozone concentrations are grouped according to the sign of the changes in the total ozone amount. From Table 1.8(b), it is seen that the day-to-day ozone changes take place mainly in the lowermost layers (5-15 km) but hardly above the 100-mb level and hence are brought about by 'weather' changes in the troposphere (and in lower stratosphere during spring and summer months).

The negative correlations between Ω and ozone concentrations in the layers 5, 6 and 7 noted in the previous section from mass plots (Fig.1.9) are seen in the day-to-day ozone changes also (see Table 1.8(a) and (b)).

C. Vertical distribution profiles in different seasons

Fig.1.10 shows the typical distributions observed in different seasons. The winter profile is different from the distributions observed in other seasons. The ozone concentrations in the troposphere and lower stratosphere are significantly larger in winter than in any other season.

The monthly mean distributions extracted from Appendix II are shown in Table 1.9 and Figs.1.11(a) and (b). The total ozone amounts available on days when umkehr observations were available (along with the number of observations) are

Table 1.9

Mean monthly vertical distribution of ozone Srinagar/Gulmarg, 1955-59

Layer-mean ozone partial pressure (in micro mb)

Month	D.U.	No.of obs.	Layer 1	2	3	4	5	6	7	8	9
Jan.	280	4	36	53	64	95	105	68	33	16	6
Feb.	277	5	9	45	80	118	126	73	30	14	5
Mar.	295	13	10	36	85	130	129	78	33	15	5
Apr.	272	7	18	34	58	108	127	83	36	14	4
May.	274	3	24	26	50	105	126	87	41	16	5
Jun.	277	10	35	31	39	95	120	88	44	15	4
Jul.	251	10	19	22	36	91	130	86	39	14	3
Aug.	255	22	14	15	39	100	138	89	39	15	4
Sep.	245	23	22	16	25	84	128	89	42	16	5
Oct.	243	19	16	18	34	89	128	84	40	16	5
Nov.	243	19	18	17	35	92	128	82	35	15	4
Dec.	270	11	21	44	65	104	117	74	32	14	5
	Total	146									

collected in Table 1.9. Fig.1.11(a) gives the average time-height cross-section showing the isopleths of layer mean ozone partial pressures (p_3) in micro-mb. It may be noted that marked ozone

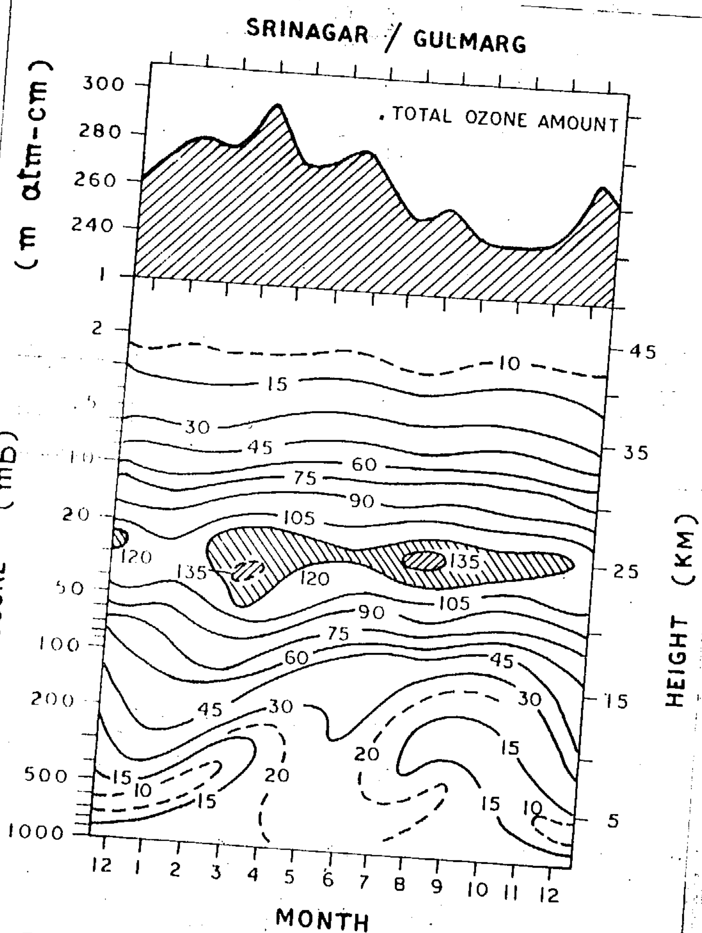

Fig.1.11(a) The mean time-height cross-section showing ozone isopleths (p_3 in μ mb) over Srinagar/Gulmarg (34^{o}N), 1955-59.

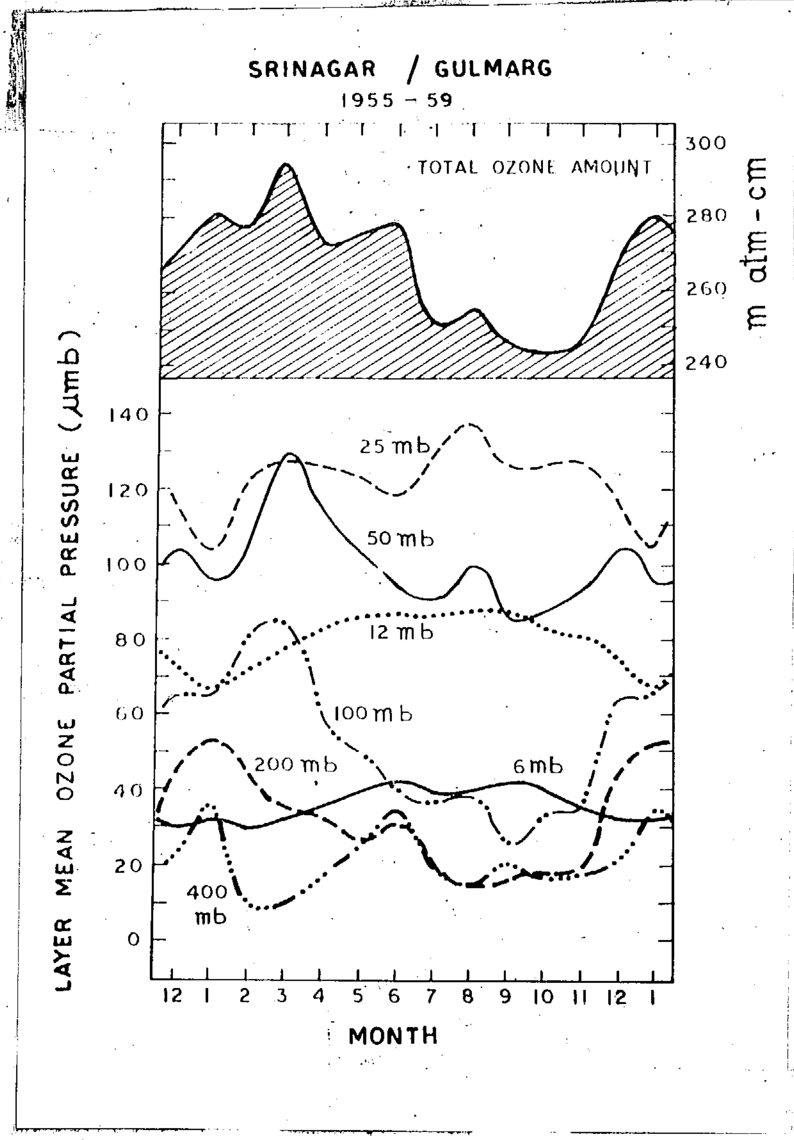

Fig.1.11(b) Changes in ozone concentrations at various pressure levels in different months.

changes take place mainly below the 25-mb level (25 km) which is seat of the main ozone peak. In the lower stratosphere the ozone variation is very similar to that in total ozone. It is mainly due to an increase between 300-60 mb levels (10-20 km).

In the 500-200 mb region, the seasonal ozone variations are large. The region with minimum ozone concentration occurs at about 700-mb in winter, at 500-mb in March and at about 250-mb in August and September.

The ozone concentrations in the middle stratosphere (above 27 km) are found to vary only slightly in course of the year. In the 30-35 km layer the ozone amount is larger in summer than in winter which is parallel to photochemical activity.

D. Secondary ozone maximum in the troposphere

In the evaluation procedure adopted to obtain the vertical distribution of ozone from the umkehr curve a good deal of smoothing has been done, and fine-structures are not discernible; only the prominent features are observable. If, however, the magnitude of the ozone bulge is large enough to survive the smearing, such feature appears as an upswelling in the vertical distribution profile. On a number of days a second ozone peak, in addition to the main peak at about 25-mb, is found present at about 200-mb (12-15 km). A few examples of such double-peaked distributions are shown in Fig.1.12.

The frequency of occurrence and its magnitude are noted to be larger in summer and autumn at Srinagar/Gulmarg than in the other two seasons (see also, Sticksel, 1966). The secondary maximum observed at these heights is believed to be

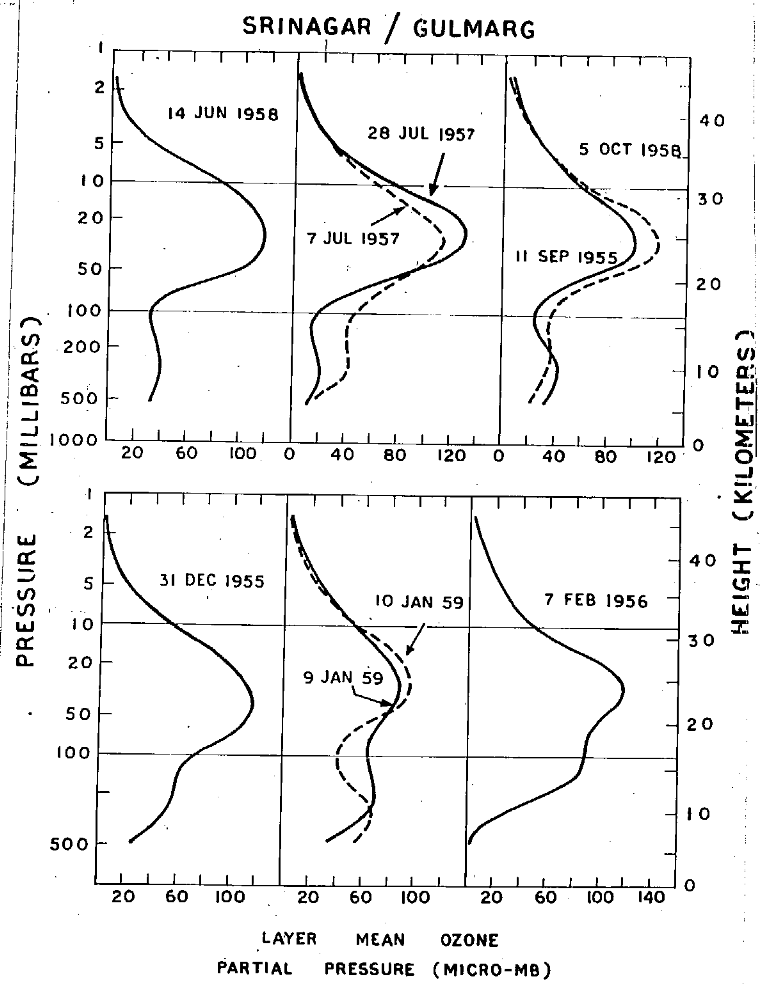

Fig.1.12 Secondary ozone maxima in the troposphere.

associated with the tropopause breaks observed in this part of the year at 35° to 40°N.

APPENDIX I TO CHAPTER I

COMPARISON OF OZONE AMOUNTS MEASURED AT DELHI (28½°N), SRINAGAR (34°N) AND TATENO (36°N) IN 1957-58*

by

R.N.Kulkarni, P.D.Angreji and K.R.Ramanathan

Abstract

A new ozone station was established in Kashmir (34°N) in 1955 in a region where double tropopauses are frequent in winter and spring. In this paper, a comparison is made of the ozone amounts measured at Delhi (28½°N) and Srinagar (34°N) in India and at Tateno (36°N) in Japan in 1957-58. The ozone amounts at Tateno are much larger than at Srinagar although the latitude of Tateno is only 2° greater than that of Srinagar. It is recalled that at Zi-Ka-Wei and Cairo, which are at lower latitudes than Srinagar, significantly higher ozone values had been recorded in winter. It is thus evident that there is a large geographical influence on the total ozone amount measured at a place. Apparently, the Himalayas and the Indian summer monsoon extert a strong depressing influence on the ozone amount south of the Himalayas and incursions of the cold Siberian anti-cyclone tend to bring with it larger amounts of ozone over China and Japan.

The seasonal variation of ozone over N.India was of an unusual character in 1957.

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* A paper published in 'Papers in Meteorology and Geophysics', Japan, Volume 10, No.2, December 1959, p.85-92.

APPENDIX II TO CHAPTER I

Vertical distribution of ozone over Srinagar/Gulmarg (34°N) on individual days*.

Date	Total ozone amount (D.U.)	p_3(μ mb) in the layer								
		1	2	3	4	5	6	7	8	9
6 Jan.56	282	20	38	74	117	122	72	30	16	6
22 Jan.56	278	19	44	75	110	117	71	33	15	5
9 Jan.59	278	43	71	65	78	86	61	36	18	6
10 Jan.59	282	60	58	41	76	94	67	33	15	6
5 Feb.56	290	-1	73	108	131	109	66	32	14	4
7 Feb.56	263	4	57	91	103	115	61	29	16	4
16 Feb.56	297	12	62	98	132	116	69	31	12	3
17 Feb.56	270	4	37	79	115	131	75	31	15	5
28 Feb.59	263	26	-5	25	109	157	93	28	13	5
9 Mar.56	266	21	27	53	102	132	78	32	14	4
10 Mar.56	253	4	19	61	110	136	77	32	14	4
23 Mar.58	304	20	21	70	132	140	99	44	11	2
6 Mar.59	291	11	29	83	136	133	83	32	12	4
7 Mar.59	289	13	32	80	129	126	77	35	16	7
8 Mar.59	283	19	38	77	116	116	69	36	18	7
12 Mar.59	308	21	51	94	131	116	70	35	17	7
13 Mar.59	299	25	53	80	124	122	78	30	12	4

* Layer mean ozone partial pressures (p_3) given here are taken from "Uniform evaluation of Umkehr Observations from the World Ozone Network" part II by Dutsch and Mateer (1964, 1965).

Date	Ω (D.U.)	p_3 (μ mb) in the layer								
		1	2	3	4	5	6	7	8	9
14 Mar.59	277	-2	35	89	129	134	77	32	14	4
17 "	298	-18	56	131	160	129	65	24	14	6
18 "	303	10	47	96	137	126	78	36	14	4
19 "	292	8	15	89	146	137	79	33	15	5
22 "	292	-1	43	95	138	126	83	41	13	3
5 Apr.56	271	25	24	44	102	134	86	36	14	4
14 "	246	14	18	39	96	135	84	31	13	3
16 "	242	23	17	18	83	131	95	41	11	1
12 Apr.58	286	13	42	82	127	127	80	32	10	2
23 "	268	12	29	54	103	131	89	46	14	2
13 Apr.59	298	15	68	94	121	106	66	37	19	7
14 "	292	25	41	77	126	123	78	31	11	3
27 May 56	249	28	24	34	89	129	83	32	11	2
8 May 58	283	28	25	45	107	126	90	47	17	5
12 "	291	15	30	72	120	123	87	44	18	7
6 Jun.55	257	23	2	25	100	144	95	42	14	3
21 Jun.57	249	6	28	58	105	134	79	29	10	1
13 Jun.58	286	43	32	29	92	116	94	50	16	4
14 "	282	36	38	33	91	118	99	53	12	1
15 "	291	54	31	37	95	112	88	44	14	4
21 "	288	55	54	44	84	93	72	42	17	6
22 "	292	47	45	49	95	103	81	46	17	5
23 "	277	32	24	39	101	126	87	43	15	4
25 "	272	25	32	41	94	126	92	46	14	2
26 "	274	32	22	30	95	129	94	47	15	3
16 Jul.55	235	13	4	20	94	140	96	42	11	0
22 "	235	28	18	19	78	123	85	38	14	3
7 Jul.57	257	24	43	46	82	114	78	42	14	2
9 "	257	29	44	52	80	106	65	37	19	6
16 "	248	9	23	42	92	127	87	47	16	3
18 "	246	18	15	27	92	136	92	38	12	2
28 "	241	18	19	16	79	131	100	46	13	2

Date	Ω (D.U.)	p_3 (μmb) in the layer 1	2	3	4	5	6	7	8	9
9 Jul.58	264	13	44	73	107	130	75	26	8	0
27 Jul.59	266	11	10	48	112	148	90	35	16	5
28 "	257	27	-1	16	96	148	95	37	15	5
24 Aug.55	226	20	8	20	83	126	81	35	16	5
26 "	230	11	16	30	84	125	83	39	17	6
2 Aug.57	260	22	20	32	95	139	94	39	11	1
3 "	260	18	7	31	103	148	95	37	13	3
4 "	264	29	8	16	94	136	101	42	12	2
5 "	248	4	14	40	102	142	94	40	13	2
15 "	249	25	11	15	88	141	99	39	10	1
16 "	249	18	19	42	96	134	79	28	15	5
17 "	239	9	5	36	101	136	82	36	16	4
30 "	253	34	21	11	74	124	94	49	16	3
31 "	238	22	10	22	83	126	82	37	19	7
9 Aug.58	262	17	19	35	96	137	96	47	14	2
17 "	268	24	22	38	93	129	87	44	19	6
18 "	274	12	27	57	109	133	90	43	15	4
19 "	260	20	24	39	87	126	84	43	21	8
29 "	282	-6	19	84	139	142	84	40	17	5
30 "	267	-15	4	71	136	162	93	36	14	4
3 Aug.59	266	12	-1	31	113	158	106	43	11	1
11 "	250	2	21	57	108	140	83	30	13	4
12 "	256	9	23	51	100	134	84	38	15	4
13 "	257	8	19	54	109	143	84	29	12	3
20 "	256	9	14	47	106	143	83	34	14	4
6 Sep.55	235	39	24	19	70	112	75	35	16	5
9 "	225	26	20	20	72	113	76	38	17	6
11 "	233	36	40	24	58	99	73	38	19	7
17 "	234	33	13	9	73	123	86	40	16	5
23 "	221	28	6	14	81	123	77	32	14	3
25 "	225	11	2	24	93	133	85	38	13	2
26 "	227	40	17	11	69	113	74	33	16	5
27 "	219	25	13	14	73	118	79	35	15	5

Date	Ω (D.U.)	p_3(μ mb) in the layer 1	2	3	4	5	6	7	8	9
4 Sep.58	248	-2	-1	33	106	150	102	47	15	3
5 "	260	-7	4	44	107	147	102	56	21	6
12 "	266	31	26	29	81	123	87	46	20	7
13 "	256	12	20	35	93	137	97	45	15	3
15 "	249	27	22	19	76	123	93	48	16	3
16 "	254	32	14	23	84	127	82	39	19	6
17 "	254	26	-3	0	85	146	108	51	16	4
18 "	254	24	21	29	86	128	89	41	15	4
19 "	257	12	24	34	87	127	99	58	16	1
20 "	254	4	22	45	95	132	92	48	18	5
13 Sep.59	250	15	7	36	102	142	87	34	14	4
22 "	258	26	19	24	90	139	98	36	10	1
28 "	265	32	22	22	82	128	94	50	17	3
29 "	254	30	26	32	88	130	84	31	11	1
30 "	245	16	12	24	91	139	97	39	12	2
3 Oct.55	223	20	17	22	76	117	79	36	17	5
8 "	226	21	14	20	79	121	82	38	15	4
20 "	223	0	12	39	97	132	81	33	13	3
23 "	213	-7	14	39	91	127	81	35	15	4
25 "	231	12	22	45	91	122	72	29	14	4
29 "	253	20	24	53	102	132	72	26	13	4
1 Oct.58	258	15	14	30	93	136	98	50	16	3
2 "	267	28	29	46	95	126	79	36	15	4
3 "	260	6	12	49	109	148	90	35	15	5
4 "	245	4	35	57	92	119	78	42	16	3
5 "	255	26	37	37	78	116	82	43	17	4
6 "	253	24	23	30	84	125	86	42	17	5
8 "	247	35	11	12	79	128	86	38	17	6
29 "	258	9	18	48	100	135	83	39	19	7
12 Oct.59	249	13	19	36	90	129	88	44	17	5
14 "	241	12	8	31	93	134	86	39	17	6
17 "	237	36	15	-3	61	115	93	53	19	4
18 "	237	19	3	9	84	135	98	47	14	2
25 "	238	6	19	39	89	124	84	46	18	5

Date	Ω (D.U.)	p_3 (μ mb) in the layer 1	2	3	4	5	6	7	8	9
8 Nov.55	233	22	11	21	85	128	83	34	14	4
9 "	229	19	-1	16	93	139	87	32	11	2
10 "	230	15	9	28	91	130	79	32	14	4
12 "	226	29	3	10	80	127	78	30	15	5
13 "	233	15	15	35	90	127	75	29	15	5
15 "	222	-5	10	48	102	132	76	30	15	5
17 "	223	22	17	19	76	120	79	32	14	4
18 "	235	-17	12	63	112	139	83	36	16	5
21 "	233	26	21	23	76	117	76	34	16	5
24 "	238	15	23	39	86	120	76	37	17	5
26 "	229	18	20	31	82	120	76	32	15	4
28 "	245	22	30	45	89	121	72	27	14	4
30 "	227	6	14	41	92	125	75	33	17	6
12 Nov.59	286	27	34	60	115	124	84	37	12	3
13 "	273	23	20	46	108	136	87	37	14	4
17 "	264	32	32	38	85	122	81	39	15	4
20 "	260	11	18	48	103	139	88	38	15	4
21 "	253	20	23	27	87	131	96	46	12	0
22 "	286	46	18	20	103	134	99	40	11	2
1 Dec.55	222	18	14	19	78	123	82	33	14	4
11 "	227	13	27	46	87	117	67	26	14	5
20 "	237	1	35	63	95	121	71	30	15	4
23 "	250	16	38	60	94	120	68	26	14	5
26 "	274	21	45	71	105	120	71	29	14	5
31 "	290	33	58	73	114	110	72	29	10	2
18 Dec.59	280	14	53	82	107	110	71	38	18	6
20 "	299	39	44	64	116	121	82	33	11	3
26 "	277	26	57	70	96	109	72	35	15	4
29 "	316	47	56	69	116	117	77	33	13	4
31 "	292	1	51	99	137	122	77	37	13	3

CHAPTER II

"MEASUREMENTS OF THE VERTICAL DISTRIBUTION OF OZONE BY UMKEHR EFFECT AT HYDERABAD (17°.4 N) DURING SPRING 1961". This was published as a paper by R.N.Kulkarni, M.G.K.Menon and P.D.Angreji in the Indian Journal of Meteorology & Geophysics, Vol.16, No.1, January 1965, p.111-16.

CHAPTER III

3.1 "THE QUESTION OF THE APPARENT INCREASE OF OZONE DURING THE NIGHT"

This was presented by K.R.Ramanathan, G.M.Shah and P.D.Angreji at the Symposium on 'Atmospheric Ozone' held at Arosa in August 1961.

This is a reprint from

"Symposium on Atmospheric Ozone - II Arosa, August 1961", Internatl.Asso.Met.& Atmo.Phys., IUGG, Monograph No.19 (January 1963), p.13.

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THE QUESTION OF THE APPARENT INCREASE OF OZONE DURING THE NIGHT

by K.R.Ramanathan, G.M.Shah and P.D.Angreji

In 1952, measurements of total ozone were made at Mt.Abu and Ahmedabad by Murty and Ramanathan (Nature, 172, p.633, 1953) on several clear nights with the moon focussed on the slit of a Dobson Spectrophotometer. Observations on each night were made at a number of zenith distances of the moon. Direct sun observations were also made on the same and succeeding days. Owing to the prevalence of clear skies and the insignificant large-particle-scattering during day, it was assumed that the effect of haze could be neglected both during day and night. A single wavelength pair, mostly 3112/3323, was used for the comparison and straight line plots of log I/I' against sec Z were obtained. The observations showed an apparent increase of absorption during night proportional to sec Z, and this was interpreted to mean that the ozone amount increased during night by about 0.030 cm.

In 1958, it was decided to make more observations using at least two pairs of wave-lengths C and D. The apparent night-time increase of ozone was found to be greater with D wavelengths than C. Later, three pairs of wavelengths, A, C and D were used. The results showed that the apparent increase during night was different for the three pairs of wavelengths, the mean excess for A being, 0.015 cm, for C, 0.031 cm, and for D, 0.069 cm. It should be noted that no correction was made for large particle

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scattering either during day or during night. The observations were repeated at three stations, Abu, Ahmedabad and Anand (50 miles south of Ahmedabad) and the same general results obtained. Plotting the valuesof ΔO_3 obtained with C against those obtained with D, it was found that the curve was a straight line with a small scatter. Examination of the apparent ozone increases with A, C and D showed that they were roughly in inverse proportion to the values of $\alpha - \alpha'$. Using the difference-method with CD or AD pairs of wavelengths showed that there was no significant systematic increase of ozone during night.

This means that the apparent increase of ozone during night is not real but the increase in attenuation is due to scattering by large particles. If the increased attenuation is wrongly attributed to ozone, it would show an apparent larger increase in ozone when $\alpha - \alpha'$ is smaller. The question arises: at what levels does the night condensation take place after sun-set and what is the material involved ?

Our thanks are due to Principal A.R.Patel of Vallabh Vidyanagar who provided all necessary facilities for taking observations at Anand.

CHAPTER III

3.2 "NOTE ON OZONE OBSERVATIONS MADE WITH MOONLIGHT"

This was presented by K.R.Ramanathan, P.D.Angreji and G.M.Shah at the International Symposium on Ozone held at Albuquerque, N.M., during August-September 1964 and published in the Indian Journal of Meteorology and Geophysics, Vol.16, No.4, October 1965, p.675-76.

CHAPTER IV

HIGHER-ORDER UMKEHRS AND CONTRIBUTION DUE TO THE SCATTERING BY THE STRATOSPHERIC AEROSOL PARTICLES*

1 Introduction

Umkehr observations for finding the vertical distribution of atmospheric ozone are made usually upto sunset. The observations can however be continued after sunset, and show some interesting results. Observations made at Mt.Abu back in 1952 by Kulkarni (unpublished) showed on some days a second reversal in the variation of log I/I' (I = 3112 Å and I' = 3323 Å) when the sun was about 3° below the horizon. Dutsch (1959) reported a similar phenomenon observed at Arosa and noted that the second 'umkehr' occurred on the C wavelength pair when the solar depression (θ) was about 3°.5 and on the D wavelength pair at θ = 4°. The presence of the second umkehr has also been reported by Wardle, Walshaw and Wormell (1963).

Observations made during 1960-61 at Ahmedabad have shown the second umkehr at θ = 2° on the wavelength pair A, with a tendency for a third umkehr also (Ramanathan and Shah, 1963).

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* Preliminary results of this study were communicated in a note by Angreji and Shah (1965) to the International Symposium on Atmospheric Ozone. Aug-Sep.1964. Albuquerque, N.M., U.S.A.

The study of this has been pursued further by the present author and the results are presented here.

2 Results and discussion

On 26 evenings during the clear seasons (January-April) of 1962 and 1963, umkehr observations were continued till $\theta = 7^{o}$ or more. The observations made in the same season in 1964, when the twilight glow was unusually bright, showed that the intensity of the second hump in the umkehr curve was much stronger. Fig.4.1 shows the enhanced intensities observed on 9 January 1964 on $\lambda\lambda$ A, C and D as compared to those on 6 January 1961. A summary of the observations of higher-order umkehrs made at Ahmedabad during 1962-64 is given in Table 4.1. It gives the times of occurrence of the umkehr points in θ (solar depression angles in degrees) and the values of $p_{\lambda}(N - N_{o})_{\lambda}$ observed at the time of the umkehrs. The difference between the mean values observed during 1962-63 and the averages for 1964 is quite significant. This becomes more conspicuous when a comparison is made with the measurements on 8-16 January 1964 only (see Table 4.1). In the period subsequent to 16 January 1964, the twilight glow in the visible part of the spectrum and the intensity of the second hump in the umkehr showed substantial decrease (see Fig.4.3).

To account for (i) the magnitude of the second hump in the plot of $p_{\lambda}(N - N_{o})_{\lambda}$ against Z^{4} and (ii) the time of occurrence of the higher-order umkehrs, consideration of primary scattering alone is inadequate. Dave (1956) has theoretically

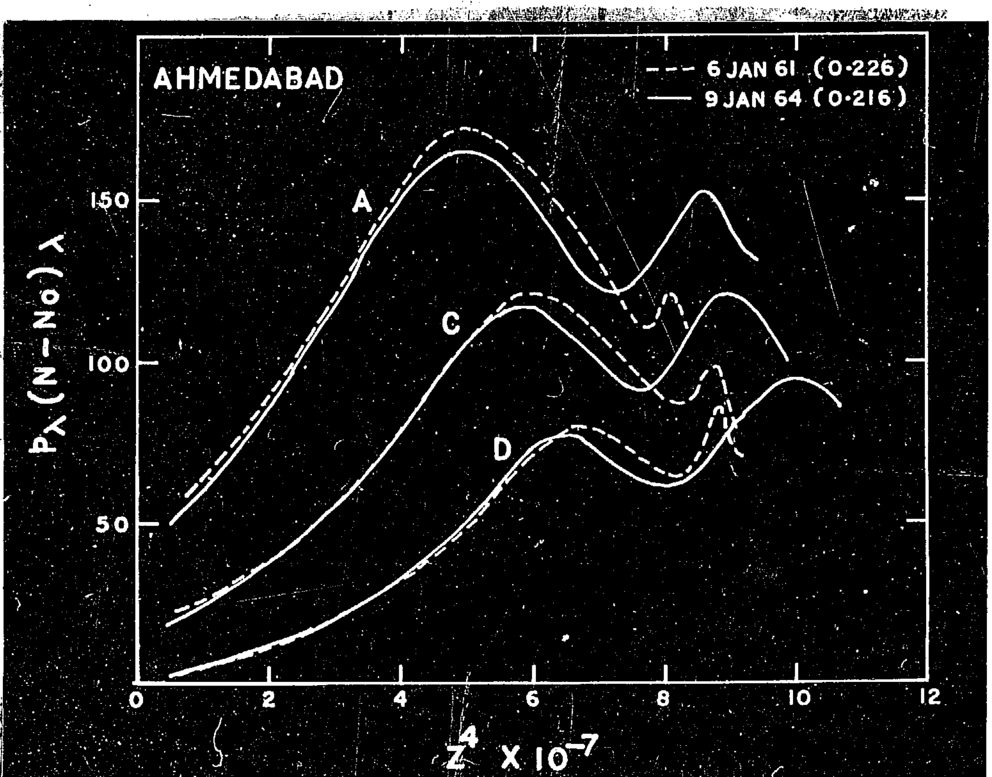

Fig.4.1 Higher-order umkehrs on 6 January 1961 and 9 January 1964. Note enhancement of the second hump on all wave-length pairs on 9 January 1964 - the period of enhanced twilight glow.

Table 4.1

Summary of Observations on the Higher-order Umkehrs - Ahmedabad, 1962-64

Wavelength pair	Period	No. of obs.	Solar depression angle θ at time of the umkehr (Deg.) I	II	III	$p_\lambda (N-N_o)_\lambda$ * at time of the umkehr I	II	III	ΔN magnitude of the 2nd hump
A	Jan-Apr. 1962, 63	11	-7.6	2.0	4.9	168	121	130	9
3055 Å/3254 Å	Jan-Apr. 1964	13	-7.5	2.0	5.8			136	15
	8-16 Jan. 1964	6			6.2			146	25
C	Jan-Apr. 1962, 63	26	-3.1	3.6	6.2	119	92	107	15
3114 Å/3324 Å	Jan-Apr. 1964	14	-2.7	3.4	7.1			115	23
	8-16 Jan. 1964	6			7.8			120	28
D	Jan-Apr. 1962, 63	23	-0.6	4.1	7.0	80	62	80	18
3176 Å/3398 Å	Jan-Apr. 1964	14	-0.4	4.5	8.2			88	26
	8-16 Jan. 1964	6			8.7			92	30

* $p_\lambda (N-N_o)_\lambda$ essentially gives the intensity ratio; where except p other symbols are as defined in Chapter 1. p is a factor correcting for differences in photomultiplier responses for different wavelength pairs. I umkehr - First Maximum, II umkehr - First Minimum, and III umkehr - Second Maximum in the plot of p N versus Z^4.

calculated the contributions of primary and secondary scattering in the twilight airglow measurements. He has shown that when $\theta > 6^{\circ}$ the secondary scattering becomes dominant at 20-25 km altitude. Thus it seems likely that the second hump observed in the umkehr observations at $\theta = 5\text{-}7^{\circ}$ is mainly due to the secondary and higher orders of scattering. It is interesting to note that in 1963-64 when the twilight glow in the visible spectrum showed enhanced intensity due to the increase of aerosol particles in the lower stratosphere at an altitude $\sim$ 20 km following the Bali volcanic erruptions (Meinel and Meinel, 1963, 1964; Shah & Ramanathan, 1965), we found substantial increase in the intensity ratio of wavelength pairs in the ultra violet also. The increase of aerosols caused increased intensity of scattered light at lower wavelength due to preferential forward scattering.

Intensity and polarization studies of the scattered sky-light during the twilight period, provide valuable information regarding the stratospheric aerosol particles. The characteristic features recorded during a typical evening twilight in the spectral band 6400-6600 Å at Ahmedabad in 1963-64 (the period of enhanced twilight glow) are shown in Fig.4.2 alongwith the higher-order umkehrs observed in the UV-wavelengths. The peculiar time variation of the rate of change of intensity ($\Delta I/I$) and the remarkably large depolarization factor seen in the wavelength band around λ 6500 Å are, no doubt, due to the forward scattering by the stratospheric aerosol layer. The curves in Fig.4.2 are typical of the photometric measurements made at

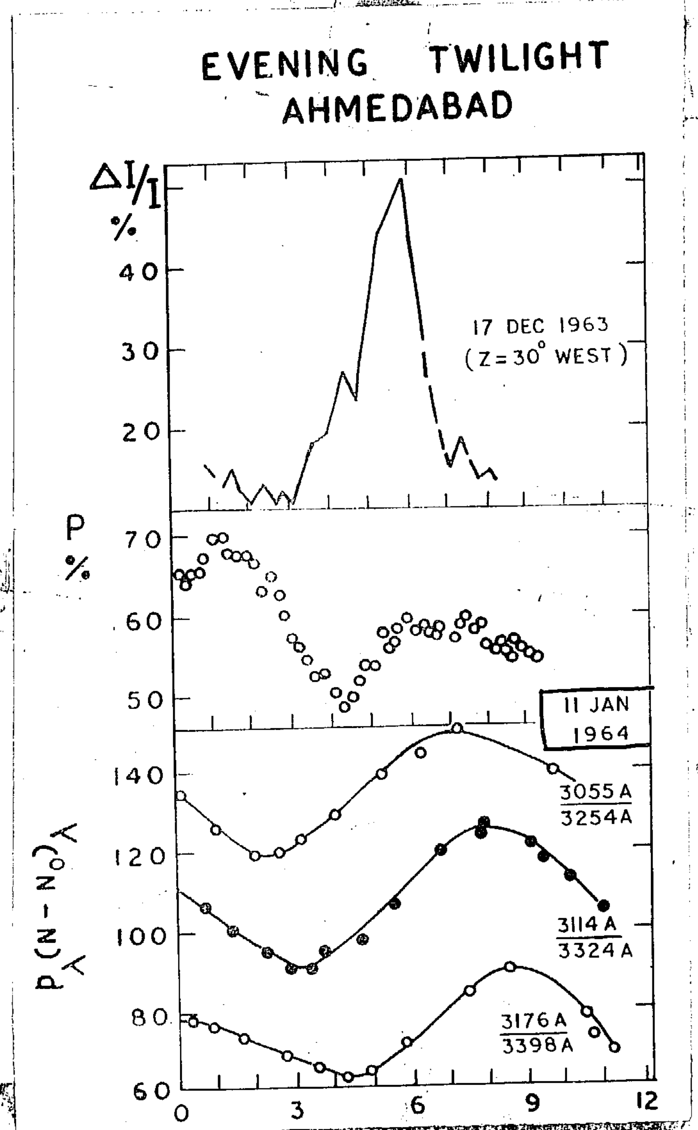

Fig.4.2 Typical time variations noted in the light scattered from the zenith. The first two measurements relate to the visible part of the spectrum (λ6400 Å to 6600 Å) and the third set shows the variation in the intensity ratio of wavelength pairs in the UV-part of the spectrum.

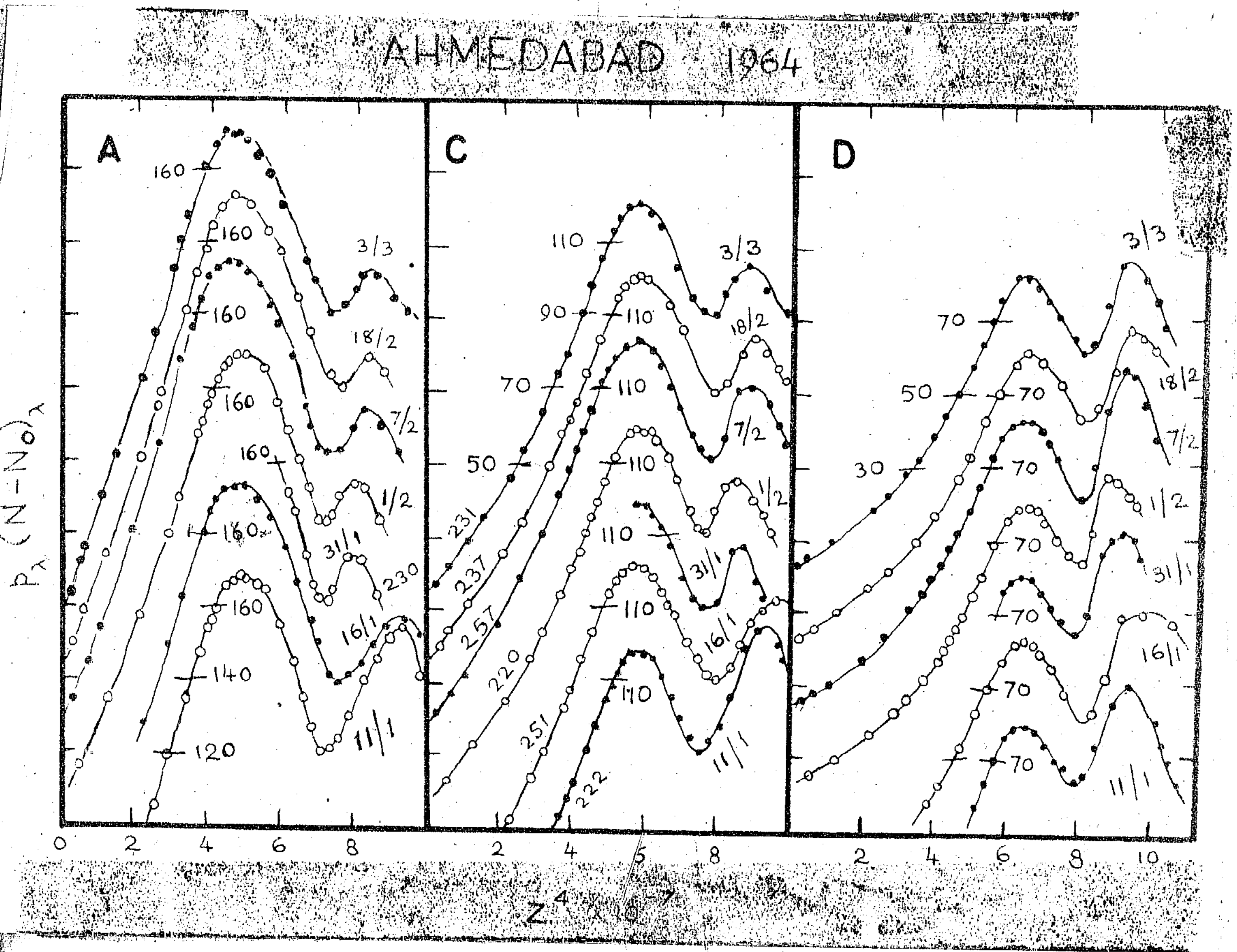

Fig.4.3 Higher-order umkehrs on a number of days during January-March 1964. Note that the observations on 11 and 16 January 1964 stand in a class apart. Twilight observations showed marked difference in the intensity of the 'glow' before and after 16 January 1964.

Ahmedabad during 1963-64 beginning from 11 November 1963. The occurrence of the higher-order umkehrs observed during this period (shown in the third block) seems to suggest that the variations in Log I/I' in the UV region are linked with the effects of the forward scattering by the aerosol layer at 20-25 km level in the visible spectrum. We should therefore expect that :

(1) the second hump should gradually attain its normal values as and when the twilight glow returns to the normal condition;

(2) the day-to-day changes in the relative intensities of the second hump, should be similar at $\lambda\lambda$ A, C and D; and

(3) the effect be most pronounced in the case of $\lambda\lambda$'D. That this is the case, can be seen from Fig.4.3 where the enhanced effect on a number of days from 11 January to 3 March 1964 are shown. The observational results shown here indicate that the second hump started to decline after 16 January 1964 (see Table 4.1), and the evening twilight glow had become almost normal by the end of March 1964.

Our results thus show that the contribution by the forward scattering by the stratospheric aerosol particles is a significant factor in determining the time of occurrence of the higher-order umkehrs and the systematic changes in the intensity ratios as shown by the second hump and changes therein (Fig.4.3), when the sun is appreciably below the horizon.

CHAPTER V

STUDIES ON BIENNIAL VARIATIONS IN ATMOSPHERIC OZONE

PART (I) METHOD OF ANALYSIS, DETERMINATION OF THE PERIOD

1. Introduction

The existence of biennial variations in atmospheric ozone over Australian latitudes was found by Funk and Garnham (1962). They plotted 12-month moving averages of the ozone series, annulling thereby the seasonal variations which have large amplitudes. Existence of such a biennial feature was attributed by them to changes in the subsidence pattern of ozone-rich stratospheric air. The ozone data used by them cover the time period 1955-61.

Ramanathan (1963) showed that there were similar variations in the subtropics and lower-middle latitudes in the northern hemisphere and that over equatorial latitudes, there were corresponding variations with an inversion of phase. The period covered by his study was 1954 to 1962. The presentation used by Ramanathan was plots of the monthly ozone values, and the biennial variation can be seen from the modulation of that period on the seasonal cycles. Ramanathan pointed out that change in the phase of the biennial oscillation of the ozone content over the equator as shown by the ozone records of Kodaikanal (10^{o}N) was connected with the biennial change of zonal winds over equatorial latitudes. The changes in the meridional transports associated with the changes in the zonal winds could cause a change in the relative ozone amounts and consequently the temperatures in the lower stratosphere (18 to 30 km) between the equator and lower-middle latitudes. This agency could also produce an ozone flux between the tropics and the middle latitudes (for example, Aspendale, 38°S, or Rome, 42°N). The existence of the biennial oscillations in ozone upto 40° latitudes north and south, was established by Ramanathan (1963).

This study was pursued further by the author*. The investigation aimed at :

(i) determining the range of latitudes over which the biennial ozone cycle extends; and

(ii) to examine the changes in the amplitude and phase of the biennial variations with latitude and time.

A 24-month cycle was found to exist at all latitudes from Spitzbergen (78°N) to Kodaikanal (10°N) in India; and the period was found to be remarkably persistent upto about 55°N latitudes. It was also observed that a phase change occurred every 11 years, e.g. in 1941, 1952 and 1963; the amount of phase-shift being π radians each time, the same phase therefore repeating after 22 years. The phase change of 1963 was confirmed

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* Mention was made of the preliminary results of these studies by the present author, reported in Chapter 5, 6 and 7, by Professor Ramanathan in his Presidential address at the International Ozone Symposium (Albuquerque, Aug-Sep.1964).

by the low ozone values recorded during the spring of 1964 in the northern hemisphere, low as compared to those observed during 1962 or 1963. The data collected in the subsequent years show the biennial oscillation with maximum now occurring in the spring of the odd year.

These findings, their interrelationship with similar periods in other geophysical data such as the zonal winds at stratospheric levels, the stratospheric warmings etc. will be presented in this and in the next two chapters. In the present one we shall describe the methods of analysis employed, illustrated by a case study, and the results obtained regarding the period (in months) of the quasi-biennial variations in the ozone-series. The results of the harmonic analysis and the consideration of the composite-curve depend very much on the accuracy of the period assumed.

Rangarajan (1964a,b) has analysed the ozone series for the 26-month period; Angell and Korshover (1964) have determined the amplitudes etc. for the trial periods of 23, 26, and 30 months. We have considered the relation merits of the two periods of 24-and 26-months only.

2. Sources of data

The monthly mean values of ozone for each month of the period prior to the IGY were obtained mainly from the summary tables published by London, Ooyama and Prabhakara (1962), those for the IGY-IGC period from the table given in the Annals of the

IGY, and those for 1960 onwards from the 'World Ozone Data' published by the Canadian Meteorological Service, Toronto and W.M.O.

The ozone-values for the Indian stations thus obtained were corrected by the author for changes in calibrations [illegible].

In case of the Australian stations, Aspendale and Brisbane, the monthly mean values given by Funk and Granham (1962) and for Arosa (47°N) the data published by Perl and Dutsch (1959) were used.

3. Treatment of the data and notations used

Monthly mean ozone amounts observed during the 12 years, 1954-65, at Arosa (47°N), Rome (42°N) and Tateno (36°N) in the northern hemisphere and at the southern stations Aspendale (38°S) and Brisbane (28°S) are shown in Fig.5.1. Comparison of the seasonal maxima in the adjoining years at each of these stations shows the biennial variation. In order to separate the biennial variation, it is necessary to filter-out the other time-variations present in the series. Some idea of the relative magnitudes of the various components can be obtained from the following case-study.

We have the longest series of homogeneous ozone data from Arosa. Consider the period 1953 to 1962. Monthly means of the ozone values (Ω) observed during this period are tabulated in Table 5.1. The annual means of each year which are given in

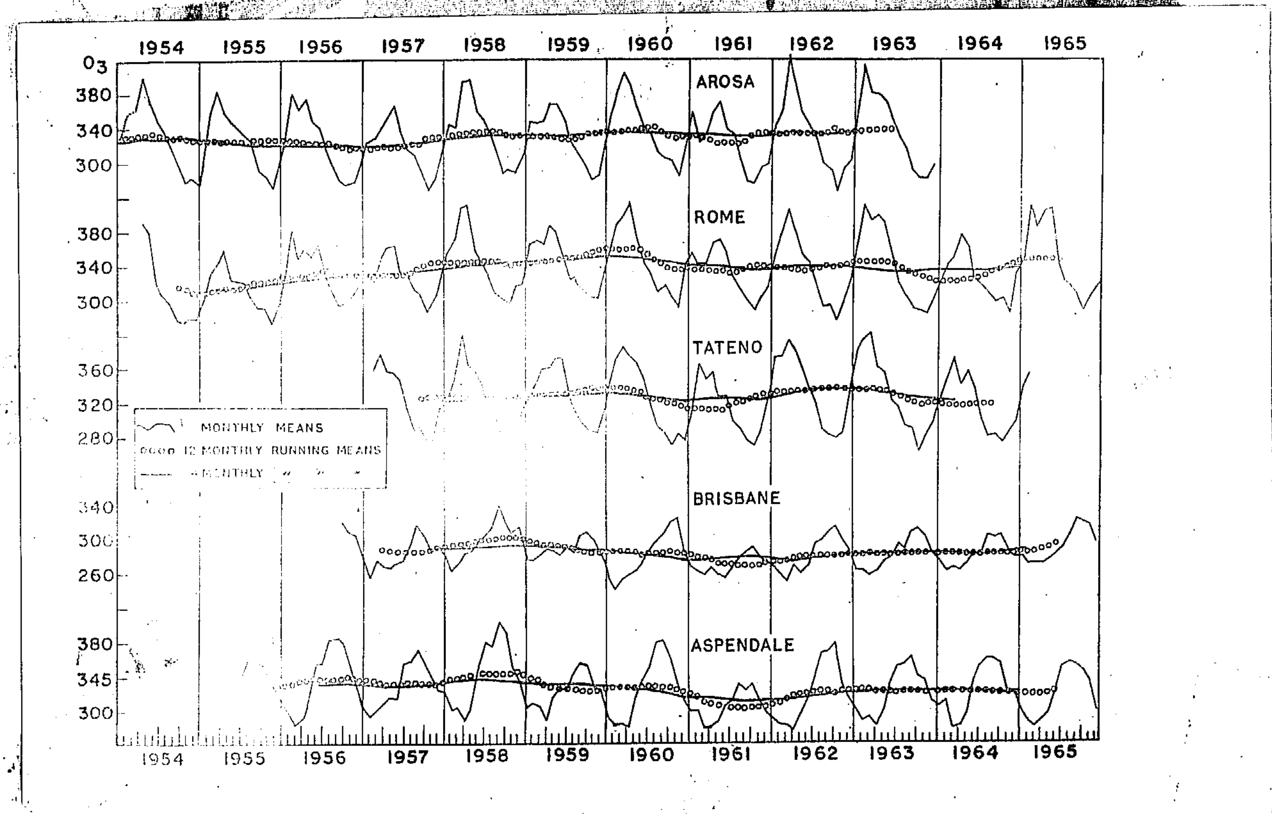


Fig.5.1 Monthly mean ozone amounts in D.U. at Arosa (47°N), Rome (42°N), Tateno (36°N), Brisbane (28°S) and Aspendale (38°S) during 1954-65. Appropriately centred 12-monthly and 24-monthly running means are also shown.

the last column show the trend. The ozone level changed from the lowest value of 319 D.U. in 1957 to the highest of 342 D.U. in 1960.

In the tabulated monthly mean values of Ω, the seasonal variation stands out clearly with a maximum in spring

Table 5.1

Monthly mean Ozone amounts, Ω , AROSA, 1953-62.
(Average of all months = 329 m atm. cm)

Month	J	F	M	A	M	J	J	A	S	O	N	D	Annual mean
						(m atm. cm)							
1953	324	362	359	367	367	345	316	306	283	269	258	-	322
1954	-	-	360	400	374	348	335	317	295	276	282	275	329
1955	305	360	384	359	348	339	328	321	290	283	269	290	324
1956	325	381	363	374	348	343	315	296	277	277	275	294	322
1957	325	328	338	354	367	335	315	308	288	267	282	317	319
1958	344	338	394	396	356	359	351	337	313	287	289	309	334
1959	349	346	347	368	367	359	324	313	298	280	284	310	329
1960	343	382	406	390	366	342	336	315	308	304	287	319	342
1961	361	327	337	359	371	342	334	307	281	279	296	300	325
1962	345	362	425	392	360	347	331	302	295	269	297	305	336
Average of five													
Even yrs. $\overline{\Omega}_E$	339	365	389	390	361	346	330	308	292	283	286	300	333
Odd yrs. $\overline{\Omega}_o$	332	344	353	361	364	344	323	311	288	275	277	306	324
$\overline{\Omega}_E - \overline{\Omega}_o$	7	21	36	29	- 3	2	7	- 3	4	8	9	- 6	9

and a minimum in autumn and an amplitude of about 50 D.U. The spring maxima are found to attain higher levels (~ 390 D.U.) in the springs of the even years - 1954, 1956, 1958, etc. as compared to the odd years (~ 360 D.U.). The spring maximum in the even year is noted to be rapidly rising one, maximum is reached in March or April and the ozone decrease is also pretty fast. On the other hand, not only the maximum is lower in the odd years (of 1953-62), but the build-up is gradual and the seasonal maximum is reached generally, during May. The biennial modulating effect is well seen from the two rows at the bottom which give $\bar{\Omega}_E$ and $\bar{\Omega}_o$ the average monthly values in the even and odd years respectively, of the decade 1953-62. The last row gives the differences $\bar{\Omega}_E - \bar{\Omega}_o$ for each calendar month. The marked difference is evident during the spring period, the even-year values being higher than the odd-year ones by about 30 D.U., resulting into a higher value for the annual mean in the even year (333 D.U.) as compared to that in the odd year (324 D.U.). Amplitude of the biennial oscillation is about 16 D.U.

The time variation of mean ozone amounts recorded at a given station can be decomposed into the following components :

(i) a seasonal cycle,

(ii) a biennial cycle, and

(iii) a long-period variation* or trend.

---

* The 11-year cycle in the ozone content, its interrelationship with the same period cycles in the solar activity, magnetic activity etc. are discussed in Chapter 8. However, in the present chapter this may be regarded as a trend only.

To extract the biennial oscillation, two analytical treatments were employed. They differ, essentially, in the procedure used to annul the seasonal variation, because in both the analyses the trend was determined by calculating the 24-month running means of Ω ($\vec{\Omega}_{24}$) centred at the middle of each period and the ozone series was expressed as departures from $\vec{\Omega}_{24}$. Representating the grand mean of all monthly mean of all years and months by Ω_0, tables of appropriately centred values of $\vec{\Omega}_{24}$ expressed as $\Omega_0 + x$ were prepared for each station. In case of Arosa (1953-62) the value of Ω_0 is 329 D.U. and the monthly values of x are as shown in Table 5.2. The 11-year oscillation is evident.

In the first method, the seasonal variation is annulled by considering the 12-month running means of Ω ($\vec{\Omega}_{12}$). The periodic oscillations of $\vec{\Omega}_{12}$ about $\vec{\Omega}_{24}$ in Fig.5.1, show the existance of the biennial variation in ozone.

Rangarajan (1964a,b) using the method of Anomalies (monthly values of departure from the mean monthly variation, also known as the normal variation), provided the first detailed description of the biennial variations seen at Kodaikanal, Brisbane and Aspendale. As stated above, we have also employed this method, but the basic material used in our investigation here are the ozone values corrected for the trend. The procedural details are like this :

Let the monthly ozone values be expressed as

Table 5.2

24-month running means of AROSA Ozone Amounts (in m atm. cm)

$$\vec{\Omega}_{24} = 329 + x = \Omega_o + x$$

Values of x

Month	J	F	M	A	M	J	J	A	S	O	N	D
1953	1	0	-1	-2	-1	-1	-1	-1	0	-1	-1	-2
1954	-2	-3	-4	-3	-4	-4	-5	-4	-4	-3	-3	-2
1955	-2	-3	-2	-2	-3	-3	-4	-5	-6	-6	-7	-7
1956	-6	-5	-6	-9	-9	-8	-8	-9	-9	-9	-10	-9
1957	-9	-8	-9	-8	-7	-7	-6	-6	-5	-5	-4	-3
1958	-3	-1	-1	0	0	0	1	1	1	2	2	2
1959	2	2	4	3	3	3	2	2	2	2	3	2
1960	3	3	2	1	1	1	2	2	3	3	3	4
1961	4	5	3	4	3	4	4	4	3	3	2	2
1962	1	2	5	7	8	8	8	8	9	9	9	9

$$= \Omega_{24} + y.$$

y, the departure from the trend, is made up of the seasonal and biennial cycles and small random fluctuations. The average value of y referring to the same calendar month ($\bar{y}$) gives the ozone normal Ω_N for that month. Departures of y from the corresponding $\bar{y}$ constitute the time series of the ozone anomalies ($\delta\Omega$).

These steps are illustrated in Table 5.3 and 5.4 for the Arosa ozone data for 1953-62. The monthly values of y ($= \Omega - \vec{\Omega}_{24}$) are shown in Table 5.3. The last row gives the values of $\bar{y}$ (or Ω_N). The departures of y from the respective values of $\bar{y}$, are given in Table 5.4. The last two rows give the grouped averages of $\delta\Omega$, $\overline{\delta\Omega}_E$ represents the average of $\delta\Omega$ of the even years and $\overline{\delta\Omega}_o$ represents the average of $\delta\Omega$ of the odd years of the decade. It will be seen that the anomalous increase in ozone in a given month of one year is balanced by the ozone decrease of the same amount in the subsequent year*. The biennial modulation of the Ω_N is seen convincingly in this illustration.

The method of anomalies was preferred in the present investigation, because it preserves the finer details of the

* The main biennial maximum occurring in March (Even year), in this example, is followed by a secondary maximum during October-November of the same year, and the second one is noted to occur during July-August (Odd year). These epochs are separated by 8 months. Apparently this is indicative of the third harmonic of 24-month period.

Table 5.3

Departures of month's mean Ozone amount (in m atm. cm) at AROSA from 24-month running means in Table 5.2.

$$\Omega - \vec{\Omega}_{24} = y$$

Month	J	F	M	A	M	J	J	A	S	O	N	D
1953	-6	33	31	40	39	17	-12	-22	-46	-59	-70	-21*
1954	12*	37*	35	74	49	23	11	- 8	-30	-50	-44	-52
1955	-22	34	57	32	22	13	3	- 3	-33	-40	-53	-23
1956	2	57	40	54	28	22	-6	-24	-43	-46	-44	-26
1957	5	7	18	33	45	13	-8	-15	-36	-57	-43	- 9
1958	18	10	66	67	30	22	7	-17	-43	-39	-42	-22
1959	18	15	14	36	35	20	-8	-18	-33	-51	-48	-21
1960	11	50	75	60	36	12	5	-16	-24	-28	-45	-14
1961	28	-7	5	26	38	9	1	-26	-51	-53	-35	-31
1962	15	32	91	56	23	10	-6	-35	-43	-69	-41	-33
$\bar{y}$	9	26	44	48	35	16	-1	-19	-38	-49	-47	-25

* Interpolated values.

Table 5.4

Monthly Ozone departures from the Ozone normals ($\bar{y}$ of Table 5.3) of the same month.

$$\delta\Omega = y - \bar{y}$$

Month	J	F	M	A	M	J	J	A	S	O	N	D	Mean of Mar-Apr
1953	-15	7	-13	- 8	4	1	-11	- 3	- 8	-10	-23		-10.5
1954			- 9	26	14	7	12	11	8	- 1	3	-27	8.5
1955	-31	8	13	-16	-13	- 3	4	16	5	9	- 6	2	- 1.5
1956	- 7	31	- 4	6	- 7	6	- 5	- 8	- 5	3	3	- 1	1.0
1957	- 4	-19	-26	-15	10	-13	- 7	4	2	- 8	4	16	-20.5
1958	9	-16	22	19	- 5	6	8	2	- 5	10	5	3	20.5
1959	9	-11	-30	-12	0	4	- 7	1	5	- 2	- 1	4	-21.0
1960	2	24	31	12	1	- 4	6	3	14	21	2	11	21.5
1961	19	-33	-39	-22	3	- 7	2	- 7	-13	- 4	12	- 6	-30.5
1962	6	6	47	8	-12	- 6	- 5	-16	- 5	-20	6	- 8	27.5
Average of 5 even years $\overline{\delta\Omega}_E$	6	11.5	17.5	14	- 2	2	3	-1.5	1.5	2.5	4	- 1	15.8
Average of 5 odd years $\overline{\delta\Omega}_o$	-4.5	-9.5	-19	-14.5	1	-3.5	- 4	2	- 2	- 3	- 3	4	-16.8

filtered-out components and the biennial period under study, and does not result in considerable smearing which is inherant in the method of moving averages.

Following the standard procedure (Conrad & Pollak, 1950), the first four harmonic components were evaluated. If the ozone amount at any time t is expressed as

$$\Omega(t) = \omega_T + a_n \cdot \cos(2\pi nt/T - \phi_n),$$

the amplitude of the n^{th} harmonic (a_n) and the phase corresponding to the occurrence of the first maximum positive deviation (ϕ_n) were determined for n = 1, 2, 3 and 4. We have later referred to a_n and ϕ_n as A_K and ϕ_K, = P_K where K is defined as $K = T/n$.

4. Determination of the period

To determine the period of the quasi-biennial variation the following analysis was done. Using all the outstanding maxima and minima in the plots of $\delta\Omega$ against time and the values in the months on either side in turn as zero epochs, the values of $\delta\Omega$ were written down for the interval extending from -3 to +30 months from the zero epoch. The period of phase shift occurring after every 11-years was not included in this analysis. Signs in the entire series were reversed when the zero epoch referred to the minima (negative deviations). The results are shown in Fig.5.2. The number (shown in parentheses) against each station gives the total number of such series that have been superposed. Distinct peaks are found to recur at 23-25 months from the zero epoch. Earlier ozone data from Mt.Montezuma (23°S) in Chile, taken from a paper by Tien (1938) when similarly analysed, showed existence of biennial period during 1923-30. The Arosa ozone data being the longest series of its kind (1932-61) gave the largest number of epochs (90); and the largest number in a single decade, 1952-61, was 36, for Oxford. The analysis reveals that the period is practically 24 months.

It is observed from Fig.5.2 that the changes taking

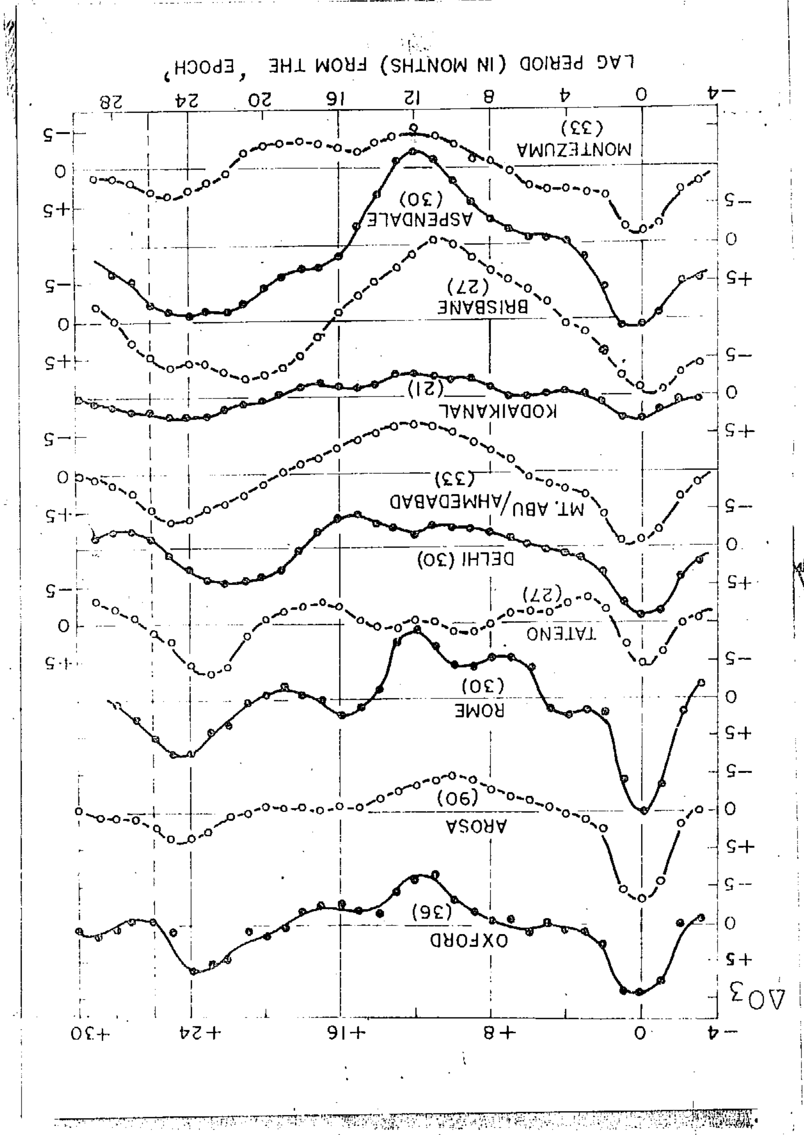


Fig.5.2 Results of the superposed epoch analysis, 52°N-38°S latitudes. Numbers in parentheses give the number of series superposed.

place with time at all stations are gradual and cyclic in nature. This justifies consideration of the harmonic analysis and consideration of composite curve (Composite curve here is a curve obtained by folding the time series at intervals having length of the assumed period.) with 24-and 26-months as trial periods. The results of the consideration of composite curve are shown in Fig.5.3. The period studied is 1952-62, and the geographic coverage is from 60°N to 40°S latitudes.

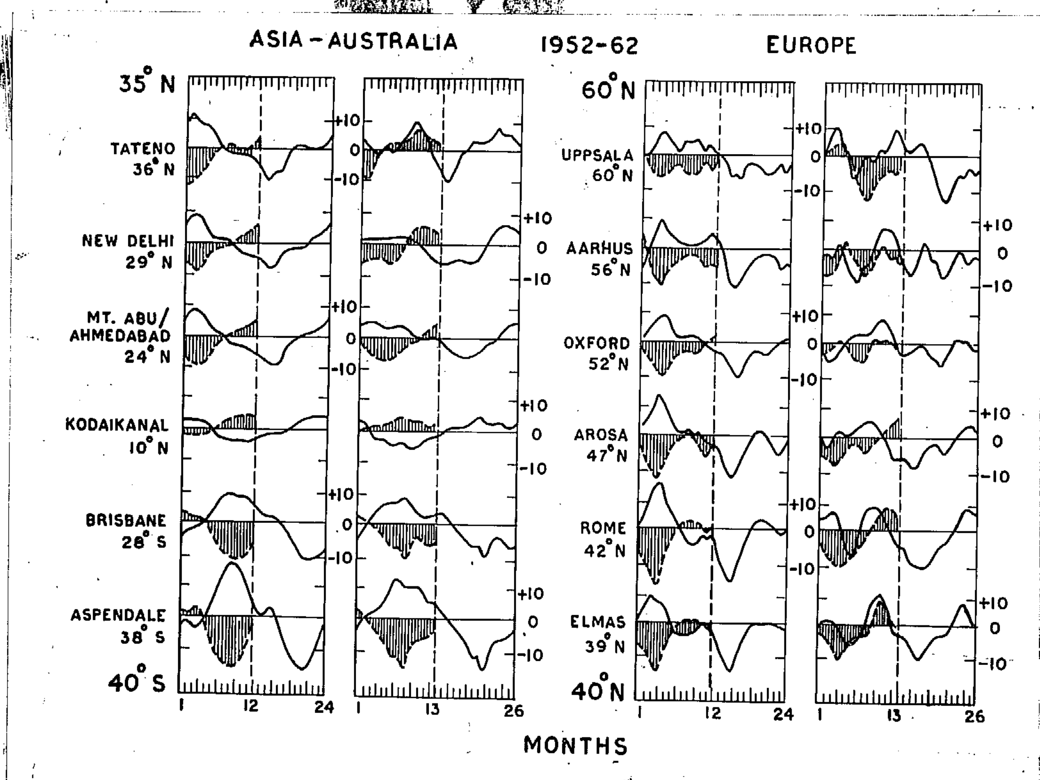


Fig.5.3 Composite curves with (a) 24-month and (b) 26-month periods of 3-month running means of ozone anomalies ($\delta\Omega$), 1952-62, for stations situated in 60°N-40°S latitudes. The first datum point corresponds to January of even year for the 24-month composite curve and January 1958 for the other one. Note that the mirror-images are seen in case of 24-month period at all latitudes.

If the trial period is the true period it is expected that (1) amplitude of the composite curve is larger compared to that in case of the neighbouring periods, and (2) after half the period the amplitude pattern should repeat in opposite sense giving the "mirror-images" over the entire length of the half-period. To check this second point, in Fig.5.3 we have retraced the second half of the composite curve (shown shaded) in the box corresponding to the first half of the period. The regular segment is not shaded to help comparison. It will be seen that the amplitude of the 26-monthly curves are smaller than that of the corresponding 24-monthly curves. Exactly equal and opposite amplitudes -"mirror images"- month after month occur in the 24-month curves only. A pseudo-period of 13 months appears at middle and high latitude stations in the northern hemisphere when 26-month composite curves are considered. Fig.5.2 shows that no such 13-month period exists.

In Table 5.5 we give the results of Fourier analysis of the composite curves obtained by folding the time series of $\delta\Omega$ at the trial periods of 24-and 26-months. Comparison of the amplitudes A_{24} and A_{26} shows that A_{24} is larger than A_{26} at all stations except at Kodaikanal. Percentage of total variance covered by the 24-month period is decidedly higher than that by the 26-month period.

In the latitude range 25°N-40°S where the difference between the percentage variance covered by the 24-and 26-month periods is marginal, the correlation ratio (η) defined as the

Table 5.5

Comparison of the 24- and 26-month composite curves 1952-62.

Station	Lat.	Period	No. of 26-m cycles	24-month period A_{24}	24-month period Time of A_{max} *	26-month period A_{26}	26-month period Time of A_{max} *	% of total variance 24-m	% of total variance 26-m	$\frac{A_{13}}{A_{26}}$	η_{24}	η_{26} **
	Deg.			D.U.	Deg.	D.U.	Deg.					
Aspendale	38 S	Jul.55-Jun.63	4	12.9	119	10.6	101	87	96	0.1	3.0	2.4
Brisbane	28 S	Jan.57-Jun.63	3	9.6	127	7.0	102	97	92	0.1	2.0	1.3
Kodaikanal	10 N	Jul.57-Jun.63	3	3.8	327	4.2	278	95	94	0.1	1.7	1.9
Mt.Abu/ Ahmedabad	24 N	Jan.52-Dec.62	5	6.9	12	5.1	40	92	85	0.3	2.3	1.4
Delhi	29 N	Jan.53-Dec.62	4½	6.3	9	4.9	7	93	71	0.5		
Tateno	36 N	Feb.57-Jul.63	3	5.8	14	2.4	351	70	14	2.0		
Rome/ Elmas	41 N	Apr.54/Sep.55 -Jul.63	4	7.5	19	4.4	42	64	28	1.5		
Oxford/ Arosa	50 N	Jan.52-Dec.62/ Dec.61	5	6.5	43	4.2	80	70	51	0.8		
Lerwick/ Uppsala	60 N	Mar.52-Dec.61/ Dec.59	4	4.8	71	3.1	110	68	16	2.2		

* For both the composite curves the time series were written in such a way that the phase angle P_{24} and $P_{26} = 0^{\circ}$ correspond to 15 January 1958.

** Correlation ratio 'η' is defined as the ratio of the standard deviation of a point in the composite curve to that of the individual data points. The higher the value of η, the trial period is nearer to the true period.

ratio of the standard deviation of the composite curve to that of the constituent elements - Ω (Whittaker & Robinson, 1962, p.346) were worked out. This criterion indicates that the period of 24 months is much nearer to the true period than the 26-month period. It is to be noted that the time of maximum deviation (P_k) in the case of 24-month period shows a consistent latitude effect.

The reality of the 24-month period can also be inferred from the criterion originally due to Schuster (Conrad & Pollak, 1950, p.398). The total number of values N are arranged in m rows of p values each. Now we analyse harmonically the first row, then the total of the first and second rows, then the total of the first, second and third rows, and so on, and finally the summation row of all the m (= N/p) complete rows. Now according to the criterion, the successive amplitudes obtained will increase as the square root of the consecutive integers, i.e. as $\sqrt{1} : \sqrt{2} : \sqrt{3} : \ldots : \sqrt{m}$, if the values are at random. Alternately, if the trial period p is a real period, the increase of amplitude will be proportional to 1 : 2 : 3 : ... : m, since in each row the period with the amplitude A_p repeats itself and is accumulated by forming the subtotal rows.

In Table 5.6 we show the results of this analysis based on the monthly ozone data corrected for the trend ($y = \Omega - \overrightarrow{\Omega}_{24}$), for Mt.Abu/Ahmedabad (24°N) and Arosa (47°N) for the decade 1953-62. The phase angle P_k of successive rows are more or less constant in both the sets, and the amplitudes observed, A_{24}, are increasing at both these locations in a manner as to support the 24-month period for the ozone variations.

Table 5.6

Phase and amplitude of 24-month period in the subtotal rows of 24 monthly ozone values, 1953-62

Period	MT. ABU/AHMEDABAD (24°N) P_{24} *	A_{24} (in D.U.) Observed	Theoretical: Random distribution	Theoretical: Periodicity	AROSA (47°N) P_{24}	A_{24} (in D.U.) Observed	Theoretical: Random distribution	Theoretical: Periodicity
	Deg.				Deg.			
Jan.53-Dec.54 (2 yrs)	212	6.4	$6 \times \sqrt{1} = 6.0$ @	6.0	246	9.4	$7.4 \times \sqrt{1} = 7.4$ @	7.4
" -Dec.56 (4 yrs)	191	15.7	$6 \times \sqrt{2} = 8.5$	12.0	220	12.8	$7.4 \times \sqrt{2} = 10.5$	14.8
" -Dec.58 (6 yrs)	190	19.2	$6 \times \sqrt{3} = 10.5$	18.0	219	20.1	$7.4 \times \sqrt{3} = 12.8$	22.2
" -Dec.60 (8 yrs)	192	22.6	$6 \times \sqrt{4} = 12.0$	24.0	224	28.7	$7.4 \times \sqrt{4} = 14.8$	29.6
" -Dec.62 (10 yrs)	190	29.8	$6 \times \sqrt{5} = 13.5$	30.0	216	39.1	$7.4 \times \sqrt{5} = 16.6$	37.0

* $P_{24} = 0°$ in these studies corresponds to January 1953 and increases by 15° for every additional month.

@ These values of A_{24} were determined by fitting least-square-line to the plots of A_{24}(obs.) versus the length of the series.

5. Biennial variation during 1952-62 at different latitudes

5.1 Temperate and low latitudes

Having established that the period of the biennial variation of ozone amount is 24 months, we now turn to the description of the biennial variation observed at different latitudes.

In Fig.5.1 itself we have plotted $\vec{\Omega}_{12}$ and $\vec{\Omega}_{24}$ (the 12-and 24-month moving averages of Ω), the regular oscillations of $\vec{\Omega}_{12}$ about the trend ($\vec{\Omega}_{24}$) showing the biennial cycle under consideration. Fig.5.4 depicts the appropriately centred algebraic differences between $\vec{\Omega}_{12}$ and $\vec{\Omega}_{24}$ for stations situated between 60°N-40°S latitudes, the time interval covered is 1952-64. The curves reveal the biennial oscillations in the ozone amount over this wide span of latitudes with the maximum positive deviations occurring in the local spring of the even years (1952, 1954, 1956, ..., 1962), except at the equatorial latitude (Kodaikanal),where there is a reversal of the phase. They also show that except for the disturbance noted in 1959 at the northern stations and in 1963-64 at the Australian stations, the perturbations do not obscure the underlying biennial periodicity at least upto Oxford latitude (52°N), beyond which the perturbations are found to increase considerably as we go to higher latitudes. Apparently there is a gradual shift of phase with latitude.

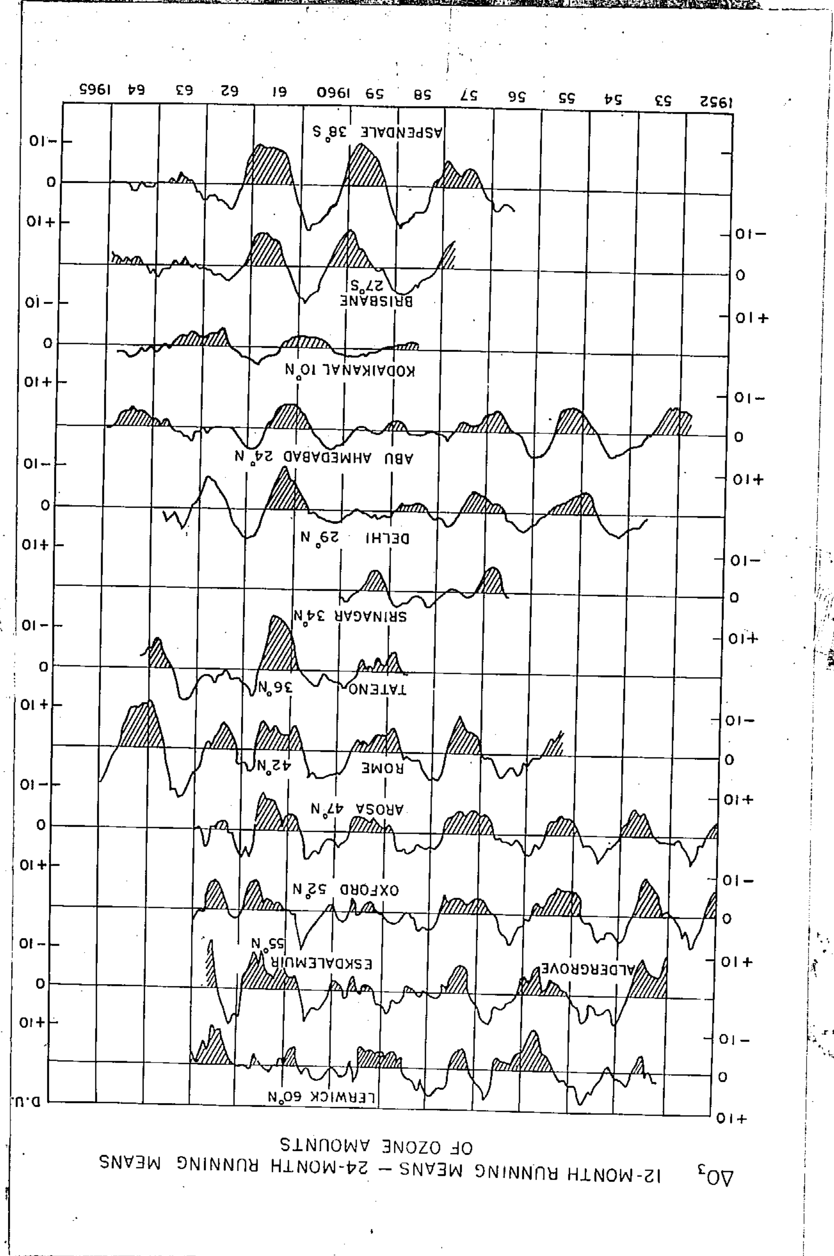


Fig.5.4 12-monthly running means minus 24-monthly running means ($\vec{\Omega}_{12}$ - $\vec{\Omega}_{24}$), in D.U., showing the biennial variations in ozone at stations situated from 60°N to 40°S latitudes during 1952-64.

Note the abnormal amplitude changes in ozone during 1959 in the northern hemisphere and a more conspicuous one in 1963 in the southern hemisphere.

3-month running means of $\delta\Omega$ for stations situated between 75°N and 40°S latitudes are shown in Fig.5.5a. The scale for $\delta\Omega$ is enlarged in the case of the equatorial station

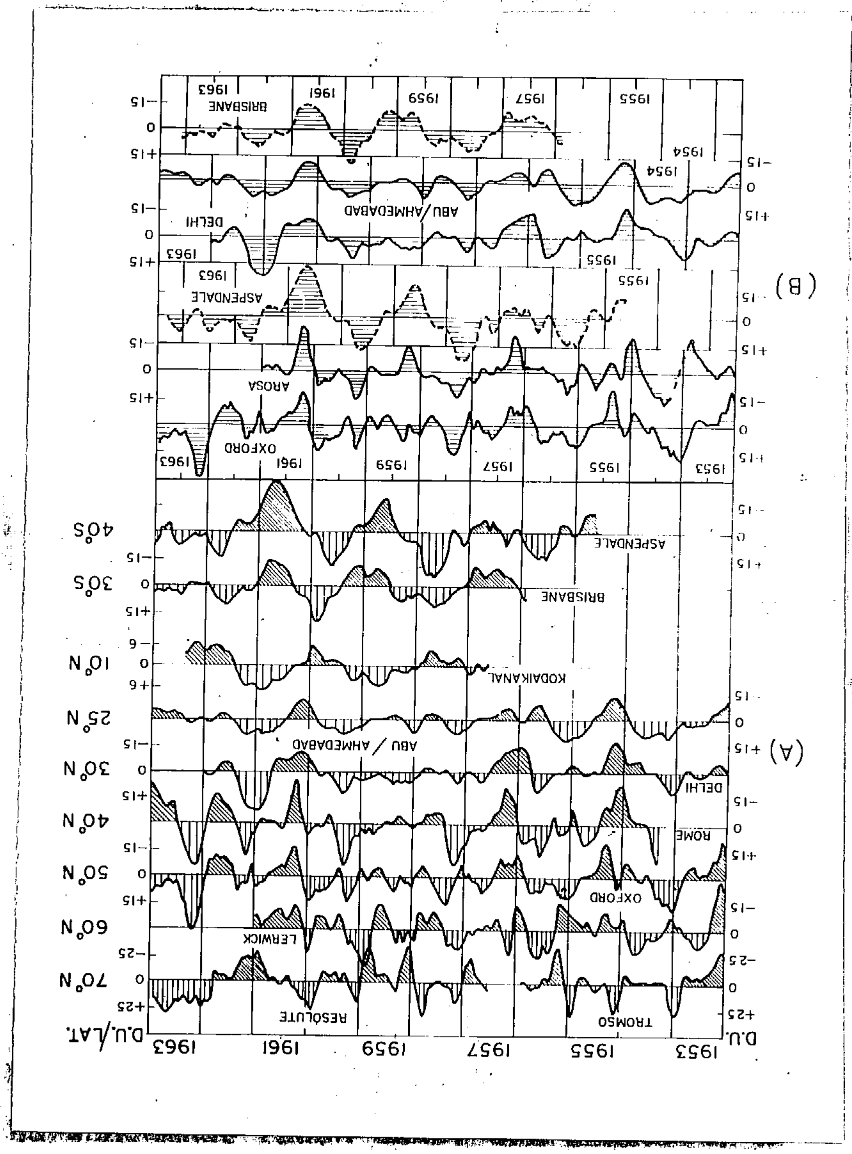


Fig.5.5a. Quasi-biennial variations in ozone amounts displayed with help of the monthly ozone anomalies (departure from normal) at various stations located between 70°/75°N and 40°S, 1953-63.

Fig.5.5b. Ozone series at Aspendale and Brisbane are seen to be lagging 6 months behind the series at northern hemispheric stations situated at the same latitudes.

Kodaikanal and is compressed in the case of the polar stations so as to facilitate the comparison of the biennial sequences observed in different latitudes. This essentially shows the same features noted above in connection with the Fig.5.4.

In Fig.5.5b, we have shown the time series of $\delta\Omega$ for Oxford (52°N) and Arosa (47°N) compared with that for Aspendale (38°S) shifted by six months, and in a similar manner the series for Delhi (29°N) and Abu/Ahmedabad (24°N) are compared with a (shifted) series from Brisbane (28°S). These comparisons show that not only the biennial maxima and minima but even the small scale perturbation mounted on the biennial wave are observed to appear in the time series for the Australian stations, after a delay of about six months.

The monthly ozone anomalies ($\delta\Omega$) tabulated in Table 5.4 for Arosa (1953-62), exhibit some noteworthy regularities. The values of $|\overline{\delta\Omega}|$ are seen to be the largest in March, second largest in April, and moderately large in February. As already noted earlier, there is also evidence suggesting existence of a 8-month period superposed over the biennial oscillation. The first maximum occurring in March of even year and the second one in October-November (even year) are separated by 8 months. These epochs roughly correspond to the time of occurrence of the stratospheric warmings in the northern and southern hemispheres respectively.

Almost equal and opposite values of $\delta\Omega$, similar to those seen in case of Arosa (Table 5.4) and giving a sort of "mirror-images", are present at other stations also (see Fig.5.6). The time-series of $\delta\Omega$ referring to the period 1952-62 for stations situated between 40°S to 70°N latitudes were used in construction of these plots of $\overline{\delta\Omega}$ shown here. The secondary maximum occurring some 6-8 months after the time of the main biennial ozone maximum (spring of the even year in the decade 1952-62) is seen at the lower-middle and higher latitudes but not at low latitude stations.

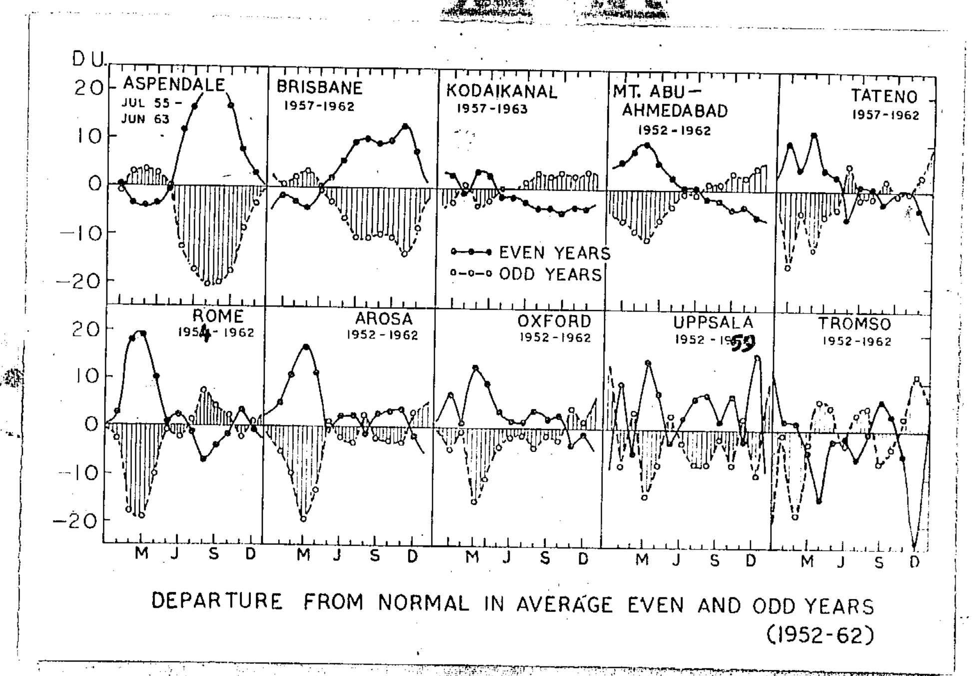


Fig.5.6 Ozone departures from normals, $\overline{\delta\Omega}$, in average even years and average odd years at stations situated between 40°S and 70°N latitudes during 1952-62.

These equal and opposite values of $\overline{\delta\Omega}$ though are interesting but not surprising, since $\delta\Omega$ has been defined as departure from the mean monthly ozone values. The results depicted in Fig.5.6, simply tell that the strong ozone surges have clear seasonal preference and are found repeating punctually after 24 months. These well defined, impressive patterns of owe their existence to the marked degree of persistence (see for example, Table 5.6) in absence of which the random component would increase considerably resulting into reduction of the resultant amplitudes of $\overline{\delta\Omega}$. It is rather amazing to find that even when individual pairs of years are considered, the values of $\delta\Omega$ in the two spring periods, in general, are not very different except in the sign. This point is illustrated in Table 5.7. The months over which $\delta\Omega$ are averaged, lie in the spring period and are selected for the large values of $\overline{\delta\Omega}$ (March and April in case of Arosa, see Table 5.4). The same criterion was applied while selecting the interval in case of Kodaikanal (10°N). The evidence at hand clearly suggests that the ozone changes (excess or deficiency) in any one year gets mostly annulled in the spring of the next year, and the residuals get corrected in few cycles as indicated by the seasonal means of $\delta\Omega$ averaged for all the even and all the odd years during 1953-62.

5.2 High latitudes

Biennial variations in ozone similar to those observed

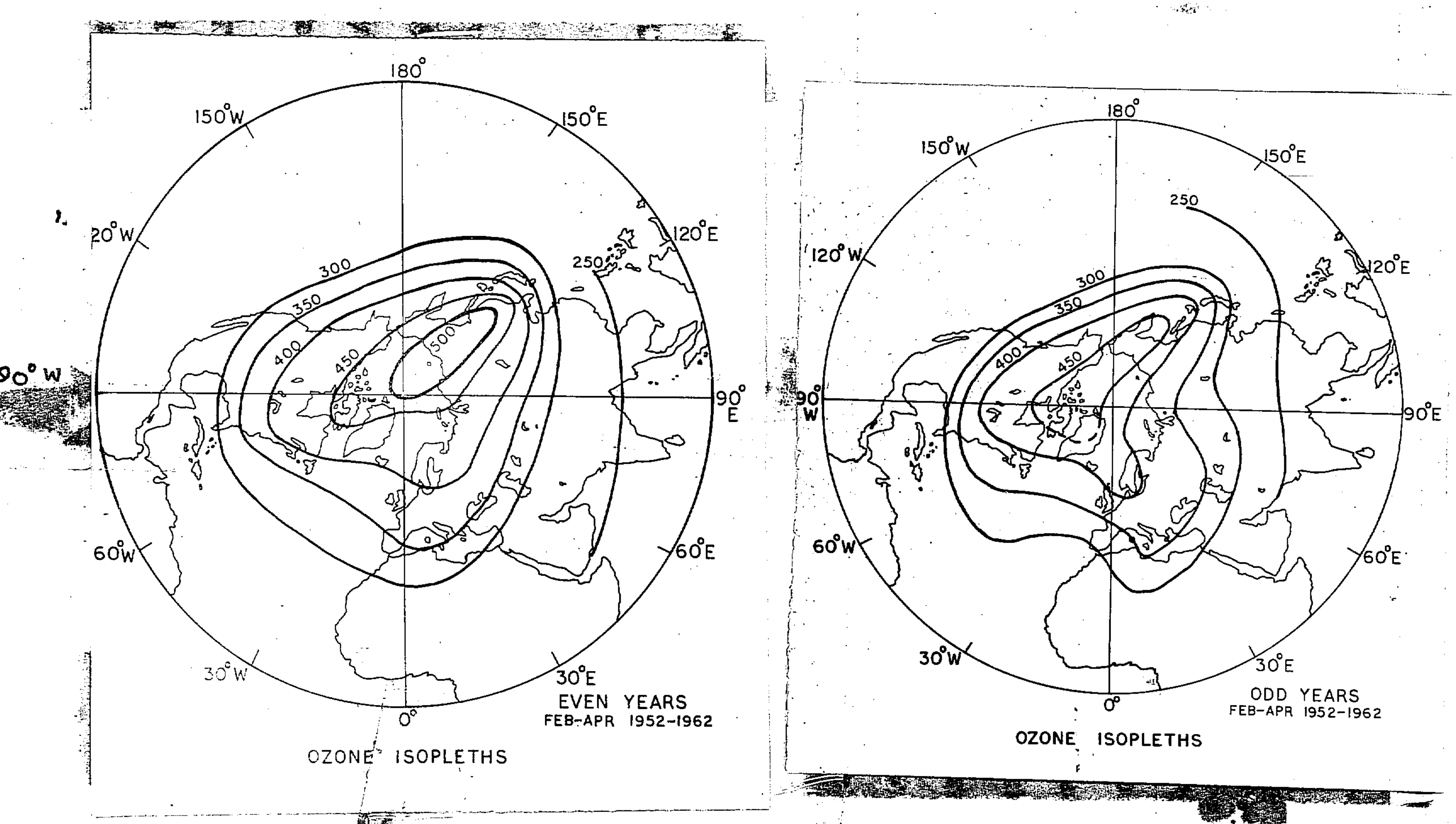


Fig.5.7 Ozone isopleths, polar projection maps of Northern Hemisphere, showing conditions during average spring time of (a) Even years and (b) Odd years during 1952-62. Note that the largest differences are seen over the eastern parts of Siberia.

at temperate and subtropical latitudes (described in section 5.1) are also found at still higher latitudes as can be seen from Fig.5.7. In these polar projection maps the ozone distributions in the northern hemisphere in the mean spring of the high-ozone years (even years during the decade 1952-62) and in the low-ozone years are depicted in Fig.5.7a and in Fig.5.7b respectively. It will be seen that the highest ozone concentrations occur during the spring of the high-ozone years over Siberia and the eastern parts of Asia; whereas in the same season of the succeeding year (low-ozone year) the high-ozone contour tends to be nearer north Canada and Greenland. The maximum differences due to these biennial oscillations are recorded at high latitudes in the Eurasian zone and in the northern parts of Canada and also at temperate latitudes in the east Atlantic. It also may be noted here that the longitudinal differences at temperate latitudes stand out most conspicuously during the spring of the low-ozone years.

Changes in the amplitude and phase of the biennial variation with latitude are summarised in Fig.5.8. The values of $\delta\Omega$ for 20^{o}-80^{o}N latitudes for the period 1952-62 have been used in constructing this diagram. The data coverage for latitudes north of 60^{o}N is not satisfactory as we have only 4 stations, namely Reykjavik (64^{o}N), Tromso (70^{o}N), Resolute (75^{o}N) and Spitzbergen (78^{o}N), and that too for different time-intervals.

The progressive delay in the month of occurrence of the biennial maximum with latitude is an interesting feature brought out by this diagram. It may also be noted that in the

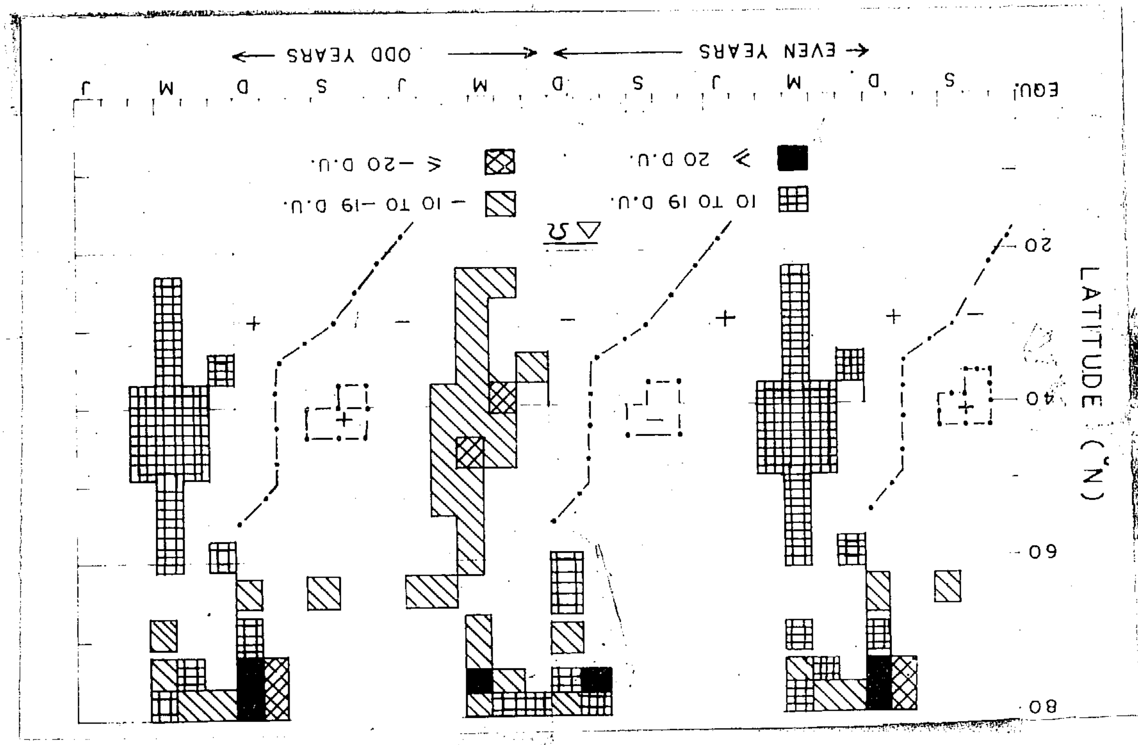


Fig.5.8 Average biennial variation at different latitudes (20^o-80^oN).

northern spring (February-April) the maximum deviations are recorded at 40-45°N latitude and also at about 65°N (coinciding roughly with the region of polar-cyclones and polar fronts). A secondary maximum follows the primary maximum after an interval of 8 months at both the locations.

The polar region is typically different, and shows sudden changes of large amplitudes. The winter months are the months of great activity coinciding perhaps with the movements of the polar vortex and the final breakdown of it and the associated stratospheric warmings. It may be mentioned in this connection that during the first few months of 1951, 1952, 1955, 1958 the ozone amounts recorded at Tromso (70^{o}N) in Norway, were conspicuously larger than the normals. It is remarkable that the stratospheric warmings were found to occur earlier (January & February) during these years (see, Wilson & Godson, 1963). While the years when the warmings occurred later (March-April), happen to be the low-ozone years.

CHAPTER VI

STUDIES ON BIENNIAL VARIATIONS IN ATMOSPHERIC OZONE

PART (II) RESULTS OF HARMONIC ANALYSIS OF THE OZONE TIME-SERIES, 1952-62

1. Introduction

In the previous chapter we have described the methods of analysis, determination of the period of the biennial variations seen in the ozone time-series and description of the biennial variations observed at various latitudes in the time interval 1952 through 1962. Before we proceed to the investigation of the changes in the phase of the biennial variation with time, it is desirable to have a quantitative description of the biennial variation at different latitudes during the decade 1953-62. The data have been subjected to harmonic analysis and the amplitudes of the 24-month period (and various harmonics) tested for statistical significance and the phases tested for persistency during the decade.

2. Existence of other harmonics

A reference to the last two rows of Table 5.4 or Figs.5.3 and 5.6 reveals existence of a distinct 8-month period superposed on the 24-month one, more clearly so at 40°N and 40°S latitudes. In Table 6.1 are given the root-mean-square values of the amplitudes

(A'_k) and the timesof occurrence of the first maximum (P_k) for the first four harmonics (k = 24- , 12- , 8- , and 6- months). the data subjected to harmonic analysis are the ozone values corrected for the trend.

From Table 6.1 we may infer :

1. Values of A'_{24} are larger at the Australian stations Aspendale (38°S) and Brisbane (28°S) than those at the corresponding latitudes of the northern hemisphere.

2. In the northern hemisphere the time of occurrence of the biennial maximum is found to occur later as the latitude increases.

3. The value of A'_{12} is about 90 D.U. in the polar region, it is found to be about 60 D.U. at about 60° latitude wherefrom it decreases uniformly with latitude, becoming 23 D.U. at 28° latitude. The amplitude of the annual cycle at the Indian stations, however, is much smaller and shows no significant change with latitude.

4. The annual maximum occurs during local spring at all stations except at the Indian stations where it occurs in May at Ahmedabad (24°N) and in July at Kodaikanal (10°N).

5. High values of A'_8 exist at latitudes 40°N and 40°S;reinforcement of the first and third harmonic components takes place at these latitudes. P_8 has a value of 26° ± 8° (Feb-Mar) in the latitude range 23°N-75°N, and 110° (Aug-Sep) in case of the Australian stations.

6. Time of maximum amplitude in case of the semiannual cycle, P_6, at all stations happens to be the equinoctial months. Conspicuously large values of A_6' are found to occur in the auroral zone, that observed at Tromso (70°N) being the largest.

Figures 6.1 and 6.2 show the first four harmonic components observed in the ozone data for January 1960 to December 1961 for 7 stations situated at latitudes ranging from 23°N to 75°N. At high latitudes (45°-75°N) except for A_{12}', the amplitude

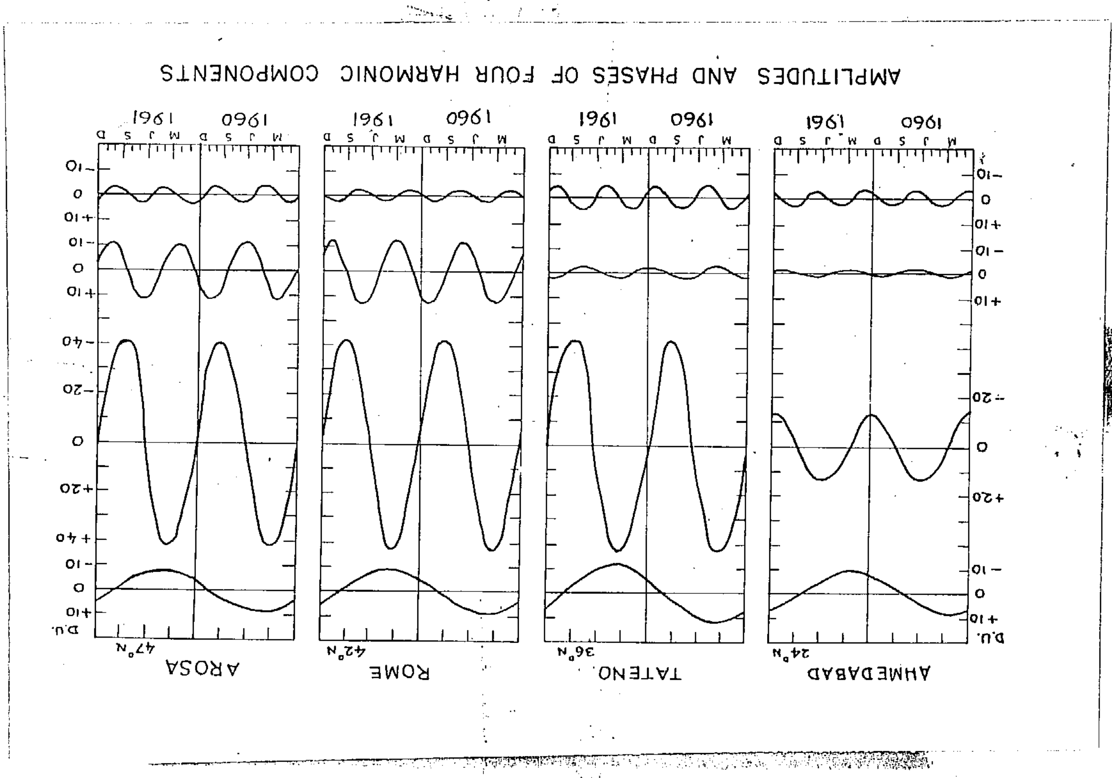


Fig.6.1 The first four harmonic components found in the monthly mean ozone amounts (corrected for the trend) for 1960-61 Ahmedabad (23°N) - Arosa (47°N).

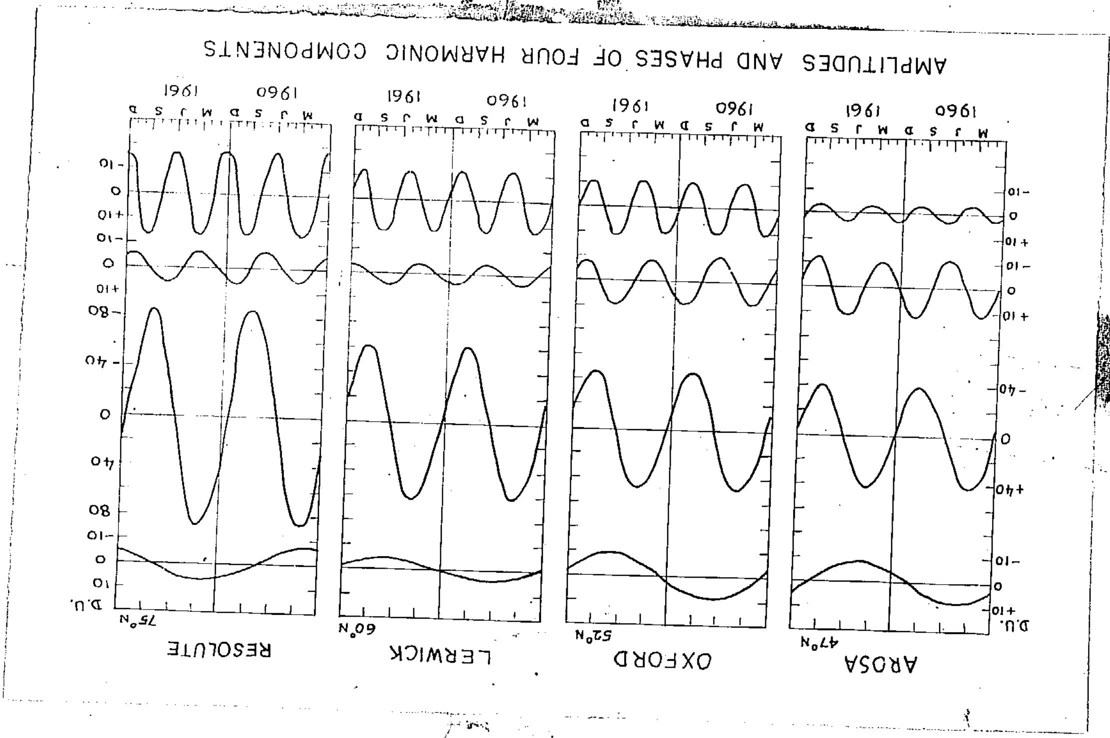


Fig.6.2 The first four harmonic components found in the monthly mean ozone amounts (corrected for the trend) for 1960-61 Arosa (47°N) - Resolute (75°N).
The scale for the second harmonic is reduced by a factor of 2.

scale in Fig.6.2 is identical to that in Fig.6.1, and same for all harmonics. The above mentioned characteristics are easy to identify.

24-month composite curves of $\delta\Omega$ for stations situated in the latitude range 50°N to 40°S are depicted in Fig.6.3. The dots represent the observed values of $\overline{\delta\Omega}$ in the average even

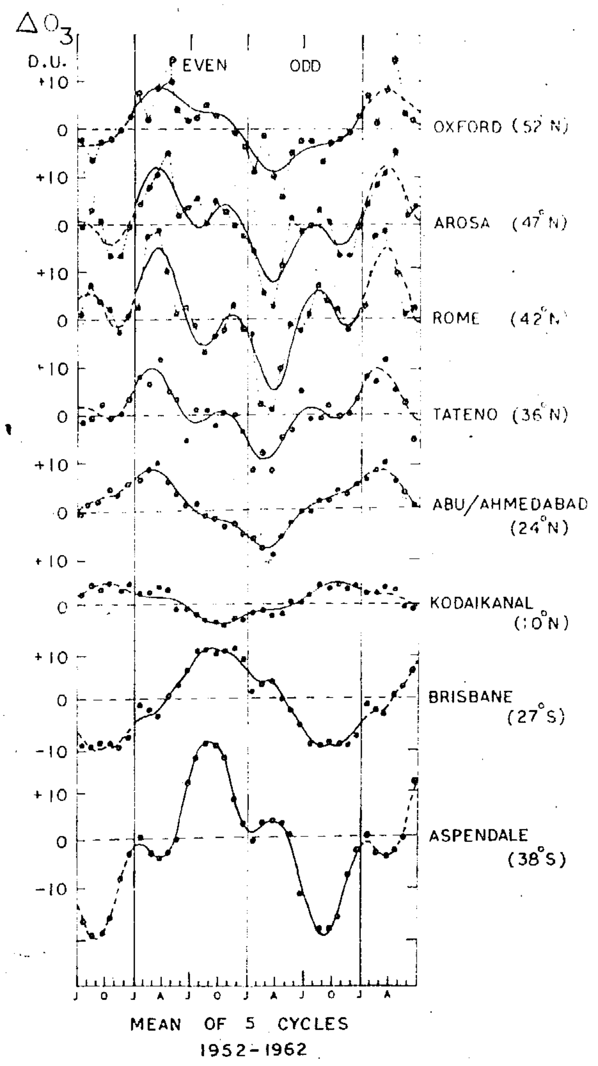


Fig.6.3 24-month composite curves (ozone departures from the Norms averaged monthwise). The dots represent the observed values and continuous curve running through them is a summation curve for the 24- and 8-month periods. Note the conspicuous presence of the 8-month period at 40°N and 40°S latitudes.

year and average odd year, the period covered is 1952-62. The continuous curves have been built-up from the 24- and 8-month harmonic components given by the harmonic analysis of the values. It will be seen that most of the variance is accounted for by the first and third harmonics. Unmistakable evidence of the 8-month period is clearly seen at the stations situated at about $40^{o}N$ and $40^{o}S$ latitudes and can be detected at other places also.

3. Significance of A_{24}

According to Chapman (1951), the amplitude may be considered significant if the length of the vector on the harmonic dial, is atleast three times its probable error. The probable error was estimated on lines suggested by Bartels (1935) [formulae given by Dyring & Rosen (1961) and Conrad & Pollak (1950, p.380)] and Whittaker & Robinson (1944) [formulae given by Rastogi (1962)]. It was found that the biennial variation is both significant and persistent at stations between $40^{o}S$-$55^{o}N$. At stations between 55-$75^{o}N$, because of large changes in P_{24} the average biennial variation is not significant.

Since sudden phase-shifts of 1 year in the biennial oscillations are found to occur after every 11 year (Chapter 7) averaging more than 5 consecutive rows is not justified. Hence the effect of the quasi-persistence in the data-series cannot be determined exactly.

CHAPTER VII

BIENNIAL VARIATION IN ATMOSPHERIC OZONE

PART (III) - VARIATION IN THE PHASE OF THE 24-MONTH PERIOD WITH TIME; CORRELATION WITH EVENTS IN THE STRATOSPHERE OVER MIDDLE AND HIGH LATITUDES

1. Introduction

In Chapters 5 and 6, we have presented the results of analysis of the ozone data for various stations, the data referring the period 1952-62. Since 1963, the biennial maxima at many places are found to occur in the spring of the odd year instead of in the spring of the even year as was the case in 1952-62. It was considered interesting to examine the phase shifts of the 24-month variation in ozone with the recent data as well as with the data of the earlier years.

Besides the quasi-biennial oscillations in the equatorial stratospheric winds, a biennial period has been noted in stratospheric warmings (Labitzke, 1965, 1966). The question whether the biennial ozone oscillations are associated with any other geophysical phenomena of a similar period occurring in the higher latitudes is also briefly considered in this chapter.

2. __Regularity in the phase shifts of the biennial variations, a suggestion of 22-year period__

Homogeneous ozone data for Arosa (Perl and Dutsch, 1959) are available from 1926 onwards with a break in 1929-31 and a short break of three months in 1953-54. Ozone data referring to earlier dates than the fifties for other stations were also examined to see the regularity with which such phaseshifts occurred in the previous decades. In Fig.7.1 the

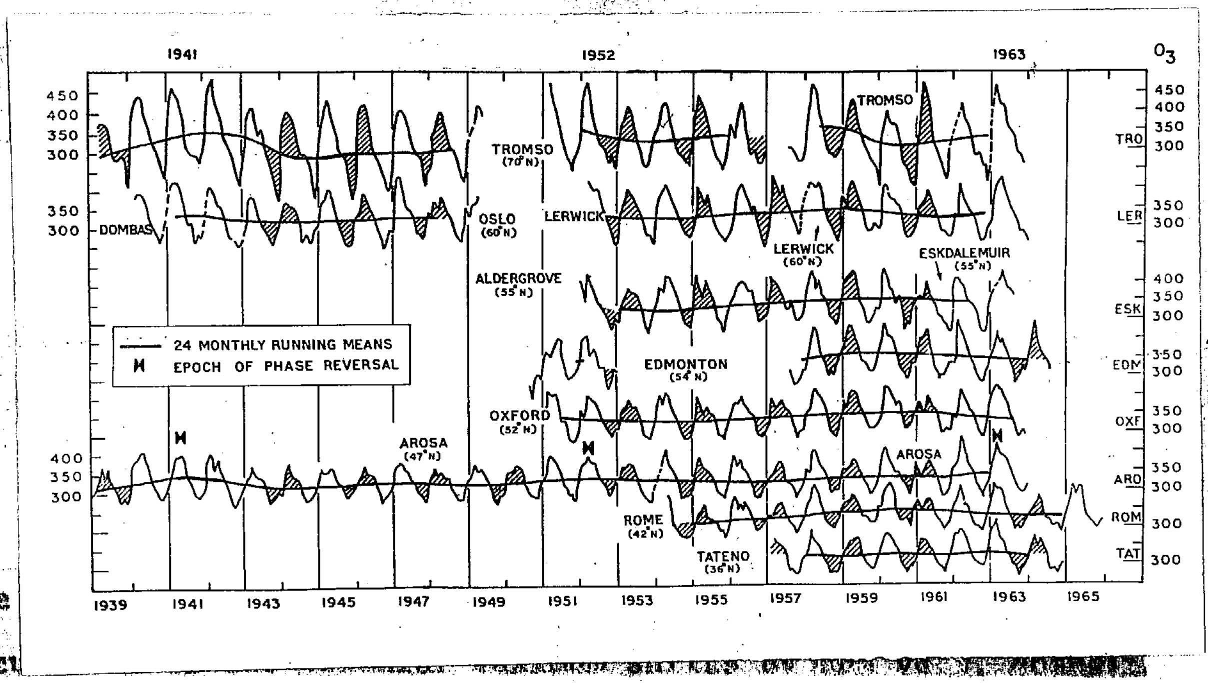


Fig.7.1 Biennial and solar cycle variations seen with the monthly mean ozone amounts 70°-35°N, 1939-64.

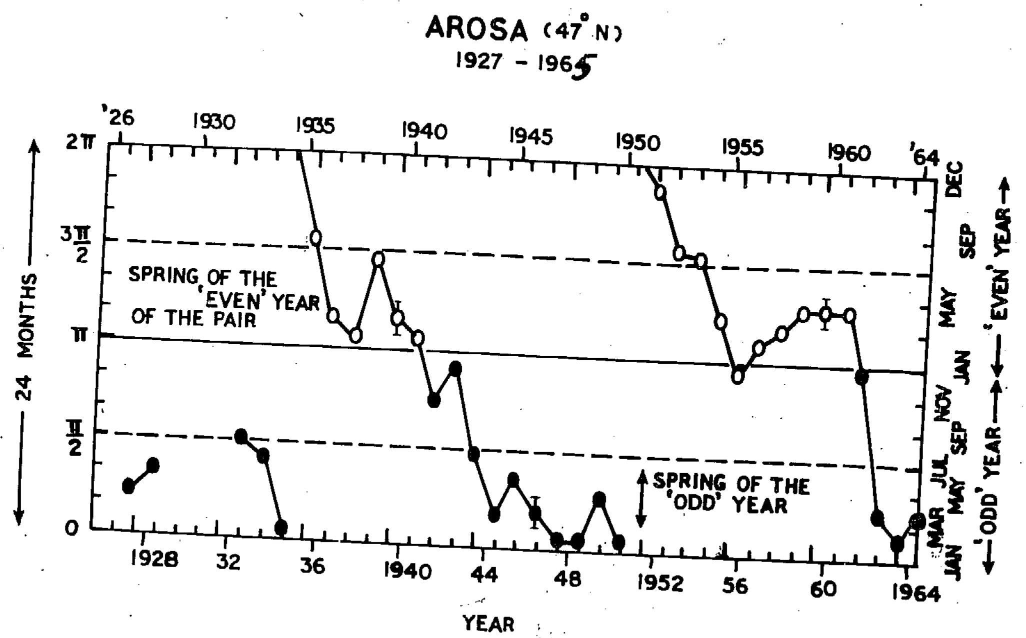


Fig.7.2 Periodic changes in the time of occurrence of biennial maxima in the Arosa ozone data, 1927-65.

(1942-51 & 1952-61) at Arosa, is brought out convincingly in Fig.7.3. The monthly (observed) ozone values, after correcting for the trend, are shown here by open circles (o) and joined by thin lines. The thick smooth curve running through these data points is the result of summing up the first four harmonics. The 24-month component is also shown separately, on a slightly enlarged scale. It is seen that the phase of the biennial period does not alter appreciably through each decade but suddenly changes into the opposite phase on passing from one decade into the other.

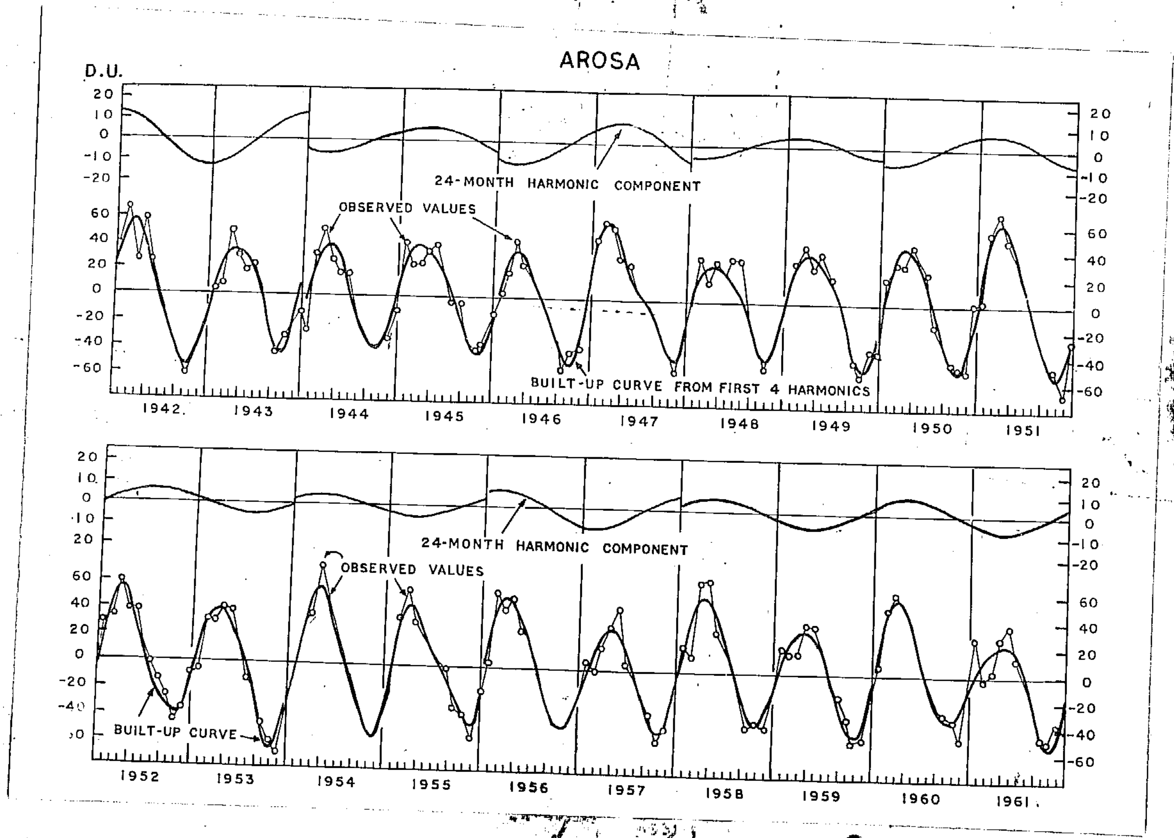


Fig.7.3 Biennial ozone variations at Arosa (47^{o}N) during two consecutive decades 1942-51 and 1952-61, and the 24-month harmonic components.

In a summation dial the length and orientation of a vector,respectively represent the amplitude and (usually) the time of occurrence of the maximum positive deviation. As compared to the harmonic dial representation, the only difference is that here the end point of one vector becomes the origin for the next one. Advantage of this particular representation is that no overlapping takes place if some persistence is there. The degree of persistence is indicated by the constancy of direction in which the train of vectors keeps on moving. Thus in the summation dial for Arosa (Fig.7.4) and other stations in the latitude range 30°N-70°N (Fig.7.5) show :

1. Persistency of the biennial sequence in a given decade;

2. Sharp change of orientation after 11 years, in the beginning of the decade; and

3. Completion of the cycle of changes in about 22 years.

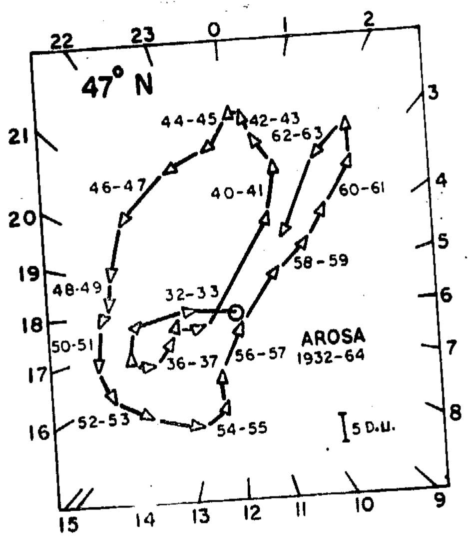


Fig.7.4 24-month summation dial for Arosa ozone data (1932-64).

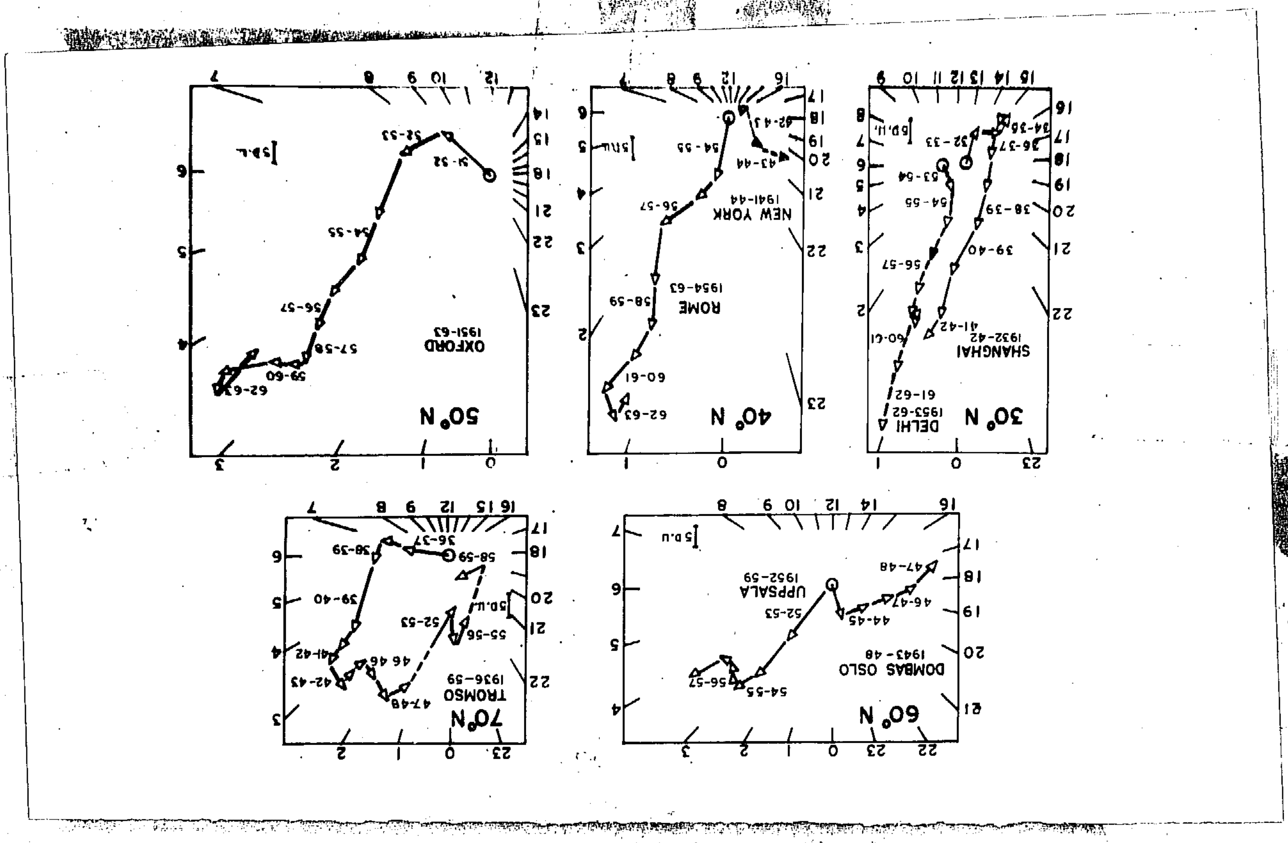


Fig.7.5 24-month summation dials for stations located in the latitude range 30°N-70°N at every 10° latitude.

The stations shown here cover the latitude range 30°-70°N. Arosa data, 1932-64, being the uninterrupted series offer the most convincing evidence in favour of the 22-year periodicity in the phase of the 24-month period. The data from other stations presented in Fig.7.5 corroborate this finding. The numbers used to label the vectors indicate the time interval studied; for example, 60-61 refers to the ozone data of 24-months, January 1960 to December 1961, 61-62 means January 1961-December 1962, and so on.

In the zone of $30^{\circ}N$ latitude, there are two trains of the 24-month vectors; one for Delhi ($29^{\circ}N$), 1953-62, and another for Shanghai ($31^{\circ}N$) in China, 1932-42. These two sequences differing by two decades are found to run parallel and indicate that the time of the biennial maximum in both the cases happens to be spring of the even year. In other four dials the time series referring to the successive decades show the inverse-phase relationships. Reference to Figs.7.2 and 7.4 reveals that the difference between two consecutive maxima is 24 months during most of the decade and during the transition period it abruptly decreases to about 20 months.

In Table 7.1 we have given the decadewise root-mean-square values of P_{24} in degrees (and also in calendar months), and their probable error determined from the differences between these and the individual values. Comparison of the decadic means of P_{24} in each zone shows the characteristics noted above. The scatter in a given decade being of the order of 15° or so ($\sim$ 1 month) is not sufficient enough to explain the difference of 180° (= 1 year) in the value of P_{24} seen in two adjacent decades. It is clear therefore that in a given decade the biennial variation is remarkably persistent, but with the beginning of the new decade a sudden change of phase occurs and the old sequence is replaced by one with a phase difference of one year.

Table 7.1

Time of occurrence of biennial maximum in different decades

Latitude zone	Station	Period	P_{24} (Deg.)	
70°N	Tromso	1936-41	51 ± 11	Apr. (Even Year)
		1941-48	251 ± 28	Jun. (Odd Year)
		1952-59	113 ± 27	Aug-Sep. (Even Yr.)
60°N	Dombas-Oslo	1943-48	260 ± 12	Jun. (Odd Year)
	Uppsala/ Lerwick	1952-59/61	77 ± 17	Jun. (Even Year)
45°N	Arosa	1932-41	28 ± 26	Mar. (Even Year)
		1941-52	239 ± 14	May (Odd Year)
		1952-62	43 ± 10	Apr. (Even Year)
30°N	Shanghai	1932-42	16 ± 24	Feb. (Even Year)
	-	1942-52	-	
	Delhi	1953-62	21 ± 7	Feb, Mar. (Even Yr.)

3. Summary of results (Part I, II and III)

(i) 24-month variations in ozone are observed at high and middle latitudes also. Results of statistical tests indicate that the amplitude A_{24} is significant and persistent up to 52°N latitude in the northern hemisphere. At higher latitudes, it is significant but the phase is not persistent. The amplitude A_{24} is likely to be large in North Siberia.

(ii) At middle and low latitudes the time of occurrence of the biennial maximum is in the spring of alternate years. The biennial sequence of ozone changes are found to change the phase angle P_{24} by 180° soon after the end of each decade by the Gregorian Calendar, (at least in Europe, Asia and Australia), changing from the spring of even year of the pair to spring of the odd year and vice versa; the longer period cycle superposed on the biennial ones takes about 22 years to complete.

(iii) The 24-month cycle observed at the equatorial station Kodaikanal (10°N) has antiphase relationship with that at the Australian stations (28-38°S) as well as the high latitude stations (70°N and north of it). The time of occurrence of the biennial maximum is observed to be delayed progressively with increase of latitude, at least, in the northern hemisphere.

(iv) Most of the deficiency (or excess) in ozone generated in one year is, usually, corrected in the next year. If this is not exactly balanced in the next year, it will be evened-out in a few biennial periods.

(v) The results of harmonic analysis clearly indicate the existence of an 8-month period. Its presence is seen in the most conspicuous manner at latitudes 40° north and south.

(vi) The amplitude A_6 is noted to be the largest at Tromso (70°N) and decreases with latitude. The semiannual maxima occur at all stations in the equinoctial months.

4. Discussion

The long period variations in ozone(as depicted in Table 5.2 and having a period of about 11-years) are in phase at different latitudes. These and the semiannual oscillations in ozone suggest a possible association between the changes in particle radiation from the sun and ozone variations. These are discussed in Chapter 8. Here, we shall confine ourselves to the biennial variations only.

Mean vertical distributions of ozone in the springs of individual years for Tateno (36°N), 1958-64, and Arosa (47°N), 1956-64 (Dütsch and Mateer, 1964; and "World Ozone Data" 1963, 1964) were compared to locate the seat of the biennial variations over these latitudes. Vertical distribution profiles of ozone, averaged for the springs of the high-ozone years (1956, 1958, 1960, 1962 and 1963) and of the low-ozone years (1957, 1959, 1961 and 1964) over Tateno and Arosa are shown in Table 7.2. The ozone excess in the high ozone years though noticable from 5 to 30 km, the main increase takes place in the 10-19 km region. Even individual pairs of years show similar results.

Table 7.2

Vertical distribution of ozone in average spring of high- and low-ozone years

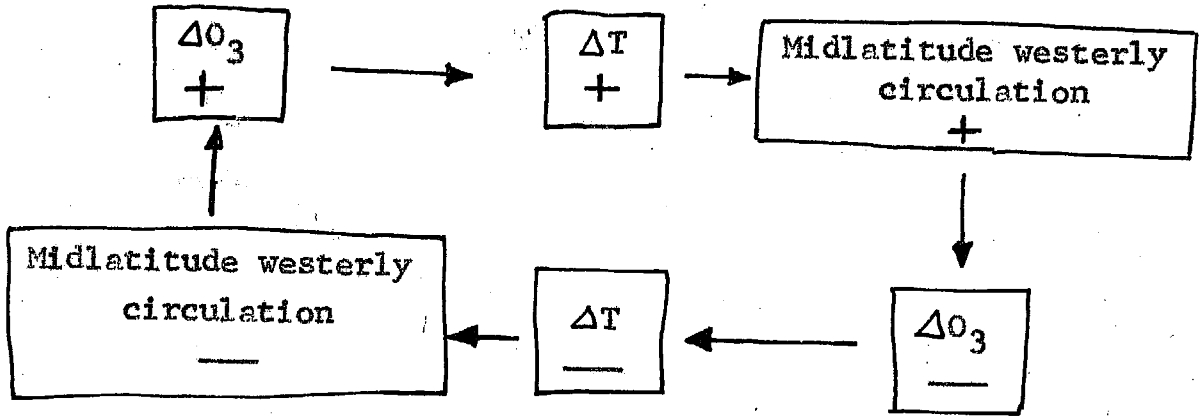
Period Feb-Apr. averages of	p_3 (μ mb) in the layer at 5-10 km	10-15	15-19	19-24	24-28	28-33	33-38
TATENO (36°N)							
High-ozone years (1958, 60, 62 & 63)	42	74	97	128	122	87	48
Low-ozone years (1959, 61 and 64)	35	66	86	122	118	83	46
Difference	7	8	<u>11</u>	6	4	4	2
AROSA (47°N)							
High-ozone years (1956, 58, 62 & 63)	32	88	110	132	120	80	44
Low-ozone years (1957, 59, 61 & 64)	25	77	99	127	117	79	43
Difference	7	<u>11</u>	<u>11</u>	5	3	1	1

Kulkarni (1966 b) has observed the biennial period in the 24-36 km layers over Aspendale (38°S) and Brisbane (28°S) in Australia. The seat of the biennial variation being in the troposphere and lower stratosphere, it may be inferred that it is closely associated with changes in the general circulation (see also, Dütsch, 1965).

4.1 Biennial variations in ozone, temperature (50-mb say) and winds- Middle latitudes

Australian stations showed a great regularity in behaviour before 1962 both as regards their spring ozone amounts and stratospheric temperatures near 50-mb level, high ozone amounts corresponding to high stratospheric temperatures (Kulkarni, 1962). Laby et al (1964) have noted that low zonal winds were preceded by a few months by high ozone amounts and vice versa. Our analysis has brought out (Table 5.7) that the deficiency (or excess) in ozone generated in one year is mostly corrected in the next year itself. These results indicate that the ozone excess or deficiency in the lower stratosphere sets in action a feed-back mechanism to maintain the ozone reservoir at a certain equilibrium level.

By virtue of its radiative properties, ozone excess can be expected to lead to a temperature rise in the lower stratosphere; and higher temperatures than normal in the stratosphere of middle latitudes will lead to increased circulation in the lower stratosphere and corresponding increased leakage of stratospheric air into the troposphere. The cycle of changes in an average biennial period will be somewhat as follows;



ΔO_3 is the change in the ozone amount in the stratospheric reservoir, ΔT is the temperature change in the lower stratosphere, say at 50-mb, and the changes in lower stratospheric circulation are those related to travelling disturbances in the upper troposphere. The upper and lower parts of the cycle take place in successive years (Ramanathan and Angreji, unpublished, abstract of which is given in the Appendix).

4.2 Departures from 'idealized picture'

This idealized picture gets disturbed on some occasions. There are deviations from normal in the biennial oscillations themselves. Larger discrepancies are seen in the phase-shifts by one year after every 11-year interval, the solar cycle changes in the biennial variations.

A reference to Fig.5.4 shows that there are certain irregularities in the biennial variation of ozone, such as in 1959 and in 1962-63, which might be due to nuclear detonations or volcanic eruptions. Ramanathan (1965) has suggested that abnormal increases in 1959 and 1962 can perhaps be due to the large scale nuclear explosions in 1958 and their resumption in 1961. Sparrow (1965) has suggested that the unusual disturbances in stratospheric temperatures and ozone amounts over Australian stations in 1964 may be due to the effect of the Bali volcanic eruption in March 1963 (see also, Pittock, 1966).

Kulkarni (1966 a) has mentioned that the biennial oscillations in ozone and temperature in lower stratosphere over Australian latitudes existed between 1954 and 1963 and not prior to 1954 and after 1963. However, the ozone data available here for Brisbane and Aspendale for 1965 and 1966, indicate that the new rhythm of the biennial variation with a phase-shift of one year, like the one seen at stations in Asia and Europe during the recent years, is perceptible at Australian latitudes also.

The earlier ozone data from Mt.Montezuma (22°S, Chili), 1923-30 (Tien, 1938), and Table Mountain (34°N, California), 1929-33 (reported by Penndorf, 1936), show that during the period 1923-33 the ozone values in the spring of odd years were higher than those in the even years. We are thus in a position to extend the data coverage to 1923-65. During these four decades the 22-year period has practically completed two cycles, and the third one has commenced since 1963 (see Figs.7.2 and 7.4).

We have seen that the shifts in the biennial rhythm have occurred in 1933, 1941, 1952 and 1963. Why a shift should occur some 4-5 years after the epoch of sunspot maximum is still not clear.

4.3 Biennial variations in ozone and stratospheric warmings

Direct connection between the biennial variations in ozone over the tropics and the quasi-biennial oscillations in the stratospheric winds over the equator, was suggested by Ramanathan (1963). The feed back mechanism already mentioned, linking the ozone and wind variations apparently maintains the observed biennial oscillations in ozone and winds of the middle latitudes.

We shall now consider briefly the evidence for circulation changes in the upper troposphere and lower stratosphere of high latitudes which have a biennial variation.

A close link between the ozone changes taking place in the late winter and early spring and the winter-summer abrupt transitions taking place in the arctic stratosphere (the stratospheric warmings), has been shown by Godson (1960). The first synoptic evidence of the existence of the quasi-biennial cycle in higher latitudes is due to Labitzke (1965). In this paper she reports that the stratospheric midwinter warmings can be divided into two types with respect to their origin and direction of movement, European and American. The warmings generally started after similar synoptic conditions when extremely strong cyclonic activity initiated the stratospheric warmings. It was also noted that the phase of the quasi-biennial oscillations in the stratospheric zonal winds over equatorial latitudes has correlation with the type of these midwinter warmings and the circulations in the troposphere at temperate and high latitudes (see also, Scherhag et al, 1963; and Labitzke, 1966).

In the 10-mb synoptic maps for the northern hemisphere, Scherhag et al (1963) have pointed out, and recently Labitzke (1966) has very clearly shown the differences between the general circulation patterns observed in March of different years. In March of 1958, 1960, 1962, 1963 and 1965, the epochs when the final (spring) warmings occurred <u>late</u>, the circulation in the stratosphere was found to be governed by the circumpolar vortex with no separately developed Aleutian high. On the other hand, in March of 1959, 1961 and 1964, the years when the final warmings took place <u>early</u>, the circulation was asymmetric, the polar vortex displaced to Siberia with a well developed high over Canada. The biennial periodicity and phase-shift of one year occurring in 1963 in the stratospheric warmings are thus evident in this report by Labitzke (1966).

In comparison with this we may note the spatial and temporal variations in the biennial variations in ozone. There seems to exist longitudinal differences in the phase of the biennial variations in ozone. Comparison of the ozone anomalies,

$\delta\Omega$, for Edmonton (54°N, Canada) and Eskdalemuir (55°N) U.K.) shows that the biennial variations in ozone over these stations are somewhat different. Dutsch (1966) has mentioned such differences existing during 1964-65 at Arosa (Switzerland) and Boulder (Colorado). Such zonal differences are also seen in the average biennial variations observed at Resolute (75°N, Canada) on the one hand and at Tromso (70°N, Norway) and Spitzbergen (78°N, north of Norway) on the other, as are shown in Fig.5.8. A reference to Fig.7.6 shows that the distribution of ozone in

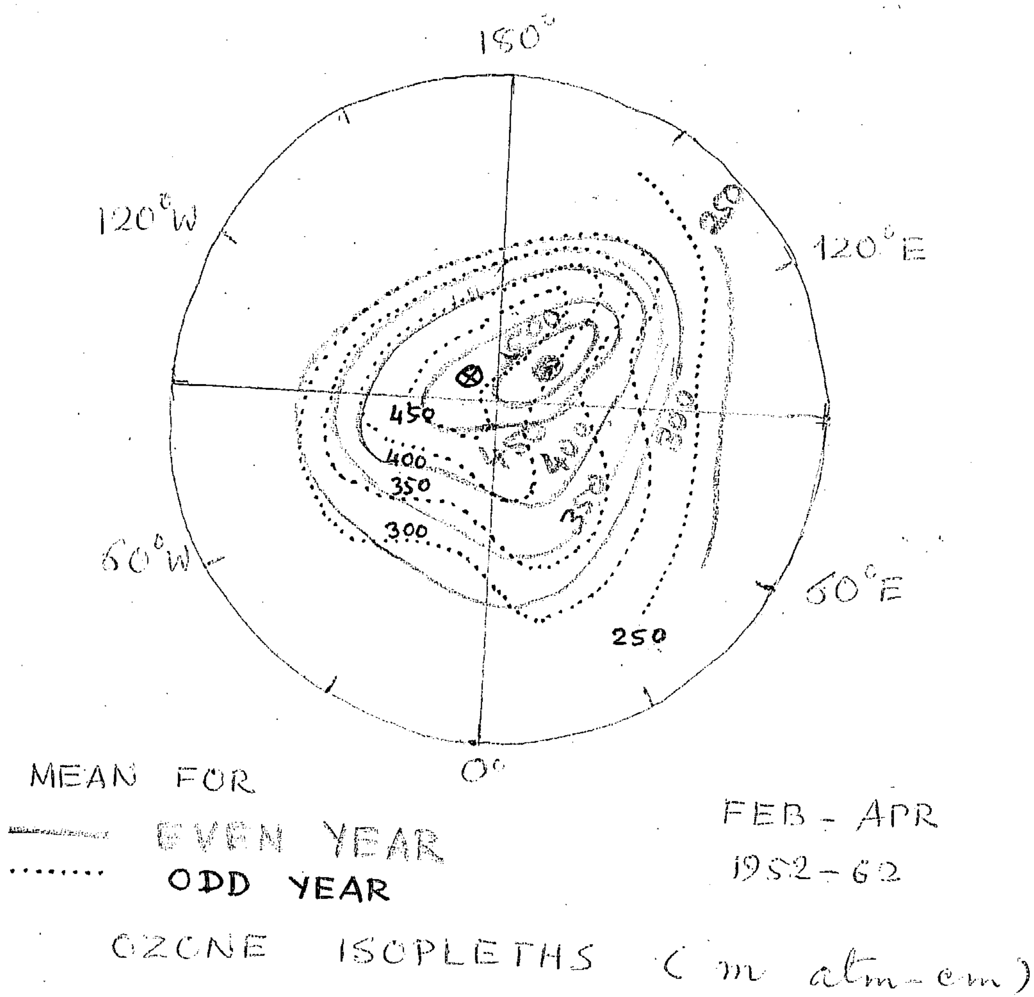


Fig.7.6 A tracing copy of Fig.5.7(a) and (b).

the average spring of even years is different from that of odd years of the period 1952-62. In the spring of odd years the high-ozone center ($\sim$ 450 D.U.) was located near north Canada and the distribution was markedly asymmetrical. In the even year, the center ($\geq$ 500 D.U. or more) was over northern Siberia and the distribution more symmetrical.

We note that at middle latitudes the high-ozone years are years of late final warming and vice versa, while at higher latitudes the high-ozone years are years of early warming. The ozone changes following a stratospheric warming are now well known. We suggest here a possibility that the biennial fluctuations in the stratospheric ozone reservoir, via changes in the circulation pattern in the upper troposphere and lower stratosphere over middle latitudes, are connected with the early or late breakdown of the polar vortex.

APPENDIX TO CHAPTER VII

The stratospheric ozone reservoir and its fluctuations*

By

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Summary

The biennial variations of atmospheric ozone are examined together with the wind and temperature data of the lower stratosphere and it is found that ozone excess or deficiency in any one year sets in action a feedback mechanism involving temperature gradients and atmospheric circulation which tend to correct the deviations, most of the corrections taking place in the course of the next year. The residuals get corrected in a few cycles. The evidence for an effect of solar activity on ozone amounts and circulation in the lower stratosphere is also briefly considered.

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CHAPTER VIII

OZONE VARIATIONS VERSUS CHANGES IN THE SOLAR CORPUSCULAR RADIATION*

1. Introduction

Close association between solar activity and terrestrial phenomena taking place at altitudes of 60 km and above, such as variation in terrestrial magnetism, auroral activity, systematic changes in ionospheric conditions etc. are now well known. On the other hand the picture of solar-terrestrial relationships in the region of the lower atmosphere is still very hazy. Atmospheric ozone owes its existence to solar UV-radiation and is situated mainly in the stratosphere below 50 km. Ozone is a recognized tracer element of movements in the stratosphere. It was considered that an examination of the correlation between solar activity and concomitant variations in ozone content may lead to some understanding of the solar-terrestrial relationships existing in the lower atmosphere.

Earlier attempts of establishing some relationship between the sunspot cycle and annual means of the total ozone content were made by Cabannes & Dufay (1927), Fowle (1929b), and Willett (1962). They, however, met with difficulties,

* Preliminary results of this investigation by the author have been reported in his presidential address by Prof. Ramanathan at the International Ozone Symposium on Aug. 31, 1964 at Albuquerque, N.M.

(Gotz, 1951; London & Haurwitz, 1963). Dobson & Normand (1962) while commenting on Willett's results pointed out a possibility that the observed changes in the ozone amounts might have been introduced by the adoption of (i) different values of I_o intensity ratio of the wavelength-pair outside the terrestrial atmosphere, and/or (ii) changes in other calibrational constants entering into the computation of the ozone amount; these 'constants' may change from time to time.

Vigroux (1963) reported a 11-year periodicity in the homogeneous ozone data from Arosa, 1926-58 (Perl & Dütsch, 1959), and noted that the epochs of maximum ozone did not coincide with those of sunspot maxima. In the current ozone data from Oxford, 1951-63, also such a noncoincident cycle can be identified.

It is observed that in all the correlation studies reported so far, including those due to Rangarajan (1965) and Dutsch (1964), the solar activity has been traced out with help of the relative sunspot number (R_z). It is well-known that the spot frequency is an index of solar activity in relation to its variable wave-radiation. Now the characteristic trends in the time variation of wave- and particle-radiations, in the course of the 11-year cycle, are somewhat different (see for example Fig.11.2 and its discussion in Chapter 11) particularly in the period immediately following the epoch of sunspot maximum. Under these circumstances, the observed break-down of the direct sunspot-ozone relationships may be related to the fact that the 11-year variation in the ozone content is partly associated with the particle radiation from the sun. When a correlation with sunspot number was sought, a complete relationship with the wave radiation was assumed.

Since the variations of the corpuscular radiation is best denoted by geomagnetic activity, correlation between the cyclic variations in the ozone content and the time variation of the particle radiation has been examined by any association between ozone variations and magnetic activity. Many attempts have been made in the past to bring out possible influence of the magnetic activity on the time variation of ozone content (Chree, 1926; Dobson et al, 1926, 1927, 1929; Fowle, 1929a; Malurkar, 1954; Ahmed & Halim, 1961; Kulkarni, 1963; Sekihara, 1963). All these studies, without exception, are based on daily ozone values. It is not surprising to find that the day-to-day ozone fluctuations of meteorological origin, which are always present in the daily values and are of considerable magnitude, have led to diverse findings. It is not possible to arrive at any well defined conclusions regarding the association of the magnetic activity on the ozone values, on the basis of the above mentioned studies.

2. The present study

As the day-to-day fluctuations in the ozone values are very much affected by weather disturbances, they can effectively be filtered out by considering only the long term averages. Such a long period average has been considered here and has enabled the author to bring out a correlation between the changes in atmospheric ozone and geomagnetic activity and hence with the time variations in the particle radiation from the sun.

Distribution of the ozone over the globe is also of special interest in this connection. The solar particles are known to be impinging mainly along the auroral belts encircling the magnetic poles. Since these poles are not coinciding with the geographic poles, magnetic latitudes alongla geographic parallel are found to very considerably, the discrepancies between the two latitude schemes are markedly large. The ozone distributions in both the hemispheres as a function of magnetic latitude is examined in this chapter.

3. Results

3.1 Time variations

The objectively derived planetary indices for the description of geomagnetic activity (K_p, C_p, A_p, etc.) are available since 1932 only, hence for the earlier period the state of magnetic activity is represented by C_i - international magnetic character index. Figs.8.1 and 8.2 show the history of ozone variations and the corresponding state of magnetic activity, the period covered by the study is 1908-61 during which the 11-year cycles in magnetic activity have been completed five times.

The earlier ozone values determined by means of the Chappius bands from the Smithsonian measurement (1) by Cabannes

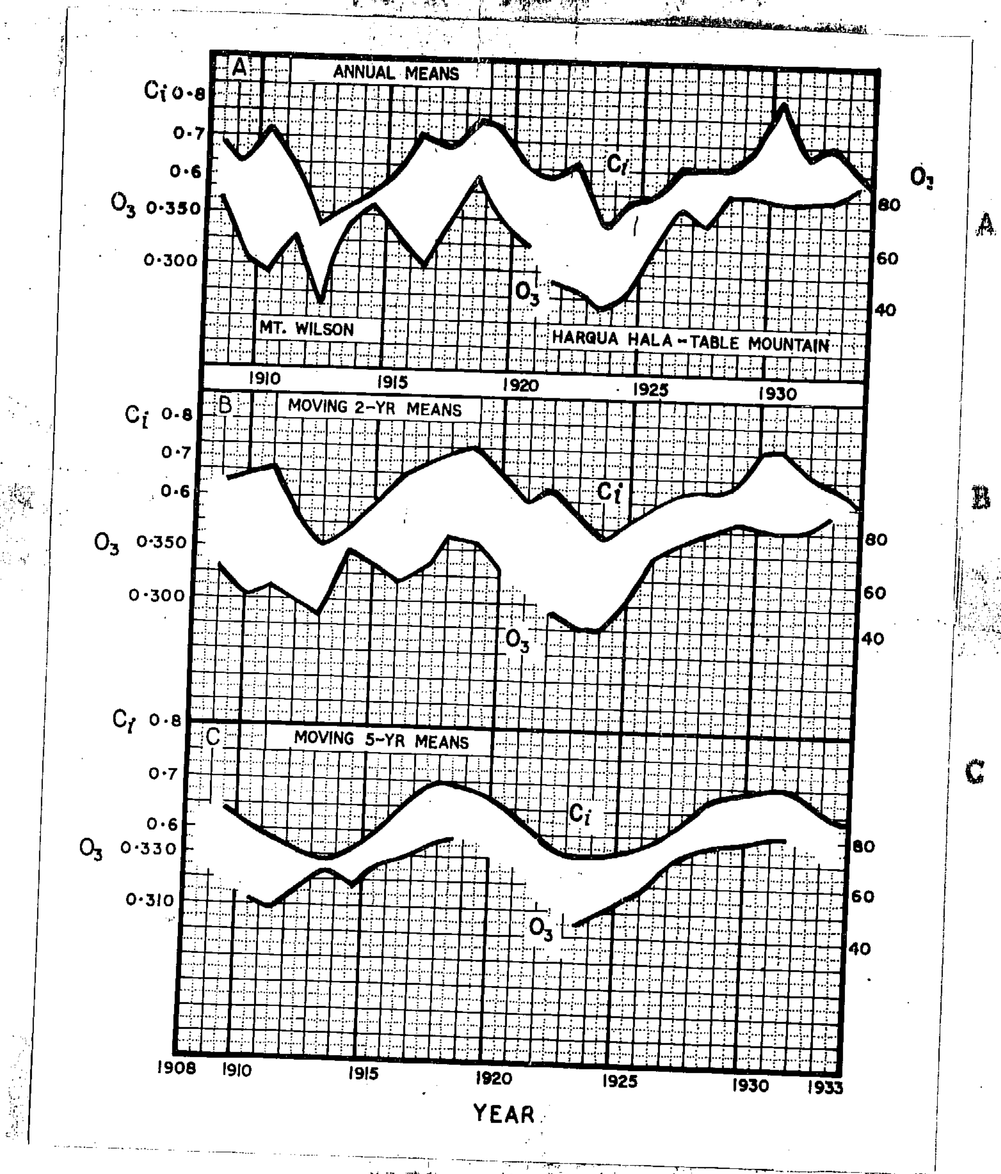

Fig.8.1 11-year cycles in ozone variation and magnetic activity (C_i), 1908-33.
A. Annual averages; B. Moving 2-year averages;
C. Moving 5-year averages.

and Dufay (1927) for the period 1908-20 for Mt.Wilson (34°N) in California, and Table Mountain (34°N) also in California, after Fowle, (read from Fig.1 of a paper by London & Haurwitz, 1963) constitute the basic ozone data of Fig.8.1. In the upper

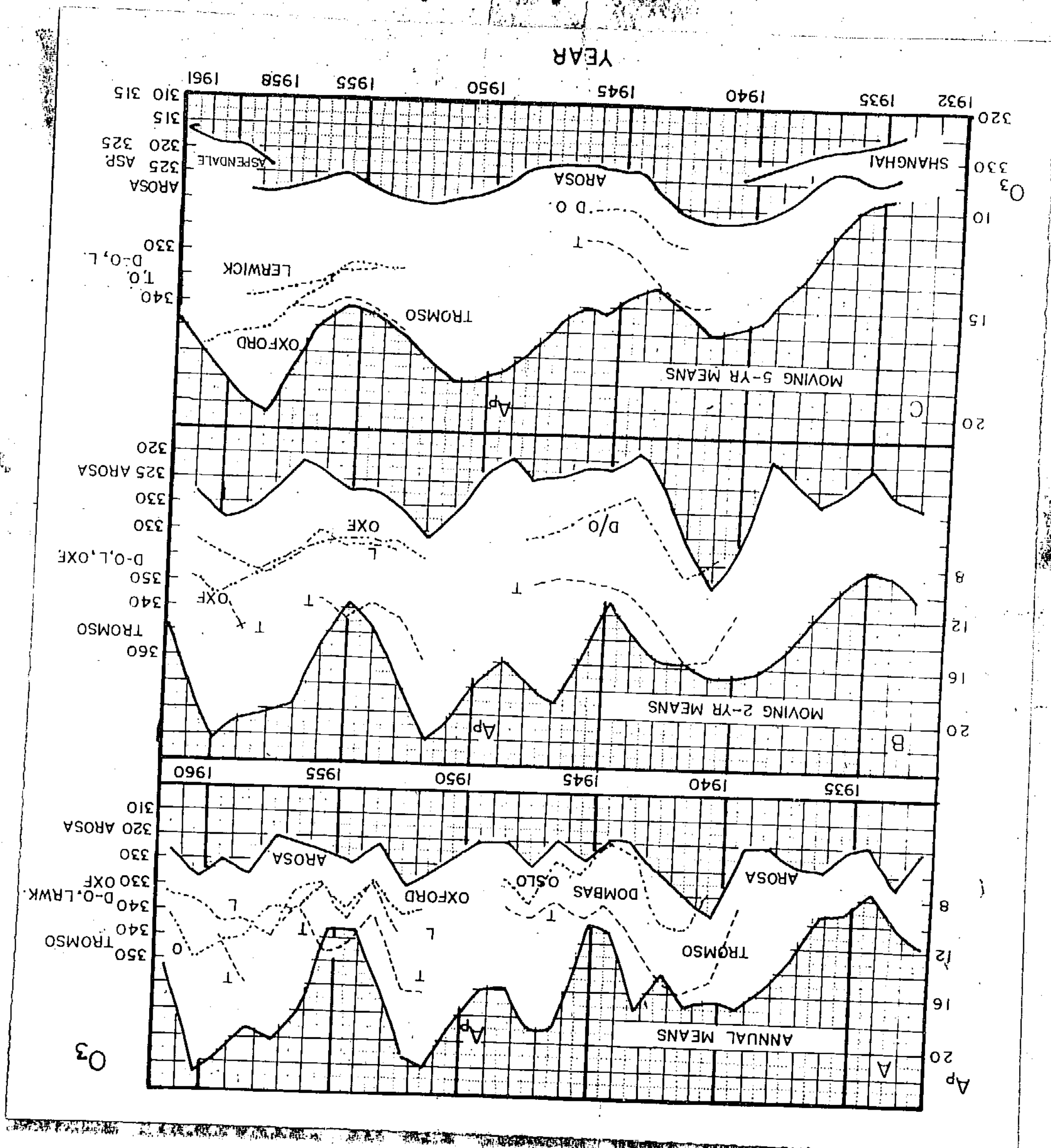

Fig.8.2 Same as Fig.8.1; but in this period,1932-61, the magnetic activity is represented by A_p.

compartment (marked A) annual means of ozone and C_I are plotted for 1908-33, while in the middle (B) and lower compartment (C) 2-year and 5-year moving averages, respectively, have been plotted. The ozone scales for Mt.Wilson (1908-20) are shown at the left and those for the second series running from 1921-33, after Fowle, at the right. Fig.8.2 in similar manner shows the variation between the 11-year cycles in A_p -average planetary amplitude-with those in the ozone time series from Tromso, Oxford, Dombas-Oslo and Lerwick, Arosa, Aspendale and Shanghai, the ozone units are Dobson units (10^{-3} atm-cm). The time interval covered by Fig.8.2 is 30 years, 1932-61.

The epochs of local extrema (maxima and minima) in these time series of total ozone amounts (O_3) and C_i and A_p, are found to be coinciding during the entire period 1908-61. Short period variations mounted on the 11-year cycles and secular variation in A_p are found to introduce some distortion. Even then positive and significant correlation for zero lag between the 11-year periods in ozone variations and magnetic activity, for over five cycles, is easily recognised (see Table 8.1).

The 24-month cycles described in Chapters 5-7 being closely associated with the meteorological phenomena, were filtered out by considering 2-year running averages centered at 6-months intervals. In all cases, this has shown marked improvement in the correlation between ozone variations and changes in magnetic activity (see Table 8.1 and middle sections of Figs.8.1 and 8.2). In Fig.8.3a the regression plots of 2-year moving averages of the observations made in the earlier period (prior to 1950) are represented by open circles (o) and those made in the recent period are shown by filled-up circles(•). Noteworthy positive correlations for zero lag, apparently exist at high latitudes, where the range of variation is also larger.

It was also observed that a large fraction of the

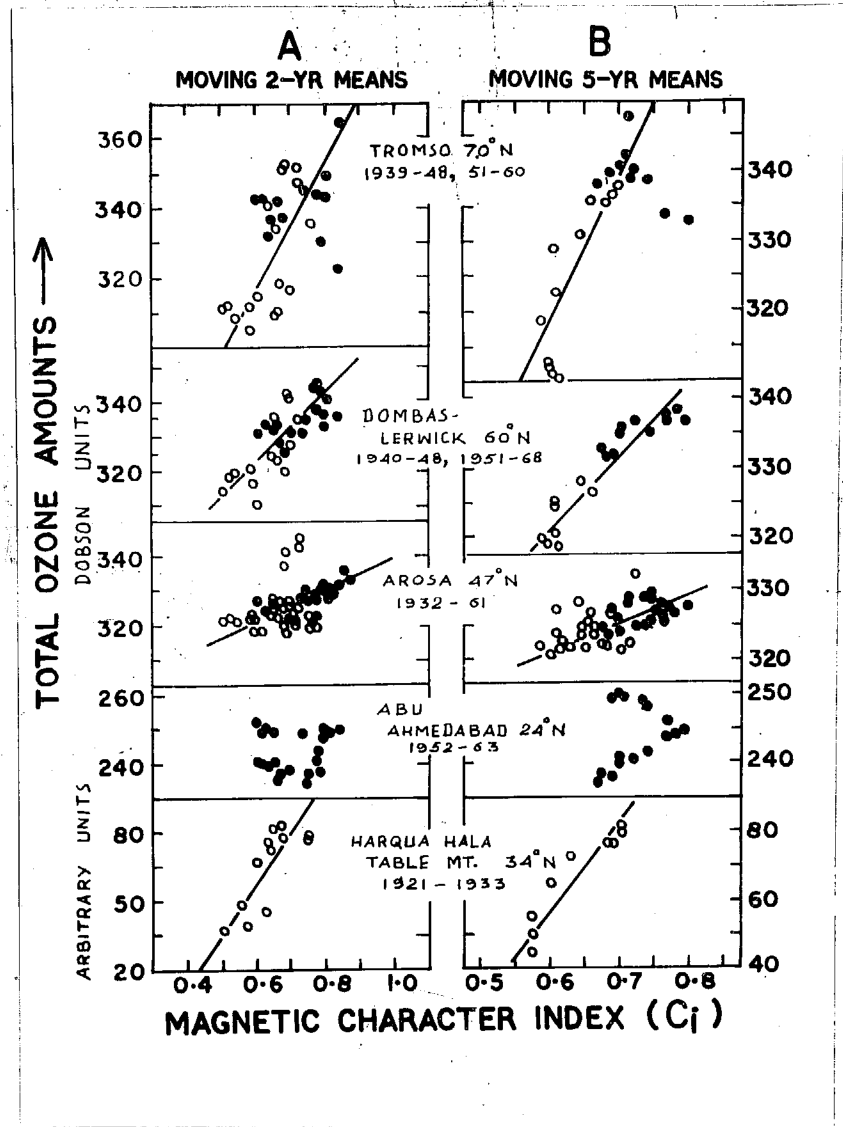

Fig.8.3 Correlation between total ozone amount (A - moving 2-year means; B - moving 5-year means) and the magnetic character index (C_i). Note that the scale in case of Block B is twice that in the Block A.

variance here is due to the presence of other cyclic variation having period of about 5 years and apperently not connected with the changes in magnetic activity. Elimination of these shorter periods by considering 5-year moving averages, leads to further improvement in the results (see Table 8.1 and compare Fig.8.3b) with Fig.8.3a). This step-by-step increment in the degree of correlation is clearly seen in Figs.8.1 and 8.2. Comparison of the correlation coefficients obtained in case of Oxford, Aspendale* and Elmas shows that the coefficients are positive and statistically significant at stations with magnetic dip latitude (μ) greater than 45°. At lower latitudes the correlation is positive but without significance. Range of the 11-year cycle, (maximum - minimum), is markedly large at higher latitudes and is seen to decrease with latitude in the middle and lower middle latitudes. In case of low latitudes, amplitude of such a period, if it exists, is too small to be determined confidently with the available data.

The particle dependence of associated terrestrial phenomena can be inferred from the semi-annual component of the time series. The 'source' regions on the sun are more favourably located twice-a-year during the equinoxes (when the earth attains maximum heliographic latitudes). This results in a semi-annual wave with maxima occurring at equinoxes and minima at solstices. It has been observed in the case of magnetic activity that the amplitude of this 6-month period is nearly the same as that of the 11-year one. In the last columns of Table 8.1 the results of harmonic analysis of monthly ozone

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* Aspendale has geographic latitude, ϕ, comparable with that of Elmas, and magnetic dip latitude, μ, (given by $\tan \mu = \frac{1}{2} \tan I$ where I is the magnetic inclination) similar to that at Oxford.

values are shown. The 6-monthly cycles in ozone at all latitudes have their first maximum occuring during the equinoctial months, and the amplitudes, as expected from above consideration, are found comparable with those of the 11-year period at most of the stations.

3.2 Latitude-effect

Though the above results suggest that seat of the induced increment in atmospheric ozone content is in the higher latitudes rather than at the equator, the underlying association is clearly brought out when the asymmetry in the ozone distribution over the globe is examined in terms of geomagnetic co-ordinates.

Minimum ozone concentration in the annual averages is found over the equator, and the ozone content is observed to be increasing on either side of it with the latitude. The presence of 'ozone-belt' in the northern hemisphere has been indicated at about 60°N, the ozone content is found to decrease slightly at higher latitudes (Gotz, 1951). London (1963) reports that recent observations indicate a flat maximum north of 60°N and extending to the Pole. Poor data-coverage in the polar region is a great handicap. Latitudinal gradient (geographic latitude) in ozone is markedly different (see Fig.8.4) in the southern hemisphere.

Ozone averages for Macquarie Is., Mirnyj, Oasis station and Kerguelen in the southern hemisphere are markedly larger

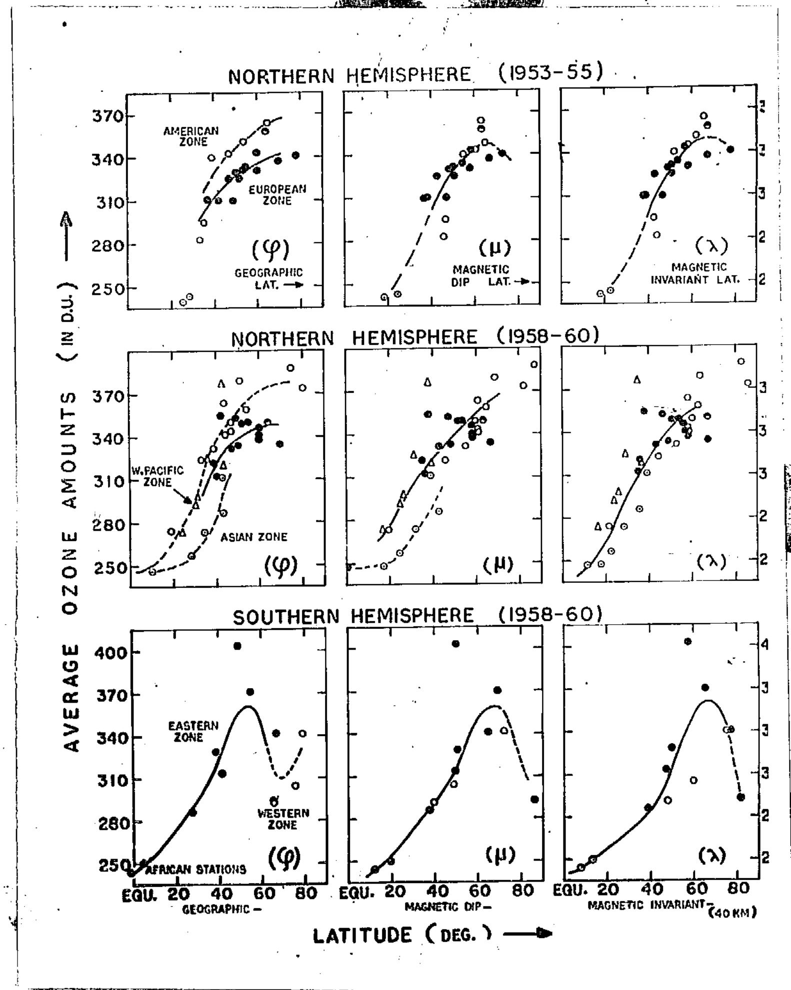

Fig.8.4 Latitudinal changes in ozone content seen in the (i) geographic latitude, (ii) magnetic-dip latitude and (iii) magnetic-invariant latitude schemes.

compared to those over the western sector (Halley Bay, Argentine Is., Little America etc.). In the northern hemisphere, the stations in the American zone have recorded larger ozone concentrations than over the European stations having identical (geographic) latitudes. Compared to these two sectors, least ozone amounts are recorded in the sector encompassing central Asia. The difference is found to be steadily increasing with latitude. The typical difference is not affected by the phase of the magnetic activity, only the base level seems to be changing with the phase of the 11-year magnetic activity-cycle.

These features are illustrated in Fig.8.4 wherein the annual average ozone amounts for the pre-IGY and IGY-IGC periods are plotted against the geographic (ϕ), magnetic dip latitudes (μ) and the magnetic invariant latitudes (λ) recently introduced by McIlwain (1961). The longitudinal discrepancies in the μ and λ arising from the magnetic (dip) poles not coinciding the geographic ones, are very much like the longitudinal differences in the ozone distributions. As a consequence, with adoption of the magnetic latitude scheme the distortions reduce appreciably, and the zonal anomalies and difference between the latitude-effect in the two hemispheres are no more present. Instead, a universal relationship appears.

Poor data coverage in the polar region does not permit definition of the ozone-belt. But there are indications that the ozone-maximum occurs near geomagnetic latitude 65^{o}N, roughly coinciding with the auroral-belt.

Murcray (1957) has reported that on 26 March 1957 a significant instantaneous rise of ozone (about 18 percent) was found to take place in association with an auroral display, with the observations made from College, Alaska.

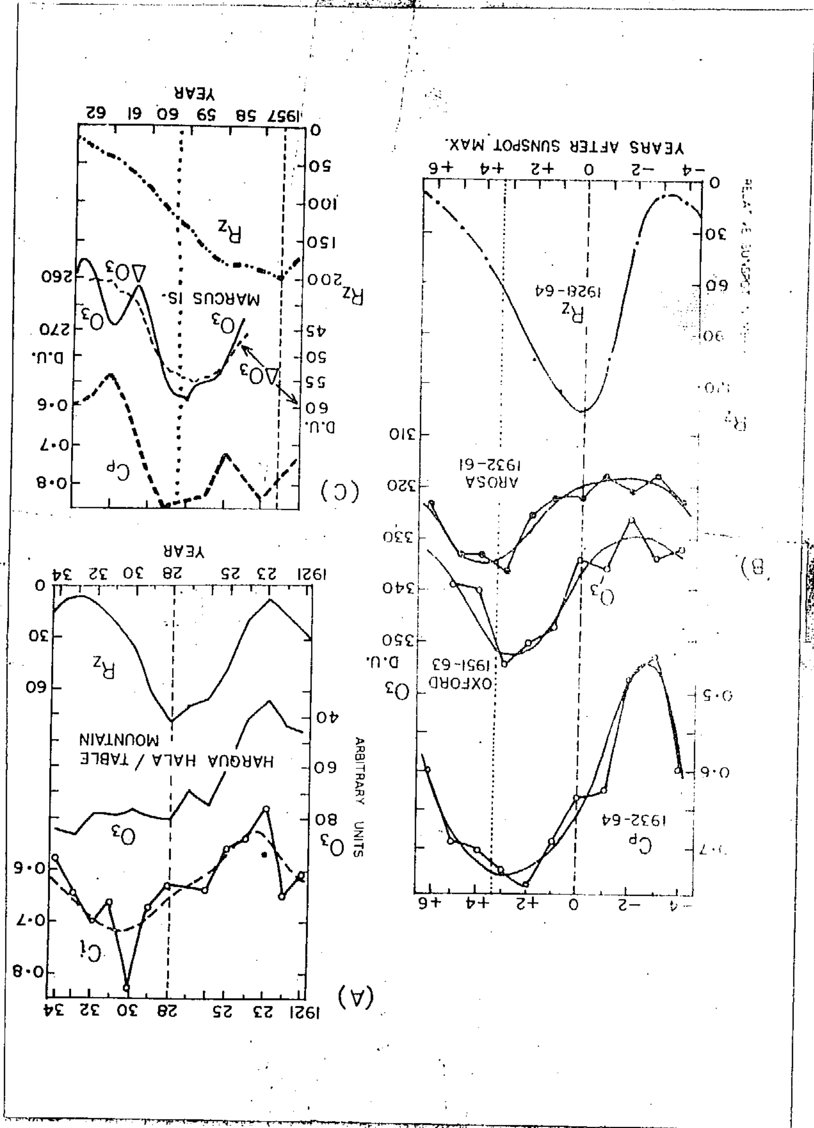

Fig.8.5 11-year cycles in (i) magnetic activity (C_i or C_p), (ii) total ozone (O_3) and ozone above 35 km (ΔO_3), and (iii) the relative sunspot number (R_z).

A - 1921-33; B - 1932-61 and C - 1957-62.

(after, Rangarajan, 1965) - and the sunspot number, the time series shown here cover the period 1921 to 1963. Section 'A' shows the ozone data for HarquaHala/Table Mountain (1921-33) after Fowle, 'B' shows the composite curve for Arosa (1932-61) and the Oxford data for the period 1951-63, while 'C' depicts the Marcus ozone data, total (O_3) as well as the fractional ($\triangle O_3$) for the period 1958-62. Vertical broken lines denote the epochs of maximum R_z, while the dotted lines indicate the epochs of ozone maximum. In the 1921-33 series, the increase in magnetic character index (C_1) is noted to continue for several years after the sunspot maximum, the trend in ozone variation is found to be similar to that in case of C_1 rather than R_z ($r_{O_3} : R_z$ = + 0.47, $r_{O_3} : C_1$ = + 0.65 which on elimination of the small-period ozone variations becomes = + 0.94, see Table 8.1). In the other two cases the epochs of ozone maximum are well defined and are found to occur some three years after the year of sunspot-maximum. It may also be noted that except for the biennial oscillations seen mounted on the trend in case of O_3 over Marcus Is., there is no difference between the large period changes represented by $\triangle O_3$ and by O_3; and the ozone-maximum happens to be in beginning of 1960 while the sunspot-maximum took place towards end of 1957.

Since the solar wave-radiation is known to arrive on the earth in about 8 minutes, this lag of a few years of the ozone maximum behind the sunspot maximum requires a rethinking. The hypothesis that time variation in solar corpuscular radiation is seen reflected in the ozone changes, has been tested in the previous section as well as in the present illustration. Bartels (1957) has described the indices of the geomagnetic activity K_p, C_p, A_p, etc., as the geomagnetic measures for the time variation of solar corpuscular radiation.

Such departures from the predictions of the photochemical theory apparently indicate a supplementary ozone production by the particle radiation from the sun and/or associated X-rays.

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SECTION I

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STUDIES ON ATMOSPHERIC OZONE

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SECTION II

STUDIES ON AIRGLOW (OI) 5577 Å

CHAPTER : IX

"AIRGLOW OBSERVATIONS ON (OI) 5577 Å AT SRINAGAR", 1958-60"

Reprint of a paper by the present author, in

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CHAPTER IX

AIRGLOW OBSERVATIONS ON (OI) 5577 Å AT SRINAGAR, 1958-60

Abstract

Airglow data on (OI) 5577 Å obtained during 1958-60 at Srinagar (ϕ 34°N) have been compared with those obtained at Mt.Abu, Tamanrasset and Kakioka. The monthly means of nocturnal and seasonal variations have also been analysed. An attempt is made to see any possible co-variation of the Airglow intensity with the magnetic activity-u_1 and the sunspot number R_z.

Introduction

As part of the IGY programme, regular observations of (OI) 5577 Å in the night airglow were started at Srinagar, N.India (ϕ 34° 05' N; 74° 50' E: 1586 m.) in March 1958 and continued till November 1960. During this period, observations were possible on about 340 clear moonless nights. On about 300 of these nights, continuous observations could be taken for 3 hr or more. The main results of the analysis of these observations are presented in this paper.

Description and calibration of Photometer

The night sky photometer, which was made at the Physical Research Laboratory, Ahmedabad and used at Srinagar, covers a circular field of $10^{\circ}.2$ diam. Its sensing element consists of a photomultiplier (RCA 931-A) combined with two interference filters. The filters are mounted on a rotatable metal disc and can be manipulated by a suitable clock mechanism to occupy positions in front of the photomultiplier one after the other after every 3 min. At every change of the filter, there is an interval of 15 sec during which all light is cut off from the photomultiplier and the dark current level recorded. The output signal is fed to a high--gain, differential type d.c. amplifier, and the amplified current is recorded by an Evershed-Vignoles recorder, the chart speed used being 1 in/hr. The filters have peak transmissions near 5600 Å and 5350 Å, the former transmits the 5577 Å line and latter is used to monitor the background continuum radiation.

The spectral characteristics of the optical filters and the net transmission of the photometer assembly are shown in Fig.9.1. The continuous lines give the filter transmissions and the broken lines show (in arbitrary units) the effective spectral response of the optical assembly taking into account the relative response of the photomultiplier. The half band widths of the 5300 Å and 5600 Å filters were 115 Å and 85 Å, and the equivalent band-widths (or integrated effective transmission in terms of the transmission at 5350 Å and 5577 Å) taking into account the photomultiplier response, were 168 Å and 129 Å respectively.

The photometer was pointed towards the celestial pole to avoid the varying stellar background. The constancy of the sensitiveness of the photometer was checked by taking records on

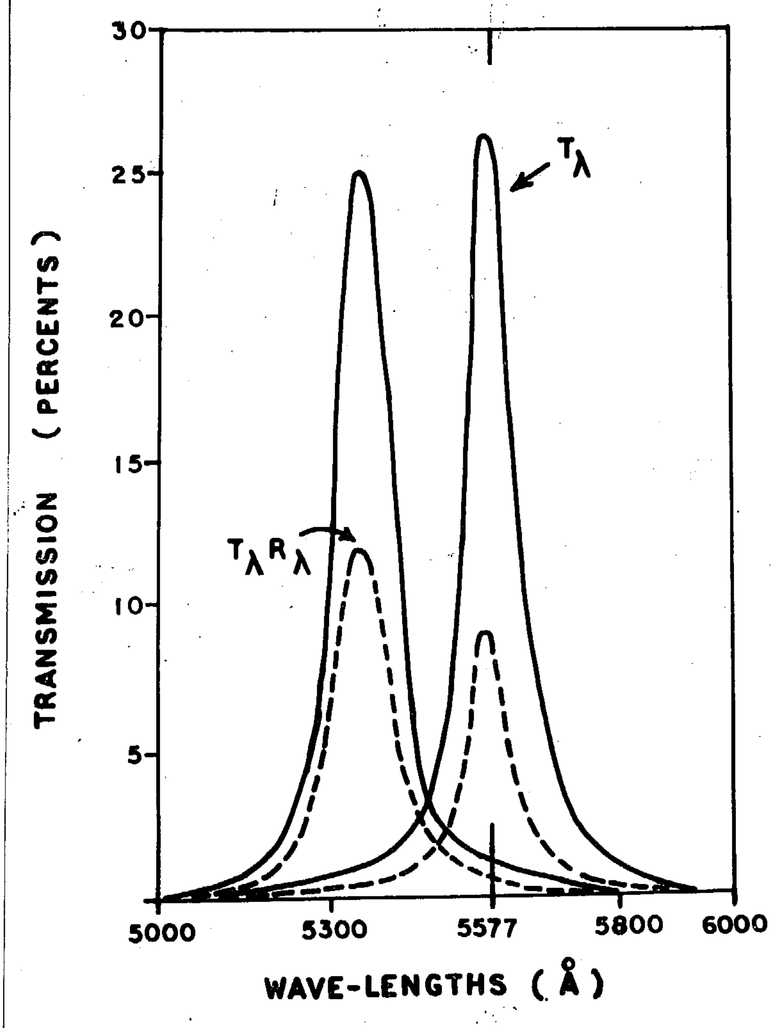

Fig.9.1 Spectral characteristics of optical filters and net transmission of photometer assembly.
T_λ - transmission coefficient of the filters.
R_λ - response of the photomultiplier at wavelengths.

the same chart, both before and after every night's observation, of the light of a radioactive luminescent source. The photometer was independently calibrated against the brightness of a magnesium oxide diffusing screen illuminated by a standard Philips type W-4 tungsten filament lamp of known spectral characteristics. It was found that a recorder current of 1 μa corresponded to 1.721 Rayleighs for 5577 Å, and to 1.316 Rayleighs for 5350 Å, the normalised equivalent band widths being 100 Å. The radioactive luminescent source at Srinagar was compared in January 1958 with the photometer at Mt.Abu. The latter was intercompared in May 1958 with the portable standard photometer of Dr.Roach (Roach, 1958).

The values of I_z/I_o relating to Cactus Peak (Roach & Meinel, 1955), which is at nearly the same latitude and elevation as Srinagar have been used for converting the poleward intensities to zenith sky intensities. The values are

$$I_{zenith} = I\ pole\ /\ 1.637 \text{ for } 5577\ Å$$

and

$$I_{zenith} = I\ pole\ /\ 1.134 \text{ for } 5300\ Å.$$

Following the two-colour method (Roach, 1958; see also, Barbier & Roach, 1950), the reported intensities for 5577 Å were corrected for the contaminating radiation due to background continuum. As the two-colour method in the case of 5577 Å very nearly eliminates the contamination due to OH band (Roach, 1957), no special correction for it was made.

Results

Nocturnal variations

The systematic trends in the nocturnal variations come out clearly, in spite of some sporadic variations of small magnitude and low frequency, their contributions being averaged out in summation. The annual and the seasonal mean variations are shown in Fig.9.2.

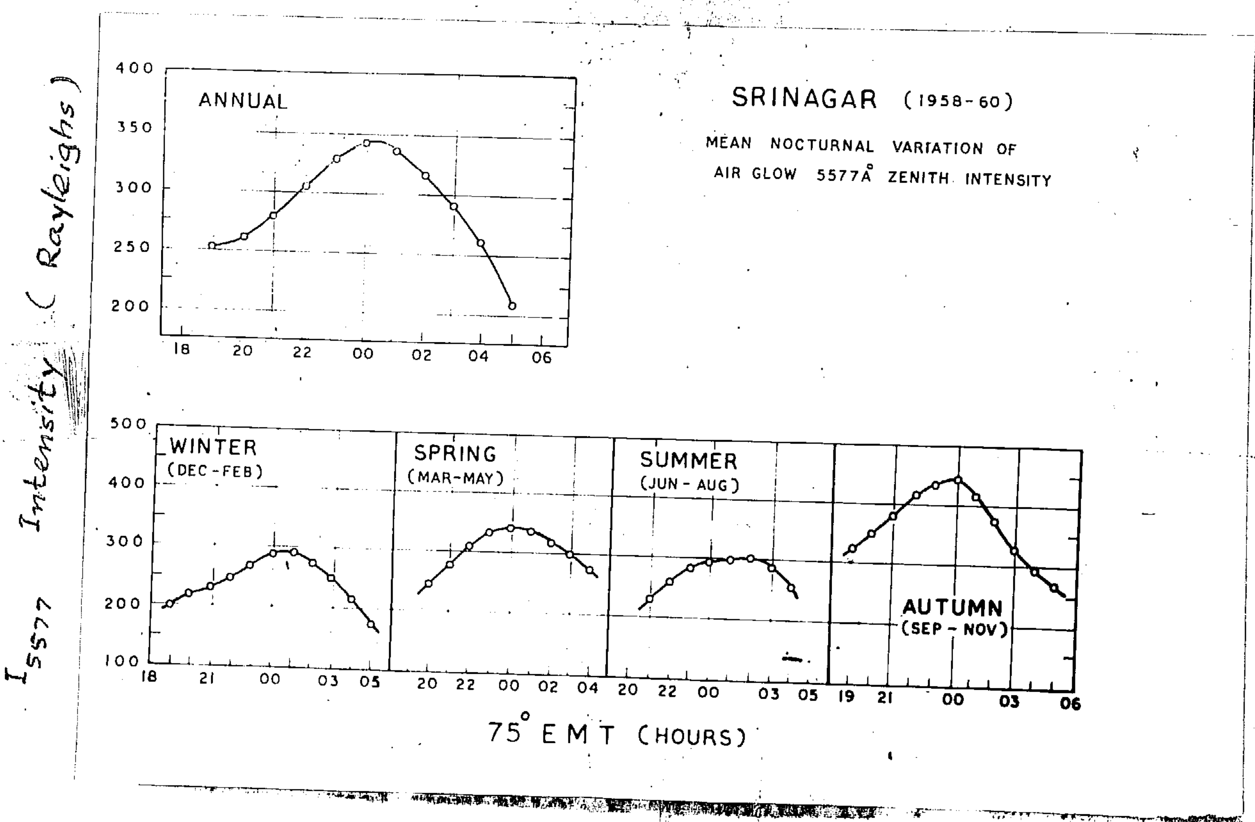

Fig.9.2 Annual mean and seasonal nocturnal variations.

A study of the figure leads to the following inferences:

1. The intensity of 5577 Å is maximum at about midnight; in the summer months, the maximum is broad and occurs later than midnight, whereas in the winter period the maximum is relatively well-defined and occurs shortly after midnight. In autumn and winter, the pre-dawn values are lower than post-dusk values, while in spring and summer, the pre-dawn values are higher.

2. In the equinoctial periods, the intensities are higher; the autumn values are the highest.

3. In the equinoctial months the rates of increase of intensity in the pre-midnight hours are higher, the highest being in September and the next highest in April.

4. In general, the earlier the time of maximum (measuring from the twilight end) the faster is the change in intensity.

Seasonal variations

The contour map (Fig.9.3) displays all the nocturnal and seasonal features. The upper part of the figure gives a pictorial resume of the variations. In the lower portion is given the actual behaviour in the individual months of the whole period 1958-60. The missing data are linearly interpolated. There is a regular annual variation with maxima in the equinoxes and minima in the solstices.

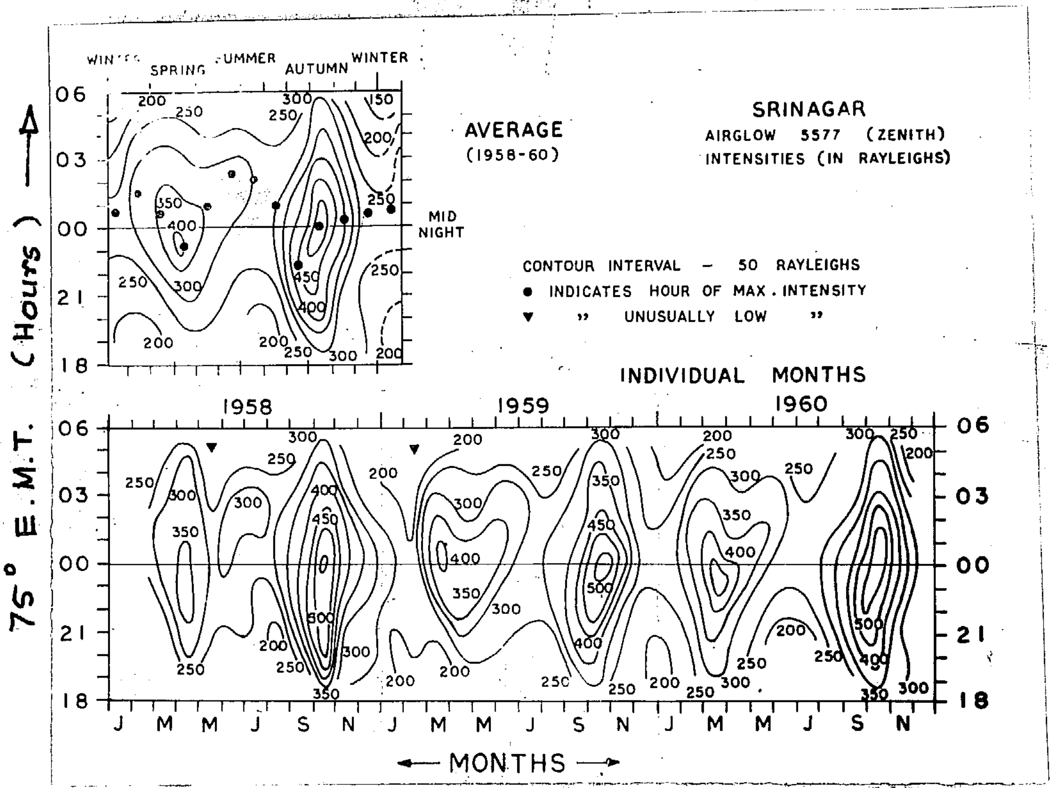

Fig.9.3 Iso-phote maps (interval - 50 R) of airglow 5577 Å intensities at Srinagar, 1958-60.

Year to year variations

In Fig.9.4 the mean values of the intensity of 5577 Å (I) for each month of the period June 1957 to December 1960, the monthly means of the Zurich relative sunspot number (R_z) and of the magnetic activity, u_1, (Geomagnetism - Chapman & Bartels, 1940, p.365) are shown along with the available concurrent data of other stations in middle and low latitudes. (The data of

Tamanrasset also are based on 2-colour method). The u_1 values plotted in the figure were obtained from the H-data of Alibag, Kodaikanal, Trivandrum and Huancayo for the period 1957 to 1959, and for 1960, they were obtained by extrapolation from R_z and C_i, the relationship between the two being derived from an analysis of u_1, R_z and C_i for the period 1884 to 1949.

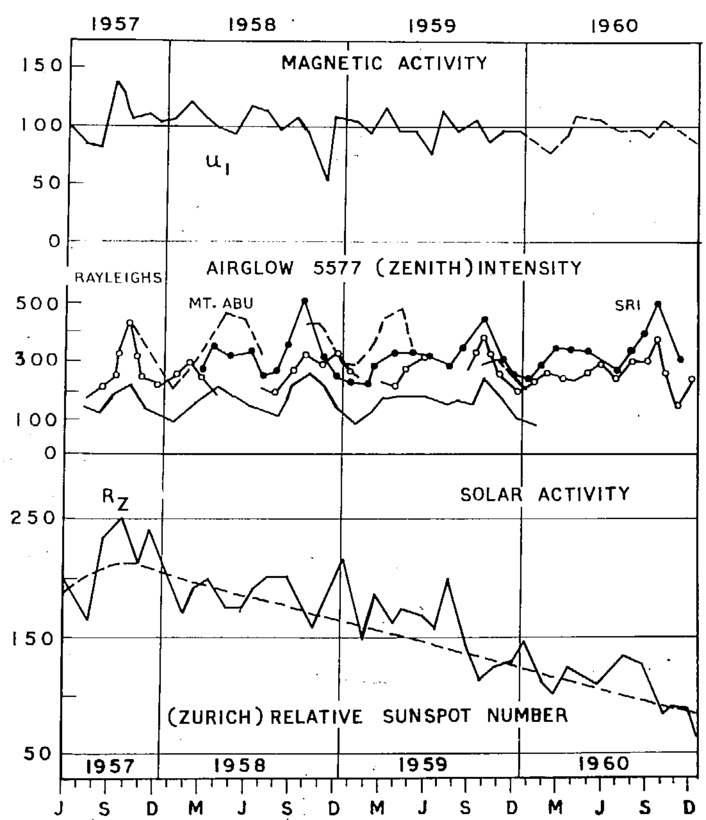

Fig.9.4 Airglow 5577 Å intensity (monthly means of middle and low latitude stations) and relative sunspot number and geomagnetic activity during IGY and IGC.

The Kakioka values, though smaller than the values at Srinagar, show very similar variations. Tamanrasset also behaves similar to Srinagar. Though a comparison on a round-the year basis is not possible with the Mt.Abu data, due to discontinuities during the monsoon months, it is clearly seen that the Mt.Abu values are markedly larger than those at Tamanrasset and Kakoika, and sometimes also, larger than the Srinagar values.

The airglow intensity does not show any large decrease from 1957 to 1960, although the sunspot number decreased to about one-third; there is, however, a suggestion of some relationship with u_1, consistent with the findings of McCaulley et al (1960).

CHAPTER X

MEAN NOCTURNAL VARIATION OF 5577 Å INTENSITY AT LOW LATITUDES

(1) Introduction

The nocturnal variations of the intensity of 5577 Å, I_{5577}, at a given observing station have been the subject of many investigations. On individual nights the maximum of intensity may be found on any hour of the night, however statistical treatment of a large amount of I_{5577} data shows that at temperate latitudes, characteristically, there is a local midnight maximum of intensity (Roach, 1963). That this is the case can be seen in the mean nocturnal variation of I_{5577} observed at Srinagar (Chapt.9) and at other similarly situated stations (see for example, Oti, 1961; Silverman et al, 1962; Ward & Silverman, 1962).

In low latitudes, the recent studies by Chiplonkar & Kulkarni (1958), and Silverman (1964) have shown that the typical nocturnal variations at low latitudes are markedly different than those generally observed at the temperate latitudes (see also Karandikar, 1934; Elvey & Farnsworth, 1942; Ghosh, 1946).

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* Preliminary results of this study have been communicated in the Note presented at the Second International Symposium on Equatorial Aeronomy, 6-17 Sept.1965, held at Brazil (Angreji, 1965).

Attempt to seek regularity in the change-over in the pattern of nocturnal variation either as a function of latitude (geographic or magnetic), or according to the location with respect to the region of maximum f_oF_2 (maximum electron density in the ionospheric F-region) has been made by Silverman (1964) with 4 stations in America with average separation of about 15-20° latitudes, one in Africa and two in India. He was aware of the inadequate geographical coverage and widely spaced stations; and stressed the need of obtaining more data and from a closely-spaced chain of stations.

To seek any dependence of the nocturnal variation of I_{5577} on the geographic or magnetic coordinates it is desirable to have a much greater spatial coverage and closely spaced chain of airglow stations preferably extending up to the equator. The data from a chain of stations along 75° East meridian were analysed by the author to find the characteristic features of the nocturnal variations at those places. These results with those reported by Silverman (1964) were used to study the latitude and longitude effects on the nocturnal variations of I_{5577} at low latitudes. We report here some of the regularities noted in the mean nocturnal variations found at low latitudes, during the IGY-IGC period.

(2) Regularities in the nocturnal variations of I_{5577} at stations along the 75° east meridian

The chain of airglow stations in India along the 75° east meridian is shown in Fig.10.1. The average distance between

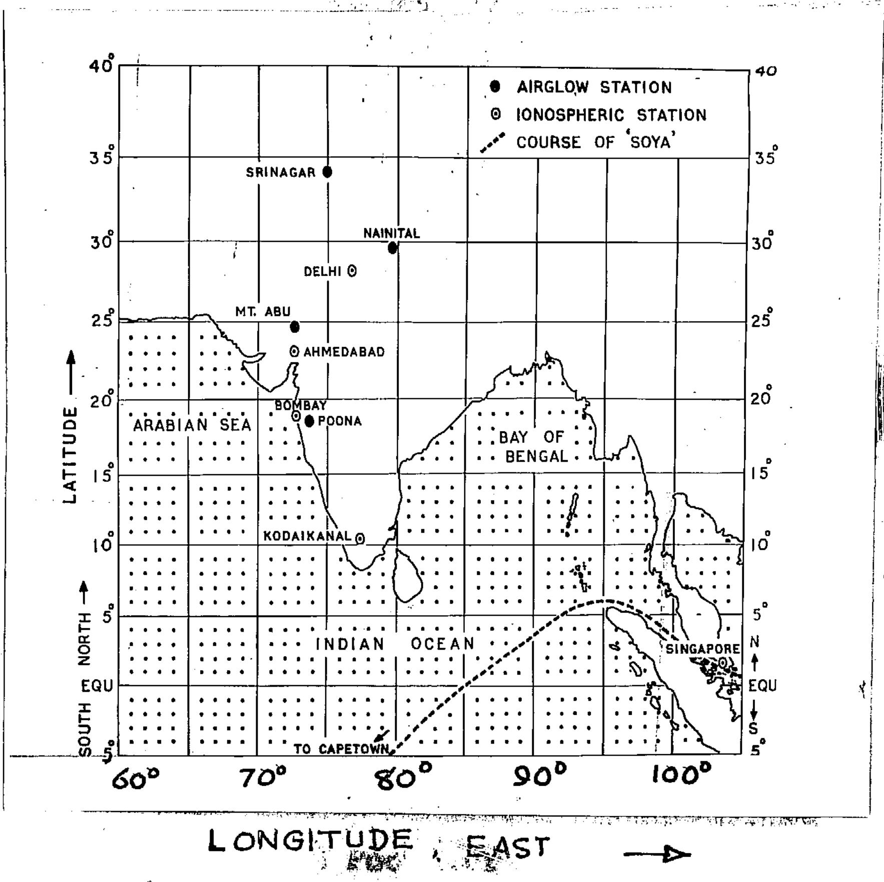

Fig.10.1 Locations of the Airglow stations operating during the IGY-IGC period along the 75° east meridian; and nearby ionospheric stations. The approximate course followed by the SOYA while sailing between Singapore and Cape Town is also shown in the same diagram.

two stations here is about 5° latitudes as against 15-20° latitudes in the case of American stations studied by Silverman (1964). During the IGY-IGC period the chain of stations was extending from 35°N to 19°N latitudes. However, it was possible to extend it upto the equator with the help of the airglow measurements made on the Japanese expedition ship 'SOYA' near 85°E.* The course followed by SOYA in the equatorial region is also shown in Fig.10.1.

Location of the airglow stations used in this study and which will figure in the subsequent discussions, and other particulars such as the extent, kind and source of the data are listed in Table 10.1.

Mean nocturnal variations for Srinagar, Mt.Abu, Poona, and in the SOYA-observations at different seasons are given in Table 10.2. The hourly values are expressed in terms of the respective midnight intensities. The number of observations are given in parantheses and the time of local maxima are underlined. The direction of observation was the zenith in case of the SOYA-observations, and poleward at Srinagar, Mt.Abu and Poona. Round-the-year observations are available only from Srinagar. Observations from Mt.Abu and Poona are available for the period October to May. Hence the comparison is confined to the winter, spring and early-summer period only. Mean nocturnal variations observed in this region during (a) Dec-Jan., (b) March and (c) May are shown in Fig.10.2.

A study of the figure and Table 10.2 leads to the following inferences :- (i) The trend observed at Srinagar

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* These data collected on-board the SOYA during 1956-62 have been compiled by Huruhata (1963). These were consulted for the studies reported in this chapter and in the next one.

Table 10.1

Particulars of the airglow stations and the data used in this study

Station	Location Geographic Lat. Longi. (Deg.)	Observation period	Kind of observation: Portion of the sky observed	Kind of observation: Data available as	Source of the data
Srinagar, India	34 N 75 E	1958-60	region around the pole star	hourly values, individual nights	Data collected at the PRL, Ahmedabad.
Mt. Abu, India	25 N 73 E	1956-59	"	"	"
Naini Tal, India	30 N 80 E	1958-59	"	" *	Sinhval (1964).
Poona, India	19 N 74 E	1956-62	" **	hourly values, monthly means	Chiplonkar (1963).
SOYA (near Ceylon)	10 N 85 E	1956-62	zenith	quarter-hourly, values, individual nights	Huruhata (1963)
Tamanrasset, Algeria	23 N 6 E	1957-59	"	hourly values, individual nights	Provisional values IGY-data sheets.
Lwiro, Congo	2 S 29 E	1957-58	"	hourly values, average for the entire period	Silverman (1964)
Tonanzintla, Mexico	19 N 98 W	1959-62	"	"	Silverman (1964)
Huancayo, Peru	12 S 75 W	1958-61	"	"	Silverman (1964)
San Juan, Argentina	32 S 69 W	1960-62	"	"	Silverman (1964)

* The observations made on some 12 individual nights from Naini Tal were discussed by Pande & Varma (1961). Dr. Sinhval S.D., in a private communication, supplied the hourly data for these 12 nights.

** Observations from Poona, except during Feb-May 1962, were made in the direction $Z = 75^{\circ}$ towards the North (Professor Chiplonkar M.W., private communication dated 19 February 1963).

Table 10.2

Mean nocturnal variation of I_{5577} during different seasons - IGY-IGC period.
The intensities tabulated here are given in percents of the midnight value; and the number of observations given here indicate the number of nights included in that season.

Station	Months	No. of obs.	1900	2000	2100	2200	Local Time 2300	Local Time 0000	0100	0200	0300	0400	0500
Srinagar (1958-60)	Sep-Nov.	70	72	78	85	94	98	100	93	84	74	67	57
	Dec-Feb.	23	82	83	83	91	99	100	104	89	84	70	60
	Mar-Apr.	35		68	78	88	99	100	99	94	88	77	
	May-Aug.	38			84	92	96	100	101	101	98	85	
Mt. Abu (1957-59)	Oct-Nov.	34	75	84	88	99	98	100	95	92	89	86	76
	Dec-Feb.	62	96	98	109	105	102	100	100	105	101	93	83
	Mar-Apr.	58		80	84	94	100	100	98	100	92	80	74
	May-Jun.	30		62	64	75	88	100	99	89	78	71	68
Poona* (1958-62)	Nov.	3			98	106	110	102	98	92	71	68	
	Dec-Feb.	38			131	131	123	107	95	95	102	97	92
	Mar-Apr.	40		104	108	109	112	103	96	90	93	85	75
	May.	8			95	106	116	109	87	89	73	71	
SOYA (10^oN-10^oS) (1957-62)	Nov.	11	129	106	110	113	110	100	87	71	75	101	143
	Mar-Apr.	9		110	115	117	106	100	96	91	84	79	95
	L.T.		1900	2000	2100	2200	2300	0000	0100	0200	0300	0400	0500

* The Poona observations were originally reported in the I.S.T.; (I.S.T. - $L.T._{Poona}$ = 30 minutes.

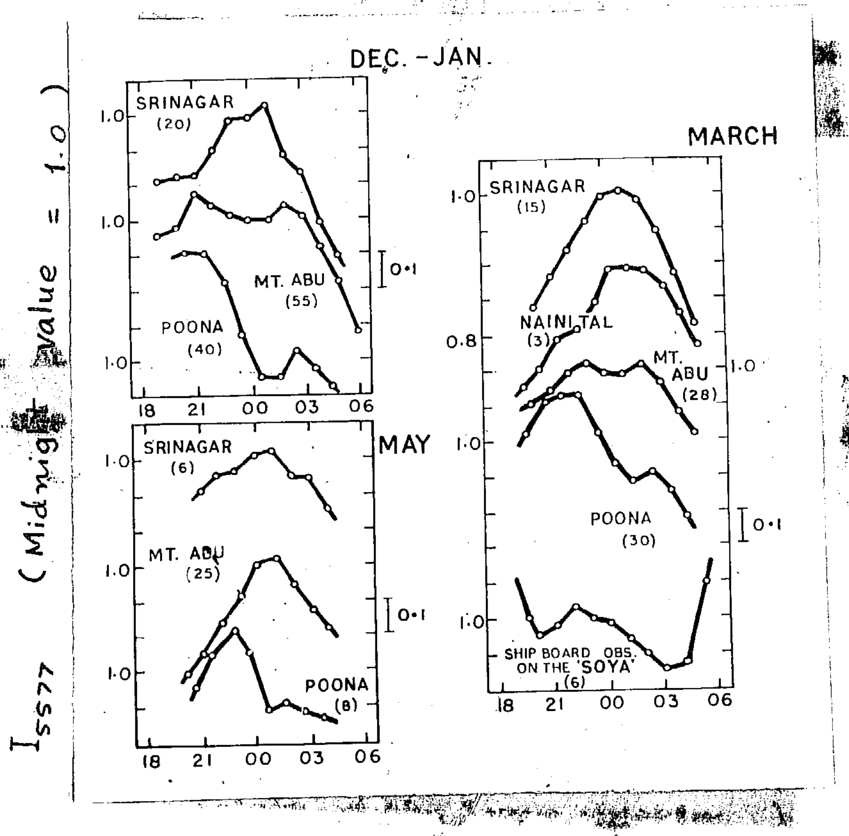

Fig.10.2 Nocturnal variation of I_{5577} in (a) December-January, (b) March and (c) May at different latitudes in the IGY-IGC period. Changes with seasons at these stations may also be noted.

(and also at Naini Tal) is similar to the one generally seen at the midlatitudes, characterized by a maximum at about 01 hr (L.T.).

(ii) A quite different trend is observed in the SOYA-observations. The characteristic features are, a continuing decline upto 03 hr with a maximum superimposed at 22 hr and a steady increase commencing from 03 hr. These features are also observed at Lwiro during 1957-58 (Silverman, 1964). (iii) The nocturnal variation observed at Mt.Abu all around the year is in-between that observed at Srinagar and Poona. The trend seen in the Poona observations is intermediate between that discernible in the observations from Mt.Abu and the SOYA. (iv) At Poona and for most of the time at Mt.Abu also, two maxima are observed during a night. The midnight trough is found to be smaller at Mt.Abu than that at Poona. At both the places it is pronounced in winter and its magnitude is found to decrease progressively as the summer conditions gradually replace the winter setting.

The hour of the first maximum is found to change systematically with (i) the season and (ii) also perhaps with the latitude.

If the height of the layer emitting λ 5577 Å in this part is taken to be 140 km (Dandekar, 1965), the 75° zenith distance observations from Poona (18°.5N) towards the north may be looked upon as the Ahmedabad (23°N) zenith observations. And similarly the observation in the direction Z = 75° south from Poona would reveal the characteristics observed over a place having the geographic latitude = 14°N. Hence to bridge the wide gap between Ahmedabad (23°N) and the equatorial region (10°N-10°S) covered by the SOYA observations, one may look into the results of meridional scanning from Poona. Such results from Poona during January to March 1956 have been reported by Chiplonkar & Kulkarni (1960). Based on the data read from their Fig.4, the nocturnal variations of I_{5577} at zenith distance 75°N, zero and 75°S as observed from Poona, are shown in Fig.10.3. The intensities shown here are relative intensities with midnight values taken as unity.

Towards Z = 75°S the maxima were recorded at 2000 and 0300 hours, while towards Z = 75°N they were found to occur at 2130 and 0200 hours respectively. At the zenith the maxima were less pronounced and occurred at 2100 and 0230 hours. In the SOYA observations (10°N-10°S) maximum intensity is observed at 1900 and 0500 hr (Fig.10.2, Table 10.2).

Thus, when we look at the stations situated progressively away from the equator in the northward direction, it is observed that the time of the first maximum (occurring in first half of the night) is progressively delayed, and the time interval between the two maxima is found to decrease with increasing latitude. The maxima seem to merge at 30-35°N latitude into a single maximum occurring at the midnight.

These features suggest meridional movements of a bright airglow patch. Starting from the equator soon after dusk, it continues to move towards the north in the first half of the night. The patch reaches the maximum latitude (about 30°N) at midnight and perhaps soon starts moving equatorwards. In the post-midnight hours the journey continues and the bright patch

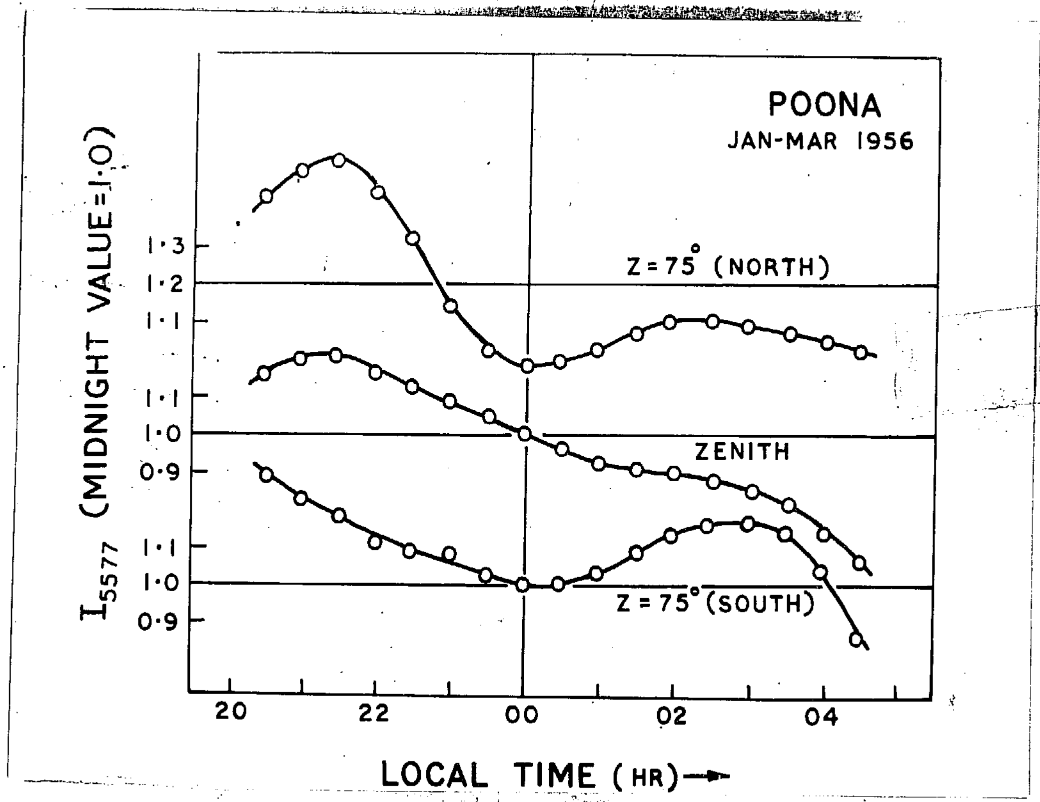

Fig.10.3 Results of meridional scanning from Poona. Average of 10 nights during January-March 1956 were read from Fig.4 of Chiplonkar & Kulkarni(1960).Note the sequential changes in the hour of maximum I_{5577} in the pre-and post-midnight hours(see Roach and Pettit, 1951).

returns to the equator at dawn. The results reported by Barbier and coworkers from the analysis of the airglow data from the African stations (see discussion) corroborate this finding. The data available at the moment in the 75°E meridian zone are not sufficient enough to enable one to decide whether these motions are real or apparent and have arose due to the growth and decay of the intensity at these places coinciding with the moving patch picture.

(3) Longitude effect on the nocturnal variation of I_{5577} at low latitudes

In the above mentioned scanning results from Poona, there is a tendency of a secondary maximum occurring at about 23 hr in case of Z = 75°S. A well defined secondary maximum is also evident at Z = 60°S at poona. This feature is also seen at Lwiro (Silverman, 1964) and in the SOYA observations (Table 10.2). However, Silverman (1964) finds no such secondary maximum at Huancayo.

The results of a similar comparison of the mean nocturnal variations of I_{5577} observed at stations around 20°N latitude are also instructive. Such stations are Tonanzintla (19°N, Mexico), Tamanrasset (23°N, Algeria), and Poona/Ahmedabad (23°N, India). The mean nocturnal variation observed at Tonanzintla (Silverman, 1964) was intercompared with similar results for Tamanrasset and Poona. At Tonanzintla, the values of I_{5577} are seen declining rapidly in the early hours of the night with relatively little variation during the middle and latter parts of the night. The annual mean nocturnal variation observed at Tamanrasset is characterised by a well developed broad maximum during the middle of the night. Nocturnal variation of I_{5577} observed at Poona has a declining trend with a marked maximum at about 2130 hr and a secondary maximum at about 0230 hr (see also, Chiplonkar & Kulkarni, 1958).

So far as the typical nocturnal variation patterns are concerned, the patterns observed at Tonanzintla and Tamanrasset are almost opposite in nature and that observed from Poona (over Ahmedabad) is of intermediate character. In case of the near equatorial stations, a well defined secondary maximum is observed at Lwiro (Congo) and in the SOYA observations (near Ceylon) an hour or two before the midnight; no such maximum is observed from Huancayo (Peru). At Lwiro and in the SOYA observations often a steady increase is observed in I_{5577} at about 0300 hr. At Huancayo such increase begins soon after midnight, which gives an impression that with respect to the other two stations the whole schedule at Huancayo is earlier by 2 to 3 hours.

4. Discussion

The above mentioned longitudinal differences in the nocturnal variation of I_{5577} observed during the IGY-IGC period, give a hint that at low latitudes the mean nocturnal variations of I_{5577} are related to those of f_oF_2 (Angreji, 1965). An analysis of simultaneously observed intensity values of (OI) 5577 Å and 6300 Å indicates positive correlation between these quantities at low latitude stations in Asia, and Africa and north America. These results are compatible with the two-layer model proposed by Kulkarni (1965), Steiger (1965), Gulledge et al (1966) see also, Barbier and Glaume, 1960; Barbier, 1964b .

From a study of Fig.10.2 and 10.3 it was infered that regular movements of a bright airglow patch along the meridian have to be postulated in order to explain the observed difference in local maxima at various latitudes in the 75° east meridian zone. The hypothesis of the meridional movements of the bright airglow patch is corroborated by the observational results reported by Barbier & Glaume (1960) and Barbier (1964b). In the scanning observations of I_{6300} from the low latitude stations in Africa, viz. Tamanrasset (23°N, Algeria) and Agadez (17°N, Nigeria), progressive meridional movement of bright airglow arc in a single night is found to take place. Starting from near the southern horizon, the east-west arc moves northward with progress of the night.

Barbier & Glaume (1960), Barbier (1964a) and Glaume (1965) have mentioned of significant temporal and spatial correlation between I_{5577} and I_{6300} over the tropics. Hence in the corroborative evidence cited above we can infer the meridional movement of bright I_{5577} arc also.

At Lwiro (2°S, Congo) also in the mean pattern of nocturnal variation (Fig.10.9), we note existence of a striking correlation between I_{5577} and I_{6300} after 2200 hr. The marked enhancement occurring between 0300 to 0400 hr at such a low latitude like this cannot be explained by the hypothesis proposed recently by Cole (1965) in which he postulates a continuous flux of photoelectrons from the magnetically conjugate sunlit atmosphere to explain the pre-dawn enhancement observed at the high and higher-middle latitudes; since the time difference between the sunrise observed at the two conjugate points at low latitudes can be of the order of a few minutes only. If the parallel increase noted in I_{5577} and I_{6300} at about 2300 and 0300 hr at Lwiro are assumed to be due to the appearance of the intertropical arc overhead there, it will be interesting to study its movement in course of a night, which probably may turnout to be similar to the one noted in case of the 75° east meridian zone.

CHAPTER XI

SOME OBSERVATIONAL RESULTS ON TIME VARIATION AND LATITUDINAL DISTRIBUTION OF 5577 Å INTENSITY SUGGESTING INFLUENCE OF MAGNETIC ACTIVITY

Solar influence on time variations of I_{5577}

(1) Summary of work done earlier

Day-to-day variations of the intensity of airglow emission at λ 5577 Å (I_{5577}) and the relative sunspot number (R_z) were studied by Nakamura (1958). He noted that the correlation between the two is not conspicuous. Influence of solar flares of class 2 + or 3 on the variation of I_{5577} was examined by Dandekar (1963) and subsequently by Dandekar & Silverman (1964); however these seem to be the only studies of this aspect of solar activity.

Since magnetic disturbances are known to be due to solar activity, studies aiming at the interrelation between variations of I_{5577} and magnetic activity are pertinent here. Study of the immediate effect of sudden commencement storms has been made by Christophe-Glaume (1963), and recently by Weill & Christophe-Glaume (1965), and Silverman & Bellew (1965). They have noted an increase of about 20 rayleighs in I_{5577} within an hour or so from the time of SC, and a second phase of increase generally begins after about two hours.

In the comparison of daily values, however, no correlation is evident (Rayleigh, 1921-22; Rayleigh & Jones, 1935; Dufay & Teheng, 1946; Duncan, 1960). Silverman et al (1962) have reviewed the literature on correlation between the day-to-day variations of I_{5577} and magnetic activity. They have noted that the results reported by various investigators are inconsistent and, at times, even contradictory. The general finding is that it is possible to have relatively low 5577 Å intensities with high magnetic activity, but the probability of high intensities increases with magnetic activity, thus leading to an increase in the spread of 5577 Å intensities as magnetic activity increases (Roach et al, 1960). In most of these studies the index for magnetic activity employed is K (local) or K (planetary); the choice of index is very important because if an inadequate index is employed, it may sometimes lead to an erroneous inference (McCaulley et al, 1960).

Regarding the large period variations between I_{5577} (annual means) and R_z or sunspot area (SS-area), positive correlation has been reported by Rayleigh (1928), Dufay & Tcheng (1946), and Barbier (1959); the data in these studies refer either to the ascending or descending portion of the 11-year sunspot cycle (referred to as 'sunspot cycle' hereafter in this chapter). Lack of correlation between I_{5577} and R_z has been noted by Roach et al (1953) and Angreji (1963). These studies are based on the data for the years following the epoch of the sunspot-maximum. Okuda (1963), dealing again with a part of the sunspot cycle, found that the interrelation between R_z and I_{5577} for Haute Provence (44°N, 6°E) was negative upto about 1959 and positive since then. Negative correlation was noted by him between R_z and the I_{5577} values for Sendai (38° N, 141° E) during 1958-62.

The results of investigations based on data covering a complete sunspot cycle are also diverse. Rayleigh & Jones (1935) have noted that the I_{5577} values observed during 1923-34 are better correlated with SS-area rather than with R_z. Hernandez & Silverman (1964) have noted the existence of positive correlation between solar activity (which is not defined) and I_{5577} data for Sacramento Peak (33° N, 106° W), 1953-62. Barbier (1965) has noted from I_{5577} data for Haute Provence, 1953-64, that the epoch of maximum I_{5577} lags behind the sunspot-maximum. The maximum I_{5577} was recorded in 1958-59 while the sunspot-maximum occurred towards the end of 1957 (see Fig.11.1).

Existence of a positive correlation between year-to-year variations of I_{5577} (low and middle latitudes) and magnetic activity was noted for the period 1957-60 (Angreji, 1963). Similarly, for Sendai, Okuda (1963) observes a positive correlation during 1957-59 and a negative one during 1960-62. To the best of our knowledge such large period variations in I_{5577} and those in the magnetic activity have not been studied by others so far.

For the instantaneous effect of solar activity on I_{5577} we have no comments to offer here. However, regarding the long-term change, a part or whole of the sunspot cycle, it is

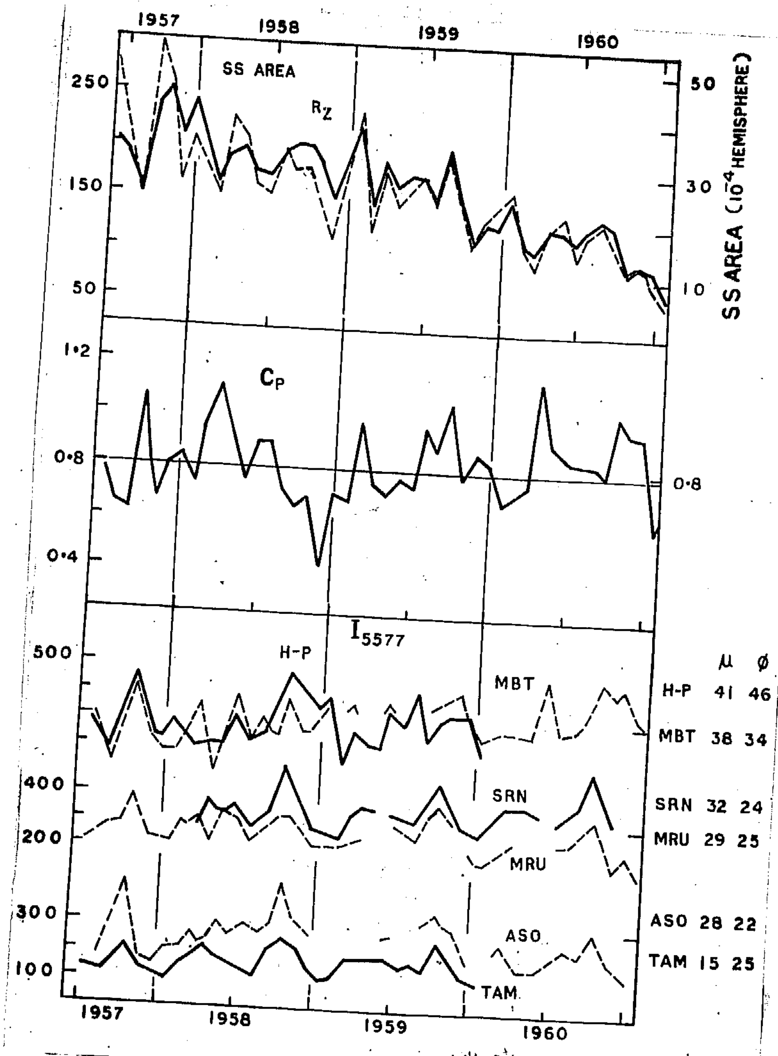

Fig.11.1 Trends in variation of the solar activity (SS-area and R_z), geomagnetic activity (C_p), and airglow 5577 Å zenith intensity (I_{5577}) at low and midlatitude stations during 1957-60. The magnetic dip latitude (μ) and dipole latitude (Φ) are shown alongside for convenience of the comparison.

observed that instead of R_z or SS area, I_{5577} follows closely the change in magnetic activity (represented by C_p or A_p). This point has been brought out and discussed in the following.

(2) Results

In Fig.11.1 we have plotted monthly means of the sunspot number (R_z), sunspot area (SS-area), the planetary character-index of the magnetic activity (C_p), and the airglow 5577 Å zenith intensity (I_{5577}), in Rayleighs, observed at middle and low latitude stations (magnetic dip latitude (μ) ranging from 45° to 15° north). The period covered is from July 1957 to December 1960.

It will be seen from Fig.11.1 that C_p level shows statistical variations of smaller amplitudes apart from the well known 6-month cycle; the general level has remained constant at C_p = 0.8 during the 3½ years, 1957-60: I_{5577} has also similar trend. On the other hand, R_z and SS-area register a more or less uniform decline decreasing to one-third of their initial values in three years 1958-60, as compared to those in the second half of 1957.

2.1. 11-year cycles in I_{5577}; SS-area and Magnetic Activity

It may be recalled here that Rayleigh & Jones (1935) stated that the variations in I_{5577} were better correlated with those in SS-area rather than those in R_z. In Fig.11.1, however, no such distinction can be seen as R_z and SS-area both have very nearly identical time-variation. This covariation of R_z and

SS-area is in agreement with the earlier result (Chapman & Bartels, 1940, page 370) that the correlation coefficient between the annual means of R_z and SS-area, 1882-1930, is + 0.98. In the years following 1930, Table 11.1 shows...

Table 11.1

Typical time variations of R_z, SS-area and C_p during the years following the sunspot-maximum

Sunspot cycle No. & the period covered.	Year	R_z	SS-area (Millionths of visible hemisphere)	C_px100
16 (1924-34)	1927	69	1060	63 *
	1929	65	1240	67 *
	1931	21	280	66 *
17 (1934-44)	1937	114	2070	55
	1939	89	1580	68
	1941	48	660	66
18 (1944-54)	1947	152	2640	77
	1949	135	2130	65
	1951	69	1140	92
19 (1954-65)	1957	196	3340	78
	1958	180	2890	79
	1959	161	2620	83
	1960	107	2330	86
	1961	54	730	61
	1962	38	440	58

* C_p values are not available for the period previous to 1932. A somewhat subjective version of C_p, (C_i) is given for the earlier period. C_p and C_i are very highly correlated (see, Bartels, 1957) and hence no difference is expected because of this substitution.

for the recent 4 solar cycles, very similar trend of variation between R_z and SS-area during the years immediately following the sunspot maximum. It may, however, be noted that the C_p values do not record any such decrease and are found to remain high for several years from the epoch of sunspot-maximum.

It may be concluded, therefore, that over a solar cycle, SS-area and R_z show more or less identical variation, but C_p has a typically different trend during the post-sunspot maximum period, which is similar to that of I_{5577}.

In case of the ascending part of the solar cycle the SS-area, C_p and I_{5577} have more or less the same trend. This is also true for the last few years of the solar cycle. However, the disagreement of SS-area with the other two noted previously, becomes obvious during the years of high magnetic activity which correspond to the central part of the sunspot cycle. This may be seen in Fig.11.2. Here a typical 11-year cycle in the I_{5577} data for Haute Provence(*) is shown in the histogram form, the smooth curve shows the 3-year moving averages and depicts the trend. The 11-year cycles in SS-area and magnetic activity (C_p) during 1954-64, are also represented in the same manner. The characteristic covariation noted earlier (Fig.11.1) between I_{5577} and C_p is now seen existing during all the phases of the 11-year cycle.

(*) I_{5577} data (annual means) for Haute Provence (July 1953 to June 1964) were read from Fig.1 of Barbier (1965).

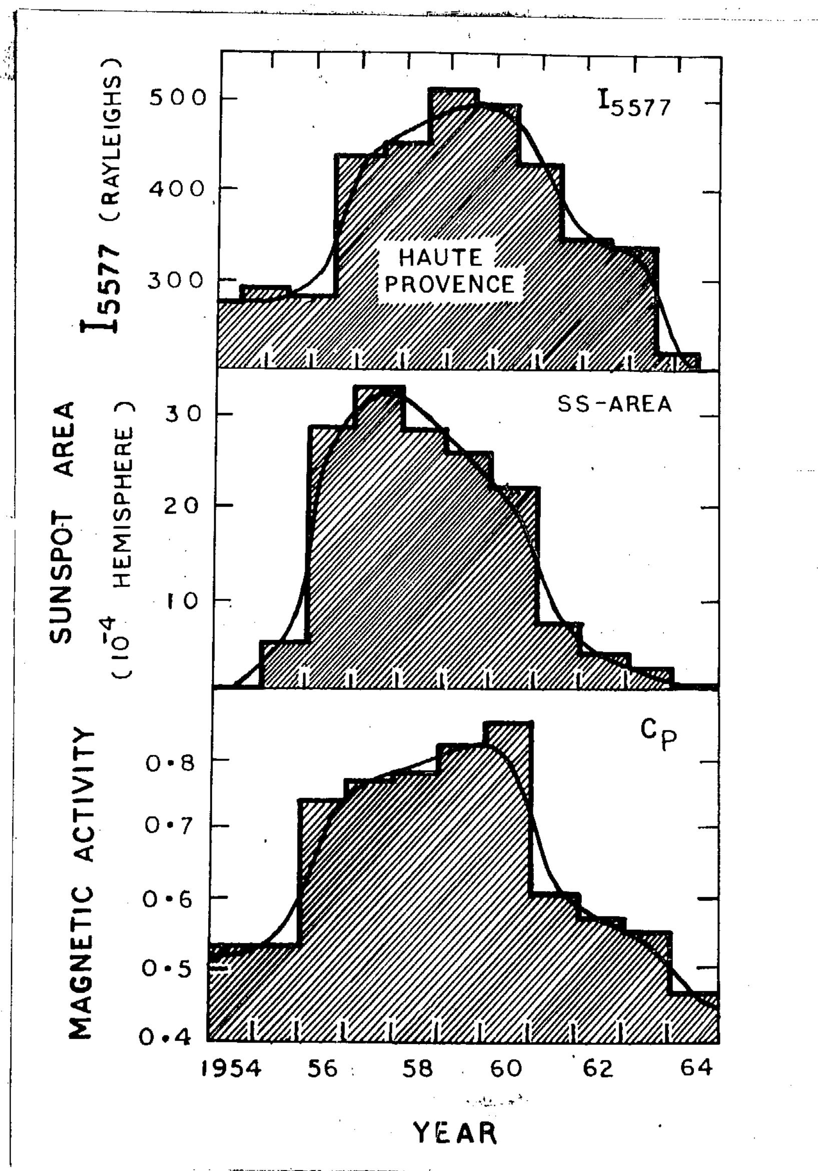

Fig.11.2 11-year cycles (histograms) in I_{5577} — Haute Provence, SS-area and C_p during 1954-64. The trends are depicted by 3-year moving averages (smooth curve).

2.2. Hysteresis-curve like formation in the plot of I_{5577} vs. SS-area

Hernandez & Silverman (1964) have plotted the I_{5577} data[(**)] for Terling, Canberra, and Cape Town, against the SS-area. These plots look like hysteresis-curves. They have given no explanation for this formation. When such a diagram is drawn for Haute Provence (see Fig.11.3) this also shows the hysteresis-loop. Such formation may be explained as follows :-

It is well known that the heliographic latitudes of the sunspot continue to decrease all through the 11-year cycle. Hence as the cycle advances, the distance between the sunspots and the sun-earth line steadily decreases. The effectiveness of the spot increases (when the particle radiation is considered) as the distance of the spot from the sun-earth line decreases. Hence for the spots having numerically same "actual area", the effect felt is more during the descending part as compared to the ascending portion of the sunspot cycle.

It is felt that the hysteresis-loop observed in the plot of I_{5577} against the sunspot area (or the sunspot number) may be connected with this difference between the 'actual' and 'effective' area depending on the heliographic latitude and hence on the phase of the sunspot cycle. If, therefore, this solar activity can be considered as a factor contributing to the observed values of I_{5577}, this particular difference between I_{5577} values

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(**) The data due to Rayleigh & Jones (1935) have been expressed in the present-day unit, rayleighs.

Fig.11.3 I_{5577} - Haute Provence (1953-64), as function of SS-area. Note two distinctly different relationships for the ascending and descending phases of the sunspot cycle. For the same SS-area the I_{5577} value corresponding to the descending phase is higher than that referring to the ascending one. [I_{5577} data for Haute Provence have been read from Fig.1 of Barbier (1965)].

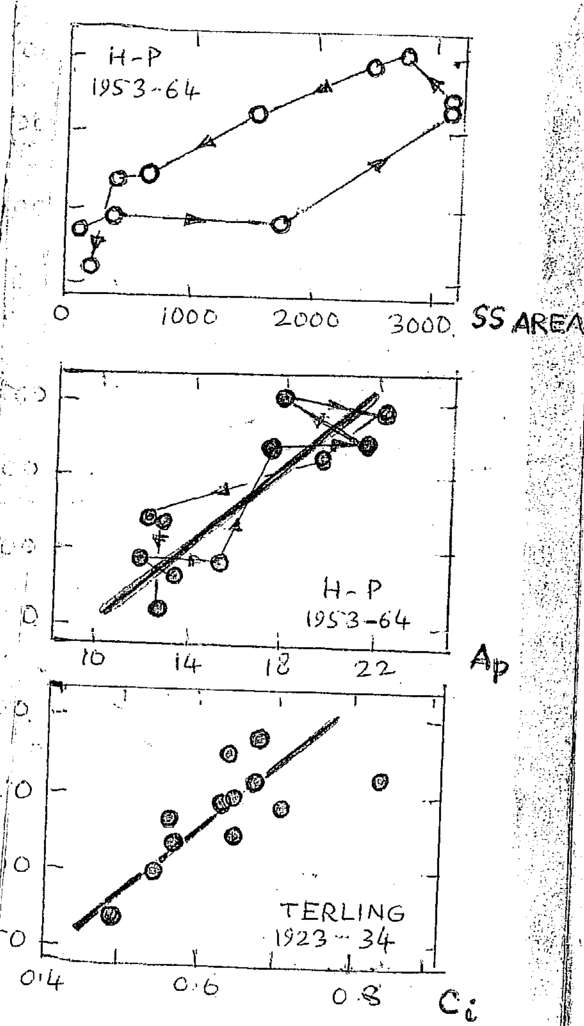

Fig.11.3

Fig.11.4

A

B

Fig.11.4 Relationship between I_{5577} and the magnetic activity, (a) Haute Provence (1953-64) and (b) Terling (1923-34). Note absence of any systematic differences in the departure from the regression line ($r = + 0.84$) depending on the phase of sunspot cycle.

corresponding to the same area in the ascending and descending part of the sunspot cycle (see Fig.11.3) can be readily explained by considering the sunspot-latitude.

The area as well as the location of the spot on the solar disc determine the geomagnetic activity (represented by the index C_p, or A_p - average planetary amplitude). Hence, if at all, I_{5577} has any dependence, direct or otherwise, on the corpuscular radiation from the sun, this might slow a similar trend of variation with the magnetic activity rather than R_z or SS-area, in the ascending and also in the descending part, including the post-sunspot maximum period, of the sunspot cycle. This is shown in Fig.11.4(a) in which the I_{5577} data for Haute Provence(1953-64) are plotted against A_p. The correlation coefficient (r) between I_{5577} and A_p, for 11 values, is + 0.85. It may also be noted that the departures from the regression line unlike in case of I_{5577} versus SS-area, does not show any dependence on the phase of the sunspot cycle. Similarly when the Terling data for I_{5577} (1923-34) are plotted against the magnetic character figure -C_i, Fig.11.4(b), a positive correlation (r = + 0.75) is found.

These results are in agreement with the findings on the immediate effects observable in the daily or shorter period values of I_{5577}, by Nakamura (1958), Dandekar & Silverman (1964), Weill & Glaume (1965), Silverman & Bellew (1965), and McCaulley, Roach & Mastushita (1960).

3. Discussions.

In light of (i) the significant positive correlations seen existing between the annual means of I_{5577} and A_p or C_p (or C_i) the 'Geomagnetic measures for the time variations the solar corpuscular radiation' as Bartels (1957) puts them over complete solar cycles in 1923-34 and 1953-64 (Fig.11.4(a) and (b) and (ii) other evidences cited above, it might be inferred that the interrelations are real. It is possible then to comprehend the apparently inconsistent-looking results in which the correlation inferred between I_{5577} and R_z is found to depend mainly on the period studied; Rayleigh (1928), Dufay & Tcheng (1946) and Barbier (1959) studying the data referring either to the ascending or the later-half of descending portion of the 11-year cycle noted positive correlation between I_{5577} and R_z, while Roach et al (1953) and Angreji (1963) concluded from examining the data for the period of high magnetic activity - the period following the epoch of sunspot-maximum, that I_{5577} remained steady over several years eventhough R_z decreased considerably at a uniform rate during this period. Discussion on the characteristic trends followed by I_{5577}, C_p and R_z (or SS-area). Fig.11.2 leads to the comprehension of these divers findings. Barbier (1965) noted that the epoch of maximum I_{5577} lags behind the year of sunspot maximum by about an year. No physical association between I_{5577} and R_z can account for the lag of several years. The significant positive correlation between annual means of I_{5577} and magnetic activity for no lag (Figs.11.2, 11.4(a) and (b)) provides the physical reason for the lag of I_{5577} maximum from the epoch of the sunspot maximum.

It is inferred therefore that in the long term variations of I_{5577}, C_p or A_p may play a prominent role which points to an interrelationship between I_{5577} and corpuscular radiation. The association may be direct or caused by associated changes in the upper atmospheric conditions such as systematic changes in density (see Priester & Cattani, 1962). The 11-year cycle in the particle radiation from the sun is not correctly described by the solar index R_z or SS-area alone; while C_p and A_p seem to describe the said cycle accurately enough for this purpose and hence are found more adequate for the purpose of correlation.

The I_{5577} data available from Poona (18.5° N, 74° E) do not cover the entire sunspot cycle, but indications are that the annual means are positively correlated with those of A_p as can be seen from Table 11.2. Hence in the I_{5577} observations from Poona a 11-year cycle very similar to the one seen in the I_{5577} data from temperate latitudes (Fig.11.2), is to be expected. If so, the lower limit of latitudes where the 11-year cycle in I_{5577} can be detected, should include Poona also.

Table 11.2

Year-to-year variations in I_{5577} observations from Poona (18.5° N, 74° E).

Observing Nov-Apr season	1957-58	1958-59	1959-60	1960-61	1961-62
I_{5577} (in rayleighs)	250	252	273	-	221
A_p	20.7	17.0	20.5	18.2	10.2

Latitude effect on I_{5577}

(1) Introduction

The study of time variation of I_{5577} in the previous section, has shown that it is synchronous with that of the solar corpuscular radiation monitored with the indices of geomagnetic activity like C_p, A_p, etc. It is likely that the association may not be direct one, but I_{5577} variations are caused by temperature and/or density changes at 100 km-level brought about by the particle radiation from the sun. If it is so, as a corollary, it follows that the distribution of I_{5577} with latitude depends on the configuration of the geomagnetic field.

(2) Work done earlier on latitude effect

In case of the auroral latitudes, the studies by Roach (1963), and by Sandford (1962, 1964) have pointed out that the latitude effect in I_{5577} there, at least, is determined by the geomagnetic field. The results of earlier studies based on the I_{5577} data for stations situated in the sub-auroral zone, however, are rather puzzling.

Lord Rayleigh (1924, 1928) noted that the intensity of the green line did not have a distinctive distribution in the latitude. Later, the studies by Rayleigh & Jones (1935), Roach et al (1953), Barbier (1957), Roach et al (1960), to name a few {see, Bates (1960), Chamberlain (1961) for extensive bibliography on the subject}, have pointed out that in general higher values of I_{5577} were observed for the stations at higher latitudes. In these studies mostly a couple of stations with widely differing latitudes were considered and the geographic latitudes, ϕ, were employed.

The analyses of the ship-board observations collected during the first six voyages of the Japanese expedition ship, the SOYA, 1956-62, have brought out new features like the first maxima in I_{5577} at about 20° N and S and secondary minima near 40° N and S latitude (Huruhata & J.Nakamura, 1957, 1961; J. Nakamura, 1957, 1958; T.Nakamura, 1961). Daily means of I_{5577} constituted the basic data. No discrimination was made on the basis of the duration of observations; and the geographic and the geomagnetic (dipole) latitude Φ (*) schemes only were employed.

(3) Present study

Available I_{5577} data were processed to form daily, monthly and the IGY-averages, and these annual means were supplemented by the annual means available in the literature. Latitudinal profiles were obtained by plotting these means against (i) the most commonly employed ϕ, and Φ - schemes,

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(*) Geomagnetic co-ordinates based on the centered dipole approximation and referring to the epoch 1945.0 have been tabulated by Vestine et al (1948). These tables were consulted for the geomagnetic dipole latitudes, Φ.

and (ii) the magnetic dip latitudes, μ (*) and the magnetic invariant latitudes, λ (**) believed to be capable of providing exact representation of the configuration of the geomagnetic field. The results of this intercomparison are presented and briefly discussed. Other available data bearing on the subject are carefully examined to bring out the underlying latitude effect in I_{5577} in the sub-auroral zone ($\mu \leq 62^{o}$).

(3.1) Latitude effect in the IGY results

The information-content of Fig.11.1 was primarily intended to illustrate the typical temporal variation seen in I_{5577} during 1957-60 at various low and mid latitude stations. Fig.11.1 also shows that when the mean level of I_{5577} are inter-compared the intensity value for a station at higher dip latitude is higher than that at the low latitude station. To facilitate the comparison, the stations are divided into three pairs and the latitudes μ and Φ are shown against names of the stations. From the three pairs presented in Fig.11.1 it may be seen that even if $\emptyset$ or 0 is same at two stations, higher I_{5577} it observed at a station with higher dip latitude, μ, in all the cases.

(*) The relationship between the magnetic dip latitude, μ , and the magnetic inclination or dip, I, is $\tan \mu = \frac{1}{2} \tan I$ The values of I, for the epoch 1945.0 were taken from Vesting et al (1948).

(**) The magnetic invariant latitude, λ , is deduced from the so-called sheet parameter, L, introduced by McIlwain (1961) according to $\cos \lambda = R/L$, where R is the geocentric distance to the emitting layer in earth radii. L is approximately the geocentric distance to the equatorial crossing of the pertinent magnetic line of force also in earth radii.

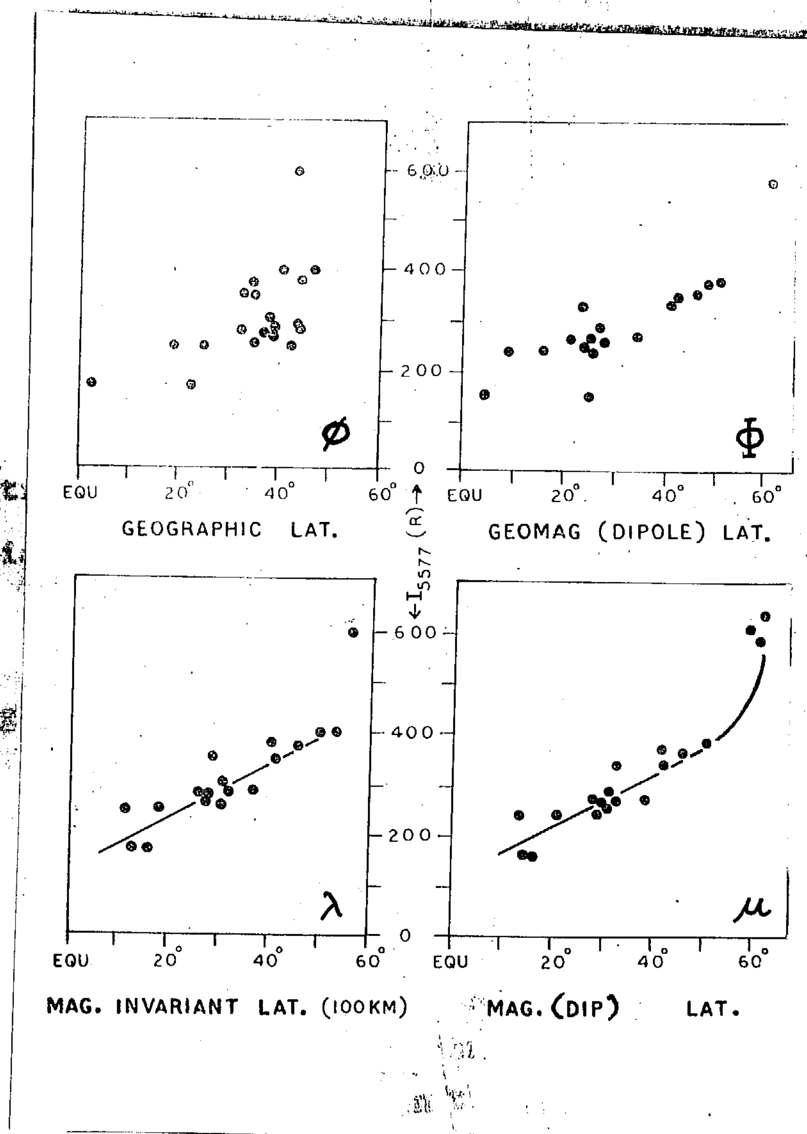

Fig.11.5 Distribution of I_{5577} (IGY means) in the sub-auroral zone with latitudes ϕ, Φ, λ and μ. The data points are seen well organized when the appropriate magnetic latitudes (λ or μ) are considered.

The effect of sporadic intensity fluctuations is considerable in the averages of individual nights, is negligible when the monthly means are considered, and is practically absent in case of the annual means. Hence to check validity of the inference drawn above that changes in the level of I_{5577} are depending on the spatial gradients in μ, the IGY-means of I_{5577} are considered as a next step. In Table 11.3 the latitudes $\emptyset$, Φ, μ and λ_{100} (assuming the layer-height to be 100 km) are given for the stations in the subauroral zone. The stations have been arranged in the descending order of μ. IGY-means of I_{5577} and other particulars regarding the data are also given there. The distribution of I_{5577} with the latitudes $\emptyset$, Φ, λ_{100} and μ are shown in Fig.11.5.

The general trend is noted to be the same, namely higher values of I_{5577} are observed at higher latitudes. Upon comparing the results by virtue of minimum scatter and better definition of the latitudinal profile, the magnetic dip-and invariant-latitude schemes depict the true latitude effect in I_{5577}, while in the other two schemes the picture is hazy. The centered-dipole model being only a first order crude approximation of the true configuration of geomagnetic field, the coarseness of presentation of the latitudinal profile in the Φ-scheme is manifested.

It may be inferred from Fig.11.5 that the value of I_{5577} is minimum at the magnetic (dip) equator and increases linearly with the latitude all through the sub-auroral zone. At the threshold of the auroral zone a rapid increase in I_{5577} is in evidence. The results are in agreement with that reported by Roach (1963).

Since accurately determined values of the magnetic dip, (inclination) I, are readily available for all places in the world, and the quality of the results obtained with the λ and μ-schemes is the same; in the following studies to determine the geomagnetic influence over the latitudinal distribution of I_{5577} only the μ-scheme has been employed.

(3.2) Latitude effect in the results of the World Survey by Lord Rayleigh

Lord Rayleigh's results of the World Survey in 1925-26 (Rayleigh, 1928) do not show any distinctive change in I_{5577} with the latitude (see also, Rayleigh, 1924). Converting his 'opacity scale' of intensity to that of the present-day units, namely rayleighs, his data are shown in Fig.11.6(a) and tabulated as the 'reported' values in Table 11.4. It may be pointed out in this connection that these observations were not taken towards the zenith. In his paper (Rayleigh, 1930, page 463) he has said the observations from Terling were made in the poleward direction. Not that Lord Rayleigh was not aware of the Van Rhijn factor but thought that atmospheric attenuation would compensate for the Van Rhijn factor (Rayleigh, 1930, page 466). These observations were made with a visual photometer with which, as such, it is

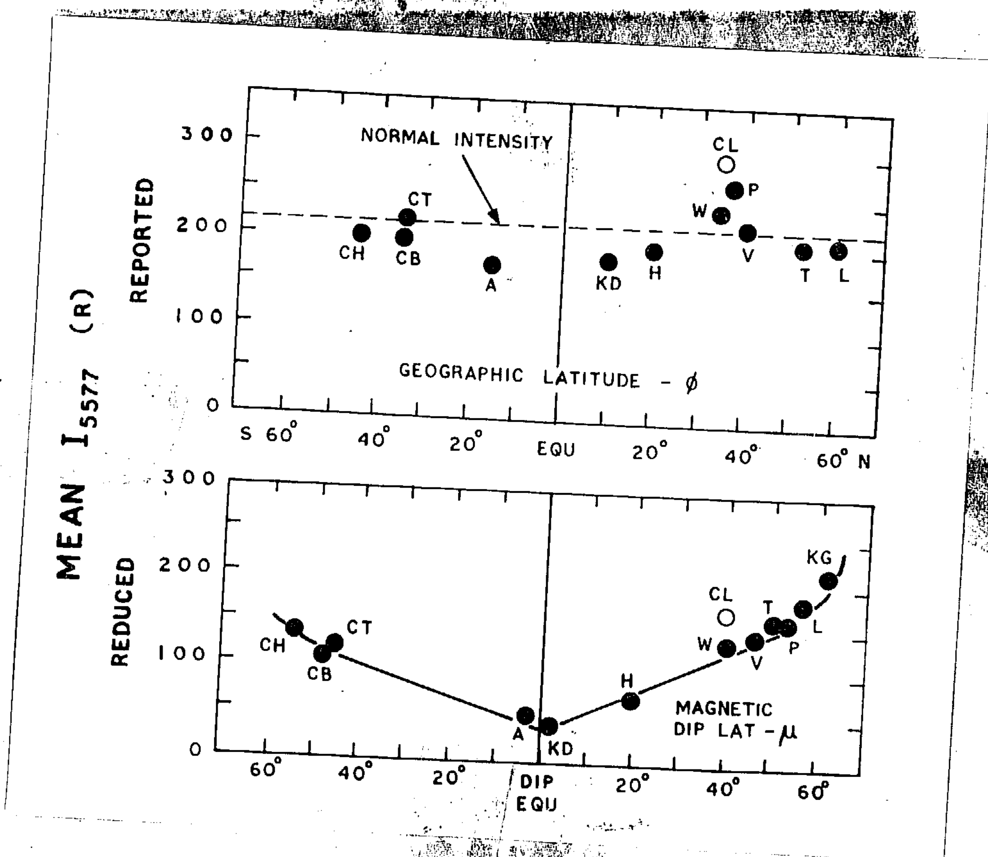

Fig.11.6 Latitude effect in the results of the World Survey (1925-26) by Lord Rayleigh.
(a) Reported intensities (in the present-day units, rayleighs) against ϕ and (b) 'reduced' intensity values (see text) against μ .

difficult to take zenith observations. Rayleigh has noted in his earlier paper that "the observations were made from a north window, and the region of the sky observed was that round the pole; thus the Milky-Way was avoided. It is better in every way to observe from a window than out-of-doors, for thus the observer is shielded from the light of the sky on either side and directly overhead" (Rayleigh, 1924, page 126). At stations other than Terling where the direction of observations was not specified the observations were taken in the direction determined by "the least number of stars in the field of view and also to avoid other obstacles such as near-by town lights, etc."

We may conclude, therefore, that in some of his papers (Rayleigh, 1924, 1930) Lord Rayleigh has clearly stated that the observations were polewards; and in the other paper (Rayleigh, 1928) he has indicated that they were made in the general direction of the pole. If, therefore, it is assumed that at all his stations the observations were made in the poleward direction, using the appropriate Van Rhijn factor his 'reported' intensities can be reduced to the zenith intensities. These 'reduced intensities' are shown in Table 11.4 and have been plotted against μ in Fig.11.6(b). This diagram shows a very similar latitude-effect as shown by the IGY data (Fig.11.5).

(3.3) <u>Latitude-effect in the SOYA Observations</u>

To study this aspect of the I_{5577} variation, the group of Japanese research workers, under the leadership of Professor

M.Huruhata, has collected airglow data from the expedition ship, the 'SOYA', during her regular voyages between Tokyo, Japan, and the SYOWA station (69° S, 41° E) in the Antarctica, in the period October 1956-April 1962.

Analysis of these data has brought to light a couple of new features in the latitudinal profile (nocturnal means of I_{5577} plotted against ϕ and Φ). Besides the equatorial minimum, first maxima in I_{5577} (at 20° N and 20° S) and secondary minima (around 40 to 50° N and S latitudes) are discernible (Huruhata & J.Nakmura, 1957, 1961; J.Nakamura, 1957, 1958; Huruhata & T. Nakamura, 1960). The first maxima and secondary minima in I_{5577} are explained by the model proposed by Tohmatsu (1958) who has attempted to rationalize the Chapman (photochemical) reaction in terms of the large-scale physical inhomogenities and movements in the 100-Km region. He suggests that regions of high 5577 intensity correspond to the regions of a meteorological type downdraft and low intensities are associated with updrafts (see also Hikosaka et al, 1958; and Tohmatsu & Nagata, 1963).

Cole (1961) suggests that the large I_{5577} values in the SOYA observations around $\phi = 15^\circ$ to 40° N and S (the first maxima) are partly due to the South Atlantic Anomaly(*). He noted that 'It seems more than a coincidence that the peaks of

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(*) Abnormally low total intensity (F) of the earth's magnetic field is observed in the region of the South Atlantic Anomaly, which extends from the South China Sea southeast across Brazil and Argentine into the Indian Ocean off South Africa and with the center of the anomaly near the south-eastern coast of Brazil. Hence it is sometimes referred to as the negative anomaly or Brazil anomaly.

Nakamura's observations (J.Nakamura, 1958) were obtained as the recording ship (SOYA) passed through the South China sea and the south African end of this anomaly'.

However, a contradictory result to that stated above has been obtained by Saito (1962) during the 1960-61 voyage of the SOYA. From his plot of daily means of I_{5577} against $\emptyset$ it was observed that I_{5577} has a minimum around 20° S, and then I_{5577} becomes stronger at higher latitudes (Saito, 1962). At about 20° N also a minimum has been indicated. Thus Saito's results give minima in I_{5577} at the locations where earlier studies indicated the first maxima, and in place of secondary minimum around 45° S found earlier Saito observes a steady rise south of 20° S (see also, the report by Markham & Anctil, (1965) their observations in the South Atlantic Anomaly region do not show any intensity enhancement over that found outside it).

It becomes necessary, therefore, to re-examine the SOYA-observations (compiled by Huruhata, 1963) more critically.

It is noted that

(1) The SOYA used to sail between TOKYO and the SYOWA station (Antarctica) via Singapore and Cape Town (See Fig.11.7). As the course followed by the SOYA runs through the Cape Town Anomaly(*), the magnetic dip latitude, μ, is found to remain

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(*) In the world map of the horizontal component, H, of the geomagnetic field, or in the contour map of the magnetic inclination (dip), I, besides the main (dip) pole at ....

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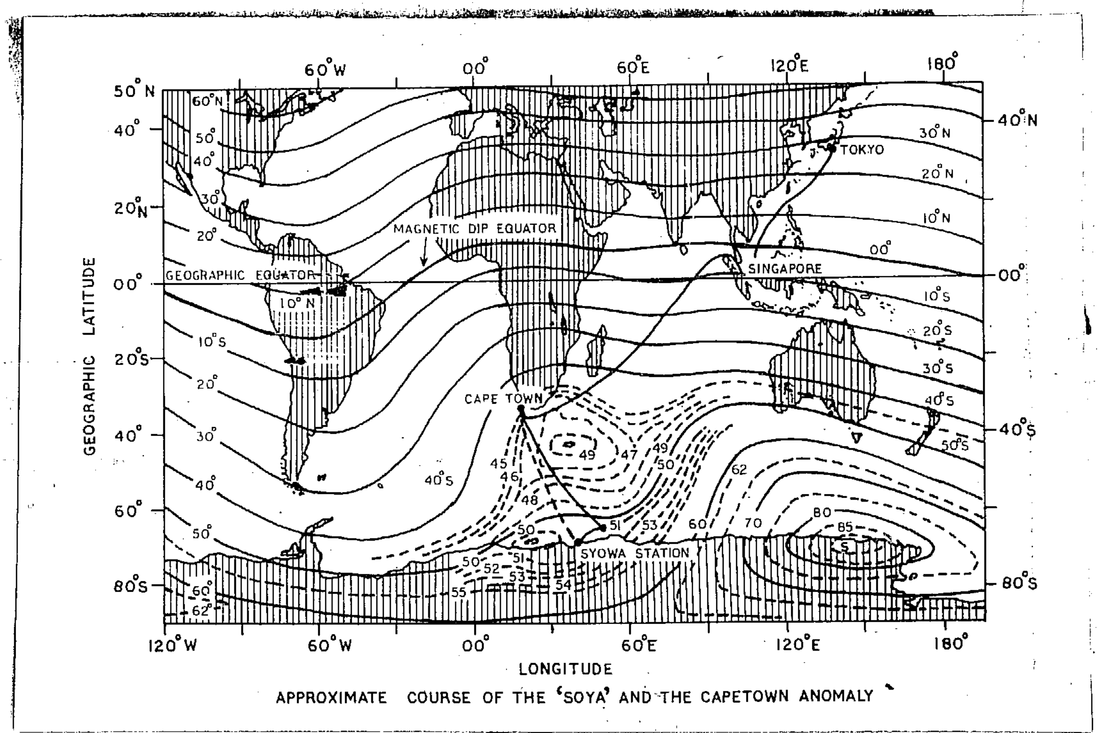

Fig.11.7 Course followed by the SOYA during the voyages made in the period 1956-62, and the Cape Town Anomaly. The contours of magnetic dip latitude, μ, based on the magnetic inclination data for the 1945-epoch [after Vestine et al.(1948)] are drawn at 10° interval except in the region of the Anomaly where the interval is reduced to 1° latitude for better definition. Note as a result of the Anomaly the value of μ remains more or less constant at 48°S though ϕ changes from 30°S to 70°S.

constant ($48^{o} \pm 2^{o}$ S) at places south of $\emptyset = 30^{o}$ S all along the course of SOYA.

(2) These are voyage observations and the ship is constantly changing her position. As a good approximation only one night observations of I_{5577} can be attributed to a particular latitude. The observations also last for different durations, ranging from half an hour to about ten hours, and refer to different parts of the night. It is a well known fact that the value of I_{5577} changes appreciably in course of a night (nocturnal variation).

(3) The basic data are nightly means and not the annual ones. Hence besides the latitude-effect there are nocturnal, night to night, seasonal, and long-term variations in I_{5577}. The schedule followed by the SOYA was such that she was in the northern hemisphere in the equinoctial months and in the southern hemisphere during December-February (local summer). Higher intensity values

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$\emptyset = 68^{o}$S, 144^{o}E in the Antarctica, there are two secondary poles. One at $\emptyset = 42^{o}$S, 32^{o}E (near Prince Edward Is., S.Africa) and another at about $\emptyset = 70^{o}$S, 20^{o}E (near the Princess Ragnhild coast in Antarctica). The anomalous configuration of the magnetic element H and I around these 'secondary South-poles' constitute the Cape Town Anomaly. The value of I (and hence of μ) remains more or less same over the region bounded by the parallels $\emptyset = 30^{o}$S and 70^{o}S, and the longitudes 20^{o} and 60^{o} East of Greenwich. In Fig.11.7 the anomaly is seen depicted by the dip latitude contours. It will be seen that there is no anomalous configuration near Brazil, and the Cape Town Anomaly is distinctly different from the South Atlantic Anomaly as can be seen the world map of the total component (F) of the earth's magnetic field.

and larger night-to-night fluctuations are found during the equinoctial months as compared to those in the solstical period.

To correct for the points mentioned in (2) above, it is necessary to discriminate the nightly means of I_{5577} according to the duration of observation. Due to nocturnal variation of I_{5577}, the average taken over only a small part of the night will, in general, differ from that over the entire night. Hence it is necessary to attach weights to the data if the entire night is not covered. Therefore, in the present study of the SOYA observations, the nightly means based on the observations covering 5 hours or more, between 3-5 hours, and less than 3 hours were respectively given full, half, and quarter weights.

When such weighted observations (I_{5577}) are plotted against ϕ and Φ the scatter is less than that with the means without any weights. A tendency to show a plateau in I_{5577} in the latitude region 35° - 60°S is discernible, which is similar to the one seen in the plot of μ versus ϕ or Φ (Cape Town Anomaly effect). If the values of I_{5577} are plotted against μ the spread in 35-70°S region reduces considerably showing again the dependency of I_{5577} on μ rather than on ϕ or Φ. However, it may be noted that the above conclusions are of suggestive nature due to the limited amount of available data.

To correct for the night-to-night fluctuations and larger-period variations (such as the seasonal and 11-year cycles), mentioned in (3) above, comparison of the SOYA-observations with a station on the ground may be employed. The assumption here is that there is a global component in the time variation of I_{5577}. Roach (1961) has intercompared the values of I_{5577} averaged over 10-day periods (IGY-IGC period) for Fritz Peak - FP (40°N, 106°W) with those for Rapid City - RC (44°N, 103°W) and Haute Provence - HP (44°N, 6°E). Positive correlations of 0.36 between FP and HP (63 points) and 0.53 between FP and RC (31 points) are noted. Roach infers that the correlation of 0.36 between FP and HP suggests a significant but small global term; the higher coefficient between FP and RC suggests that these closer Spaced stations are (also) influenced by variations having spacial extensions of a few hundred kilometers.

Since the typical size of the "airglow cells" has been reported to be about 2500 km (Roach, 1963) to identify the presence of the global term in the I_{5577} means referring to individual nights we have intercompared the nocturnal means reported by stations separated by 5000 km, or more. The nights with observations lasting 5 hours or more only are considered. Sources of the data are same as have been listed in Table 11.3. The results are shown in Table 11.5. The correlation coefficients are all positive and range from 0.38 to 0.55 (each based on about 120 nights), which imply presence of perhaps a slightly larger global term than the one inferred by Roach (1961).

Identical effects observed associated with the SC storms and on the next day from on-set of the intense solar-flares, similar seasonal and 11-year cycles (noted in previous section of the present chapter) all support such an inference.

Table 11.5

Intercomparison of nocturnal means* of I_{5577} (1957-60)

Stations (separation more than 5000 km)	Correlation coefficient (r)	No. of nights
Tamanrasset (Algeria) - Mt.Abu (India)	0.38	171
" - Srinagar (India)	0.50	110
" - Sendai/Niigata (Japan)	0.46	135
Haute Provence (France) - "	0.42	101
Srinagar - "	0.55	83

*Nights with the observations lasting 5 hours or more only are considered.

When such intensity ratios are plotted against μ, in several cases they show latitudinal distribution of I_{5577} very similar to the one seen in the IGY results (Fig.11.5).

4. Concluding Remarks.

Before the evidence can be said to be conclusive, more observational material, of course, is needed. Still, it may be noted that the available evidences taken on their face-value indicate the distribution of I_{5577} with latitude is determined by the spatial gradients in the magnetic dip latitudes. The data points are seen most organized when the magnetic-latitude schemes μ and λ, are employed. The latitudinal profile shows a minimum in I_{5577} at the dip equator, a linear increase with latitude all through the sub-auroral zone, and a systematic sharp rise at the threshold of the auroral zone (see Fig.11.5 and Fig.11.6(b)).

SECTION II - STUDIES ON AIRGLOW (OI) 5577 Å

Summary of the results reported in section II

The studies reported in Chapters 9-11 are primarily concerned with (i) the temporal (and spatial) variations of I_{5577} at Srinagar and the sub-auroral stations and (ii) the correlations of I_{5577} variations with the solar and other geophysical phenomena. They have revealed :

(1) A gradual transition in the nocturnal variation with latitude; and presence of systematic time-shifts in local maxima with latitudes, which suggest a meridional movement of a bright airglow patch from the equator to about 30°N before midnight and vice versa thereafter.

(2) The 11-year cycle seen in annual means of I_{5577} is synchronous with that in C_p and A_p — the geomagnetic measures of the solar corpuscular radiation.

(3) The distribution of I_{5577} with latitude is found to depend essentially on the magnetic dip latitude.

SECTION II

STUDIES IN THE AIRGLOW (OI) 5577 Å

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2815

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