

## Ozone Variations associated with the Equatorial Stratospheric Wind Oscillations

S. RANGARAJAN

*Meteorological Office, Poona*

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**ABSTRACT.** With a view to elucidate the bi-annual or possibly 26-monthly oscillation in the ozone content of the atmosphere corresponding to the recently discovered equatorial stratospheric wind oscillation, an analysis was made of the monthly mean total ozone values of five stations, three in India and two in Australia covering the years 1958-1962. When the effects of the annual oscillation are suitably eliminated, it has been found that the long-period variations show a 26-month cycle in the case of four out of the five stations studied. The oscillation seems to extend as far south as 38° Latitude in the southern hemisphere but only as far as 20°N in the northern hemisphere. The amplitude of the 26-month oscillation is greater in the southern hemisphere. Further, the phase of the oscillation is mutually opposite in the two hemispheres. During epochs when the easterly stratospheric winds over the equator at the 25-km level weaken and change over to westerlies, the ozone content increases in the northern hemisphere and decreases in the southern hemisphere. The opposite effect is produced when the westerly stratospheric winds weaken and change over to easterlies.

### 1. The discovery of the equatorial stratospheric oscillation

Regular aerological observations extending to heights above 25 km in the stratosphere have been possible during the past 4 or 5 years on account of progressive improvements effected in the balloon-borne sounding instruments. Such observations, though covering only limited areas of the earth, have revealed some new and hitherto unknown features in the wind and temperature regimes of the stratosphere. One such remarkable feature discovered very recently has come to be known as the equatorial stratospheric wind oscillation. The winds in the equatorial stratosphere between 20-30 km which are mostly zonal in character have been found to alternate in direction between east and west with a long period of about 26 months. The phenomenon was reported independently by Ebdon and Veryard (1961) and by Reed *et al.* (1961). The former analysed the stratospheric wind data of Canton Island (Lat. 3°S), Christmas Island (Lat. 2° N) and Nairobi (Lat. 1° S) and by the use of 12-monthly running means demonstrated the 26-month periodicity. The latter constructed vertical time sections using mean monthly wind data

and were able to show graphically not only the existence of the oscillation but also its downward progression from the uppermost observable level of about 30 km. In a subsequent investigation Veryard and Ebdon (1961) showed the existence of a temperature oscillation of similar period at Canton Island and San Juan. Veryard (1961) confirmed the extensive character of the 26-month oscillation by analysing the upper wind data of north Australian stations and Farkas (1962) subsequently found identical features in the limited series of stratospheric wind data of Nandi (18° S) in the Fiji Islands. Reed and Rogers (1962) have made a more thorough investigation of the wind oscillation by harmonic analysis of wind data of a large number of low latitude stations in the equatorial belt. The broad features of the phenomenon as revealed by investigations made so far can be summarised as follows—

(1) The zonal component of the wind in the equatorial stratosphere (covering latitudes from 15°N to 20° S) at heights between 20 and 30 km undergoes periodical reversals from fairly steady easterly to fairly steady westerly direction and *vice versa*, the period for a complete reversal being about 26 months.

(2) The zonal winds at any stratospheric level tend to be of the same direction all round the earth, so that the easterly or westerly winds may be regarded as vast globe-encircling currents.

(3) The phase of the oscillation is different at different levels in the stratosphere. The reversal wave is first observed at the highest level for which observations are available, *viz.*, 30 km and descends slowly downwards at the rate of about 1 kilometre per month. Upon reaching the tropopause the oscillation becomes indistinct and irregular.

(4) The westerly current and to a lesser extent the easterly currents attain their maximum intensity near the 25-km level. At this level, the amplitude of the 26-month cycle over the equator is about 20 m.p.s. which is several times greater than that of the annual cycle (about 2 m.p.s.)

(5) The amplitude of the 26-month cycle decreases polewards rapidly in the northern hemisphere. The factors responsible for the apparent disappearance of the oscillation north of about Lat. 15° N are — (a) The presence of prevailing easterlies in the lower stratosphere with a maximum intensity in the zone between 10° and 15° N, (b) Northward increase in the amplitude of the annual oscillation and (c) The gradual weakening of the oscillation itself. Over the Southern Hemisphere, the position is not clearly known on account of lack of observational data.

## 2. Possible relationship of the 26-month oscillation with long period ozone changes

The levels in the equatorial stratosphere which are most affected by the 26-month oscillation, *i.e.*, 25-30 km also happen to be in the region of maximum relative concentration of atmospheric ozone. There is also evidence of a downward propagation of the reversal wave. As vertical movements in the stratosphere below the region of photochemical equilibrium of ozone can affect the total ozone content, it is only logical to examine whether there are any systematic variations in the total ozone content of equatorial regions. Funk and Garnham (1962)

reported a 24-month periodicity in the total ozone at two Australian stations, Brisbane (Lat. 23½° S) and Aspendale (Lat. 38° S). They discovered this by an examination of 12-monthly running means of a series of monthly mean ozone values extending over the period 1956 to 1961. Although both the stations are located outside the low latitude belt now considered to be affected by the wind oscillation, it is of considerable significance to find an oscillation in the ozone with a period closely approximating to the wind oscillation. This interesting result encouraged the author to take up an analysis of total ozone at three Indian stations for which a continuous series of observational data are available for the period 1958 to 1962. The stations are : Kodaikanal (Lat. 10° N), Abu/Ahmedabad (Lat. 22—23° N) and New Delhi (Lat. 28½° N). The results of the analysis and certain features concerning mutual relationship of the wind and ozone oscillations will be presented in this paper. Before discussing the ozone variations, however, it would be relevant to devote two sections in this paper, one relating to the available observational evidence for the existence of the wind oscillation in the southern part of India and the other relating to the peculiar features of ozone in the low latitude equatorial belt.

## 3. The stratospheric wind oscillation over the southern parts of India

Upper wind data for the stratospheric levels where the oscillation can be detected, *viz.*, 20 km and above have been very meagre over India. Some data for the 21-km level are, however, available for Trivandrum (Lat. 8° N) which comes well under the influence of the 26-month oscillation and which is located close to Kodaikanal (Lat. 10° N) the ozone data of which have been analysed and presented in a subsequent section of this paper. Prior to 1961, the number of wind observations at 21 km was extremely small and monthly means could not be worked out. From 1961 onwards, however, a larger number of observations have become available. These indicate that regimes of easterly and westerly winds do occur alter-

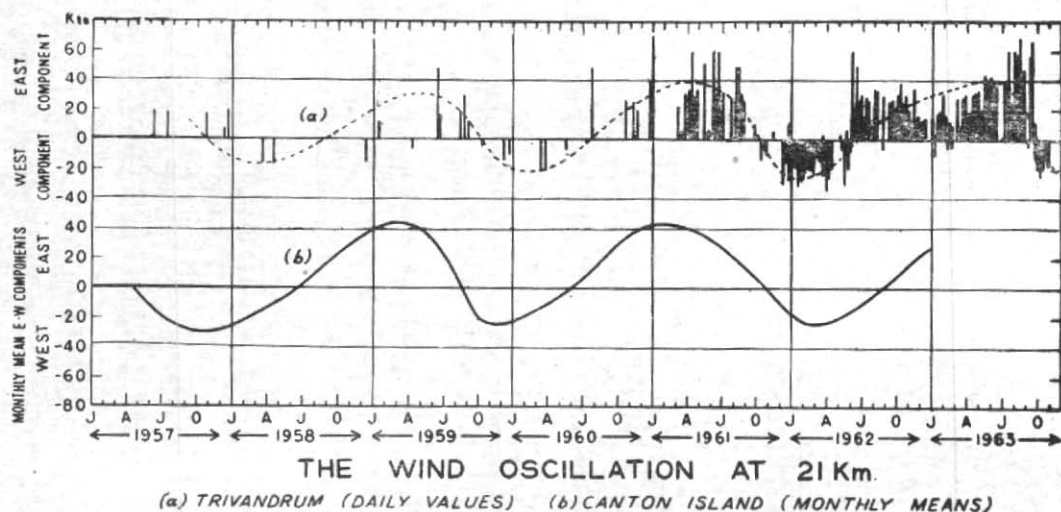


Fig. 1

nately. Fig. 1 shows a plot of easterly components of all individual wind observations recorded at Trivandrum from mid-1957 onwards up to the middle of 1963. For a comparison with the wind oscillation observed elsewhere with better observational coverage, the monthly mean zonal components of Canton Island (Lat.  $3^{\circ}$  S) have also been plotted in the same figure in the form of a continuous curve. The values up to 1961 were extracted from the mean cross section of Reed and Rogers (1962) and those for 1962 were determined from the mean rawinsonde data published by the U.S. Weather Bureau. It will be seen from Fig. 1 that the meagre wind data of Trivandrum fits in fairly well with the world-wide stratospheric oscillatory pattern. However, the regime of westerly wind is distinctly shorter than the regime of the easterly wind. The long-period mean wind at 21-km level thus turns out to be an easterly one only. Another notable feature is that during the southwest monsoon period, June to September, the westerly component is practically non-existent and the oscillation takes the form of variations in the speed of the easterlies only. The reason for this appears to be the occurrence of the belt of strong easterly winds in the lower stratosphere

as a continuation of the easterly jet stream. This strong belt is a feature of the south-Asian region only and constitutes an annual oscillation of considerable amplitude. The 26-month oscillation thus gets suppressed at 21 km. Perhaps at higher levels the oscillation might be more clearly observable. Owing to the paucity of stratospheric wind data a more detailed analysis could not be made. But it may be inferred from the behaviour of Trivandrum winds that the stratospheric wind oscillation does exist over the southern parts of India also roughly in phase with that observed elsewhere over the equatorial region.

#### 4. Some features of ozone in low latitudes

Unlike in middle and high latitudes of northern hemisphere, the total ozone over the equatorial and low latitude areas undergo only small fluctuations, whether on a day-to-day, month-to-month or year-to-year basis. Table 1 shows the standard deviations of daily total ozone with respect to monthly mean in the case of four stations, Kodaikanal (Lat.  $10^{\circ}$  N), New Delhi (Lat.  $28\frac{1}{2}^{\circ}$  N), Srinagar (Lat.  $34^{\circ}$  N) and Oxford (Lat.  $52^{\circ}$  N) for the year 1958. The progressive decrease in day-to-day variations as we go equatorwards from

**TABLE 1**  
Standard deviations of daily ozone from monthly means for four typical stations  
in different latitudes for the year 1958

Station	Standard deviations of total ozone <sup>-3</sup> in cm STP											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Oxford (Lat. 52° N)	57.3	50.0	37.1	33.7	24.4	20.6	22.9	18.8	16.5	24.3	29.4	51.4
Srinagar (Lat. 34° N)	12.5	11.1	20.8	13.5	15.3	13.1	7.5	7.9	8.4	7.6	13.8	11.3
New Delhi (Lat. 28½° N)	14.1	19.7	20.5	16.2	12.2	15.8	10.3	9.7	10.6	11.5	9.1	10.7
Kodaikanal (Lat. 10° N)	5.7	6.7	5.0	5.2	6.4	4.5	4.5	4.8	4.8	3.2	2.4	3.6

**TABLE 2**  
Monthly mean total ozone at Kodaikanal (Lat. 10° N) for five consecutive years (cm<sup>-3</sup>STP)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1958	226	223	234	247	239	249	245	245	241	239	237	217
1959	224	234	239	249	260	262	266	266	260	256	235	230
1960	229	235	248	248	258	258	254	256	250	251	229	226
1961	226	241	242	259	265	271	274	271	271	266	254	242
1962	238	241	255	263	265	268	265	264	261	253	246	232

high latitudes is evident from the table. The small order of month-to-month and year-to-year changes at the low latitude station Kodaikanal are shown in Table 2 in which are given the mean monthly ozone amounts for the 5-year period 1958—1962. Further, the pattern of seasonal variation of ozone in low latitudes is quite different from that in middle and high latitudes. In the former case, the maximum occurs in May-July and the minimum in December-January as pointed out by Ramanathan (1954) and Rangarajan (1963). Fig. 2 shows the pattern of annual variation of ozone at low latitude stations Abu, Kodaikanal, Mauna Loa (Hawaii) and Marcus Island derived from the mean of 4 to 5 years' data. The pattern of annual variation at all the four stations is

more or less similar. However, appreciably higher total ozone content in all the months is found at the Pacific stations Mauna Loa, and Marcus Island.

The vertical distribution of ozone at equatorial stations is again in marked contrast with that prevailing at higher latitudes. The low latitudes vertical distribution is characterised by a sharp peak in the 24—30 km layer (Ramanathan and Kulkarni 1960). To study the month-to-month variations in the vertical distribution of ozone in low latitudes, 32 individual Umkehr observations of Kodaikanal, Abu and Marcus Island covering the period 1958 to 1961 were evaluated. The computations were made by the method of

curve-fitting with the aid of first order partial derivatives as suggested by Mateer (1960) using the 9-layer atmospheric model of Ramanathan and Dave (1957). In all cases the maximum ozone was located in the 24-30 km layer only. Fig. 3 illustrates the block distribution of ozone for six typical occasions from four different low latitude stations. The diagram of Hyderabad has been reproduced from a recent paper by Kulkarni *et al.* (1962) giving the results of ozone observations made at the place during the Joint Indo-American Balloon Programme of March-April 1961. It is further found that any appreciable increase of total ozone over low latitudes is brought about by an increase in the ozone content above 24 km. This feature is to be contrasted with the well-known fact that in middle latitudes of the Northern Hemisphere at least most of the increases in total ozone is accompanied by corresponding increases in the layers 12 to 24 km (Ramanathan and Kulkarni 1960, Dutsch 1960). Thus over low latitudes, systematic long period variations in total ozone may be considered to be brought about by changes taking place in the stratosphere above 24-km level. This is the region which is also of interest in the study of the stratospheric wind oscillation.

##### 5. Analysis of total ozone data

For a study of the total ozone variations in relation to the 26-month oscillation, the monthly mean values of ozone at New Delhi, Kodaikanal and Abu for the period 1958 to 1962 were used for analysis. In addition, for a comparative study of southern hemispheric conditions, the data of Aspendale and Brisbane as published by Funk and Garnham were also analysed. Being free from the effects of day-to-day variations which arise from short-period changes of meteorological origin, the monthly means can be considered to be sufficiently representative of the general ozone level so far as longer period changes are considered, *viz.*, (a) seasonal variations, (b) 26-month oscillations and (c) other irregular changes.

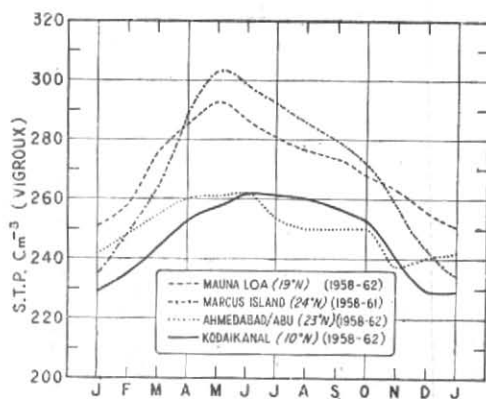


Fig. 2. Mean annual variation of ozone at low latitude stations based on data for 1958-1962

Two methods of analysis were adopted each having a distinct advantage over the other. These were—(1) A technique of using monthly anomalies and (2) The conventional harmonic analysis. The first method which is very simple has the advantage of providing a graphical representation of the long period ozone changes. The variations can also be compared easily with the stratospheric wind changes. On the other hand, the second method gives quantitatively the magnitude of the different components of variation that enter into the observed total ozone changes at the different stations. The two methods will be taken up separately.

5.1. *Analysis using monthly anomalies*—Since each ozone measuring station has its own distinctive pattern of annual variation depending on its location, it was considered necessary to eliminate this from the series of monthly mean data. For this purpose, short-period averages or 'normals' were calculated for each calendar month based on all available data which was, however, restricted to 5 or 6 years only. With respect to such 'normals' the departure or anomaly for each month of each year was obtained in the case of all the five stations. This procedure appeared to be justified in view of the fact that the pattern of seasonal variations at all the five stations followed

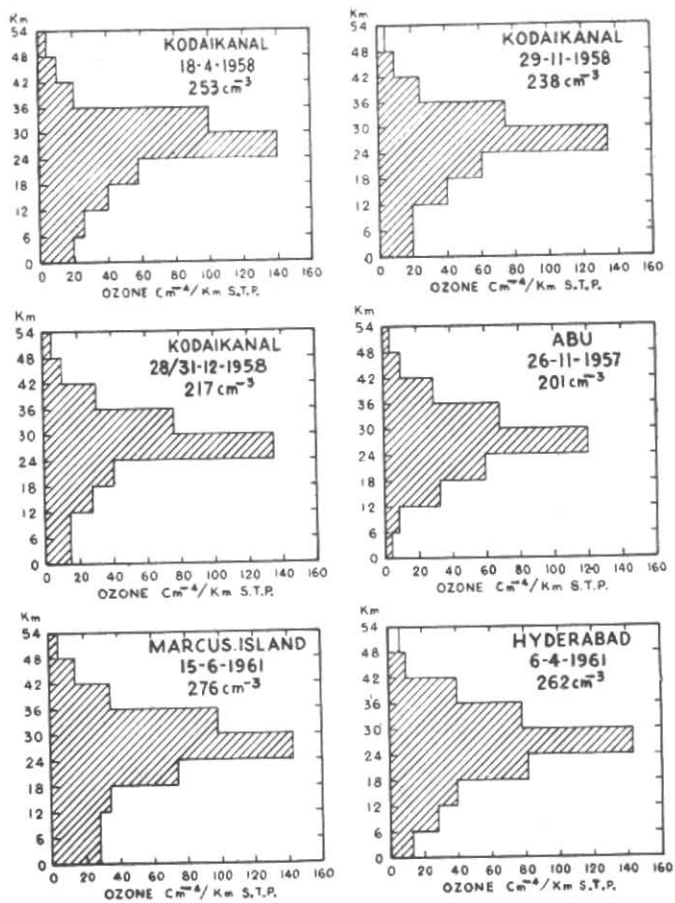


Fig. 3. Vertical distribution of ozone in low latitudes

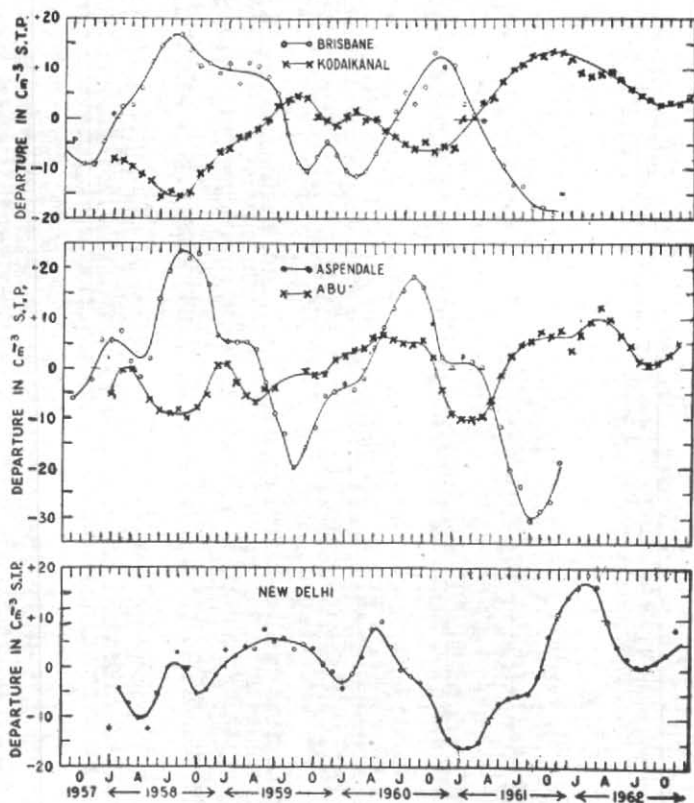


Fig. 4

the same general trend from year to year. The uniformity was more in evidence in the case of Kodaikanal, Brisbane and Aspendale, than in the case of Abu and New Delhi. It is of interest in this context to point out that the constancy or steadiness in the pattern of annual variation for a middle latitude station like Aspendale in the southern hemisphere is more than that in the case of northern hemispheric stations. This difference in the behaviour of total ozone between the two hemispheres is in accordance with the findings of Funk and Garnham (1962).

The series of monthly anomalies were subjected to a slight smoothing process by converting them into 3-month over-lapping means. This smoothing was done in order

to (1) eliminate short-period changes, and (2) counteract possible errors arising from the use of the arbitrary calendar month interval as the time unit. Fig. 4 shows a plot of the smoothed anomalies for the five stations.

5.2. *Discussion of the results*—The outstanding feature revealed by Fig. 4 is the occurrence of mutually opposing phases in the long-period variation of ozone at Kodaikanal and Brisbane. At epochs when the general level of ozone increased at Kodaikanal, it seems to have decreased at Brisbane and *vice versa*. A quasi-period of 25 to 26 months is discernible at both the stations with the phases in mutual opposition. During the period September 1959 to February 1960 the smooth run of

TABLE 3

Correlation coefficients between smoothed monthly anomalies of total ozone at five different stations

	New Delhi	Abu, Ahmedabad	Kodaikanal	Brisbane	Aspendale
New Delhi	..				
Abu/Ahmedabad	+·58*	..			
Kodaikanal	+·33	+·53*	..		
Brisbane	-·24	-·68*	-·86*	..	
Aspendale	-·085	-·39*	-·84*	+·81*	..

\*Significant at 1% level

the 26-month oscillation is seen to have been interrupted by some irregular changes at both stations, but even so the phases of these variations have been in opposition. This high degree of correlation is confirmed by the fact that the correlation coefficient between the smoothed anomalies worked out with 48 pairs of values from January 1958 to December 1961 comes out to be as high as  $-0.86$ , which far exceeds the limit of significance at 1% level. The range of the 26-month oscillation at Kodaikanal is about  $18 \text{ cm}^{-3} \text{ STP}$ . It is further seen from the figure that there has been a secular *increase* of ozone at Kodaikanal during the period 1958 to 1961 and a corresponding *decrease* at Brisbane. Whether these secular trends are real or not may have to be confirmed by subsequent observational data. In the case of Aspendale the range of the 26-month oscillation is higher being about  $32 \text{ cm}^{-3} \text{ STP}$ . At Abu/Ahmedabad, the variations as depicted graphically do not show up clearly the 26-month periodicity but an approximate in-phase relationship with Kodaikanal and an out-of-phase relationship with the southern hemisphere stations are in evidence. The correlation coefficients between the smoothed anomalies of the different stations are given in Table 3. The correlation coefficient between the three northern hemis-

pheric stations are positive and similarly the correlation coefficient between the two southern hemispheric stations are also positive. The correlation coefficient between any station in the northern hemisphere and another in the southern hemisphere is negative in all cases, the highest correlation being  $-0.86$  between Brisbane and Kodaikanal. It is of interest to find a correlation coefficient of nearly zero between Aspendale and New Delhi. The physical explanation of this might be that at New Delhi the long-period variations are erratic and that these do not form part of the world-wide changes that affect the stations to the south of it. The correlation coefficient between New Delhi and Abu is  $+0.58$  while that between Abu and Kodaikanal is  $+0.53$ , both the coefficients being significant. On the other hand that between New Delhi and Kodaikanal is only  $+0.33$  which is not significant. Abu seems to be in the region separating two regimes, *viz.*, one covering the southern hemisphere up to  $\text{Lat. } 40^\circ \text{ S}$  and the northern hemisphere up to  $\text{Lat. } 20^\circ \text{ N}$  and the other to the north of  $\text{Lat. } 25^\circ \text{ N}$ . In the former regime, the 26-month oscillations is detected but not in the latter.

5.3. *Harmonic analysis of the data*— Assuming that the mean ozone level is made up of regular and irregular components, the mean monthly total ozone at any station



may be represented by the relation,

$$O_3(t) = \bar{O}_3 + a_1 \sin \frac{2\pi}{12}(t + \phi_1) + \\ + a_2 \sin \frac{2\pi}{6}(t + \phi_2) + \\ + a_3 \sin \frac{2\pi}{26}(t + \phi_3) + \\ + O'_3$$

where,

$O_3(t)$  = Mean monthly ozone for any month represented by  $t$

$\bar{O}_3$  = average monthly mean considering the entire period

$a_1, \phi_1$  = amplitude and phase angle of the 12-monthly component

$a_2, \phi_2$  = amplitude and phase angle of the 6-monthly component

$a_3, \phi_3$  = amplitude and phase angle of the 26-monthly component

$O'_3$  = residual arising from irregular changes

From the data of the 5-year period, the average monthly mean ozone for each month of the year was obtained. The series of 12 equidistant monthly averages of each station were subject to harmonic analysis for 12-monthly and 6-monthly periods using the standard procedure (Conrad and Pollak 1950). Analysis for higher harmonics, *e.g.*, 3-monthly period was not attempted because of (1) the lack of a physical basis for the assumption of 3-monthly oscillation in ozone, and (2) the first two terms being found to account for the bulk of the mean annual variations as confirmed by a synthesis of the first two terms of a harmonic series. The synthetic curve was assumed to represent the theoretical annual variation for the station concerned and this was filtered out from the series. The resulting residuals were arranged serially in exact multiples of 26 and harmonic analysis was done for the 26-month period. From the available data only two series of 26-months each

could be obtained. Using the amplitudes of the 3 periods, *viz.*, 12-monthly, 6-monthly and 26-monthly, the residual variance due to irregular changes was obtained using the relation

$$\sigma t^2 = \frac{1}{2} a_1^2 + \frac{1}{2} a_2^2 + \frac{1}{2} a_3^2 + \sigma r^2$$

where,

$\sigma t^2$  = the total variance and

$\sigma r^2$  = the residual variance, due to irregular variations.

5.4. *Discussion of results*—Tables 4 and 5 contain the results of the harmonic analysis in respect of the 5 stations studied. From Table 4 it is seen that the amplitude of the 26-month oscillation in the southern hemisphere is appreciably higher than that in the northern hemisphere. A rather surprising result which may have a fundamental bearing on the world-wide 26-month oscillation is that at Aspendale which is at 38°S latitude, the amplitude is nearly double of that at Kodaikanal which is only 10°N of equator. Apparently, the 26-month oscillatory circulation in the middle and upper stratosphere is not symmetrical with respect to the equator. Sufficiently long series of stratospheric observations are not available from the southern hemisphere to verify whether the wind oscillation also extends more polewards. In the northern hemisphere, Reed and Rogers (1962) found that the amplitude of the wind oscillation is negligible to the north of Lat. 25°N but Scherhag (1962) has been able to detect a small biannual oscillation in the temperature and height of the mean 30 millibar charts of the northern hemisphere during the period 1958-1962.

Table 5 reveals some interesting features regarding the relative magnitudes of the different components that constitute the total observed ozone changes. At Aspendale, the 12-monthly oscillation accounts for nearly 80 per cent of the total variance while the 26-monthly oscillation accounts for another 13 per cent. The irregular changes are very small and amount only

TABLE 4

Harmonic components of the 12-monthly, 6-monthly and 26-monthly oscillations

Station	12-monthly		6-monthly		26-monthly	
	ampl. cm <sup>-3</sup>	phase	ampl. cm <sup>-3</sup>	phase	ampl. cm <sup>-3</sup>	phase*
Aspendale (Lat. 38° S)	39.7	214° 21'	4.3	4° 24'	16.1	311° 28'
Brisbane (Lat. 27° S)	21.8	198° 14'	7.0	270° 00'	11.5	287° 33'
Kodaikanal (Lat. 10° N)	16.3	274 23'	3.8	287° 29'	9.35	184° 29'
Abu/Ahmedabad (Lat. 22-23° N)	10.0	316° 00'	2.7	270° 00'	6.1	128° 54'
New Delhi (Lat. 28½° N)	15.2	68° 51'	0.73	66° 36'	6.2	141° 27'

\*Phase angle reckoned from January 1958 in the case of Indian stations  
and September 1957 in the case of Australian stations

TABLE 5

Total variance of total ozone (S.T.P. cm<sup>-6</sup>) and percentage of variance in annual cycle, semi-annual cycle, 26-month cycle and irregular changes

Station	Total variance cm <sup>-6</sup>	Annual (per cent)	Semi-annual (per cent)	26-month (per cent)	Residual due to irregular variations (per cent)
Aspendale	971.2	81.1	0.9	13.3	4.7
Brisbane	368.1	64.5	6.6	18.0	10.9
Kodaikanal	210.0	62.1	7.0	20.8	10.1
Abu	105.3	47.5	3.4	17.7	31.4
New Delhi	222.2	52.0	0.1	8.7	39.2

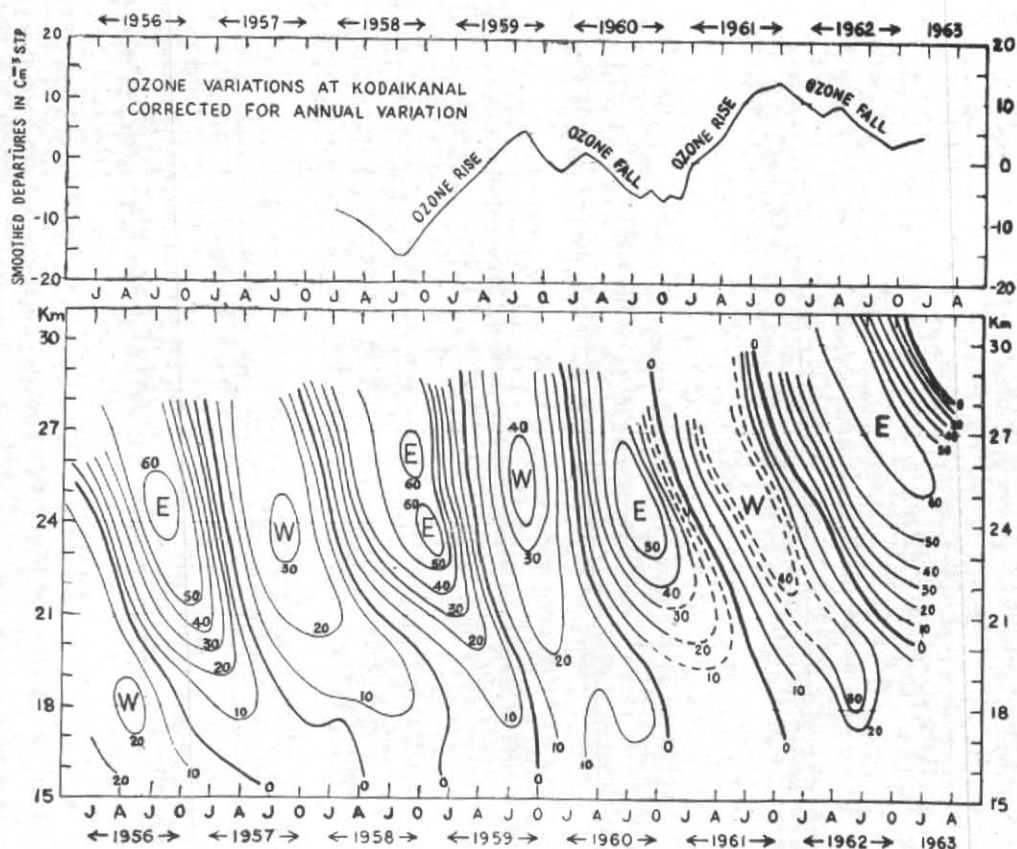


Fig. 5. Monthly mean zonal components of stratospheric winds (kt) at Canton Island (Lat. 3°S)

(Isopleths at 10 kt intervals)

to 5 per cent. It is probably on account of the very small magnitude of the irregular changes that the 26-month oscillation is easily detectable from the series of monthly mean observations at Aspendale although the annual variations have a large amplitude and the total variance is also large. On the contrary, at New Delhi, the annual oscillation contributes 52 per cent and the 26-month oscillation 9 per cent leaving a large fraction of 39 per cent for irregular changes. Because of the preponderance of the irregular changes over the 26-month oscillation, the latter is considerably suppressed, in spite of the fact that the total variance is much less than that at Aspendale. At Kodaikanal and Brisbane, the irregular variations amount to 10 per cent of the total variance. It is

further seen that at both these stations, the 6-monthly oscillation contributes to 6 to 7 per cent of the total variance. The 6-monthly component in total ozone might probably be linked with the 6-monthly temperature oscillation found by Reed (1962) in the temperature of the equatorial stratosphere.

#### 6. Comparison of the wind and ozone oscillations

The phase relationship between the ozone oscillation and the world-wide wind oscillation will be evident from Fig. 5 wherein the vertical stratospheric time section at Canton Island (Lat. 3° S) is shown alongside the ozone variations at Kodaikanal. The choice of Canton Island was made in view

of the fact that the aerological data of this station happens to be the most extensive both as regards time coverage as well as height coverage. Part of the material used in the construction of the chart was from the diagram of Reed and Rogers (1962) while the remaining part extending up to the end of 1962 was prepared using the data kindly supplied by the United States Weather Bureau. From the figure, it is seen that at Kodaikanal, the rise of ozone takes place when the easterly equatorial stratospheric winds at about 25-km level weaken and change over to *westerlies*. The fall of ozone takes place during the epochs when the westerly winds weaken and give place to easterly winds. As pointed out already, the sequence of ozone rise and fall in the southern hemisphere is the opposite of that at Kodaikanal. From the isopleths of winds depicted in Fig. 5, it may be seen that the maximum rate of change of wind (judged by the relative closeness of the isopleths) takes place between 24 and 30 km. From earlier studies referred to in this paper, it may be assumed that the pattern of winds found at Canton Island may also be prevailing all over the entire equatorial belt. Despite the constancy of the phase of wind oscillations at any stratospheric level, the ozone oscillation has been found to have opposite phases in the two hemispheres. This significant feature can perhaps be qualitatively explained only on the basis of a vertical-cum-meridional circulation in the stratosphere covering both the hemispheres which also undergoes a 26-month oscillation. When there is descending motion accompanied by increase of ozone in one hemisphere, there could be an ascending motion and a decrease of ozone in the other hemisphere. Such a meridional circulation pattern should necessarily have an asymmetrical location with respect to the equator in order to account for the fact that the ozone oscillation extends much more polewards in the southern hemisphere than in the northern hemisphere. The above picture is purely speculative. To gain further insight into this important strato-

spheric phenomenon, it might be necessary to embark on an extensive programme of collection of wind and temperature data up to 30 km over a larger area of the tropical and sub-tropical areas and particularly in the Southern Hemisphere.

#### 7. A note on possible relationship with solar activity

The available observations of Canton Island indicate a downward propagation of the 26-month wave from about the 30-km level. The region of origin might well be further higher in the stratosphere or the mesosphere. Considering this high altitude, Shapiro and Ward (1962) have suggested a solar electromagnetic energy source as a possible originator of the oscillation. The fact that the periodicity is not a simple multiple of the year but a slightly longer one has prompted them to suggest a solar origin in preference to the internal dynamics of the earth's atmosphere itself. Variations in the solar ultra-violet radiation could be expected to affect the equatorial regions preferentially. The authors have tried to discover a 26-month periodicity in the series of recorded historical sunspot number and have obtained a 25-month component, though the rather small amplitude of this has not been particularly impressive. If such a periodicity could be real, other geophysical phenomena which are more intimately linked with solar activity should also reveal a similar periodicity. Indeed Hope (1963) has mentioned of a cycle of period slightly longer than two years in geomagnetic activity the discovery of which is attributed to Kalinin (1952, 1954).

Evidence for a solar hypothesis has been further strengthened by the recent findings of Owen and Staley (1963) that the stratospheric winds over the planet Jupiter do show reversals with a period approximating to 26-months. Their conclusions are based on the fluctuations in the zonal components of high atmospheric winds over the planet as determined by spectroscopic methods. That the period of wind reversal should be about the same in the case of the terres-

trial stratospheric as well as the high atmosphere of a planet several times bigger than the earth lends support to the hypothesis that the ultimate cause is more likely to be of solar origin than one arising purely from the internal dynamics of the earth's atmosphere.

#### 8. Summary and Conclusions

The broad results of the above investigations could be summed up as follows—

- (1) When the annual changes are suitably eliminated, the total ozone content of the atmosphere undergoes an approximate 26-month oscillation in the low latitude regions of both hemispheres. The seat of the ozone changes seems to be in the upper stratosphere above 25 km and appears to be intimately related to the 26-month wind oscillation.
- (2) The amplitude of the 26-month ozone oscillation is greater in the southern hemisphere than in the northern hemisphere.
- (3) The oscillation is clearly observable at least as far as Lat. 38° S in the

southern hemisphere whereas in the northern hemisphere, it is hardly observable to the north of Lat. 20°N.

- (4) The phase of the ozone oscillation as far as can be inferred from this limited study is mutually opposite in the two hemispheres.
- (5) During epochs when the easterly stratospheric winds above 25 km weaken and change to westerlies, the ozone content increases in the northern hemisphere and decreases in the southern hemisphere. During epochs when such westerly winds weaken and change to easterly winds the ozone content falls in the northern hemisphere and rises in the southern hemisphere.

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