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A climatological study of the Macquarie Island ozonesonde record 1994-2000

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An ozonesonde program was implemented at Macquarie Island during the period December 1993 to the present from various collaborations. The resultant data set facilitated an analysis of the climatology of the ozone altitude profile up to approximately 35 km. The monthly means of ozone partial pressure and mixing ratio have been presented as a function of both altitude and potential temperature and uncertainties have been calculated for the altitude climatologies. The general features of the analyses are consistent with our current understanding of seasonal ozone variations in the southern mid-latitudes. Because the dominant signal in interannual variability of stratospheric ozone is under-sampled the presented results must be regarded as preliminary.

Introduction

Macquarie Island (55°S, 159°E) is situated in a data-sparse geographic region that provides a unique and valuable data record for measuring southern high mid-latitude ozone (Lehmann et al. 1992a). Apart from ozonesonde measurements at the most southern limit of South America, it is the only ozonesonde station in the 45°-65°S latitude range. Ozonesonde measurements from Macquarie Island provide ozone altitude profile information that is essential for documenting the structure and variability of stratospheric ozone over the Southern Ocean and have direct relevance to atmospheric chemical and climate change models. It is also an important source of validation for global ozone profiling satellite instruments since measurements from space are unable to provide reliable ozone estimates for altitudes below approximately 15 km (*WMO Report No. 44*, 1998). Also, because surface UV-B radiation exposure is closely related to variations of stratospheric ozone, both on long and short timescales, an improved knowledge and understanding of variations of stratospheric ozone will help to understand variations of UV-B radiation. In addition to the ozone data, the high vertical resolution of wind and temperature measurements, to altitudes often in excess of 35 km, has enabled studies of inertia-gravity waves (Guest et al. 2000). Most importantly, modelling results indicate that ozone measured in the southern mid-latitudes will provide the first stable indicator of global ozone recovery (Weatherhead et al. 2000), and therefore accurate ozone altitude profile measurements will provide an invaluable data record for the future.

Apart from a short measurement campaign by the Commonwealth Scientific and Industrial Research Organisation in August 1970, no historical ozonesonde records exist for Macquarie Island, and it was not until December 1993 that a substantial ozonesonde program was undertaken in collaboration with the NASA/NOAA Airborne Southern

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Hemisphere Ozone Experiment (*WMO Report No. 44,* 1998). Although this program ended in December 1994, it provided an appraisal of the feasibility of installing a long-term routine ozonesonde program at Macquarie Island. In late November 1996 the ozonesonde program was recommenced under funding from the Bureau of Meteorology, the Australian Cooperative Research Centre for Southern Hemisphere Meteorology, and the Antarctic Science Advisory Committee. Although this joint funding ended in June 2000, the program has been continuously and solely supported since then by the Bureau of Meteorology.

Ozonesonde launches from Macquarie Island have been carried out generally at a frequency of one flight per week. However, because of funding limitations, occasional two-week gaps in the data record result from flight failures that are not supported by repeat flights. The ECC chemical cell type and the Vaisala data acquisition system were adopted as a generally more reliable and accurate system than the Brewer-Mast ozonesonde equipment used in Australia prior to 1990.

Data analysis

The prime concern in performing a climatological analysis of a data sample is that the sample is large enough to statistically represent all the dominant physical processes that contribute to the observed variate (e.g. Zwiers 1990). In the case where a data sample is not of sufficient size, estimates of the mean may not be stable from sample to sample within the estimated range of uncertainty of the mean. This is indicated by significant non-zero lags in serial correlation across the data sample (Solow 1985). A quantitative estimation of the degree of statistical stationarity of the Macquarie Island ozonesonde data record sample against the dominant signal components in ozone would involve statistical modelling, the outcome of which would be highly uncertain because of the comparative shortness of the time series (Weatherhead et al. 2000). An appraisal of ozone profile climatological uncertainties using statistical modelling was therefore considered beyond the scope of this paper.

The effect of solar variability on the ozone profile over any period is comparatively small at high mid-latitudes (Bojkov and Fioletov 1998) and is therefore of no concern to this climatology analysis. However the current Macquarie Island ozonesonde dataset spans approximately two periods of the quasi-biennial oscillation (mean period ~2.3 years; Bowman 1989), the dominant interannual signal in stratospheric ozone in the southern high mid-latitudes (Lehmann et al. 1992b). It is therefore not possible to argue that this time series is statistically stationary in regard to interannual variability as is ideally required in the determination of a climatological mean. This problem cannot be simply removed by increasing the period of the Macquarie Island ozonesonde record, because a possible negative trend in stratospheric ozone may exist over the sample period (Lehmann et al. 1992a, 1992b), the effect of which may increase as the sample period is increased. This trend is associated with a possible chemically induced ozone loss over Macquarie Island (Lehmann et al. 1992b, Lehmann 1994) that may be comparable in magnitude to the effect of the quasi-biennial oscillation. In view of this, the results presented below must be considered preliminary.

Quality control of the Macquarie Island ozonesonde data for the purpose of deriving a climatology involved screening data against: (a) extreme departures between the integrated ozone profile and total ozone measured by the Macquarie Island Dobson spectrophotometer; (b) extreme values of ozone change with altitude; and (c) ozonesonde balloons that burst at altitudes above which the approximate assumption of constant ozone mixing ratios could not be made. Both (a) and (b) were determined by identifying outliers that departed from the means in excess of the 99 per cent confidence limits, and in (b), the means and confidence limits were determined as a function of altitude.

The climatological ozone means and 95 per cent confidence limits were calculated as a function of altitude (1/3 km resolution), potential temperature and season (monthly resolution) in both ozone partial pressures and ozone mixing ratios. Choice of a one-month period for the seasonal resolution was based on an appraisal of the resolution of apparent structural features in the climatologies and stability in the monthly means compared to longer-period means.

In any given ozonesonde flight data record, data is terminated at a maximum altitude either because the balloon bursts or because the data fails to satisfy some data acceptance criterion. A plot of the distribution of altitudes of data termination, for the period 1994-2000, is given in Fig. 1. This distribution was assumed to be approximately valid for any month of the year for the climatological analysis presented here, even though some seasonal dependence may in fact exist. Such seasonal dependence could not be reliably estimated with the current data record. Inspection of Fig. 1 indicates the peak in the distribution to be close to 35 km, above which altitude the number of ozone profiles that contribute to the climatological mean decrease most rapidly. Above 29 km, uncertainty in the monthly mean ozone increases progressively with altitude, the greatest uncertainty

Fig. 1 **Distribution of termination altitudes of Macquarie Island ozonesonde flight data for the period 1994-2000.**

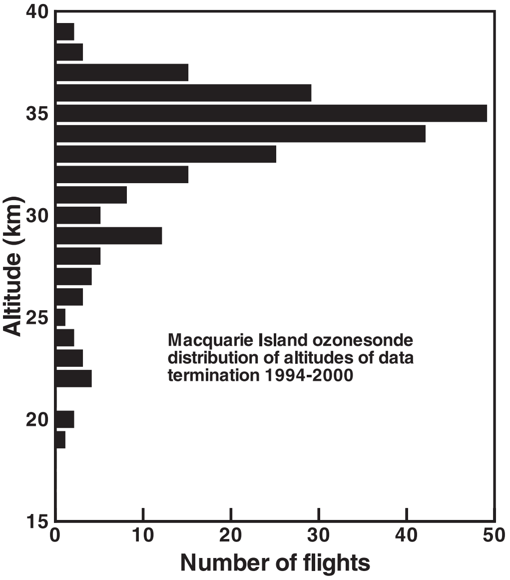


Fig. 2(a) **Monthly mean ozone partial pressure (mPa, solid) superimposed on monthly 95 per cent confidence intervals of ozone partial pressure (mPa, contour shaded).**

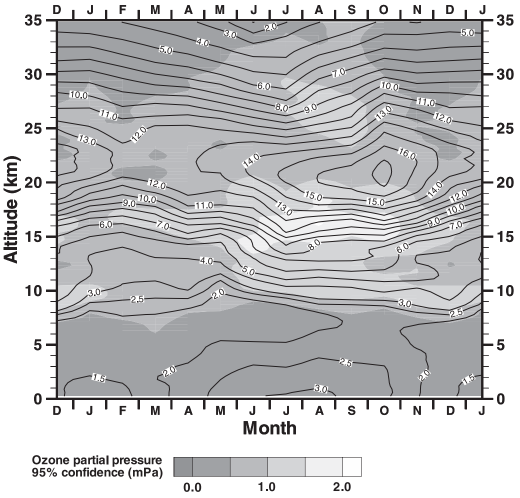
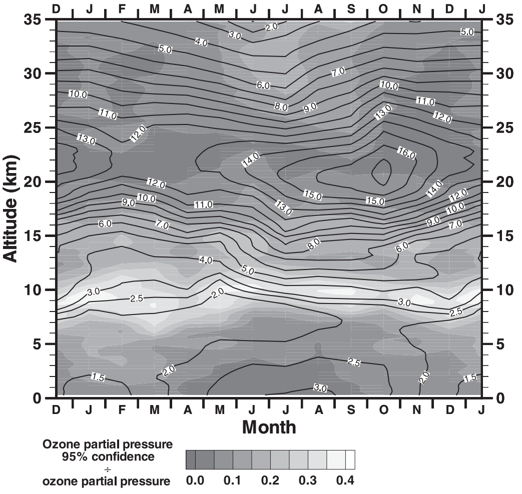


Fig. 2(b) **Monthly mean ozone partial pressure (mPa, solid) superimposed on fractional monthly 95 per cent confidence intervals of ozone partial pressure (contour shaded).**



occurring above the median altitude of the distribution in Fig. 1. For this reason the present climatology analysis was restricted to altitudes below 35 km.

The upper and lower 95 per cent confidence limits of the climatology means were computed using a bootstrap algorithm (Efron 1979, 1987). Because the resultant distributions of the mean for each month and altitude were approximately symmetrical, the magnitude of the upper and lower 95 per cent confidence limits were averaged.

Figures 2 and 3 show contour plots of the monthly climatological mean ozone partial pressures (mPa) and mixing ratios (ppmv), respectively. These have been plotted over the 95 per cent and fractional 95 per cent confidence intervals in Figs 2(a), 3(a) and 2(b), 3(b), respectively. The confidence interval shaded contour plots depict the variability about mean values. Some smoothing has been applied to the contour plots to reduce irregularities that are small compared to the 95 per cent uncertainties.

The ozone mixing ratio has been graphed against potential temperature in the vertical direction in Fig. 4. Because ozone mixing ratio is a quasi-conserved quantity (Brasseur and Solomon 1984), Fig. 4 effectively indicates time-averaged sources and sinks of stratospheric ozone. The use of potential temperature as the ordinate effectively removes the effects of vertical atmospheric motion for the ozone mixing ratio (Brasseur and Solomon 1984) and it provides a general description of the seasonal variability of the monthly mean ozone profile associated with horizontal transport.

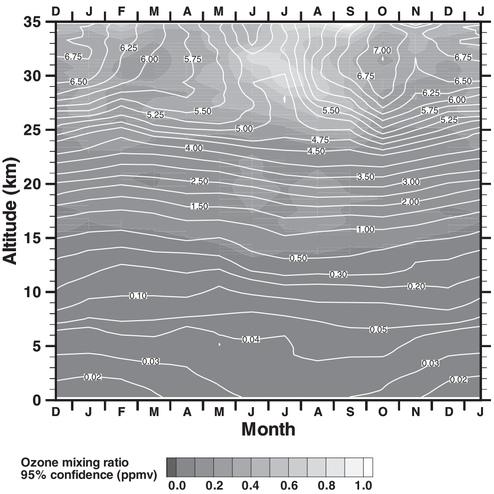


Fig. 3(a) Monthly mean ozone mixing ratio (ppmv, solid) superimposed on monthly 95 per cent confidence intervals of ozone mixing ratio (ppmv, contour shaded).

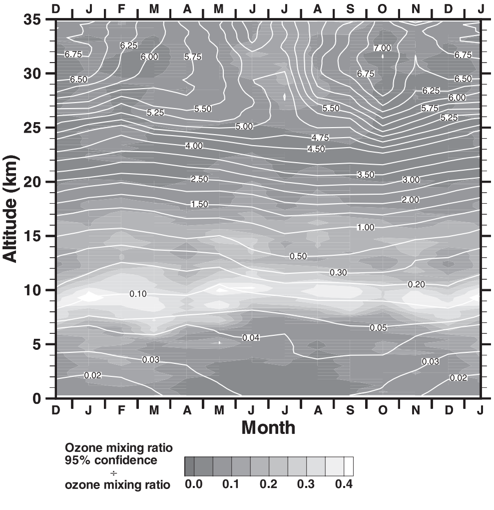


Fig. 3(b) Monthly mean ozone mixing ratio (ppmv, solid) superimposed on fractional monthly 95 per cent confidence intervals of ozone mixing ratio (contour shaded).

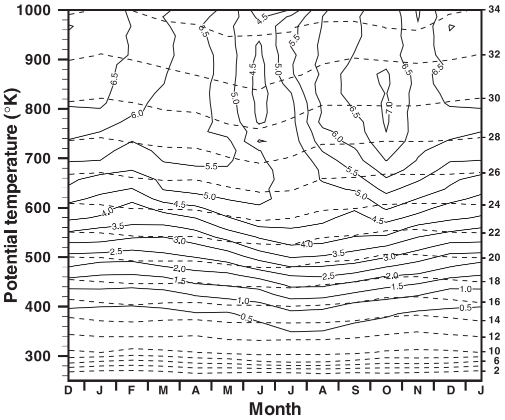


Fig. 4 Monthly mean ozone mixing ratio (ppmv, solid) and monthly mean altitude (km, dashed) as a function of month and potential temperature.

Discussion

The most dominant dynamical influence on stratospheric ozone variations in mid-latitudes results from the transport of ozone from the tropics via the upper stratosphere. Here the vertical propagation of planetary waves, and their dissipation, induces a poleward and descending atmospheric circulation over the course of the winter. These waves irreversibly 'break' (Salby and Garcia 1990), and can facilitate poleward transport of ozone only when planetary wave propagation into the stratosphere is permitted by the prevalence of westerly winds that do not exceed a critical speed (Plumb 1989; Andrews et al. 1987). Above this critical wind speed, vertical penetration of planetary waves into the stratosphere, and therefore meridional transport, is impeded. As a result, two periods of maximum ozone transport occur in the southern hemisphere in May and September-October (Hirota et al. 1983; Geller et al. 1989; Randel 1988). However, because the quasi-biennial oscillation controls the propagation of waves and ozone transport closer to the tropics (Bowman 1989), this ozone maximum is interannually modulated depending on the phase of the quasi-biennial oscillation during spring.

A dominant feature apparent in the ozone partial pressure and ozone mixing ratio plots of Figs 2(a), 2(b) and 3(a), 3(b), respectively, is the maximum in stratospheric ozone in September-October. This is consistent with the timing of the maxima observed in the 50 hPa (approximately 20 km in altitude at Macquarie Island) climatological stationary and transient wave heat flux (Randel and Newman 1998). It is also consistent with the control of meridional transport from the tropics by zonal wind speed, as mentioned above, in conjunction with the modulation of ozone transport from year to year by the quasi-biennial oscillation during the period of maximum ozone transport (Bowman 1989). Both the timing and the interannual modulation of the September-October ozone maximum are evident in the historical total ozone records from Macquarie Island (Lehmann et al. 1992a, 1992b) and in the calculated 475K transient eddy heat flux (Lehmann et al. 1992b). An ozone maximum in May is not evident in the climatology plots, though it is possible this feature is no longer apparent due to southern hemisphere winter ozone loss since the 1970s (Lehmann et al. 1992a).

A maximum in tropospheric ozone partial pressure or concentration/density appears during July-August (Figs 2(a),(b)). The cause of this maximum is unclear.

Conclusion

A climatological study has been presented that provides an estimation of the average seasonal variation of the ozone profile over Macquarie Island. The analyses presented in this paper must be considered preliminary in that further extension of the climatological averaging period may significantly alter aspects of the results. The September-October stratospheric maximum in ozone is consistent with current understanding of the physics of atmospheric dynamics.

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