Climatology of the vertical distribution of ozone over Aspendale
(38°S 145°E)

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SUMMARY

Data from the first eight years (1965–73) of an ozone sounding programme at Aspendale, Victoria, have been analysed. The mean annual cycle is compared with that derived from similar data from the northern hemisphere. Close agreement is found at similar latitudes in the two hemispheres for the stratosphere at and below the primary ozone maximum, whereas in the free troposphere there is a much smaller seasonal variation in the southern than in the northern hemisphere. There appears to be a marginally higher ozone concentration around the 10 mb region in the northern as compared with the southern summer.

The variance about the overall mean vertical distribution has been partitioned between various timescales. The seasonal contribution dominates the variance around the level of the primary ozone maximum, with substantial contributions also in the stratosphere at lower altitudes. The synoptic and other shorter timescale variance (including instrumental 'noise') is low above the 50 mb level, where ozone and pressure sensors are least reliable, but it exceeds the seasonal contribution below 70 mb. This suggests that the maximum contribution of the shorter timescales to the variance around the 100 mb level is largely synoptic in character.

Significant linear trends in the data are discussed briefly. No evidence for quasi-biennial or 10 to 11 year solar cycle periodicities is found but significant correlations between ozone variations and the position of the subtropical surface high pressure belt (Pittock’s L index) are shown to occur in the stratosphere at and below the level of 50 mb.

1. INTRODUCTION

An adequate description of the global distribution of ozone, and of its natural variability, has become of major importance with the prospect of increasing pollution of the stratosphere and in the light of existing uncertainties as to the photochemical and dynamical processes involved. Global monitoring, and photochemical and dynamical modelling of the stratosphere should ideally proceed on the foundation of an adequate baseline description of the natural stratosphere (World Meteorological Organization 1976).

Information on the vertical distribution of ozone is largely confined to that obtained by the Umkehr method, which is of limited information content and subject to some climatologically influenced sampling bias. Regular direct soundings of the vertical distribution of ozone are essentially limited to a relatively short-lived North American network (Hering and Borden 1965; Dütsch et al. 1970), a European network initiated in 1966 (see, e.g., Dütsch et al. 1970; DeMuer 1976; Atmanspacher and Hartmannsgruber 1976), and more recent sounding programmes undertaken in India and Japan. In the southern hemisphere there are some regular soundings in Antarctica at Syowa (Japanese Meteorological Agency 1969–) and a single Australian station at Aspendale (38°0'S 145°1'E).

The Australian soundings commenced in June 1965 using Mast–Brewer Model 730–6 ozone sondes. Scheduled on a regular once-weekly basis, with additional soundings each Quarterly World Interval, some 443 soundings reached above the 18·1 mb level (27 km) during the first eight years of the programme. Since December 1973 the programme has been reduced to one sounding every two weeks.

An early description of the derived ozone climatology over Aspendale was given by Pittock (1968). Discussion was extended by Pescod (1972) to include the first four years of data, and various other studies (Pittock 1969, 1970a and b, 1971; Kulkarni and Pittock 1970) have been based on data which have been published in Ozone data for the world.
These studies were based on the data as originally published, which had been 'corrected' to ensure agreement of the integrated amount found by the sondes (extrapolated to the top of the atmosphere) with the total amount in a vertical column as measured simultaneously by a Dobson spectrophotometer at Aspendale. This correction is necessary because the sensor is not 100% efficient. The method of correction was outlined by Pittock (1968), and differed from that used by Dütsch et al. (1970) in that it was assumed that the ozone amount in the upper layers was constant for any given calendar month from one year to another. This assumption has now been invalidated by the data. Consequently all the data have now been reprocessed using the Dütsch correction method. The revised data have been published in Ozone data for the world, Vol. 15, No. 2. This leads to an average increase in the corrected ozone concentrations of about 14% at all observed altitudes and renders the present results strictly comparable with similar direct sounding data as evaluated by Dütsch. In general, the papers referred to above, which used Aspendale sounding data, remain valid provided allowance is made for the average absolute increase of 14%. A more detailed discussion of the correction procedures is given in the Notes and Correspondence section of this issue.

The present paper, which expands on an earlier conference report (Pittock 1974a), gives the results corrected by the Dütsch method for the first eight years of the Aspendale sounding programme, discusses the resulting climatological picture of the ozone variations, and relates these to the general circulation.

2 Aspendale climatology

The mean time-height cross-section of the annual cycle of ozone over Aspendale, based on the eight years of data from June 1965, is shown in Fig. 1. This shows the usual primary spring maximum in ozone partial pressure around the level of 30–40 mb, and a weak secondary maximum around the 180 mb level corresponding to the 'double tropopause' situation common at that time of year. Concentrations near the surface are influenced to a significant extent by photochemical pollution from the greater-Melbourne urban area (total population about 2.500000), particularly in late summer and autumn (Galbally 1971).

Fig. 2 shows the mean annual cycles at 10 mb and at 40 mb for Aspendale, for the mean of Boulder and Albuquerque (37.5°N), and for Thalwil (47°N). Error bars are given for the estimated means at Aspendale. The Aspendale results have been displaced six
Figure 2. Mean annual cycle of ozone partial pressures (nb) at the 10 mb level (upper) and 40 mb level (lower) for Aspendale (38°S), Boulder/Albuquerque (37°N), and Thalwil (47°N) as indicated. Standard error bars are shown for Aspendale.

Figure 3. As for Fig. 2, but for 200 mb level (upper) and 800 mb level (lower).
months with respect to the northern hemisphere data. Fig. 3 shows the corresponding results for 200 and 800 mb.

The Boulder data are those presented by Dütsch et al. (1970) based on the years 1963–66; the Albuquerque data come from Hering and Borden (1965) for the years 1963–64; while those for Thalwil are for the years 1966–72 and were supplied by Dr H. U. Dütsch (see also Dütsch and Ling 1973a, and note that the Thalwil data have been adjusted by Dütsch and Ling to represent long-term climatological values).

These results using the revised Aspendale data show much closer agreement between corresponding latitudes in the two hemispheres than the previously published results for the same stations. At the 10 mb level the Aspendale data show some 10% less ozone in summer than for Boulder/Albuquerque, but this is only marginally significant on the existing statistical sample. Considering that comparable secular trends are observed at this level and that there are significant longitudinal differences in total ozone distribution (London 1963; London and Kelley 1974; Bojkov 1967) the observed differences are not necessarily representative of a real inter-hemispheric difference at 10 mb.

The summer maximum observed at 10 mb at all three stations indicates that the annual cycle at this level is essentially controlled by photochemistry, although a weak secondary maximum at Thalwil in January suggests that circulation influences extend to 10 mb at that latitude, at least in winter. At 40 mb, circulation processes dominate, leading to a winter/spring maximum at all three stations.

The Aspendale and Boulder/Albuquerque annual cycles are not significantly different from each other at the 40 and 200 mb levels. However, a very substantial difference is found at Thalwil at 200 mb, where the spring increase continues much later in the season, leading to about twice the concentration of ozone found at the lower latitude stations.

At the level of 800 mb, which may be regarded as representative of the free troposphere at Aspendale and possibly at Thalwil (elevation 515 m) but not at Boulder/Albuquerque (which are both at about 1600 m), there are marked and statistically significant differences

![Diagram](image)

Figure 4. Mean vertical distribution of ozone partial pressure (mb) (solid line) and the percentage variability about the mean (dashed line), for Aspendale June 1965 to May 1973.
between the three sets of data. An annual cycle with an amplitude of about 50% is present at Boulder/Albuquerque and also at Thalwil, where the average concentration is some 25% higher; each has a summer maximum and winter minimum. On the other hand, Aspendale has only a slightly higher average concentration at the 800 mb level than Boulder/Albuquerque, but practically no annual cycle.

At 500 mb all three sets of data (not shown) have a winter minimum, while at the 1000 mb level at Aspendale a fairly sharp minimum occurs in June and July. The latter is not representative of the free troposphere, and the winter minimum in this case is at least in part due to the close approach of the 1000 mb level to the earth’s surface. Unlike Aspendale, there is no level in the free troposphere at Boulder/Albuquerque or Thalwil where there is not a significant annual cycle.

This inter-hemispheric difference in the lower part of the free troposphere is most plausibly related to the much higher proportion of the southern hemisphere which is covered by ocean, as water surfaces have an ozone destruction rate about one order of magnitude less than that observed over soil and vegetation surfaces (Aldaz 1969). This results in a significantly longer mean tropospheric residence time for ozone in the southern hemisphere, with a consequent tendency to smooth out the annual cycle (Mr I. E. Galbally of CSIRO, Aspendale, personal communication). Differences in the general circulation of the two hemispheres, notably greater poleward transport by standing eddies in the northern hemisphere (Adler 1975) and probably greater seasonal variations in transport processes there, also need to be considered.

3. Ozone Variability at Aspendale

The ozone distribution is highly variable, particularly on the synoptic and seasonal timescales. This is illustrated in Fig. 4 which shows the overall mean vertical distribution of ozone partial pressure (full line) together with a plot of the total percentage variability (dashed line), defined as the ratio of the standard deviation of the mean to the mean value at each level, expressed as a percentage. For the Aspendale data, the variability exceeds 75% in the lowest layers of the stratosphere, with minima of about 20% in the mid-troposphere, and about 10% at the 20–30 mb level. In our experience, the relative variability increases rapidly in the lower troposphere due primarily to increased synoptic-scale variability but also to increased seasonal variations. Both these effects are presumably related to surface and subsidence inversions which affect vertical transport into the surface and the occurrence of photochemical pollution. At 10 mb the relative variability is increasing upwards, presumably due to an increase in the seasonal variability due to photochemical effects. Instrumental noise is also increasing at these levels due to variations in pump efficiency and uncertainties in total pressure determinations.

The magnitude of these variations serves to underline the need for careful statistical evaluation of the results, based on adequate random sampling, particularly if information is sought on the more minor contributions to the total variance, such as the long-term trends.

The total variance, i.e. $\sigma^2$ about the overall mean of all 443 individual soundings, is made up of contributions on the scales of: (a) the long-term linear trend for the data period (eight years); (b) the inter-annual variability; (c) the seasonal variability; and (d) the synoptic-scale plus mesoscale and ‘noise’ contributions which cannot readily be separated.

The total variance can be approximately allocated between the four groups as follows:

(a) A minimum estimate of the variance due to trend is $r^2$ times the total variance, where $r$ is the correlation coefficient between time and the deviations of short-term (two-month) means from the means for the corresponding calendar months over all eight years.
(b) The inter-annual variance is the variance of the deviations of the short-term (two-month) means from the means for the corresponding calendar months, for all months over all eight years, minus that due to the long-term trend.

(c) The seasonal variance is the difference between the total variance and the variance of the deviations of all the individual soundings about the means for the corresponding calendar months in all eight years.

(d) The combination of synoptic, mesoscale and noise contributions is the difference between the variance of the deviations of all the individual soundings about the means for the corresponding calendar months in all eight years and the variance of the two-month means about the eight-year means for the corresponding months.

![Graph showing vertical distribution of variance](image)

**Figure 5.** Vertical distribution of the total variance, $\sigma^2$, and the variance in various timescales as indicated. Units: (mb)$^2$. See text for details. Standard deviations, $\sigma$ (nb), are also indicated.

The resulting allocation of the total variance between the various scales is shown in Fig. 5. The seasonal variance and the synoptic plus mesoscale plus noise contributions are comparable, and dominate the total. The seasonal variance dominates around the level of the primary ozone maximum, with substantial contributions also in the stratosphere at lower altitudes. The synoptic + mesoscale + noise contribution, on the other hand, is quite low above the 50 mb level and is a maximum at 100 mb in the lower stratosphere. It also domi-

**TABLE 1.** Percentage of total variance in various timescales at standard levels as indicated

<table>
<thead>
<tr>
<th>Level (mb)</th>
<th>Trend</th>
<th>Inter-annual</th>
<th>Seasonal</th>
<th>Synoptic + mesoscale + noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>3-8</td>
<td>21-2</td>
<td>24-4</td>
<td>50-6</td>
</tr>
<tr>
<td>40</td>
<td>2-7</td>
<td>8-7</td>
<td>66-3</td>
<td>22-2</td>
</tr>
<tr>
<td>200</td>
<td>0-91</td>
<td>7-5</td>
<td>44-9</td>
<td>46-6</td>
</tr>
<tr>
<td>500</td>
<td>3-5</td>
<td>8-3</td>
<td>24-2</td>
<td>64-0</td>
</tr>
<tr>
<td>1000</td>
<td>0-13</td>
<td>11-3</td>
<td>16-3</td>
<td>72-4</td>
</tr>
</tbody>
</table>
lates in the lower troposphere and in the stratosphere above about 27 mb. This latter contribution to the variance at the 10 mb level may safely be taken as an upper limit to the 'noise' contribution at all levels since most possible sources of instrumental error will be greatest at high altitudes. The noise contribution is probably appreciably less than this upper limit even at 10 mb, and much less at lower altitudes.

Table 1 summarizes these results expressed as percentages of the total variance at a number of standard levels.

4. TRENDS AND PERIODICITIES

Although the proportion of the total variance due to the long-term trend does not exceed 4% at any measured level, the existence of such a trend is of considerable interest. Preliminary results of a trend analysis on the present data have been reported elsewhere (Pittock 1974b). These reveal a statistically significant linear decrease of the order of 10 to 20% per decade in the free troposphere and in the stratosphere below 17 mb. Above 17 mb significant increases are indicated. No conclusive evidence has been adduced as to the causes of these trends, although Kulkarni (1976) has suggested possible circulation changes. The statistical limitations of such trend analyses should be borne in mind (see Birrer 1974; Pittock 1974a) as well as the possibility that such trends have reversed since 1973 (Angell and Korshover 1976).

Beyond the above linear trend estimates, it is of interest to look for nonlinear effects that might be associated with the quasi-biennial oscillation or the 10 to 11 year solar cycle. The former was in evidence in the Aspendale total ozone data in the years 1955–62 (Kulkarni 1966) and an earlier analysis (Pittock 1968) suggested that it might have continued in existence at various levels in the atmosphere even though it vanished in the integrated total amount.

Eight years of data is not sufficient to justify the application of sophisticated statistical techniques to the question of periodicities on these timescales. Nevertheless, a simple plot

![Figure 6. Time series of deviations of two-month mean ozone partial pressure, $\delta P_3$ (nb), from the eight-year means for the corresponding calendar months, at the 10, 40, 200 and 500 mb levels.](image-url)
of the time series of deviations of 2-month mean ozone partial pressures from the 8-year means for the corresponding calendar months is sufficient for a visual inspection which might reveal any large nonlinear trends or periodicities. Such plots are shown in Fig. 6 for the 10, 40, 200 and 500 mb levels. While the linear trends can be seen by eye, no other systematic variations are obvious. There is little support for a continuing quasi-biennial oscillation and no evidence of a significant change in the sign of the trend within two or three years of the sunspot maximum in 1969, even at the 10 mb level which the annual cycle (Fig. 2) suggests is dominated by photochemistry. This does not necessarily preclude the possibility of ozone variations associated with the solar cycle at higher altitudes such as have been suggested by Dütsch and Ling (1973b).

5. Relation to Variations in the General Circulation

Using data for the years 1956 to 1972, Pittock (1973) reported a significant correlation of minus -61 between year-to-year variations in annual mean total ozone content over Aspendale and the corresponding mean latitude, $L$, of the surface subtropical high pressure belt down the east coast of Australia. (Note the correction to the tabulated $L$ values in Quarterly Journal, 1977, p. 218; updated values may be obtained from the author.) It is clearly of interest to see how such correlations are associated with the vertical distribution, but there are severe statistical limitations imposed by having only eight years of sounding data, in which inter-annual variations make up only a small fraction of the total variance.

Regression analysis based on the 48 successive departures of the two-month means from the eight-year means for the corresponding calendar months results in the regression coefficients of ozone partial pressure against $L$ as shown in Fig. 7. Error bars indicate ± one standard error of the estimates of the regression coefficients. At the five standard levels from 50 to 90 mb the correlation is significantly different from zero at less than 5% chance probability. It is significant at better than the 0.1% level at 90 mb (Student’s $t = 3.7$, with 46 degrees of freedom), where the correlation coefficient is minus -48, and accounts for some

![Figure 7. Vertical distribution of regression of ozone partial pressure on Pittock's (1973) L index. Units: nb per degree L. Error bars indicate ± one standard error of the estimated regression coefficient. Based on 48 successive departures of two-month means from means of corresponding months over eight years.](image-url)
20% of the inter-annual variance in the ozone concentration at that level. Fig. 7 suggests that larger L values correspond to smaller ozone concentrations in the 50-100 mb layer, and to an upward displacement of the lower boundary of the stratospheric mean plateau in the region around 150-200 mb (see Fig. 4), which is associated with the occurrence of secondary ozone maxima above the winter/spring tropopause.

These findings agree with the interpretation by Pittock (1973) that a larger L value corresponds to a reduced mean meridional transport of ozone polewards and downwards into the mid-latitude lower stratosphere, particularly in winter and spring. One standard deviation of the two-month mean L departures is about 2.5 degrees of latitude, so the maximum magnitude regression coefficient of ozone partial pressure on L, which occurs at about the 90 mb level where the mean partial pressure is about 70 mb, corresponds to about −5% per standard deviation of L. Integrating in the vertical produces a mean variation over all months of total ozone with L of about −1% per standard deviation of L, which is about one-third the variation found previously from 'spring' (August, September and October) total ozone data. Fig. 7 indicates that the influence of the mechanism suggested by Pittock (1973) does not extend at mid-latitudes above the level of the primary ozone maximum. It must be stressed however that more data are needed to improve the statistical significance of this result, and to enable an examination of the seasonal variation in the correlation of ozone concentration with L to be made.

6. Conclusions

Data from the first eight years of an ozone sounding programme at Aspendale, Victoria, have been analysed using the correction procedures used by Dütsch et al. (1970). The data show essentially similar annual cycles in the stratosphere at Aspendale (38°S) and Boulder/Albuquerque (37.5°N) with the possible exception of a marginally higher concentration at the 10 mb level in summer in the northern hemisphere, but there are highly significant differences in the troposphere. The latter are probably due to the lower rate of destruction of ozone over oceanic surfaces, which cover much more of the southern than of the northern hemisphere.

The very high variability of the ozone distribution, particularly in the stratosphere below 100 mb, has been documented and the variance partitioned between various timescales for each standard level. The seasonal cycle dominates around the 30 to 50 mb levels, and also contributes greatly in the stratosphere at lower altitudes. This is consistent with the winter/spring increase in the primary ozone maximum and in ozone transport polewards and downwards in the winter hemisphere.

Synoptic and shorter timescale variance (including that due to instrumental 'noise') is quite low above 50 mb where instrumental noise should be greatest. This suggests that the maximum at 100 mb is largely synoptic in character. These timescales dominate in the lower troposphere and above about 27 mb. The inter-annual variance (with linear trend removed) contributes at most only about 20% of the total variance (at the 10 mb level) and generally less than 10%. The linear trend over the eight years of data contributes at most only about 4% of the total variance, and has been discussed more fully elsewhere.

Correlations of the inter-annual variations with the corresponding latitudes of the subtropical high pressure belt give support to the mechanism suggested by Pittock (1973) and indicate that it probably does not extend above the level of the primary ozone maximum in middle latitudes.

References


