Ozone fluctuations in relation to upper air perturbations in the middle latitudes of the southern hemisphere

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ABSTRACT

From the correlation coefficients obtained between ozone and 100 and 20 mb temperatures for Brisbane and Aspendale, it is seen that in middle latitudes, on a short-term basis, the ozone changes are not only governed by lower stratospheric waves but also by middle stratospheric perturbations which are most of the time independent of each other. At Brisbane, however, ozone changes are essentially governed by lower stratospheric waves.

On a seasonal basis, the comparison of the mean distributions of ozone with height in autumn over Aspendale (38.0° S, 145.1° E) and Brisbane (27.5°S, 153.0° E) with Tateno (36.1° N, 140.1° E) and Torishima (30.5° N, 140.3° E) in Japan shows significant differences in the ozone content not only in the lower stratosphere but also in the middle stratosphere above about 25 km. Also, at Aspendale ozone content increases at about 30 km in the middle stratosphere after August each year. Ozone and tropopause pressures are not very well correlated on a seasonal basis although there is a good correlation between short-term variation of ozone and tropopause height. All these suggest the significance of the effective changes produced by middle stratospheric circulation.

The mechanisms involved for the daily ozone oscillations are different at least in part from those involved for seasonal oscillations.

Introduction

Studies on ozone-weather relationships made in the middle latitudes of the southern hemisphere show that the total ozone content is well correlated with meteorological parameters of the upper troposphere and lower stratosphere (Kulkarni, 1963) and are correlated less closely at Halley Bay in the Antarctic (MacDowall, 1960). Investigations made in the middle latitudes regarding the relationships of the content and the variation of ozone with such processes in the upper troposphere and lower stratosphere as passage of cyclones, origination of the type of airmasses, temperature and pressure at various levels, testify to the existence of a definite relationship between ozone and the general circulation of the atmosphere. Apparently the causes of the daily variations in ozone content which are associated with tropopause topography and the lower stratosphere perturbations are different from the causes that determine the seasonal changes in ozone. It has also been observed that the long-term oscillation in ozone in high middle latitudes are due to middle stratospheric waves, which are usually independent of the wave disturbances of the upper troposphere and lower stratosphere (Boville & Hare, 1961). However, very little is known about the effects of middle stratospheric perturbations on ozone fluctuations of different scales in the middle latitudes of the southern hemisphere. At some low and middle latitude stations over Australia, vertical temperature soundings have on many occasions reached a height of about 20 mb since 1964. The present paper is an account of the further relationships observed between ozone content and upper air measurements made at these stations on daily and seasonal bases.

Short-term variation in ozone and upper air measurements

Table 1 gives the correlation coefficients between the deviation of daily ozone from the seasonal mean and the deviation of temperatures from the seasonal mean at 100 and 20 mb levels at Aspendale and Brisbane for different

Table 1. *Correlation coefficients between ozone and upper air temperatures at Aspendale and Brisbane*

The figures in brackets indicate the number of observations

Corr. between	O_3–100 mb temp.	O_3–20 mb temp.	20–100 mb temp.
Aspendale 1964			
D. J. F. (Summer)	+0.77(88)	+0.19(72)	+0.30(70)
M. A. M. (Autumn)	+0.76(86)	+0.32(72)	+0.26(73)
J. J. A. (Winter)	+0.24(82)	+0.54(77)	−0.05(74)
S. O. N. (Spring)	+0.72(82)	+0.47(73)	+0.33(72)
Brisbane 1964			
D. J. F.	+0.56(84)	+0.07(68)	−0.13(68)
M. A. M.	+0.52(77)	+0.16(70)	+0.21(68)
J. J. A.	+0.69(80)	+0.15(73)	+0.22(69)
S. O. N.	+0.59(81)	+0.03(78)	−0.21(75)

seasons in 1964. The correlation coefficients between temperatures at 100 and at 20 mb levels are also given. The figures in brackets indicate the number of observations during each season. As is generally accepted, it can be taken that the 100 mb level represents the lower and the 20 mb level represents the middle stratosphere.

The following points are of interest:

1. As noted earlier for the years 1957, 1958 and 1959 (Kulkarni, 1963), the correlation coefficient between ozone and temperature at 100 mb level in various seasons in 1964 at Aspendale is found to be much lower for winter than for other seasons. But at Brisbane during winter a somewhat higher correlation is obtained than for the remaining seasons.
2. At Aspendale, the correlation coefficient between ozone and temperature at 20 mb is highest in winter and spring implying that the perturbations at the 20 mb level are more important in affecting the ozone variations in these seasons. At Brisbane, however, the correlation between ozone and 20 mb temperature is generally poor.
3. At Aspendale, the correlation coefficient between temperatures at 20 and 100 mb levels is lowest and negligible in winter. This suggests that the short period fluctuations at these levels in winter are practically independent of each other whereas in other months it is possible that the disturbances at the 100 mb extend up to the 20 mb level. At Brisbane the correlation coefficients are poor indicating practically little relationship between 100 and 20 mb temperature fluctuations.

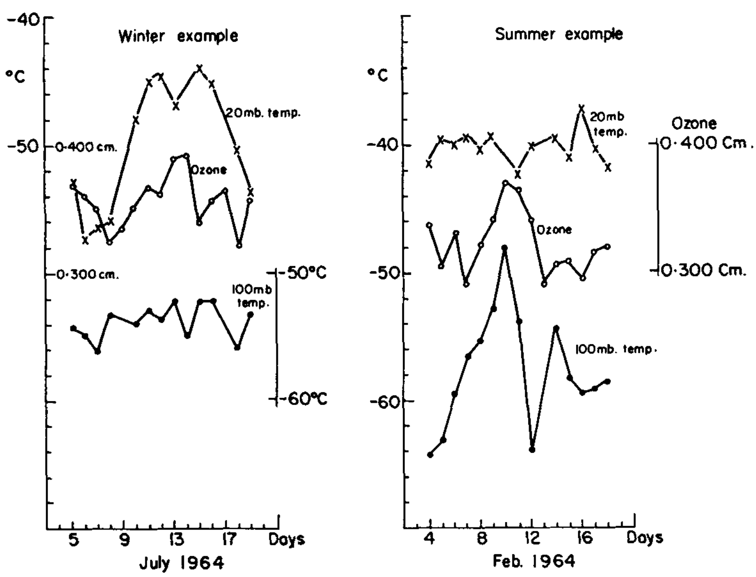


Fig. 1. Variations of ozone values with 100 and 20 mb temperatures at Aspendale.

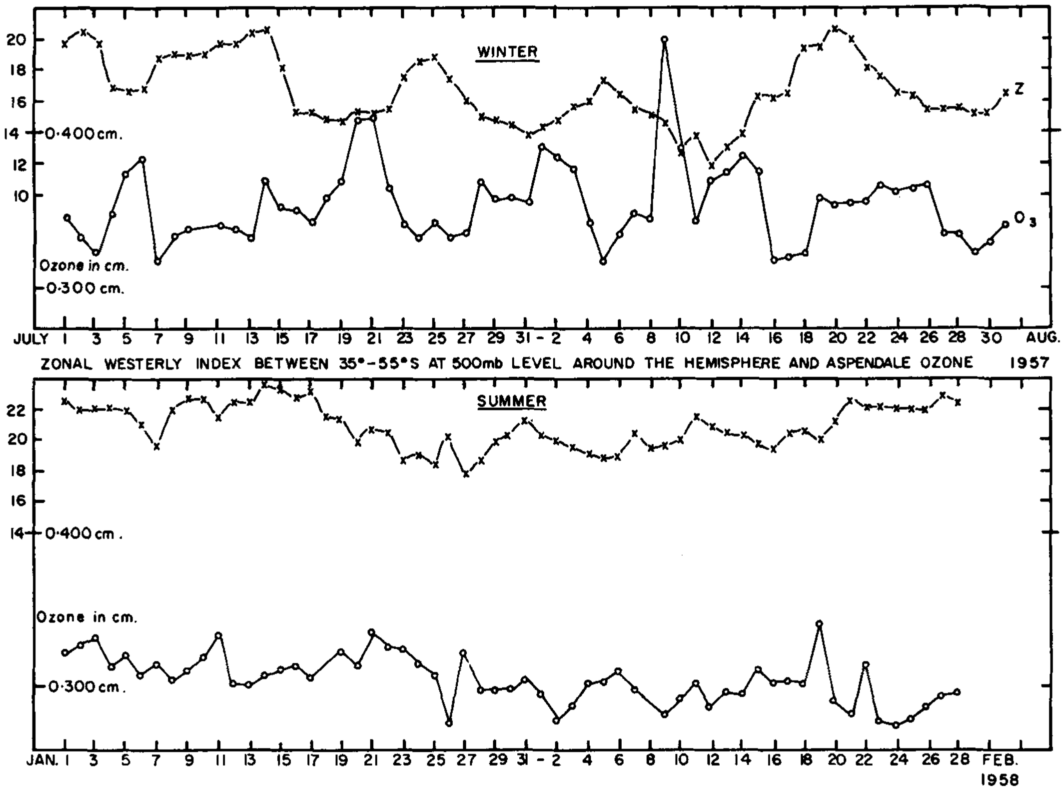


Fig. 2. Zonal westerly index between 35°–55° S at 500 mb level around the hemisphere and Aspendale ozone.

The above-mentioned relationships will be demonstrated by two specific examples at Aspendale, one in summer when ozone followed the temperature trend at the 100 mb level and another in winter when temperature at 20 mb and ozone were related with each other.

Winter example

The temperature at the 20 mb level rose to −44°C on the 15th July, 1964, from −56°C on the 8th. Correspondingly the ozone amount rose to 0.392 cm on the 14th from 0.324 cm on the 8th. During that period the temperature at 100 mb was unaffected and was steady at −53°C

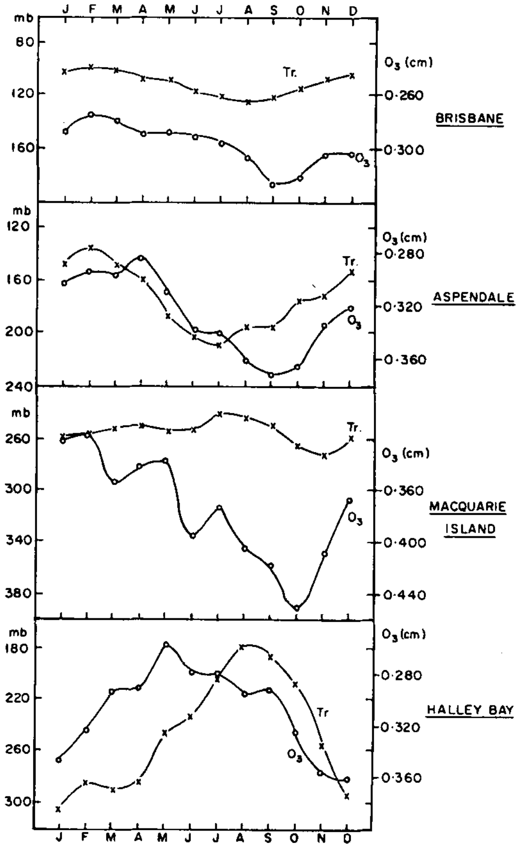
Summer example

The temperature at the 100 mb level rose from −64°C on the 4th February to −48°C on the 10th and decreased to −64°C on the 12th. Correspondingly ozone values also rose from a minimum of 0.290 cm on the 7th to 0.370 cm on the 10th and decreased to 0.290 cm on the 13th. During that period the temperature at 20 mb was fairly steady.

From the established statistical relationships it is known that high ozone coincides with the passage of high level troughs and low ozone with the passage of high level ridges in the lower stratosphere. There are however periods when this relationship breaks down as in the winter example shown above. Also the examples clearly demonstrate that the vertical motions associated with the temperature fluctuations at these levels are independent of each other.

Circulation index and ozone

Fig. 2 gives the plot of the zonal westerly index between 35°–55° S at the 500 mb level around the hemisphere and the ozone amounts at Aspendale for two periods one in July–August (winter) and another in January–February (summer). The data for zonal index were taken from those published in Notos Vol. 8, 1959. The correlation coefficients obtained for these



OZONE AND TROPOPAUSE PRESSURE VARIATIONS

Fig. 3. Ozone and tropopause pressure variations.

periods are -0.43 in winter and -0.15 in summer. The fluctuations in both the zonal westerly index and the ozone amounts are small in summer but large in winter. These correlation coefficients obtained for Aspendale are of the same magnitude as those given for stations at similar latitudes in the Northern Hemisphere for the corresponding seasons by Kuznetsov (1961). Seasonally, as the correlation coefficient in winter is pronounced and significant, and is rather poor in summer it implies that in winter there is a greater influence of currents in the troposphere on ozone than in summer and the process by which the ozone amount changes negatively with the zonal index is essentially due to advection. In winter, as the correlation between ozone and 100 mb temperature is poor and is significantly high between ozone and circulation index at 500 mb level, it would imply that the system of lower stratospheric and tropospheric waves are extending rather weakly at the 100 mb level at Aspendale.

From the above study of short-term oscillations in ozone with other meteorological parameters the following conclusions can be drawn: At Aspendale, the vertical motions associated with temperature changes at the 20 mb level have greater influence on ozone during winter than in other seasons. Advection in the middle stratosphere would not affect the ozone changes significantly as the latitudinal gradient of ozone at this level is small (Kulkarni, 1966) although the temperature might change depending on the direction of the flow of air masses. In the troposphere, the effect of advection on ozone is more pronounced in winter than in summer. In the lower stratosphere, however, both advection and vertical motions will be responsible for changes in ozone.

At Brisbane, it appears that the ozone changes are essentially controlled by advection and vertical motions in the lower stratosphere.

Ozone variations in relation to seasonal changes in the lower and middle stratospheres

It is generally known that on a short term basis high ozone is associated with the sinking of the tropopause and low ozone with the rising of the tropopause; the correlation coefficient between tropopause height and ozone at Aspendale being about -0.5. At Aspendale the ten day running means of ozone and tropopause height were well correlated although at Halley Bay they were almost unrelated. As dynamical processes are of primary importance in the production and maintenance of the tropopause, the radiative processes being only secondary in importance (Godson, 1963), and as the dynamical processes are mostly responsible for changes in ozone in the lower stratosphere where most of the ozone changes are known to occur, it is of interest to study the relationship between ozone and tropopause height seasonally.

Fig. 3 gives the average monthly tropopause pressures for Brisbane (27.5° S, 153.0° E), Aspendale (38.0° S, 145.1° E), Macquarie Island (54.5° S, 159.0° E) averaged over ten years from 1951 to 1960 and for Halley Bay (75.5° S, 26.6° W) for five years from 1959 to 1964, and the

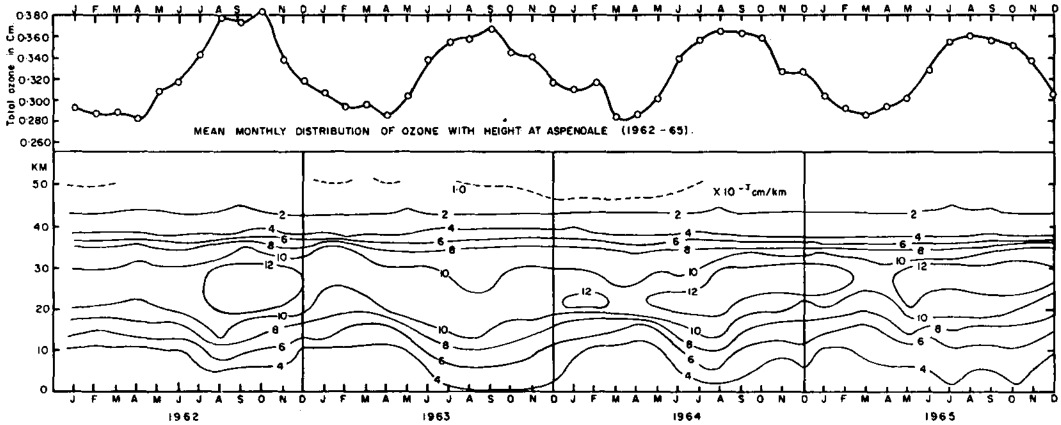


Fig. 4. Mean monthly distribution of ozone with height at Aspendale 1962–1965. Ozone in 10^{-3} cm/km.

average monthly ozone values averaged for all the available years since 1955.

The scale for ozone is reversed, ozone increasing downwards. It can be seen from the figure that:

1. At Brisbane, the tropopause is lowest in July, August and September whereas ozone is highest in September and October.
2. At Aspendale the tropopause is lowest in June, July and ozone is highest in September and October. At Aspendale and Brisbane the ozone amount was increasing in July, August, September, when the tropopause heights were already increasing.
3. At Macquarie Island there is practically no relationship between tropopause and ozone since there is no significant seasonal change in tropopause pressure (see also Fig. 7) and the seasonal change in ozone is from a maximum of about 0.390 cm to a minimum of about 0.260 cm.
4. At Halley Bay, the minimum ozone is observed in May and the highest tropopause in August. From May to August when the ozone is increasing the tropopause pressure is gradually decreasing.

It is apparent from these that ozone and tropopause pressures on a seasonal basis are not very well correlated although the short-term variations of ozone at these places excepting Halley Bay are well correlated indicating that the mechanisms responsible for day to day changes are quite different from those responsible for seasonal changes in ozone.

The fact that ozone is built up in the months September and October at Brisbane and Aspendale when the tropopause is going up and that at Macquarie Island seasonal change in ozone has no relationship with the seasonal change in tropopuase height, indicates that the build up of ozone at these places might be taking place either by horizontal advection from regions of higher ozone, perhaps longitudinally, without involving vertical motions or by processes at higher levels (at levels higher than about 25 mb) which would not influence the change in tropopause level.

These implications can be studied in terms of the month to month changes in the vertical distributions of ozone in the middle latitudes of of the southern hemisphere. Fig. 4 gives the mean monthly distribution of ozone with height at Aspendale for the years 1962 to 1965 as calculated from umkehr observations by method B. The computational work using the tables given by Ramanathan and Dave and applying appropriate multiple scattering corrections was programmed for the CSIRAC computing machine and the actual ozone distribution was determined by trial and error.

It is well known that the umkehr method is rather insensitive to changes in ozone concentration in the lower atmosphere and that it does not yield a unique result from a set of data points (Mateer, 1964). Nevertheless, the umkehr data are adequate for the study of large scale features such as seasonal trends, or trends in layer concentration with changes in total ozone.

It is significant to note in Fig. 4 that in the

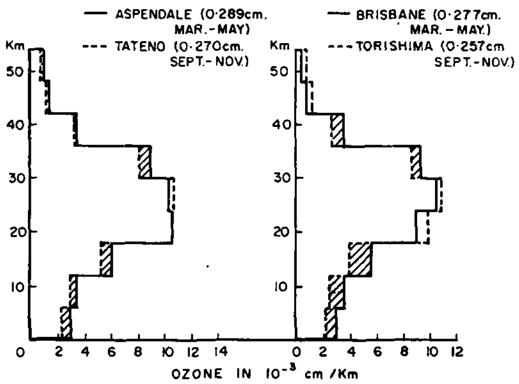


Fig. 5. Comparison of vertical distributions of ozone at Aspendale, Tateno, and Brisbane and Torishima in autumn.

years 1962, 1963, 1964 and to a lesser extent in 1965 ozone amount after August each year at about 30 km increases although below 18 km it decreases as also the tropopause pressure decreases. The possibility that ozone changes are taking place at higher levels quite independent of the tropopause oscillation is important in that it bears out, as has already been speculated, that the middle stratosphere plays an important role in ozone changes not only on a short-term basis but also on a seasonal basis. Incidentally, it can be seen from Fig. 4 that ozone amount builds up in the lower stratosphere after May each year and maximum ozone is situated between 20–30 km height in the spring season when the total ozone is greatest.

It was observed that total ozone was greater in late summer, autumn and early winter in the middle latitudes of the southern hemisphere than in the middle latitudes of the northern hemisphere (Kulkarni, 1962). Comparing the average vertical distributions of ozone in autumn between Aspendale and Tateno (36.1° N, 140.1° E) and between Brisbane and Torishima (30.5° N, 240.3° E), it can be seen that in the 18–30 km interval there is less ozone at Aspendale and Brisbane than at Tateno and Torishima and the greater total ozone at Aspendale and Brisbane is distributed below 18 km and above 30 km.

As there is no reason to expect any greater production of ozone above 30 km in the southern hemisphere in low latitudes than in the northern hemisphere, it is apparent that the difference in the middle stratospheric circulation is important in ozone amount being greater in the southern hemisphere. However, below about 25 km, the difference in the strength of the lower stratosphere circulation is, no doubt, the cause of the difference in ozone amounts.

The greater ozone observed in the lower stratosphere of the middle latitudes of the southern hemisphere than in the northern hemisphere in late summer, autumn and early winter is perhaps due to lesser destruction of ozone in the southern hemisphere from winter to summer on account of the smaller amplitude of the seasonal variation of the tropopause height and hence smaller incorporation of lower stratospheric airmass into the troposphere where ozone is destroyed. This can be seen in Fig. 6 which gives the tropopause pressure differences between summer and winter in both hemispheres in 1958. The difference for the average of 10 years data for the southern hemisphere has also been included. In the northern hemisphere the pressure differences from winter to summer are larger than in the southern hemisphere for latitudes greater than 30°. In the middle latitudes between 30–35°, the difference is largest while it becomes negative in higher latitudes in the southern hemisphere. The patterns of the differences in the two hemispheres are more or less similar. The reason for the smaller tropopause pressure difference in the middle latitudes of the southern hemisphere than in the northern hemisphere may be found in the seasonal variation of the tropopause over the Antarctic.

Discussion

The lower stratosphere which will be defined as the stratosphere below roughly about 25 km

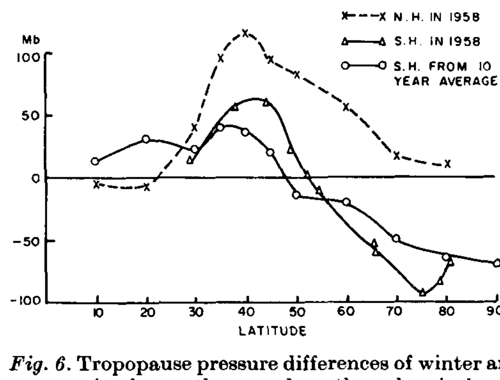


Fig. 6. Tropopause pressure differences of winter and summer in the northern and southern hemispheres.

and equatorward from the boundary of the polar regime defined by the ridge of the warm belt, is under tropospheric control. As has already been noticed the negative correlation between ozone and 300 mb temperatures and a positive correlation of a similar magnitude between ozone and 100 mb temperature (Kulkarni, 1963) would be evidence that the lower stratosphere and the troposphere act in unison. Apart from the vertical motions, cold air advection in the troposphere accompanying flow from the south would be accompanied by warm advection in the lower stratosphere because of the reversed horizontal temperature gradient immediately above the tropopause.

As regards the fluctuation of ozone on a short-term basis in relation to lower and middle stratospheric waves at various places in different latitudes, the following picture emerges. At subtropical latitudes (as at Brisbane) the lower stratospheric motions are the only important mechanism in defining ozone fluctuations. The middle stratospheric motions are less significant. At middle latitudes (as at Aspendale) the middle stratospheric motions are also significant in the fluctuations of ozone. As a matter of fact, in winter, it appears that the middle stratospheric perturbations are more important than the lower stratospheric waves. In high middle latitudes (as at Macquarie Island) it was pointed out earlier from a specific instance that the middle stratospheric waves contributed to the unexplained variance in total ozone. Godson (1962) has observed excellent correlation between ozone and middle stratospheric temperatures at high latitudes in both hemispheres. On a short-term basis then, it appears that the middle stratospheric thermal field is important in ozone oscillations in middle and high middle latitudes, the physical processes producing major changes in ozone and in middle stratospheric temperatures being associated with vertical motions only in both the cases.

Now the question arises what kind of relationship holds between ozone and the seasonal scale of motions in low and middle stratospheres.

We have seen already that there is a phase difference between the seasonal variation of tropopause pressure and ozone at Brisbane and Aspendale with a poor linear correlation, which is practically non-existent at Macquarie Island. The correlation is poor at Halley Bay also. Nevertheless, in a general way the relationship

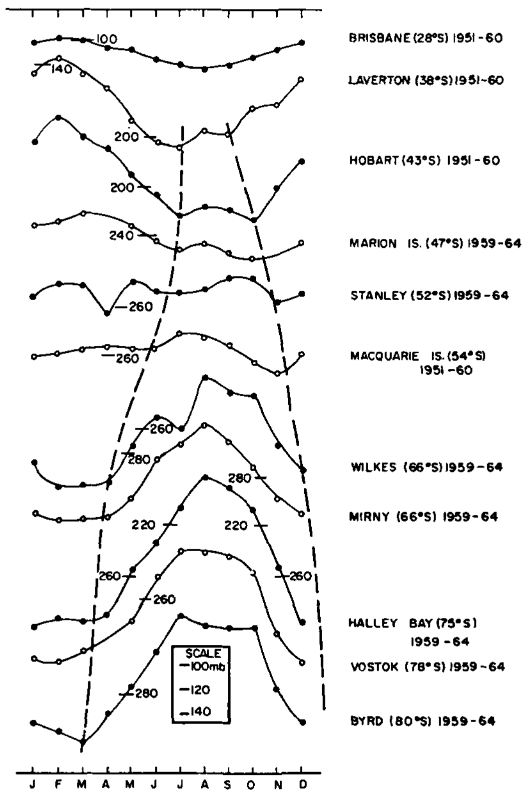


Fig. 7. Average tropopause pressures in mb in the southern hemisphere.

of low tropopause with high ozone and high tropopause with low ozone is still obeyed. As the formation and maintenance of a tropopause is considered to be essentially a dynamical process, the air motions associated with the meridional and seasonal variations of tropopauses would also be responsible for the latitudinal and the seasonal behaviour of ozone. It is known that most of the changes in ozone latitudinally and seasonally take place in the lower stratosphere and the upper troposphere. In Fig. 7 are given monthly mean tropopause pressures from the data of a large number of years at various places in the southern hemisphere. The tropopause behaviour itself could be interpreted in terms of three groups.

1. "Tropical" type group from Brisbane (28° S) to Marion Island (47° S) where the tropopause is highest in summer and is lowest in late winter and early spring, indicating a greater subsiding air mass in later winter and early spring.

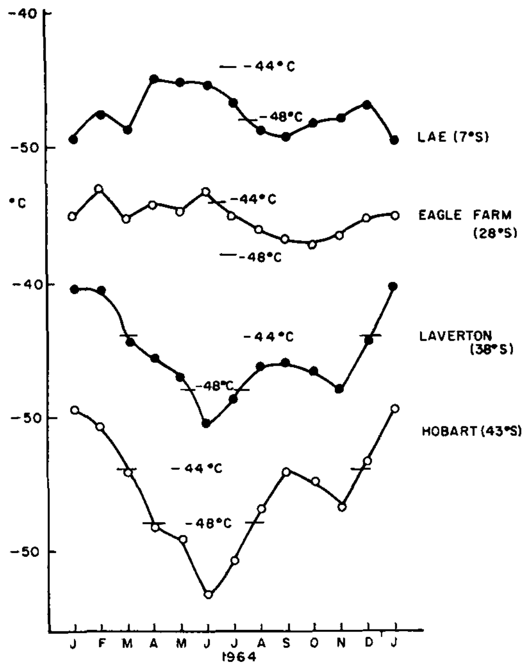


Fig. 8. Mean monthly values of 20 mb temperatures in 1964 at Lae 67°S, 147.0°E), Eagle Farm (27.5°S, 153.0°E), Laverton (38.0°S, 145.1°E) and Hobart (42.9°S, 147.3°E).

2. The high middle latitude group around 50–55° S (Stanley and Macquarie Island) where there is not much of a change in the tropopause height. This indicates the influences and the balance between the subsiding equatorial tropopause and the rising polar tropopause in late winter and spring.
3. The Antarctic tropopause which is highest in late winter and early spring and lowest in summer.

That the air motions responsible for the tropopause variations are also responsible for changes in ozone is shown by the following:

Significantly, the influence of the higher polar tropopause extends even at the latitude of Laverton for two months in August and September giving a slightly higher tropopause when the ozone amount decreases from somewhat a higher level in July giving a secondary maximum in ozone in June and July. This indicates the advection of cold ozone-poor air mass from the Antarctic even up to the latitude of 38° S.

As regards the behaviour of the seasonal variation of ozone with respect to the thermal structure of the middle stratosphere of the middle latitudes of the southern hemisphere, Fig. 8 gives the monthly mean temperatures at the 20 mb level in 1964 at Lae (6.7° S, 147.0° E), Eagle Farm (Brisbane), Laverton (Melbourne) and Hobart (42.9° S, 147.3° E).

It is interesting to note that at Lae and Eagle Farm there is no significant seasonal change in 20 mb temperature structure as both the stations are presumably under the influence of the equatorial cold pool all the time whereas there is considerable seasonal change in the temperatures at Laverton and Hobart with the lowest temperatures in June and highest temperatures in January. It is unlikely that direct radiative processes could completely explain the lowest temperatures at 20 mb in middle latitudes in winter. It is, however, more likely that the interlatitudinal mixing with the Antarctic middle stratosphere at this level is taking place, which could give rise to colder temperatures in winter. Such large scale motions in the middle stratosphere could affect ozone significantly as suggested by ozone analysis in its seasonal behaviour. This is in addition to the mean and eddy transport mechanisms of the lower stratosphere which are of primary importance in the seasonal pattern of ozone variation.

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REFERENCES

Boville, B. W. & Hare, F. K. 1961. *Q. J. Roy. Met. Soc. 87*, 490.
Godson, W. L. 1963. *Met. Abhandl. Berlin Symposium on Stratospheric and Mesospheric Circulation*, p. 161.
Kulkarni, R. N. 1962. *Q. J. Roy. Met. Soc. 88*, 522.
Kulkarni, R. N. 1963. *Q. J. Roy. Met. Soc. 89*, 473.
Kulkarni, R. N. 1966. *Q. J. Roy. Met. Soc. 92*, 363.
Kuznetsov, G. I. 1961. *Izv. Geophys. Ser.*, 467.
MacDowall, J. 1960. *Proc. Roy. Soc.* A 145, 416.
Mateer, C. L. 1964. *Tech. Rep. No. 2*, Dept. of Met., University of Michigan.
Ramanathan, K. R. & Kulkarni, R. N. 1960. *Q. J. Roy. Met. Soc., 86*, 144.
Ramanathan, K. R. & Dave, J. V. 1957. *Annals IGY 5*, 23.

ФЛУКТУАЦИИ ОЗОНА В СВЯЗИ С ВОЗМУЩЕНИЯМИ БОЛЕЕ ВЫСОКИХ СЛОЕВ ВОЗДУХА В СРЕДНИХ ШИРОТАХ ЮЖНОЙ ПОЛУСФЕРЫ

Из коэффициентов корреляции между озоном и температурой на поверхностях 100 и 20 мб, полученных для Брисбейна и Аделаиды, видно, что в средних широтах кратковременные изменения озона определяются не только волнами в нижней стратосфере, но и возмущениями в средней стратосфере, которые независимы друг от друга большую часть времени. Однако в Брисбейне изменения озона определяются существенно лишь волнами в нижней стратосфере.

Сравнение на сезонной основе средних распределений озона с высотой осенью над Аспендэйлом (38,0° ю. ш., 145,1° в. д.) и Брисбейном (27,5° ю. ш., 153,0° в. д.) с распределениями над Татено (36,1° с. ш., 140,1° в. д.) и Торишима (30,5° с. ш., 140,3° в. д.) в Японии показывает существенные различия в содержании озона не только для нижней, но и для средней стратосферы для высот, больших 25 км. В Аспендэйле также содержание озона увеличивается на высоте около 30 км каждый год после августа. Озон и давление на уровне тропопаузы коррелируют не очень хорошо при рассмотрении всего сезона, хотя для кратковременных изменений озона и высоты тропопаузы наблюдается хорошая корреляция. Все это предполагает существенность эффективных изменений, производимых циркуляцией в средней тропосфере.

Механизм, ответственный за суточные колебания озона отличается, по крайней мере, частично от механизма, вызывающего сезонные изменения.