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Ozone Measurements at British Antarctic Survey Stations

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Ozone measurements at British Antarctic Survey stations

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Ozone measurements have been made regularly at Argentine Islands and Halley Bay since 1957. A recent critical review of the data revealed inconsistencies in the extra-terrestrial constants adopted for the various spectrophotometers used. These have been resolved and the data recalculated to give consistent series.

The variations in total ozone on differing time-scales, and their relation to variations in the temperature of the lower stratosphere, are discussed. A major increase in total ozone occurs in the course of the breakdown of the winter polar stratospheric vortex. It is often preceded by large quasi-periodic fluctuations associated with baroclinic waves in the vortex. The response of the vortex to these waves is discussed and comparisons made with conventional data from lower latitude stations and with satellite data on Southern Hemisphere sudden warmings.

Long-term trends in total ozone are shown to be small at both stations. A recent global analysis of ozone trends is noted.

1. Introduction

The British Antarctic Survey has made systematic measurements of total ozone amount at two stations, Argentine Islands (65° S, 64° W) and Halley Bay (75° S, 27° W) since 1957. The data have been critically reviewed recently, and instrumental constants revised retrospectively to give near-homogeneous series (Farman & Hamilton 1975). The revisions are insignificant for variations of time-scale less than 1 year, but are important for the estimation of long-term trends.

2. Variations in total ozone amount

Daily mean values of ozone are available for some 3 months either side of the (austral) summer solstice, starting with September 1957. There are radio-sonde ascents daily at 12 U.T. at each station. The highest level attained with sufficient regularity to allow changes in the lower stratosphere to be followed from day to day is 100 mbar (10^4 Pa). It has been argued (Godson 1960) that smoothed 100 mbar temperatures reflect, at least approximately, variations characteristic of higher levels.

(*a*) *Synoptic scale variations*

There is considerable day-to-day variability in ozone amount. At Argentine Islands, changes of 100 matm cm in a day have occurred. Much of the variance may be attributed to motion of the lower stratosphere forced from below by weather systems. Both ozone mixing ratio and potential temperature are conservative quantities for such (largely) vertical motions, and the relation between total ozone and other meteorological parameters arising in this way is known as the Reed–Normand effect (see, for example, Craig 1965). There is a positive correlation between changes in total ozone amount and 100 mbar temperature, of order 5 matm cm/°C. The correlation is good when the forced motions are large, e.g. peak-to-peak temperature changes of 6 °C or more, but deteriorates rapidly below this level. It may be conjectured that in the smaller disturbances, the effects of horizontal advection are comparable to or perhaps exceed the Reed–Normand effect. Substantiation of this conjecture must await vertical profiles of ozone distribution from a close network of stations, or reliable satellite data.

Argentine Islands lies near the mean circumpolar depression track and the Reed–Normand effect is often well-marked there, e.g. ozone/temperature correlation coefficients for November and December 1958 were 0.82 and 0.87 respectively, and for October, November and December 1960 were 0.78, 0.75 and 0.71. At Halley Bay, the correlation is rarely significant over such long periods.

(*b*) *Meso-scale and annual variations*

The Reed–Normand effect noted above may be regarded for the purpose of this subsection as unwanted noise. The figures presented here show 10-day running means of the original series.

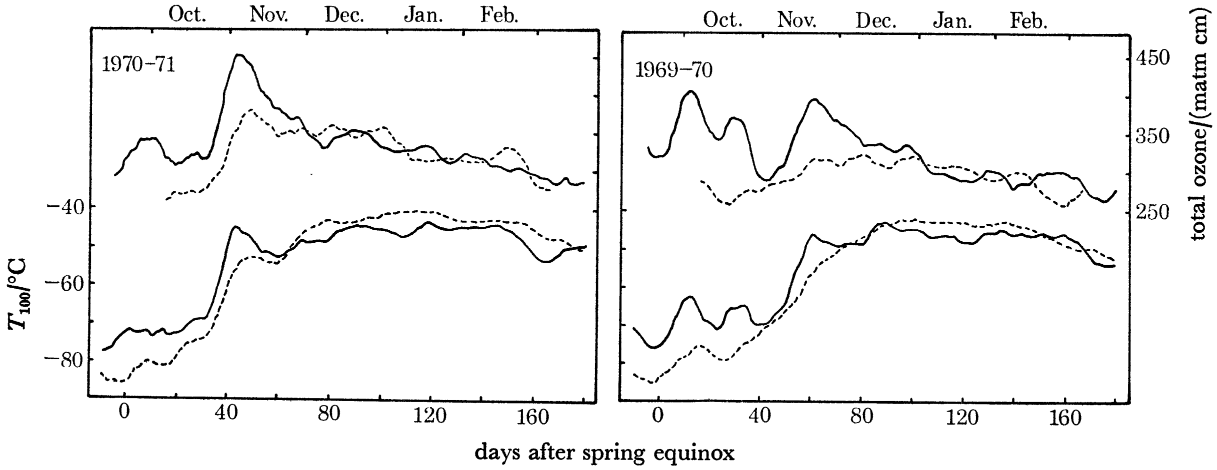

FIGURE 1. Breakdown of the winter polar stratospheric vortex. 10-day running means of total ozone (above) and of the temperature at the 100-mbar level, T_{100} (below), are shown. Full lines are used for Argentine Islands data, broken lines for Halley Bay.

Figures 1*a* and 1*b* are examples of the variations seen in individual years. At the vernal equinox, the lower stratosphere is cold over both stations. Temperature decreases towards the pole, and there are strong thermal westerly winds at 100 mbar and above. This state is known as the winter polar stratospheric vortex. By January, the temperature at Halley Bay has risen by some 40 °C, the temperature gradient has reversed, and is much weaker. Upper air maps at this time of the year show light easterly winds, but the contours are rarely closed over the polar cap. The transitional period is known as the breakdown of the polar vortex. In 1970/1 the breakdown is relatively simple. Most of the warming occurs between days 30 and 45, numbered from the equinox. Before the warming, ozone values were low, and decreasing towards the pole. Coincident with the warming there is a large increase in ozone, of order 5 matm cm/°C. In contrast to the temperature, ozone values then fall, from day 45 at Argentine Islands, and by the end of January have returned to pre-warming levels. There is by then no definite latitude gradient of ozone.

In 1969/70 at Argentine Islands most of the warming occurs between days 45 and 60. There is a coincident increase in ozone, of about 4 matm cm/°C. At Halley Bay, the warming is much slower, and extends from day 30 to day 100. There is a corresponding slow rise in ozone, amounting to little more than 1 matm cm/°C. However, perhaps the most significant difference between the two breakdowns, is the occurrence of large perturbations at Argentine Islands in 1969 prior to the final warming. They are particularly marked in ozone, and amount to some 7 matm cm/°C. The ozone peak on day 14 is the maximum for the year. The perturbations are not strictly periodic, the interval between successive extremes ranging from about 8 to 13 days in this year. Such perturbations are hemispheric rather than local. In 1959 strong perturbations observed at Argentine Islands and Wilkes (66° S, 111° E), on almost opposite meridians, were nearly out of phase.

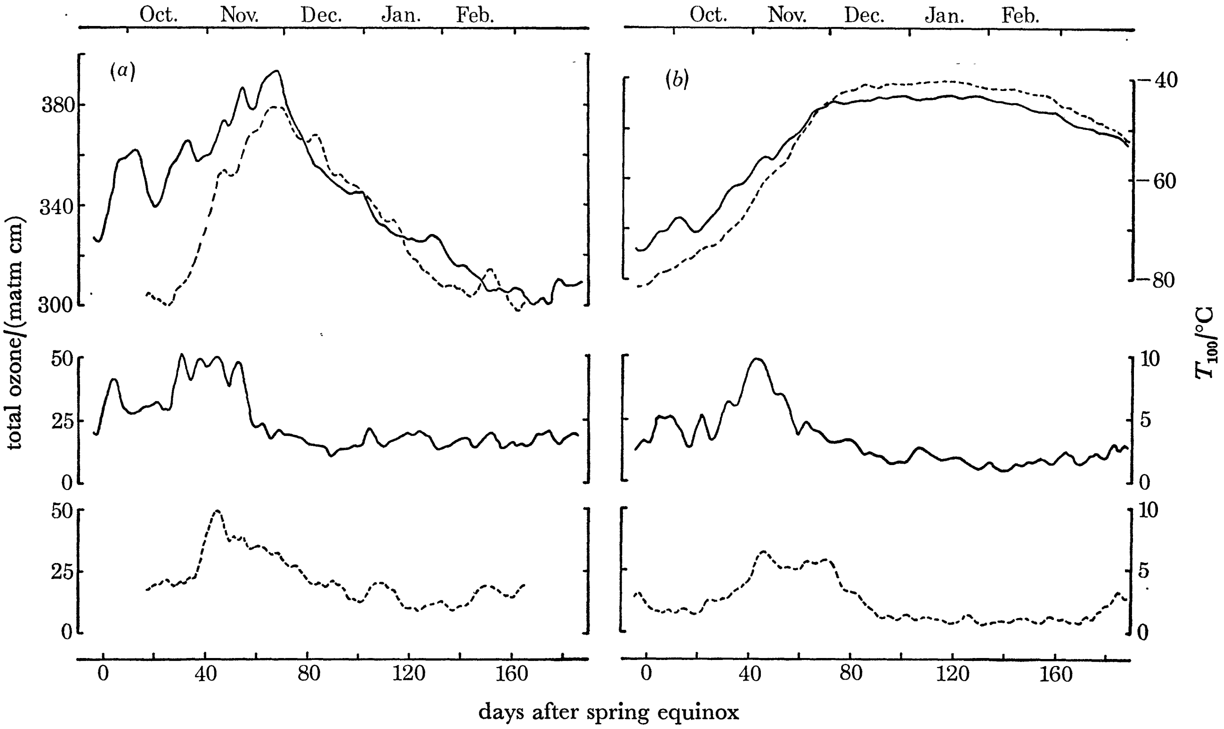

FIGURE 2. Breakdown of the winter polar stratospheric vortex. (*a*) Ozone variations, mean values for 16 years (above) and standard deviations (below); full lines show Argentine Islands data, broken lines Halley Bay. (*b*) Temperatures at the 100 mbar level, T_{100}, otherwise as (*a*).

These 2 years illustrate many features of the variability of the breakdown of the winter vortex in the lower stratosphere. A complete series for 1957/8 to 1972/3 is given in Farman & Hamilton (1975). Mean variations for the 16 breakdowns are shown in figure 2, together with the standard deviations. The perturbations in temperature are less pronounced than those in ozone. The peaks in the standard deviations for temperature reflect variations in the timing of the final warming. There is a hint of bimodality at Halley Bay, with peaks at day 45 and around day 70, which may be associated with movement of the vortex. During the winter, the centre is usually located over the Antarctic Continent. It may remain relatively static during the breakdown or drift bodily to lower latitudes; all pronounced drifts to date have been towards the Atlantic (longitudes 0–70° W). A good example occurred in 1957/8, when the vortex drifted over Argentine Islands, a 100 mbar temperature of −70 °C being recorded there as late as 10 November (day 50). This breakdown has been described in some detail by Taylor (1960). The 1969/70 warming at Halley Bay, figure 1*b* above, is another example of a late warming with weak ozone variation. This is typical of near-central location within the vortex. The weakness of ozone variations associated with late warmings is also evident from the variation of the standard deviation of ozone at Halley Bay. At Argentine Islands, the early parts of the ozone curves (figure 2*a*) for both mean and standard deviation, are dominated by the meso-scale perturbations; these are negligible at Halley Bay. Clearly the stability of the circulation increases rapidly with latitude at this time of year.

Table 1. 100 mbar temperatures for winter months, 1957–72, in °C

	April		May		June		July		August	
	mean	max s.d.	mean	max s.d.	mean	max s.d.	mean	max s.d.	mean	max s.d.
Argentine Islands	−54.8	2.5	−62.0	3.5	−67.2	3.6	−72.0	3.9	−74.4	5.5 (†3.4)
Halley Bay	−57.8	2.4	−67.8	3.5	−74.8	3.6	−80.1	2.6	−83.0	2.8

† Excluding 1972.

Table 1 shows temperature data for those months when ozone data is not available. The temperature difference between the stations is a measure of the strength of the vortex; it reaches a maximum in late August. A measure of the perturbations is given by the maximum of the daily standard deviations for the month. The perturbations are weak in April, when the vortex has only just formed. At Argentine Islands, the activity is almost constant for the four winter months (May to August), if one large warming event in August 1972 is disregarded. At Halley Bay, July and August are markedly less disturbed than May and June. The August 1972 event had a range there of only 5 °C, in contrast to the range of almost 20 °C at Argentine Islands. The warming was in phase at the two stations, both recording their highest temperatures on 15 August.

Large and rapid temperature changes of this kind, 'sudden warmings', have been observed frequently in the Northern Hemisphere in winter. They are most prominent at the level of the stratopause (45 km, 1.5 mbar), but usually perturb a substantial thickness and often the whole of the stratosphere. Stratopause temperatures, from 80° N to 80° S, have been monitored continuously by satellite-borne radiometers since April 1970. Barnett (1974) has listed the largest sudden warmings seen by satellites, using the standard deviation of temperature around a latitude circle as a measure of (eddy) activity. The first high-altitude winter warming reported for the Southern Hemisphere was centred on 29 July 1972, with maximum activity at 64° S. The range in temperature was about 30 °C. The delay of 17 days between the maximum activity near the stratopause and the peak temperature at 100 mbar, is rather larger than might be expected (waves associated with the breakdown of the vortex typically traverse 180° of longitude in some 12 days), especially as there is no sign of prior cooling at 100 mbar.

There have been two subsequent winter warmings reported, 16 August 1973 and 26 July 1974. Neither event can be seen in the 100 mbar data from Argentine Islands. Examination of the spring warmings in Barnett's list, four in September–October 1970, and one centred on 7 September 1971, suggests that the response at the 100 mbar level increases rapidly from early September onwards. Peak temperatures at 100 mbar occur within a few days of the reported dates of the warmings, except for 18 October 1970, when there was cooling at 100 mbar over Argentine Islands, immediately before the final warming and breakdown of the vortex. It may be noted that the breakdowns of 1971, 1972 and 1973 were not classified as large warmings, nor was a prominent wave in the 100 mbar temperature and ozone data in September 1972.

Quiroz, Miller & Nagatini (1975) distinguish between major warmings, in which poleward movement of planetary scale thermal systems results in a reversal of the polar circulation at 10 mbar or below, and minor ones, in which the trajectories of warm cells retain a basically zonal (eastward) direction. They remark that major warmings are almost impossible in winter in the Southern Hemisphere. The circulation there is more intense, and the vortex penetrates to much lower levels than in the north. Barnett (1974) noted that the eddy activity at stratopause level in July 1974 was as large as that preceding many major warmings in the Northern Hemisphere, yet no poleward movement of the warm cell ensued. The warming at 100 mbar in August 1972 thus seems distinctly anomalous. It may be recalled that there were intense solar events in late July and early August 1972, with a sequence of large magnetic storms. Proton fluxes were the largest yet recorded. There is currently much speculation on possible linkages between these phenomena and the lower atmosphere. A detailed re-examination of this sudden warming might be rewarding.

While the lower stratosphere well within the southern vortex is relatively free from winter disturbances, it is much more active at lower latitudes. Baroclinic waves with periods between 17 and 30 days, which can sometimes be traced through several successive circuits of the continent, are a regular feature of the 100 mbar temperature records in the winter at Macquarie Island (54° S, 160° E) and Stanley (52° S, 58° W), and can be seen to much lower latitudes in many years (Godson 1963). The associated ozone variations, as seen at Macquarie Island (Webster & Keller 1975), are large. Measurements at South Georgia (54° S, 36° W), started in 1971, show similar winter activity. Annual ozone maxima at these stations occur generally in August or September, when the wave activity is largest. The later rise in ozone associated with the breakdown of the vortex in October or November is much less pronounced than that at higher latitudes.

The meso-scale variations of ozone and temperature discussed in this sub-section are linked, as are the synoptic scale variations in § 2*a*, by vertical motion in the stratosphere. But whereas the synoptic scale motion, forced from below, dies out rapidly with increasing height above the tropopause, the meso-scale motion is apparently initiated at or near the level of the stratopause, and may pervade the entire stratosphere. This distinction may seem to be merely one of scale, but it carries an important implication. Craig (1965) remarks of the Reed–Normand effect that it looks as if, in the subsidence of a vertical column in which ozone mixing ratio increases with height, one is getting ozone for nothing. He goes on to point out that a more accurate picture must be one of horizontal convergence of ozone-rich air at the top of the column, with horizontal divergence of air poor in ozone at the bottom. The net gain is at the expense of a neighbouring region where the reverse process is occurring. This description is justified if the vertical motion is confined to levels where ozone mixing ratio is conserved. Much uncertainty remains (cf. § 2*d*) but a maximum height of 25 km is perhaps appropriate. Photochemical control increases with height above this level, until at about 40 km photochemical equilibrium is maintained permanently. When vertical motion extends to these levels, then a true source or sink of ozone is available, and non-conservative variations of ozone are possible.

The ozone maxima at Argentine Islands and Halley Bay are much smaller than those, in excess of 500 matm cm, which are observed at corresponding latitudes in the Arctic. They are also usually less than the maxima observed at Macquarie Island or South Georgia. Godson

(1963) suggested that, since equilibrium mixing ratio decreases polewards, this indicates *in situ* subsidence in the Southern Hemisphere, and high latitude subsidence of air advected from middle latitudes, in the Northern Hemisphere. This is consistent with the different behaviour of northern and southern sudden warmings discussed above.

Early warming waves appear to be reversible, that is, there is little net gain in temperature or total ozone. The wave energy is obtained at the expense of the zonal flow, but radiative cooling can apparently restore the flow. By mid-September solar heating of the upper stratosphere is sufficient to prevent this, and now the waves show net gains in both ozone and temperature. The vortex shrinks, the reduction in horizontal extent being greater at the higher levels. This sequence appears to account qualitatively for the decline in the ratio of ozone changes to temperature changes during the breakdown. In the early winter there is little ozone in the lower stratosphere, and the mixing-ratio gradient to equilibrium levels is steep. Waves in middle latitudes may extend through the entire thickness of the stratosphere; at higher latitudes they are restricted to the higher levels. Ozone changes are large relative to temperature changes, and may well be non-conservative. In later warmings, net gains in ozone will have weakened mixing-ratio gradients, and with the shrinkage of the vortex the vertical motion will be restricted in height. Both effects will reduce ozone changes relative to temperature changes at the 100 mbar level. The final disappearance of the vortex core, when this is late in the season, is quite unspectacular. Subsidence is restricted to a shallow layer around 100 mbar, and ozone changes are minimal. Qualitative support for these views is available from the rather infrequent Umkehr measurements of vertical distribution of ozone (e.g. Farman & Hamilton 1975). Satellite observations of ozone have been made for some years past (Barnett 1977) and could be used for quantitative tests. Unfortunately, the necessary data have not yet been published.

Vertical motion appears to be the key to interpreting the breakdown of the vortex but there is little understanding of how the vertical motion is initiated, although there is general agreement that planetary waves in the troposphere must have a significant rôle. Horizontal advection seems to be of minor importance in the southern vortex. Pittock (1970) has argued otherwise, claiming that at Macquarie Island there is a significant advective component in ozone changes, but no such component in temperature changes. It is difficult to see how the required horizontal gradients can be attained from initially zonal distributions. There must be a high correlation between ozone and temperature changes in the horizontal, if the large-scale subsidence plays a dominant rôle in producing either. The claim rests on an assumed vertical distribution of ozone, for the minimum value of total ozone during the passage of a baroclimic wave. The distribution does not reflect this situation, showing more ozone in the lower stratosphere than would be expected after several days of ascending motion.

At the higher latitudes more direct evidence is available. The small increase in ozone at stations under the core of the vortex suggests that there is little transfer of ozone from the surrounding regions, where the final warming may have been abrupt with large increase in ozone.

Evidence using an independent tracer comes from the transport of volcanic dust into the polar stratosphere after the eruption of Mount Agung (8° S, 115° E), Bali. The eruption took place in March 1963, and dust spread rapidly across low and middle latitudes, some reaching Stanley (52° S, 58° W) in July 1963. Figure 3 shows the arrival of the dust at Halley Bay, as indicated by its effect in increasing the diffuse radiation received from cloudless skies. It seems clear that no significant advection of dust took place within the vortex, the dust arriving only after the vortex had broken down.

The ozone variations during the breakdown have attracted most attention. The decline in ozone once the summer circulation has been established is as interesting, and is in striking contrast to the maintained temperatures. There can be little transfer to lower latitudes, for horizontal gradients are weak and eddy activity is small. There is no doubt that much of the ozone is in the lower stratosphere, where it should be quasi-conservative. If so, this requires a weak upward flow to take the ozone back to levels where photochemical destruction can occur. The temperature could perhaps be maintained against the implied adiabatic cooling by radiative heating, but the solar component of this is diminishing quite rapidly in the autumn. Hence there must be a suspicion that photochemical changes are more important in the lower stratosphere than has been supposed.

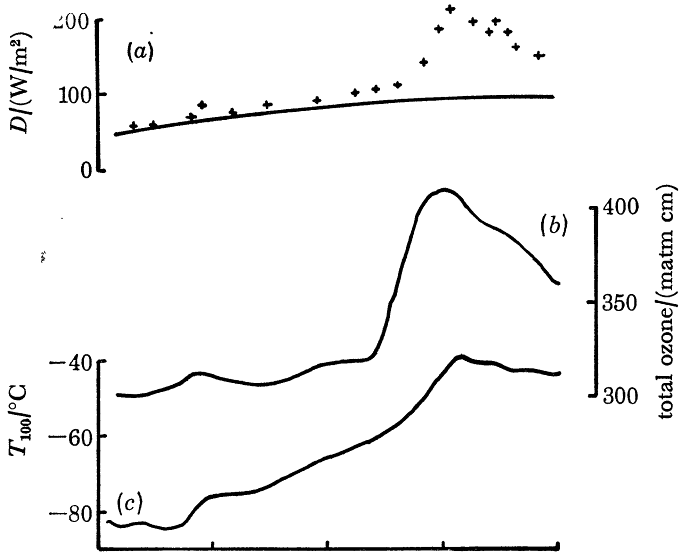

FIGURE 3. Arrival of volcanic dust at Halley Bay, 1963, following the eruption of Mt Agung. (*a*) Diffuse radiation values at local apparent noon under cloudless skies. Continuous line shows estimated effect of Rayleigh scattering, for albedo of 0.8. (*b*) 10-day running mean of ozone. (*c*) 10-day running mean of temperature at 100 mbar level.

(*c*) *Long-term trends*

The data presented in § 2*b* show that, during the austral spring, ozone amount is very variable, and, it has been argued, largely under dynamic control. In the analysis for long-term trends, only autumn data have been used. The interval 22 December to 6 April (22 March at Halley Bay, where the observing season is shorter) has been divided into 7(6) sets of 15 or 16 days. (These sets are the sigma-groups of Bartels.) Figure 4 shows the variation of the means for the complete interval, plotted as deviations from the overall means for the 16 years. Vertical bars show the range of departure of the means of the separate sets from their long-term mean.

Least-squares linear approximations are shown for 1958–73, and also for 1965–73. The overall means are the same at the two stations, 317 matm cm. The trends are given in table 2.

The errors are compounded from residual calibration errors, assessed as ± 3 matm cm in Farman & Hamilton (1975), and ozone variance, ± 9 matm cm for 1958–73 and ± 6 matm cm for 1965–73 at both stations. The calibration errors in the original series were assessed as ± 9 matm cm at Argentine Islands, and ± 15 matm cm at Halley Bay. The combination of persistent cloud cover, making days suitable for calibration of the instruments rather infrequent, and of large day-to-day changes in ozone during half the observing season, make calibration more difficult at these stations perhaps than at many others. It is felt, nevertheless, that there is a strong case for regular review of such errors in all ozone data series.

As shown in table 2, the 16-year trend is not significant at either station. However, the two series are completely independent, and in combination yield a near-significant trend for the region of − (3.0 ± 1.7) % per decade. The yearly extreme deviations are distributed fairly evenly over the sets, and trends and error estimates are stable with respect to the omission of any single set.

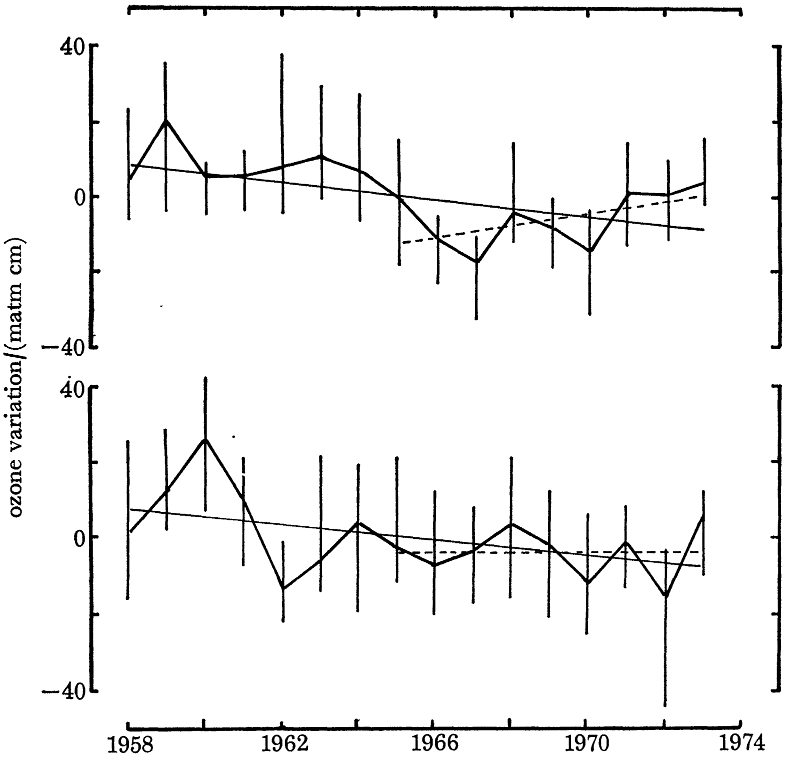

FIGURE 4. Trends in ozone at Halley Bay (top) and Argentine Islands (bottom), plotted as deviations from 16-year mean values. Vertical bars show range of 15-day means; see text for full details.

TABLE 2. TRENDS IN OZONE AMOUNT

		matm cm per year	% per decade
Argentine Islands	1958–73	− 1.0 ± 0.8	− 3.5 ± 2.5
Halley Bay	1958–73	− 0.9 ± 0.8	− 2.8 ± 2.5
Argentine Islands	1965–73	0.0 ± 1.1	0.0 ± 3.5
Halley Bay	1965–73	+ 1.5 ± 1.1	+ 4.7 ± 3.5

The trends for 1965–73 were calculated for comparison with Aspendale, Australia (38° S, 145° E). The results are in conflict with the decrease reported there of (3.1 ± 1.1) % per decade (Pittock 1974). However, it appears from the review of Angell & Korshover (1976) that the Aspendale result is not representative of the Australian region, the average trend there being much smaller. The estimated error for the Aspendale trend is very low and presumably refers to ozone variance alone. It appears reasonable to assign a lower limit of ± 1.4 % per decade, as the minimum trend detectable with a Dobson spectrophotometer.

1965 was sunspot minimum, and the difference between the overall trends and those for 1965–73 might suggest a variation of ozone related to the solar cycle. However, any such variation must be small. It has been noted above that the two series presented here are completely independent. They are also apparently unrelated, the correlation coefficient for 1958–73 is 0.16. It may be inferred that the amplitude of any solar cycle variation is less than the variance, and that a calculated value would have little significance. The correlation coefficient for 1965–72 is 0.42, reflecting the emergence of a biennial component from 1969.

Angell & Korshover (1976) have presented a global analysis of recent ozone fluctuations. They have used unrevised Argentine Islands and Halley Bay data in deriving their results for Antarctica. Their conclusions are not affected, since the trends are scarcely altered by the revision. The reduction in variance would pass unnoticed, since they use means of all available observations, rather than the quiet interval selected here. It is noteworthy that, nevertheless, Antarctica shows lesser ozone fluctuations than any other region. It is significant, perhaps, that it also shows the smallest trend. At low latitude stations, where day-to-day variability in ozone is almost negligible and where indeed, the shortest significant variation appears to be the annual one, most of the variability is associated with the quasi-biennial oscillation. The irregularity of this so-called oscillation (fluctuation is surely to be preferred?) hinders considerably the identification of longer-term trends.

Figure 4 shows no evidence of anomalous ozone variation following the eruption of Mt Agung (see § 2*c* above for details). Angell & Korshover speculate that an irregularity [*sic*] in the quasi-biennial fluctuation might be linked to this event. The difficulty of identifying the fluctuation in antarctic ozone data, only 2 of the 4 seasonal means being available, precludes comment. By using data for a single season, as in figure 4, the fluctuation would be apparent only when the 'period' and the phase were both favourable – the interval 1969 to 1973 is of this kind.

(*d*) *Discussion*

There has been a revival of interest in stratospheric processes, following the suggestion that the artificial injection of certain chemical species might affect ozone concentrations. Johnston (1973) estimated that oxides of nitrogen emitted by aircraft flying in the stratosphere could reduce ozone shielding of ultraviolet radiation by a factor of about 2. The possible effects of chlorine have been discussed (Molina & Rowland 1974; Clyne 1974). This may be released in the stratosphere by photo-dissociation of freons. These are inert halocarbons used as aerosol propellants and refrigerants; they have no known tropospheric sink.

There is no general agreement on the details of the photochemistry. According to Ackermann (1975), a later estimate of the effects for the same aircraft considered by Johnston puts the reduction factor at around 1 %. It has been suggested recently that chlorine and oxides of nitrogen may interact so as to have negligible effect on ozone (Eggleton, Cox & Derwent 1976).

An indication of the complexity of the problem of modelling atmospheric ozone is that all current models are compromises between including a detailed account of the photochemistry on the one hand, and a realistic treatment of stratospheric dynamics on the other. The models have been used mainly to assess the effects of changes in concentration of critical contaminants. 'Criticality' varies from model to model, and since few if any measurements of natural concentrations of such species were ever made, it is often not clear to what extent the current complex models have improved on Chapman's (1930) pioneer work in accounting for the uncontaminated ozone layer.

Amid this theoretical confusion, it is natural to ask what changes could occur before they were identified in the observations. The answer depends to some extent on the nature of the change. One of say, 10%, over 10 days should be immediately obvious at low-latitude stations, yet could easily escape notice at a high-latitude station, especially in late winter or spring. On the other hand, a change of 5% over 2 years would be significant at a high-latitude station, yet could be confused with the quasi-biennial fluctuation at low-latitude stations. Clearly it is necessary to keep an extensive network of observing stations in being. The need for frequent and careful checks on instrumental behaviour cannot be overstated. Ozone trends are meaningless if this is neglected. Angell & Korshover (1976) show an apparent increase of 12% at Kodaikanal for 1957–69 without comment. This result should be critically reviewed.

Komhyr, Grass & Slocum (1973) in presenting the case for an increase of ozone over North America in the 1960s, give a good account of the difficulties in maintaining long-term control of spectrophotometers. It appears that their practice is to use one spectrophotometer as a reference for their network, and to derive calibrations for their station instruments by comparison. This procedure is dictated to some extent by operational conditions, and there seems to be a tendency for other networks to adopt this policy. This is regrettable, since the individual station trends are not then independent.

Perhaps, however, the major difficulty in assessing ozone trends in middle and high latitudes arises from the very different courses which the breakdown of the winter polar vortex may take from year to year. It has been suggested above that total ozone is not necessarily conserved during the breakdown, and in any case the variations in total ozone are essentially dynamic in origin. Most analyses for trends have been based on three-monthly, or annual, mean values. For this purpose, the procedure adopted in § 2*c* seems preferable: namely, to select an interval when ozone variance is minimal, and when horizontal gradients over the region of interest are weak.

3. Conclusions

The difficulties of establishing ozone trends have been critically discussed, and it is suggested that the trends identified in published routine data are probably not significant. The selection of periods when ozone variation is minimal has been advocated. Further investigation is needed to establish when and to what extent, total ozone is conserved. The need for careful and continuing reappraisal of ozone data has been stressed.

The observations discussed in this paper were made and worked up by many different people, serving under contract with the British Antarctic Survey. Their contribution is gratefully acknowledged.

It was a sad occasion when members of the Survey learned, earlier this year, of the death of Professor G. M. B. Dobson, F.R.S. Several of us were privileged to receive our introduction to ozone measurements from him at his home in Oxford. In his retirement, he retained a keen interest in ozone data from Antarctica, and he gave freely of his time in discussion and encouragement.

Successive Directors-General of the Meteorological Office have allowed the Survey to use facilities at Bracknell and Lerwick Observatory for calibrating instruments and training personnel. The Meteorological Office staff involved in these operations are thanked for their whole-hearted cooperation.

I am grateful to Mr W. R. Piggott for his many helpful comments on the manuscript and to Miss M. Turton for her careful collation of the results.

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