A seasonal climatology of the Melbourne 1965-1975 ozonesonde record

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A seasonal climatology of the 1965-1975 Melbourne ozonesonde ozone profile record is presented, spanning a period when minimal stratospheric ozone chemical depletion existed and prior to adequate satellite ozone profiling. Results are presented as monthly isentropic weighted means of ozone mixing ratio and partial pressure, with associated uncertainties, plotted against potential temperature and altitude. Corrections for pump inefficiency and referencing to the current ozonesonde type are included. The general seasonal and altitudinal features of the results are consistent with our current understanding of ozone variations in the southern mid-latitudes. These results are of value to atmospheric chemical and climate change models.

1. Introduction

The Melbourne ozonesonde station (37.814° S,144.963° E) is situated in a data-sparse geographic region and has provided a unique and valuable record of southern mid-latitude ozone profiles since 1965, when it was first located at suburban Aspendale (38.024° S, 145.118° E). Following a change in management in the early 1980s, the station was moved at different times in the Melbourne area (Lehmann and Easson 2003). The value of the Melbourne ozonesonde record is indicated by the results of others that show the most stable indicators of ozone recovery will be obtained by ozone measurements in the southern mid-latitudes (Weatherhead et al. 2000). Melbourne ozonesonde data has been generally available internationally via the World Ozone and Ultraviolet Data Center (Toronto, Canada).

The present study was undertaken to estimate a historical climatology of the seasonal change in the mean vertical ozone profile in order to provide a reference against which later changes in the ozone profile may be compared, and as a resource for atmospheric chemical and climate change models. Of particular concern to the latter is the ability to estimate historical atmospheric vertical infrared radiative transfer for the southern hemisphere.

The original (1965-1992) Australian ozonesonde system was the Brewer-Mast (BM) ozonesonde (Brewer and Milford 1960, Lehmann and Easson 2003) combined with the Philips radiosonde. In 1993 the Electrochemical Concentration Cell (ECC) type ozonesonde, combined with the Vaisala radiosonde and data acquisition system, replaced the original BM system (Lehmann and Easson 2003). Because concerns exist (Lehmann and Easson, 2003) regarding intercomparison of the Australian BM measurements with historic BM data from other agencies, corrections were applied that referenced the Melbourne BM measurements to the ECC ozonesonde according to Lehmann, 2005.

For both the BM and ECC Melbourne ozonesonde programs, launches from Melbourne have been generally carried out at a frequency of one flight per week, though repeat flights covering ozonesonde failure have not always been supported because of funding limitations. As a result, frequent gaps exist in the data record due to flight or equipment failures. Of particular note here is the appreciable reduction in frequency of Melbourne ozonesonde flights after 1975 that imposed an upper limit to the time period of the present climatological study. However, because of the probable onset of significant anthropogenic chemical ozone depletion in the mid to late 1970s (Bojkov and Fioletov 1998), inclusion of data after 1975 was probably not justified, and so this 1975 limit on data availability was fortunately of little concern. Similarly, inclusion of ozonesonde data from prior to 1965 into this climatology, had it been available, would not have

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been an advantage because of residual chemical effects on stratospheric ozone from southern hemisphere atmospheric nuclear tests prior to 1963 (e.g. Whitten et al. 1975). It was therefore fortuitous that the available 1965-1975 Melbourne ozonesonde climatological data avoided periods of probable significant anthropogenic stratospheric ozone loss.

2. Data Analysis

The present climatology was constructed from the isentropic monthly means of ozone mixing ratios between 300-800 K potential temperature levels, in 5 K intervals, over the period 1965-1975. Because the natural variability of ozone in a given month changes from year to year due to changing atmospheric dynamical influence, the variance of ozone in a particular month changes from year to year. Therefore, for a given month, the individual monthly means covering the climatology period should not be considered as samples from the same statistical process, and should not be simply averaged. Therefore ideally the climatological average for a given month should be created by a weighted average (Press et al. 1992) of monthly means from the individual years, with the weighting being the inverse monthly variance. Because generally a maximum of four (occasionally greater) ozonesondes were flown per month, any estimate of monthly variance from these samples would be unreliable, and therefore the weighted isentropic mean could not be used, and all observations from all the years in a given month were simply interpolated at the set isentropic altitude levels and averaged. This effectively assumes for a given month that the means have the same variance irrespective of the year, and this may have increased the error of the computed final climatology.

Of prime concern in carrying out a climatological analysis is that the data sample is sufficiently large to be statistically representative of all the dominant physical processes that contribute to the observed variate (e.g. Zwiers 1990). With the dominant interannual signal in stratospheric ozone in the southern mid-latitudes being the Quasi-Biennial Oscillation (QBO, Bowman 1989), the mean period of which is approximately 2.3 years, the 1965-1975 seasonal climatology sample only covered approximately five QBO cycles, resulting in the stationarity of the data sample being questionable. Also, it would seem fortunate that the 1965-1975 sample period is approximately one solar cycle, facilitating first order removal of solar bias from the climatology by averaging. However, the ozone solar variability component in stratospheric ozone is relatively small (Bojkov and Fioletov 1998).

When a data sample is not of sufficient size (e.g. Weatherhead et a1. 2000), estimates of the mean may be unstable from sample to sample within the estimated range of uncertainty of the mean, and this is indicated by significant non-zero lags in serial correlation across the data sample (Solow 1985). For this eleven-year climatological time series, in any given month it can be shown that the 2-sigma autocorrelation uncertainty will be greater than 0.5 for correlations less than about 0.65, rendering an autocorrelation stationarity test useless. Instead, the sample period was simply divided into two and monthly weighted means at each potential temperature level were computed for the two periods and compared with that of the overall period 1965-1975. Figure 1 shows the results of this with the seasonal-altitude (potential temperature) ozone mixing ratio distributions for the epochs 1965-1969, 1970-1975, and 1965-1975. The selected and total number of flights per month over the period 1965-1975 is indicated below the distribution plots. Stationarity of the 1965-1975 climatology distribution is indicated by the general pattern of consistency between the three seasonal distributions, implying averaging the ozone distributions for the 1965-1969 and 1970-1975 epochs would provide an improved distribution estimate, although greatest consistency appears between 400 K and 650 K. This was reinforced by paired t-tests of the potential temperature differences between the two periods across the season along constant ozone mixing ratio contours (Figure 1). Because the test statistic falls below the $\alpha = 0.05$ critical value of 2.201 (eleven degrees of freedom), except at the higher ozone mixing ratio levels above approximately 5ppmv, it appears reasonable to accept the null hypothesis that the twelve-month mean potential temperature differences are not significantly different from zero in the majority of chosen ozone mixing ratio contours indicated in Figure 1.

An increased divergence between the 1965-1969 and 1970-1975 monthly means apparent above about 650 K (~26 km), was possibly due to the lower number of samples contributing to the means at these altitudes (shown on the right in Figure 1). Because stratospheric stability is expected to increase with altitude as photochemistry becomes more dominant over the influence of dynamics (Brasseur and Solomon 1984), non-stationary process were considered less likely for the increased discrepancy above 650 K.

Quality control of the Melbourne 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 Melbourne Dobson spectrophotometer; (b) ozonesonde balloons that burst at altitudes above which the approximate assumption of constant ozone mixing ratio could be unacceptably inaccurate. In (a), because the integrated ozonesonde profile should ideally equal the total column ozone measured by a Dobson spectrophotometer, and because the stability of the spectrophotometer measurements was higher than that of the ozonesonde (Lehmann and Easson 2003), the integrated ozonesonde profile was normalized to the total column ozone by multiplying the ozonesonde profile by the ratio:

γ = (Dobson total column ozone)/(integrated profile ozone), e.g. Attmannspacher and Dütsch 1970. The total ozone correction factors γ used for the BM were screened according to $1.0 \leq \gamma \leq 1.32$. This range was similar to that adopted by Logan (1994) and, Logan (1994) and Veiga (1995), and estimated using a minimum variance optimization method similar to that of Lehmann 2005. In (b), ozonesonde data for flights that failed to exceed the altitude of peak ozone concentration (maximum ozone partial pressure), and above which the ozone mixing ratio was assumed to be approximately constant, were rejected. Comparison of the combined (a) and (b) selected flight numbers with the unfiltered total are given in Figure 1.

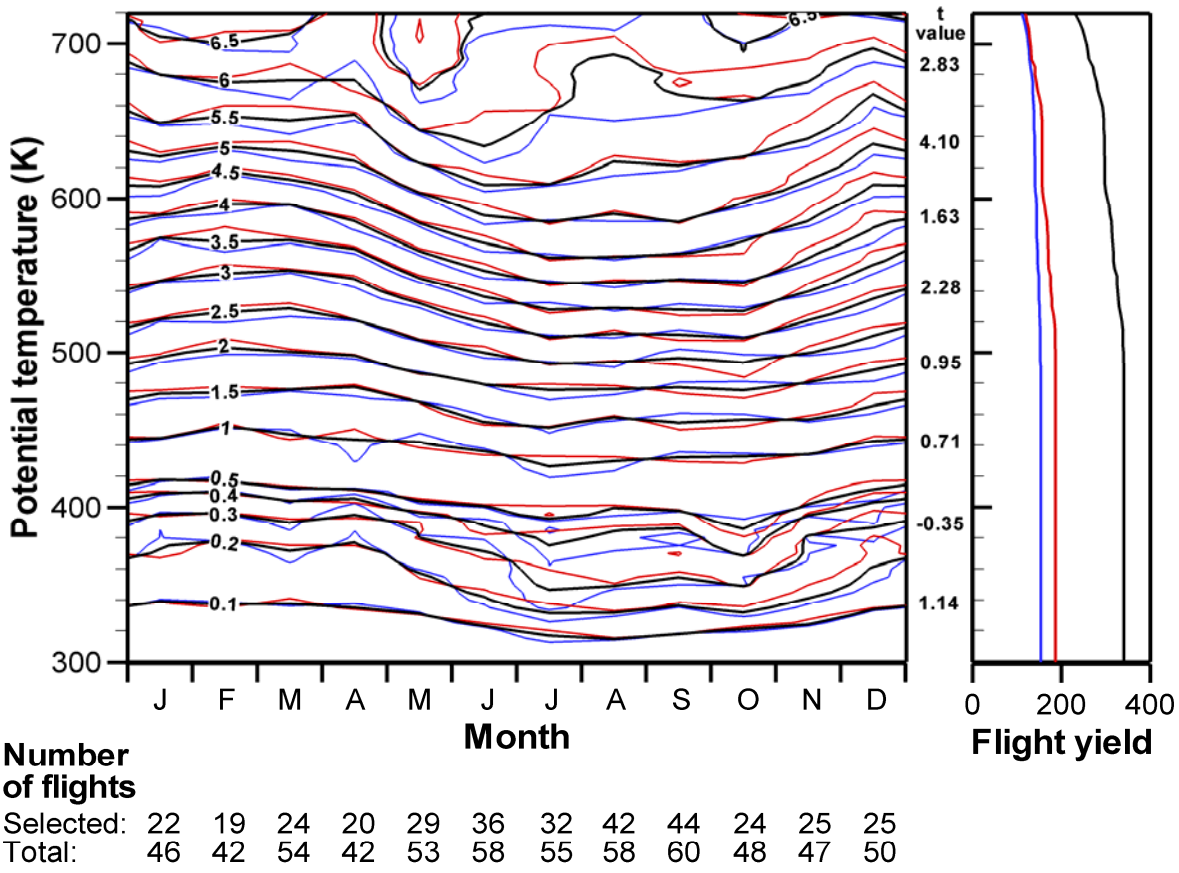

Figure 1 Comparison of (left) seasonal variation of weighted-mean volumetric ozone mixing ratios (ppmv) for the epochs 1965-1975 (black), 1965-1969 (blue), and 1970-1975 (red) as a function of potential temperature with the selected and total number of flights per month for 1965-1975, and (right) the number of flights that reach a given potential temperature during the climatology period 1965-1975. Paired t-test parameters of mean potential temperature differences between the two epochs are indicated in the vertical column between plots adjacent to the associated constant mixing ratio contour.

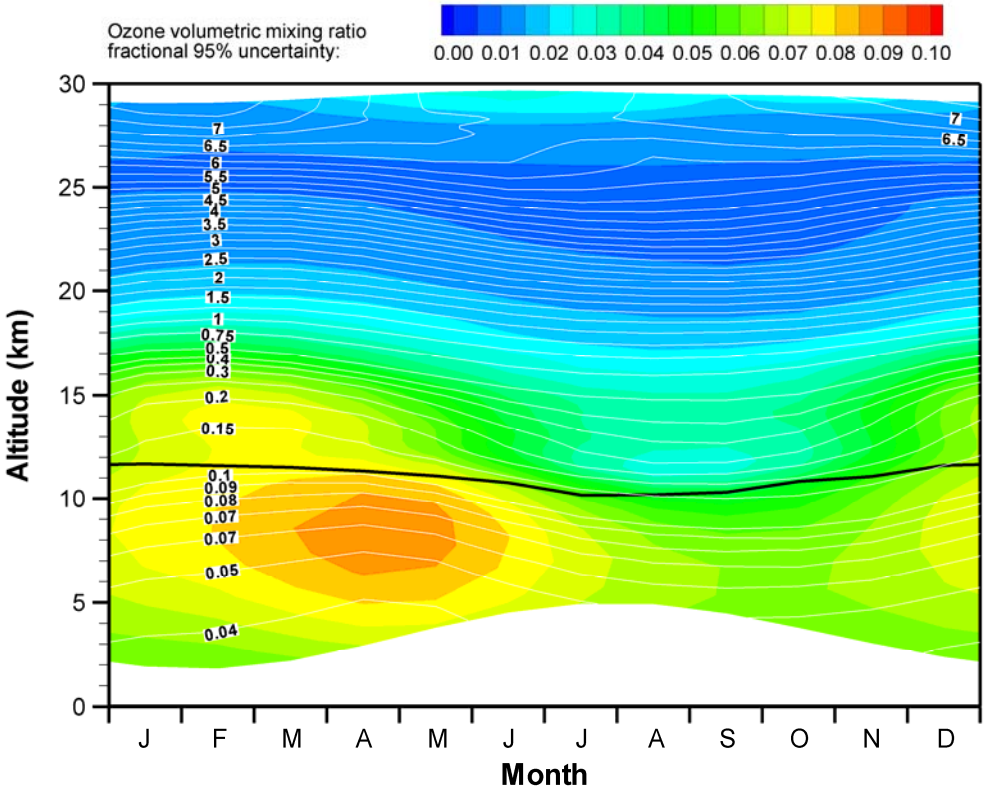

Figure 2 Seasonal climatology of Melbourne ozonesonde ozone volumetric mixing ratio (ppmv) as a function of altitude (km). Black solid lines join 1965-1975 radiosonde monthly mean thermal tropopause heights.

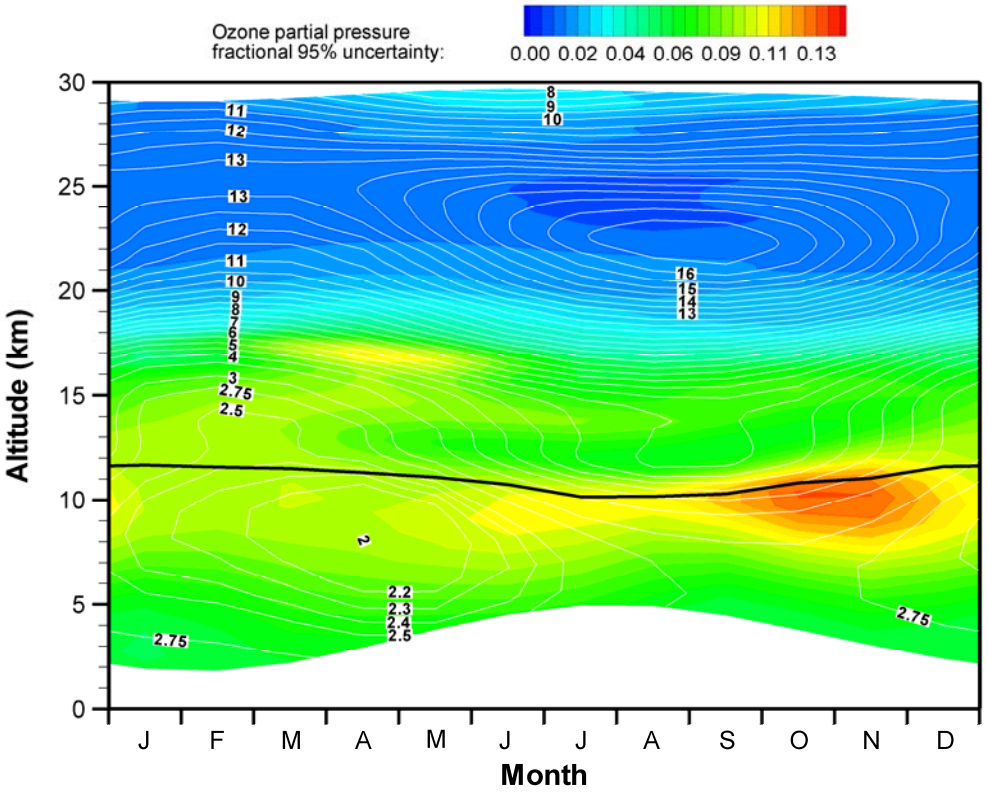

Figure 3 Seasonal climatology of Melbourne ozonesonde ozone partial pressure (mPa) as a function of altitude (km). Tropopause heights depicted as in Figure 2.

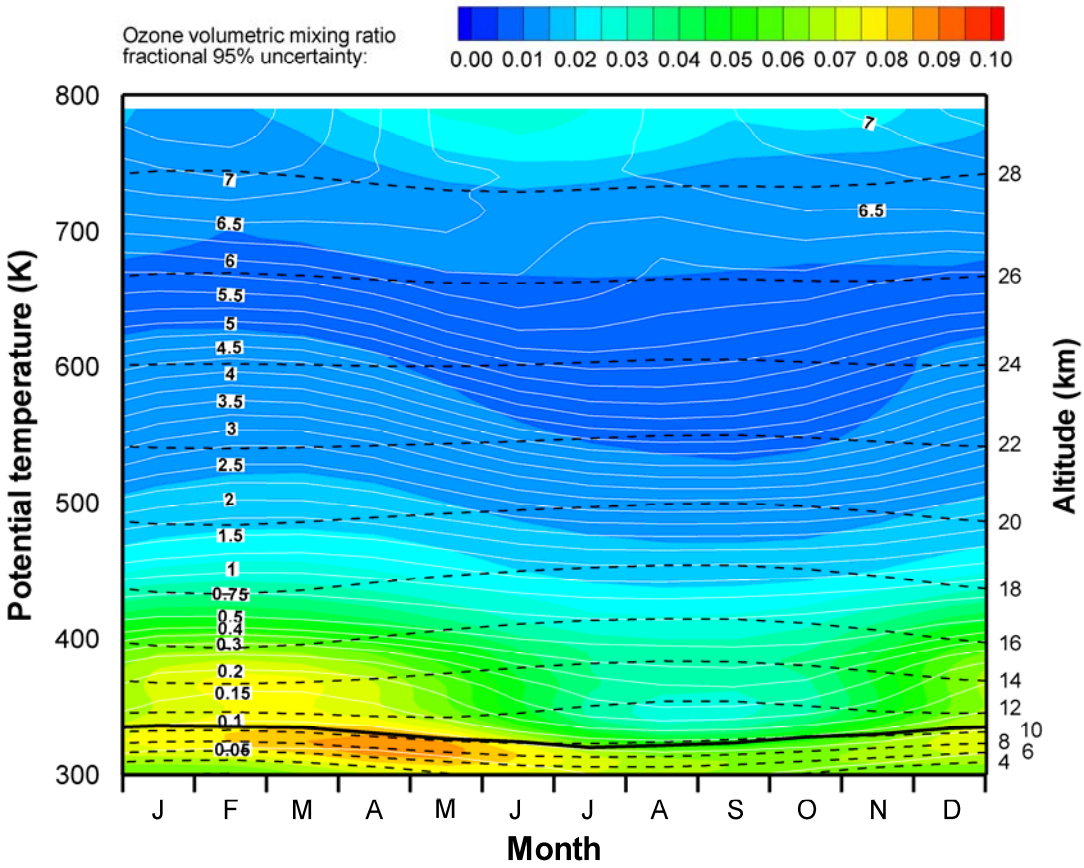

Figure 4 Seasonal climatology of Melbourne ozonesonde ozone mixing ratio (ppmv) as a function of potential temperature (K). Black solid/dashed lines contour tropopause/altitude.

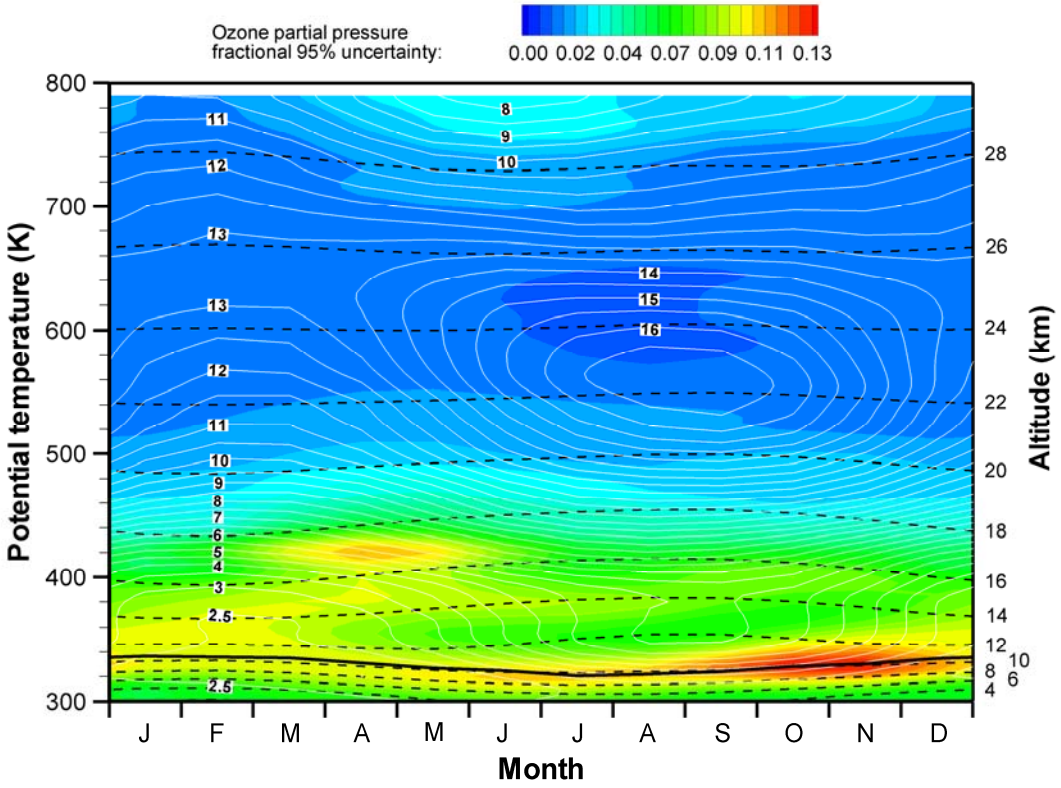

Figure 5 Seasonal climatology of Melbourne ozonesonde ozone partial pressure (mPa) as a function of potential temperature (K). Black solid/dashed lines contour tropopause/altitude.

The Melbourne BM ozone profiles as retrieved from the World Ozone and Ultraviolet Radiation Data Centre (WOUDC, www.woudc.org) were extrapolated above the maximum flight altitude assuming a constant ozone mixing ratio since knowledge of ozone above these levels for 1965-1975 was not available. Pump efficiency corrections (Dütsch 1966) were applied in accordance with the results of Lehmann and Easson 2003 and the resultant integrated ozone profiles were individually factored to agree with the corresponding Melbourne Dobson total ozone measurement (WOUDC). Additive corrections (Lehmann 2005) were then applied to compensate for the altitude-dependent differences between the Australian BM and ECC ozone vertical profiles.

The data acquisition method utilized by the Australian BM ozonesonde resulted in unreliable temperature profile measurements. Temperature data used to compute potential temperature was therefore obtained from radiosonde flights (Australian Bureau of Meteorology data archive) separated by four-five hours from the time of the ozonesonde launch, the assumption being that ozone profile changes are comparatively small over this period.

The climatological ozone monthly-weighted means and associated 95 percent confidence limits were calculated as a function of altitude, potential temperature, and season in both ozone partial pressure and ozone volumetric mixing ratio using a bootstrap algorithm (Efron 1987). Because the resultant distributions of the ozone mixing ratio mean for each month and altitude were approximately symmetrical, the magnitudes of the upper and lower 95 percent confidence limits were averaged.

Figures 2 and 3 show altitude (km) contour plots of the monthly climatological mean ozone mixing ratios (ppmv) and partial pressures (mPa), respectively. These have been plotted over their respective fractional 95 percent uncertainty contours. Figures 4 and 5 similarly show the same plots with potential temperature (K) as the vertical axis. With the premise that the seasonal climatology of the present analysis was slowly varying in both season and altitude compared to superimposed uncorrelated noise, a 5x5 point filter was applied to all Figures 2-5 according to the method of Savitzky-Golay (Savitzky and Golay 1964, Press et al. 1992). The first three rows and columns of this filter utilized the weighting coefficients (-0.0743, 0.0114, 0.0400, 0.0114, -0.0743), (0.0114, 0.0971, 0.1257, 0.0971, 0.0114), and (0.0400, 0.1257, 0.1543, 0.1257, 0.0400), the remaining two rows/columns being a reflection of the first two about the centre (third element). The time (horizontal) and potential temperature/height (vertical) intervals between filtering elements was 1 month and 5K (~0.3km to ~1km), respectively. This method was designed to reduce the level of noise while minimising smoothing-induced bias. Careful inspection of these figures against the original unfiltered data revealed that the range of amplitude variation of the contours had not been significantly compromised by the filtering process.

Because ozone mixing ratio is a quasi-conserved quantity (Salby 1996, Brasseur and Solomon 1984), Figure 4 effectively indicates time-averaged sources and sinks of stratospheric ozone. The use of potential temperature as the (isentropic) ordinate effectively removes the effects of vertical atmospheric motion (Salby 1996) for the ozone mixing ratio and it provides a general description of the seasonal variability of the monthly mean ozone profile associated with horizontal transport. The ozone partial pressure climatology shown in Figures 3 and 5 were computed from the isentropic average of ozone mixing ratios using the isentropic average atmospheric pressure, and were therefore also independent of vertical motion over the 1965-1975 averaging period.

3. Discussion

The most dominant dynamical influence on stratospheric ozone variation 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.

The seasonal modulation in meridional ozone transport results in a peak in the observed seasonal variation of total ozone in August-September, and this is evident in the ozone vertical profile partial pressure climatology of Figure 4. This effect is also consistent with the timing of the maxima observed in climatological 100hPa transient wave heat flux for Melbourne over the same period, and also the control of meridional transport from the tropics by zonal wind speed coupled with interannual modulation of ozone transport by the quasi-biennial oscillation during the period of maximum ozone transport (Bowman 1989). Both the timing and the interannual modulation of the August-September ozone maximum are evident in the historical total ozone record for Melbourne. The maximum in tropospheric ozone evident in Figure 4 may be attributed to the combined effects of enhanced meridional ozone transport and enhanced stratosphere to troposphere ozone exchange during the August-September period of increased stratospheric planetary wave activity.

A recent analysis (Tully et al. 2015) of sources of variability in Melbourne's Dobson spectrophotometer total ozone record for the period 1978-2012 appraised ozone-forcing parameters of relevance to the above discussion, albeit spanning a different period to that of the present analysis when their proportional influence may have been different. The present climatology data may be obtained from the corresponding author.

4. Conclusion

A climatological study has been presented that provides an estimation of the mean seasonal variation of the ozone profile over Melbourne (Aspendale) during the period 1965-1975 when stratospheric ozone depletion due to anthropogenic trace gases was considered to be minimal. Two sets of statistically similar results were found when the data was split into the two periods 1965-1969 and 1970-1975 and analysed, providing some confidence in the statistical stationarity of the 1965-1975 analysis. The results have been referenced to current ECC ozonesonde and are therefore useful for comparative studies of ozone change since historic times and for models that require an estimate of the seasonal profile variation of southern midlatitude ozone in pre-ozone depletion times.

Acknowledgements

Melbourne ozonesonde data has been generally available internationally via the World Ozone and Ultraviolet Data Center (https://www.ec.gc.ca/air-sc-r/default.asp?lang=En&n=5E7C0D28-1, Toronto, Canada). Melbourne temperature profile data was obtained via the Australian Bureau of Meteorology METARS radiosonde records. (http://web.bom.gov.au/cob/ncc/srds/index.shtml).

References

Andrews D.G., Holton J.R. and Leovy C.B. (1987). Middle Atmosphere Dynamics. Intern. *Geophys*. Series **40**, Academic Press: Orlando.

Attmannspache W. and Dütsch H.U. (1970). International ozone sonde intercomparison at the observatory Hohenpeisenberg. *Ber. Deutsche. Wetterdienst* **120**: 1-85.

Bojkov R.D. and Fioletov V. (1998). Latitudinal and regional total ozone trends from quality controlled ground-based data, in Atmospheric Ozone. Bojkov R.D., Visconti G. (eds). *Proceedings of the XVIII Quadrennial Ozone Symposium, LAquila, Italy 12-21 September 1996: pp. 13-16.*

Brasseur G. and Solomon S. (1984). Aeronomy of the Middle Atmosphere. D. Reidel Pub. Co.: Dordrecht, Holland.

Brewer A.W., Milford J.R., 1960. The Oxford-Kew ozone sonde. *Proc. Roy. Soc. London* **256**: 470-495.

Bowman K.P. (1989). Global patterns of the quasi-biennial oscillation in total ozone. *J. Atmos. Sci.* **46**: 3328-3343.

Dütsch H.U. (1966). Two years of regular ozone soundings over Boulder Colorado. *Rep. **10.**, NCAR*: 55 pp.

Efron B. (1987). Better bootstrap confidence intervals. *J. Amer. Stat. Assoc.* **82**: 171-185.

Lehmann P. and Easson J.R. (2003). A comparison of pump efficiency corrections for the Australian Brewer-Mast ozonesonde data record. *Aust. Met. Mag.* **52**: 259-264.

Lehmann P. (2005). An estimate of the vertical ozone profile discrepancy between the Australian Brewer-Mast and Electrochemical Concentration Cell ozonesondes. *J. Atmos. Oceanic Tech.* **22**: 1864-1874.

Logan J.A. (1994). Trends in the vertical distribution of ozone: An analysis of ozonesonde data. *J. Geophys. Res.* **99**: 25553-25585.

Plumb R.A. (1989). On the seasonal cycle of stratospheric planetary waves. *Pure Appl. Geophys.* **130**: 233-242.

Press W.H., Flannery B.P., Teukolsky S.A. and Vetterling W.T. (1992). Savitzky-Golay smoothing filters. Numerical Recipes: The Art of Scientific Computing. Cambridge University Press, New York, NY: 644-649.

Savitzky A. and Golay M.J.E. (1964). Smoothing and differentiation of data by simplified least squares procedures. *Analytical Chemistry* **36**: 1627–1639.

Solow A.R. (1985). Bootstrapping correlated data. *Math. Geol*. **17**: 769-775.

Salby M.L. and Garcia R.R. (1990). Dynamical perturbations to the ozone layer. *Physics Today* **43**: 38-46.

Salby M.L. (1996). *Fundamentals of atmospheric physics,* Dmowska, R. and Holton, J.R. (eds). International Geophysics Series, Vol. 61, Academic Press: San Diego, California.

Solow A.R. (1985). Bootstrapping correlated data. *Math. Geol*. **17**: 769-775.

Tully M.B., Klekociuk A.R. and Rhodes S.K. (2015). Trends and Variability in Total Ozone from a Mid-Latitude Southern Hemisphere site: The Melbourne Dobson Record 1978-2012. *Atmosphere-Ocean* **53**: 58-65.

Veiga R.E., Cunnold D.M., Chu W.P. and McCormick M.P. (1995). Stratospheric Aerosol and Gas Experiments I and II: Comparisons with ozonesondes. *J. Geophys. Res.* **100**: 9073-9090.

Weatherhead E.C., Reinsel G.C., Tiao G.C., Jackman C.H., Fleming E.L., Bishop L., DeLuisi J., Keller T., Herman J., McPeters R., Hollandsworth-Frith S., Oltmans S.J., Wuebbles D.J., Kerr J.B., Miller A.J., Nagatani R.M. and Frederick J.E. (2000). Detecting the recovery of total column ozone. *J. Geophys. Res.* **105**: D17: 22201-22210.

Whitten R.C., Borucki W.J. and Turco R.P. (1975). Possible ozone depletions following nuclear explosions. *Nature* **257**: 38-39.

Zwiers F.W. (1990). The effect of serial correlation on statistical inferences made with resampling procedures. *J. Climate* **3**: 1452-1461.