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.

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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

![Biennial and solar cycle variations seen with the monthly mean ozone amounts 70°-35°N, 1939-64.](image-url)

Fig.7.1 Biennial and solar cycle variations seen with the monthly mean ozone amounts 70°-35°N, 1939-64.
ozone data for the period 1939-65 have been plotted. It shows that at Arosa and less clearly at Tromso, there were anomalous changes in 1941, 1952 and 1963, when the biennial sequence of alternate-high-and-low ozone years was shifted by one year. To distinguish from the high-ozone years, the low-ozone years in the time-series for mid-latitude stations are shown hatched, and then the hatching is extended to higher latitudes also. The epochs when the sudden phase-shifts are observed are also marked. The ozone records of Tateno, Roma, Oxford, Aldergrove/Eskdalemuir, and Dombas/Oslo/Lerwick also show the phase-shifts occurring in 1963 and/or 1952. It is interesting to note that the shift of the biennial periodicity by one year, took place at intervals of 11 years, some 4-5 years from the epoch of sunspot maximum.

The changes in $P_{24}$ observed in the Arosa data during the last four decades, 1927-65, are depicted in Fig.7.2. The biennial maxima in 24 monthly values of $S_O$ (departures from mean monthly ozone amounts) occurring in the odd year of the pair are shown by appropriately centred filled circles (•) and those in the even year by open circles (o). The error associated with the determination of $P_{24} (\sigma A/A$, radians) is also indicated by the vertical bar. It will be seen from Fig.7.2 that three or four years after the sunspot maximum (e.g. 1927, 1937, 1947, 1957), the time of occurrence of the biennial maximum shifts by one year, changing from the spring of even years to the spring of odd years and vice versa. The same schedule of the biennial period is found to recur after an interval of two decades.

The difference in $P_{24}$ in two adjoining decades
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 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°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 keep 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. Arora 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°N latitude, there are two trains of the 24-month vectors: one for Delhi (29°N), 1953-62, and another for Shanghai (31°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 diads 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 it abruptly decreases to about 20 months.

In Table 7.1 we have given the decadalwise 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 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

<table>
<thead>
<tr>
<th>Latitude Zone</th>
<th>Station</th>
<th>Period</th>
<th>P24 (Deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70°N</td>
<td>Tromso</td>
<td>1936-41</td>
<td>51 ± 11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1941-48</td>
<td>251 ± 28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1952-59</td>
<td>113 ± 27</td>
</tr>
<tr>
<td>60°N</td>
<td>Bombas-Oslo</td>
<td>1943-48</td>
<td>260 ± 12</td>
</tr>
<tr>
<td></td>
<td>Uppsala/Lerwick</td>
<td>1952-59/61</td>
<td>77 ± 17</td>
</tr>
<tr>
<td>45°N</td>
<td>Arosa</td>
<td>1932-41</td>
<td>28 ± 26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1941-52</td>
<td>239 ± 14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1952-62</td>
<td>43 ± 10</td>
</tr>
<tr>
<td>30°N</td>
<td>Shanghai</td>
<td>1932-42</td>
<td>16 ± 24</td>
</tr>
<tr>
<td></td>
<td>Delhi</td>
<td>1942-52</td>
<td>21 ± 7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1953-62</td>
<td></td>
</tr>
</tbody>
</table>
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 $52^\circ$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 $180^\circ$ 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 ($10^\circ$N) has antiphase relationship with that at the Australian stations ($28-38^\circ$S) as well as the high latitude stations ($70^\circ$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 $A_8$ 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 (Dutsch 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 noticeable 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

<table>
<thead>
<tr>
<th>Period</th>
<th>$p_3$ (h mb) in the layer $z$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5-10</td>
</tr>
<tr>
<td>Feb-Apr. averages of</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(km)</td>
</tr>
<tr>
<td>TATENO (36°N)</td>
<td></td>
</tr>
<tr>
<td>High-ozone years</td>
<td></td>
</tr>
<tr>
<td>(1958, 60, 62 &amp; 63)</td>
<td>42</td>
</tr>
<tr>
<td>Low-ozone years</td>
<td></td>
</tr>
<tr>
<td>(1959, 61 and 64)</td>
<td>35</td>
</tr>
<tr>
<td>Difference</td>
<td>7</td>
</tr>
<tr>
<td>AROSSA (47°N)</td>
<td></td>
</tr>
<tr>
<td>High-ozone years</td>
<td></td>
</tr>
<tr>
<td>(1956, 58, 62 &amp; 63)</td>
<td>32</td>
</tr>
<tr>
<td>Low-ozone years</td>
<td></td>
</tr>
<tr>
<td>(1957, 59, 61 &amp; 64)</td>
<td>25</td>
</tr>
<tr>
<td>Difference</td>
<td>7</td>
</tr>
</tbody>
</table>
Kulkarni (1966b) 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, Dutsch, 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 feedback 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:

\[ \Delta O_3 \rightarrow \Delta T \rightarrow \text{Midlatitude westerly circulation} \]

\[ \text{Midlatitude westerly circulation} \rightarrow \Delta T \rightarrow \Delta O_3 \]

\( \Delta O_3 \) is the change in the ozone amount in the stratospheric reservoir, \( \Delta T \) 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 feedback 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 late, 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 early, 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,
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 (≈ 450 D.U.) was located near north Canada and the distribution was markedly asymmetrical. In the even year, the center (≈ 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
K.R.Ramanathan and P.D.Angreji

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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