The vertical distribution of atmospheric ozone over Christchurch, New Zealand

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SUMMARY

The results of a limited series of ozone-sonde ascents made at Christchurch, New Zealand (latitude 43·5°S) during 1965-66 with Brewer-Mast electro-chemical sondes are discussed. It is found that the vertical distribution of ozone and the pattern of its seasonal variation is similar to that found at Aspendale (south-eastern Australia, latitude 38·0°S), but that the Christchurch ozone concentrations are greater at all atmospheric levels. It is further shown that at Christchurch the horizontal transport of ozone by transient eddies is southward at all levels and that the annual average vertically integrated flux is not very different from that observed at a comparable latitude in the Northern Hemisphere. Consideration of the middle latitude ozone budget tends to indicate a coefficient of vertical eddy diffusion in the lower stratosphere of the order of 10^{7} cm^2 s^{-1} for the Southern Hemisphere middle latitudes. Major assumptions involved in this estimate are pointed out.

1. INTRODUCTION

A knowledge of the vertical distribution of ozone in the Earth's atmosphere is useful in many kinds of atmospheric investigations.

In the Northern Hemisphere much information in this field has recently been obtained by the use of ozone-sondes of various types. However, in the Southern Hemisphere the available data are still very inadequate. The most comprehensive data are those of Pittock (1968) for south-eastern Australia (Aspendale, latitude 38·0°S).

The purpose of this paper is to describe the results of a series of ascents made with Brewer-Mast electro-chemical ozone-sondes at Christchurch, New Zealand (latitude 43·5°S), during 1965-66. These results, and their significance for the ozone budget in Southern Hemisphere middle latitudes, are discussed in the following Sections.

2. DATA AND ITS TREATMENT

In principle the electro-chemical sondes used at Christchurch provide an absolute measure of the vertical distribution and total amount of ozone above the station. However, in practice the values of total ozone obtained from soundings (extrapolated to the top of the atmosphere) are normally less than those obtained from the Dobson spectrophotometer. It thus seems reasonable to infer that the recovery of ozone by the sonde is not complete and that soundings should be corrected by reference to the corresponding total ozone values obtained from the Dobson instrument. In considering the Christchurch data only soundings which reached the 25 km level were used. These were then corrected by (i) extrapolating the sounding to zero pressure along a line of constant mixing-ratio, (ii) determining planimetrically the corresponding total ozone \( \Omega_a \) on an ozonogram and (iii) applying a constant correction factor at each level equal to \( \Omega_a / \Omega_a \), where \( \Omega_a \) is the Dobson value. As Dobson measurements are not made at Christchurch, those for Wellington (300 km north-east of Christchurch) were used. Pump-rate corrections, Pittock (1968), have not been applied to the present data as such corrections are small and still rather uncertain.

3. VERTICAL DISTRIBUTION AND ITS SEASONAL VARIATION

The corrected soundings available from Christchurch are distributed throughout the period 1965-66 as follows: March (1), June (2), July (2), August (2), September (4), October (2), December (4), February (3). The terminal pressures for these soundings ranged between 23 mb and 7 mb, the average for the series being 12 mb. For these data the correction factor averaged 1·26 ± 0·08.

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Representative mean profiles showing ozone partial pressure against total air pressure (height) are plotted in Fig. 1 together with selected lines of constant ozone to air mixing ratios. It is clear that the number of soundings in each group is too small to be of absolute significance. Nevertheless the profiles show clearly the nature of the vertical distribution of ozone and its characteristic variation throughout the year. All the profiles are characterized by a primary maximum around the 40-50 mb level whose magnitude varies markedly with the season. The data in Fig. 1 show that representative values for this maximum during winter (July, August) and spring (September, October) are about 25-30 per cent greater than the corresponding values for summer (December, February) and autumn (March, June). In addition, the profiles for winter and spring

Figure 1. Representative mean vertical ozone distributions, Christchurch 1965-66. Selected mixing ratio isopleths are shown by thin curved lines.

Figure 2. Mean vertical ozone distributions for (a) summer-autumn and (b) winter-spring: Christchurch (open circles), Aspendale (dashed lines), 1965-66. Crosses show standard deviations for Christchurch. Mean tropopause levels indicated by arrows.
show well marked secondary maxima between the 100 and 300 mb levels. These latter features normally occur in close association with characteristic jet stream-tropopause structures as shown on the relevant upper-level synoptic charts.

Average ozone distributions for summer-autumn and winter-spring are shown in Fig. 2 and may be compared with the corresponding averages obtained at Aspendale. These latter have been read from the diagrams for the 1965-66 period given by Pittock (1968) and are also shown in Fig. 2. It is seen that the distributions obtained at Christchurch and Aspendale are very similar but that (as would be expected from its higher latitude) ozone values are rather greater over Christchurch at all atmospheric levels.

In general the individual ozone profiles obtained at Christchurch show low ozone values in the troposphere with an abrupt increase in partial pressure near the tropopause boundary. This effect is also noticeable in the corresponding average ozone distributions (Fig. 2) although, as would be expected, the correspondence between the abrupt increase in ozone partial pressure and the mean tropopause is not as close as on individual occasions. It seems likely that the rather abrupt increase in partial pressure noticeable between the 150 mb and 100 mb levels in Fig. 2 is associated with the extension into temperate latitudes of the higher tropical tropopause (Gabites 1953).

The variability of the Christchurch individual ozone soundings about their seasonal means is shown in Fig. 2 by curves representing the standard deviation (in mb) of ozone partial pressures. Notable features shown in these distributions are the higher percentage variability of tropospheric ozone during summer-autumn and the strong variability around the 200 mb level during the winter-spring period. Rather similar features occur in the Aspendale data given by Pittock (1968).

4. Horizontal transport of ozone

Quasi-simultaneous wind and ozone observations taken at Christchurch have been used to compute the local annual average eddy flux of ozone at a number of atmospheric levels. These results are shown in Fig. 3. Although the distribution with height shows some chance irregularities (as would be expected from the small data sample), it is clear that the local eddy flux is poleward at all levels and reaches maximum values of around $25 \times 10^{-9}$ g cm$^{-2}$ s$^{-1}$ at the 200 mb level. This region is well known to be one of maximum wind velocities and great variability of tropopause heights. Eddy fluxes are of moderate magnitude in the troposphere but tend to become small at higher stratospheric levels. The vertically integrated eddy flux at Christchurch is $193 \times 10^{-4}$ g cm$^{-1}$ s$^{-1}$ (surface to 70 mb) and $232 \times 10^{-4}$ g cm$^{-1}$ s$^{-1}$ (surface to 20 mb).

Fig. 3 also shows the vertical distribution of the average annual (mean of winter and summer for two years) local eddy flux of ozone averaged over three stations on the North American continent with a mean latitude comparable to that of Christchurch (Hering 1966). On the whole the distributions are similar, although the Christchurch data are more irregular and show systematically higher fluxes in the troposphere. The vertically integrated eddy flux for the North American data is $194 \times 10^{-4}$ g cm$^{-1}$ s$^{-1}$ (surface to 70 mb) and $205 \times 10^{-4}$ g cm$^{-1}$ s$^{-1}$ (surface to 20 mb).

Fig. 3 also shows the vertical distribution of the average annual local eddy flux of ozone at Aspendale. The data for the 50, 100 and 200 mb levels are averages for the four seasons (1965-66) from Pittock (1968), while the values at other levels have been independently computed. The values for Aspendale are considerably smaller than those at Christchurch but in view of the smaller day-to-day variability of wind and ozone in the lower latitudes such a decrease is to be expected. The vertically integrated eddy flux at Aspendale is $101 \times 10^{-4}$ g cm$^{-1}$ s$^{-1}$ (surface to 70mb) and $112 \times 10^{-4}$ g cm$^{-1}$ s$^{-1}$ (surface to 20 mb).

If the observed eddy fluxes at Christchurch and Aspendale were assumed to represent the total transports of ozone across their respective latitudes, the difference between these quantities would imply a substantial outflow of ozone from such a middle latitude zone.

5. Vertical transport of ozone

In middle latitudes a vertical ozone flux may be brought about partly by eddy motion (on all scales) and partly by mean vertical motion of the air. The flux due to eddy motion can be assessed from a knowledge of the average vertical gradients of ozone mixing ratio and the appropriate coefficients of vertical eddy exchange.

In the lower troposphere the data do not permit a very accurate determination of average ozone gradients and it is not possible to distinguish between the two seasons. Thus at Christchurch, above the planetary boundary layer, the vertical ozone gradient averages about $0.9 \times 10^{-2}$ g g$^{-1}$ km$^{-1}$ with a standard error of around 15 per cent. In the lower stratosphere, around the 70 mb
(18.4 km) level, accuracy is higher and vertical ozone gradients average $100 \times 10^{-2} \mu g \text{ g}^{-1} \text{ km}^{-1}$ in winter-spring and $84 \times 10^{-2} \mu g \text{ g}^{-1} \text{ km}^{-1}$ in summer-autumn with a standard error of around 2-3 per cent.

Figure 3. Vertical distributions of local annual average eddy fluxes of ozone.

Appropriate values for the eddy exchange coefficient $A$ in different regions of the atmosphere are still rather uncertain. In the lower troposphere the effects of large-scale eddy motion in the vertical direction can for the most part be neglected while for small-scale eddies, above the planetary boundary layer, a value of $A$ around 50 g cm$^{-1}$ s$^{-1}$, Lettau (1950), seems appropriate. For the Christchurch data this corresponds to an average downward flux of ozone to the planetary boundary layer of about $45 \times 10^{-13}$ g cm$^{-2}$ s$^{-1}$. Considering the limited accuracy of lower tropospheric vertical ozone gradients this value is not significantly different from the small-scale turbulent flux of ozone to the ground, $48 \times 10^{-13}$ g cm$^{-2}$ s$^{-1}$, estimated by Kroening and Ney (1962).

In the lower stratosphere studies of the spread of tungsten-185 by Spar (Newell 1963) have yielded an effective eddy diffusion coefficient of around $4 \times 10^{4}$ cm$^{2}$ s$^{-1}$. This corresponds to an eddy exchange coefficient at the 70 mb level of about $4.5$ g cm$^{-1}$ s$^{-1}$ and would include the effects of both large and small scale turbulence. For the Christchurch data this gives an average downward flux of ozone at the 70 mb level of about $450 \times 10^{-13}$ g cm$^{-2}$ s$^{-1}$ in winter-spring and $380 \times 10^{-13}$ g cm$^{-2}$ s$^{-1}$ in summer-autumn.

The flux due to mean vertical air motion can be assessed from the Christchurch ozone
concentrations and independent computations of the mean vertical motion for the corresponding circle of latitude. For the Southern Hemisphere the only calculations available are those of Gilman (1965). These do not provide sufficient information in the stratosphere and in this region have been supplemented by the more detailed (Northern Hemisphere) calculations of Vincent (1968).

In the lower troposphere near the top of the planetary boundary layer, the average ozone mixing ratio is very small. Consequently at this level the flux of ozone due to mean vertical air motion may be neglected.

For the lower stratosphere around the 70 mb level, at latitude 43°S, the figures given by Gilman and Vincent indicate an average downward motion of about $4 \times 10^{-2}$ cm s$^{-1}$ during the winter-spring and about $0.5 \times 10^{-2}$ cm s$^{-1}$ during the summer-autumn. For Christchurch this corresponds to a downward flux of ozone at the 70 mb level of about $160 \times 10^{-13}$ g cm$^{-2}$ s$^{-1}$ in winter-spring and $15 \times 10^{-13}$ g cm$^{-2}$ s$^{-1}$ in summer-autumn.

Thus at Christchurch, on an annual average basis, we have a total flux of ozone at the 70 mb level of around $500 \times 10^{-13}$ g cm$^{-2}$ s$^{-1}$, (about $415 \times 10^{-13}$ g cm$^{-2}$ s$^{-1}$ representing eddy flux), and a tropospheric flux to the planetary boundary layer of about $45 \times 10^{-13}$ g cm$^{-2}$ s$^{-1}$. Similar calculations for Aspendale show a total ozone flux at 70 mb of around $400 \times 10^{-13}$ g cm$^{-2}$ s$^{-1}$, (about $355 \times 10^{-13}$ g cm$^{-2}$ s$^{-1}$ representing eddy flux), and a tropospheric flux to the planetary boundary layer of about $40 \times 10^{-13}$ g cm$^{-2}$ s$^{-1}$. If these fluxes are representative of a middle latitude zone between Christchurch and Aspendale, limited above by the 70 mb level, they indicate a significant net inflow of ozone into this region as a result of vertical transport processes.

6. OZONE BUDGET IN MIDDLE LATITUDES

For the zonal region between latitudes 43°S and 38°S, limited above by the 70 mb level, the flux calculations made in the previous Sections imply a net inflow of ozone by vertical transport processes and a corresponding outflow by horizontal eddies. These latter processes are mainly concentrated in the layer between the temperate and tropical tropopauses (Fig. 3). However, before the ozone budget for such a region can be determined it is necessary to consider the effect of other horizontal transport processes - the standing eddy flux and mean meridional circulation of air.

No data are at present available that would indicate the magnitude of the standing eddy flux of ozone in the Southern Hemisphere. However, for the angular momentum flux, Obasi (1963) found the standing eddy flux to be much smaller than that due to transient eddies. This is a reflection of the considerable degree of symmetry possessed by the average southern atmospheric circulation in middle latitudes. It thus seems likely that the standing eddy flux is not a very significant item in the ozone budget of this region.

The effects of mean meridional motions on the ozone balance of the above region may be assessed using the data of Gilman (1965) for the Southern Hemisphere supplemented by the Northern Hemisphere stratospheric data from Vincent (1968). Derived values of the mean meridional wind are given in Table 1.

<table>
<thead>
<tr>
<th>TABLE 1. MEAN EQUATORWARD WIND COMPONENT (cm s$^{-1}$)</th>
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<tr>
<td><strong>Pressure interval (mb)</strong></td>
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<tr>
<td>8S</td>
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<td>Winter 43°S</td>
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<td>Spring 38°S</td>
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<td>Summer 43°S</td>
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<td>Autumn 38°S</td>
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Using the ozone data for Christchurch and Aspendale as representative of their respective latitudes we obtain an equatorward ozone flux (up to the 70 mb level) due to mean meridional air motion of $20 \times 10^{-4}$ g cm$^{-1}$ s$^{-1}$ at latitude 43°S and $10 \times 10^{-4}$ g cm$^{-1}$ s$^{-1}$ at latitude 38°S. This leads to equatorward ozone transports across the vertical boundaries of the region (latitudes 43°S and 38°S) of $5 \times 10^{5}$ g s$^{-1}$ and $3 \times 10^{5}$ g s$^{-1}$ respectively, and a net gain of around $0.3 \times 10^{7}$ g s$^{-1}$ for the zone.
The horizontal eddy flux calculations in Section 4 lead to transports of ozone (surface to 70 mb) across the vertical boundaries of the region amounting to \(5.6 \times 10^7\) g s\(^{-1}\) and \(3.2 \times 10^7\) g s\(^{-1}\) respectively, with a net loss of \(2.4 \times 10^7\) g s\(^{-1}\). Thus the transport by mean meridional circulations makes only a minor contribution to the ozone budget of this region.

A tentative ozone budget based on these flux calculations, for the region 43.5\(^\circ\)S – 38.0\(^\circ\)S, surface to 70 mb is given in Table 2.

**TABLE 2. OZONE BUDGET FOR THE REGION 43.5° S – 38.0° S, SURFACE TO 70 MB (10\(^7\) G S\(^{-1}\) UNITS)**

| (1) | Loss by horizontal transient eddy flux | 2.4 |
| (2) | Gain by horizontal mean motion | 0.3 |
| (3) | Gain by downward mean motion (through 70 mb level) | 0.1 |
| (4) | Gain by downward eddy flux (through 70 mb level) | 0.7 |
| (5) | Loss by transfer to planetary boundary layer | 0.1 |

It is seen from Table 2 that the net gain from vertical transport processes is not nearly sufficient to compensate for the net loss by horizontal transport out of the zone. Various suggestions may be advanced in explanation of this discrepancy. In the first place it seems possible that the eddy transport for Christchurch is somewhat too high or may not be representative of the entire latitude. However, the value obtained (up to the 70 mb level), \(5.6 \times 10^7\) g s\(^{-1}\) is the same as the corresponding transport given by the North American data (Hering 1966) at an average latitude of 43.5\(^\circ\)N. Moreover, uncertainties in the Christchurch data are likely to be in the same sense as those for Aspendale and it thus seems unlikely that item (1) would be greatly affected. Again, the contribution from item (2) may have been underestimated. But the mean motions on which it depends are based on large amounts of data and it does not seem possible to make any substantial change in this item. Items (3) and (5) are of a minor nature. The most likely source of the discrepancy is that the eddy diffusion coefficient used in item (4), \(4 \times 10^4\) cm\(^2\) s\(^{-1}\), is too small and should be replaced by a considerably larger value. To obtain a balance in Table 2, the coefficient would need to have a value of \(1.2 \times 10^5\) cm\(^2\) s\(^{-1}\) — about three times that obtained from the tungsten-185 tracer. However, in making such a comparison it is relevant to note that the value \(4 \times 10^4\) cm\(^2\) s\(^{-1}\) was obtained during the (Northern Hemisphere) summer-autumn season for the diffusion of tungsten-185 over a wide range of latitude. It is thus more properly regarded as a summer-autumn latitudinal average value and in the circumstances the possibility of larger annual mean values for a limited Southern Hemisphere middle latitude zone is not excluded.

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