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A comparison of pump efficiency corrections for the Australian Brewer-Mast ozonesonde data record

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The Brewer-Mast (BM) ozonesonde has been used in Australia for measuring the profile of atmospheric ozone to above the middle stratosphere from the mid-1960s to 1990. An important experimental parameter in the interpretation of the measured ozone profiles is the pump efficiency correction. An analysis is presented here that tests two different pump corrections by comparison with SAGE II ozone satellite data. Results indicate that the Dütsch pump efficiency correction produces adjustments to these BM ozonesonde profiles that are in better quantitative agreement with the SAGE II satellite data.

Introduction

The Brewer-Mast (BM) ozonesonde evolved from balloon-borne sondes, originally developed by Brewer and Milford (1960) to measure the variation of atmospheric ozone with altitude. They have been commercially produced since the late 1960s by the Mast Development Company, Iowa, and were extensively used during the 1970s and 1980s for vertical ozone profiling (Angell and Korshover 1983; Logan 1994). The BM ozonesonde, as well as the improved electrochemical cell (ECC; Komhyr 1969) ozonesonde, are still important instruments for stratospheric ozone measurements and remain the main source of tropospheric ozone data. This is despite the fact that there are now more sophisticated methods of measuring atmospheric ozone profiles, such as ground-based differential lidar (McDermid 1987; Carswell et al. 1991) and satellite profilers (Frederick et al. 1986; Mauldin et al. 1985).

The BM apparatus consists of a small electric piston pump, driven by a constant-speed motor, that forces the external air into an electrochemical cell. In this cell the reduction of ozone in an alkaline buffered potassium iodide solution produces an electric current between a silver anode and a platinum cathode that is then measured by electronics. In theory, with each ozone molecule that enters the solution, two electrons are released, whence the ozone partial pressure p_0 (mPa) is proportional to the cell current I (μA) (e.g., Claude et al. 1987). In the nomenclature of Steinbrecht et al. (1998):

$$p_0 = \alpha \frac{IT}{F} \qquad ...1$$

where T is the temperature (K) of air in the pump, F is the rate (ml s^{-1}) at which outside air is pumped through the cell, and $\alpha = 4.307 \times 10^{-6}$ (mPa ml) (μA°K s)$^{-1}$ is the proportionality constant.

The rate of flow F is measured prior to launch on the ground at surface atmospheric pressure p_0, and it is assumed that it remains approximately constant up to altitudes where the atmospheric pressure p decreas-

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es to about 150 hPa. Above these altitudes, a World Meteorological Organization (WMO) standard pump correction *K(p)* factor (Claude et. al. 1987) has been utilised to compensate for a reduced flow rate resulting from decreasing pump efficiency of the BM ozonesonde. The pump correction at pressure *p* is given by:

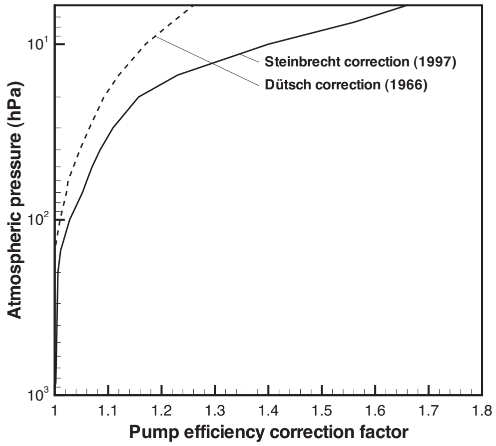
$$K(p) = \frac{F(p_0)}{F(p)} \qquad \text{...2}$$

It is evident from the definition of *K(p)* in Eqn 2 that the pump correction increases as the flow rate *F(p)* decreases with reducing pump efficiency, and this occurs as the atmospheric pressure decreases. However, the pump efficiency is also dependent on the temperature of the pump itself (Brewer and Milford 1960), and both the pump and chemical cell were enclosed in a thick polystyrene case in order to stabilise the internal temperature during flight.

The WMO standard pump correction *K(p)* for BM ozonesondes originated from measurements carried out by Komhyr and Harris (1965) and later developed by Dütsch (1966). This efficiency adjustment, hereafter referred to as the Dütsch pump efficiency correction, was applied to BM ozonesondes when pump efficiencies for individual ozonesonde were not determined. This procedure was still current in the WMO recommendations on measurement of ozone profiles published in 1987 (Claude et al. 1987). However, arguments exist suggesting the original estimates of the pump efficiency corrections may be inaccurate and revised values have been produced (Steinbrecht et al. 1998). The Steinbrecht pump corrections, derived primarily using laboratory pressure chamber measurements, and also satellite, lidar and ECC sonde data intercomparisons, are larger than those determined by Dütsch. The relative magnitude of the Dütsch and Steinbrecht pump correction factors is shown in Fig. 1.

A consequence of inaccuracy in the pump efficiency correction that is applied to measured ozonesonde profiles is that an erroneous ozone profile extrapolation results at altitudes above the burst altitude of the balloon. At these higher altitudes where ozone has not been measured by the ozonesonde, a model of either constant ozone mixing ratio or an appropriate ozone climatology is assumed to add on the residual ozone. It is clear that an error in the pump efficiency correction factor will result in error in the extrapolated ozone above the burst altitude, and, because the integrated ozone from the surface to the very top of the profile is known from ground-based instrument measurements, an error in the ozone profile at lower altitudes must result when the profile is re-scaled.

Fig. 1 **Plots of the Dütsch and Steinbrecht pump efficiency corrections as a function of atmospheric pressure.**



BM ozonesonde profiles were extracted from the World Ozone and Ultraviolet Radiation Data Centre (WOUDC), Canada. These had all been corrected for pump efficiency effects by the Dütsch correction, and scaled to an independently measured column ozone amount.

Similarly to Steinbrecht et al. (1998), where data from independent instruments were intercompared with the BM sonde data, the intent of the present paper is to compare Australian BM ozonesonde records with satellite data from the Stratospheric Aerosol and Gas Experiment II (SAGE II; Mauldin et al. 1985) Version 6.0 ozone dataset (Zawodny et al. 2000) in order to estimate the pump corrections. Steinbrecht et al. (1998) derived two pump corrections, one based on pressure chamber measurements and the other on independent instrumental measurements, namely SAGE II, lidar, HALogen Occultation Experiment (HALOE; Brühl et al. 1996), and ECC ozonesondes. Both corrections were reported to be similar (Steinbrecht et al. 1998).

Because the only independent instrumental data available for intercomparison with the Australian (Laverton; -37.9°S, 144.8°E) BM ozonesonde dataset were the SAGE II measurements, the results presented in this paper are restricted to a comparison with the second set of Steinbrecht pump corrections, i.e. those determined from measurements made by independent instruments. A statistical test is performed to appraise the applicability of the Steinbrecht and Dütsch pump corrections for the Laverton BM ozonesonde dataset for the period of the comparison.

Method of analysis

The period of comparison between the Australian BM ozonesonde and the SAGE II ozone profile data was constrained by the time of launch of the SAGE II NASA Earth Radiation Budget Satellite (ERBS) in October 1984 and the closing of the Australian BM ozonesonde program at the end of 1990. Insufficient quasi-simultaneous Laverton ozonesonde and SAGE I overpass measurements were available, over the lifetime of the earlier SAGE I (1979-81) ozone profiler, to include this period in this analysis.

The altitude resolution (0.5 km, Version 6.0) afforded by the SAGE II dataset is the highest currently available of all satellite measurement techniques (Newchurch et al. 2000). This permits a specific choice in altitude range for comparison between SAGE and ozonesonde profiles, an important facility in analysing the comparatively narrow altitude range over which the two different pump correction profiles differ significantly (Steinbrecht et al. 1998). This altitude range is in the region of highest accuracy of the SAGE II Version 6.0 ozone data (Wang et al. 1996).

Similarly to the convention of others (e.g. Veiga et al. 1995; Steinbrecht et al. 1998), the measure of the discrepancy between the BM ozone profiles o and the SAGE II ozone profiles ω adopted here is the fractional difference at atmospheric pressure p:

$$\Delta(p) = \frac{o(p) - \omega(p)}{\omega(p)} \qquad \ldots 3$$

From a comparison between the measured standard deviation of $\Delta(p)$ and the magnitude of the Dütsch and Steinbrecht correction factor with respect to atmospheric pressure (Steinbrecht et al. 1998), it was estimated that the difference between the two corrections would not become significant for p greater than about 12 hPa. A useful statistical variate that was more stable than $\Delta(p)$ was produced by averaging $\Delta(p)$ between the lowest pressure $P' = 5$ hPa reached by the Laverton BM ozonesondes and $P = 12$ hPa. If d (in km) is the spatial separation between the ozonesonde launch site at Laverton and the effective geographic location of the SAGE measurement, and t (in days) is the time lag between the ozonesonde and corresponding SAGE measurement, then as the limits D and τ of the ranges of $0 \leq d \leq D$ and $-\tau \leq t \leq \tau$ were increased in magnitude, the yield of approximately coincident ozonesonde and SAGE measurements increased. Summing over the yield of $N_{D\tau}$ approximately coincidental pairs of BM ozonesonde and SAGE ozone profiles, the mean fractional difference between them may be represented as:

$$\bar{\Delta}_{P'-P} = \frac{1}{N_{D\tau} N_P} \sum_{n=1}^{N_{D\tau}} \sum_{p=P'}^{P} \frac{o_{np} - \omega_{np}}{\omega_{np}} \qquad \ldots 4$$

where N_P is the number of pressure levels over the range $P' \leq p \leq P$.

Because the variance in the mean $\bar{\Delta}_{P'-P}$ increases as both D and τ increase, yet decreases as the yield number $N_{D\tau}$ increases, optimal values of D and τ were expected. Using bootstrap procedures (Efron 1982), optimal values D^* and τ^* were estimated by computing the variance $S^2_{P'-P}$ of the mean $\bar{\Delta}_{P'-P}$ with respect to D, and τ, and determining the minimum by the process:

$$\frac{\partial}{\partial D} \frac{\partial}{\partial \tau} S^2_{P'-P} = 0 \qquad \ldots 5$$

Inspection of Fig. 2 illustrates the progressive increase in the number $N_{D\tau}$ of BM and SAGE approximate coincidences with geographic separation and the clear minimum in $S^2_{P'-P}$ that results in an optimal estimate of $D^* = 2000$ km. Similarly a value of $\tau^* = 2$ days was estimated. This is consistent with limited SAGE II comparisons against Laverton BM ozonesonde data carried out by Veiga et al. (1995) and Harris et al. (1998). The mean ozone difference $\bar{\Delta}_{P'-P}$ for the optimal values D* and τ^* was then calculated from Eqn 4 for both Dütsch and Steinbrecht corrections. The 95 per cent confidence limits of the means $\bar{\Delta}_{P'-P}$ were determined using bootstrap analysis.

Results

Figures 3(a) and 3(b) show scatter plots of the fractional difference $\Delta(p) = \frac{Sonde}{SAGE} - 1$ between the BM ozonesonde and SAGE II ozone profiles, for ozonesonde profiles corrected by the Dütsch and Steinbrecht corrections, respectively. In the Steinbrecht case of Fig. 3(b), a curvature in the $\Delta(p)$ distribution, away from the mean of the distribution at higher atmospheric pressures (40-20 hPa), is evident at pressures below about 12 hPa. This is due to the larger correction factor applied to the ozonesonde profiles in the Steinbrecht case (Fig. 1), and the ratio of the Steinbrecht to Dütsch correction has been plotted for comparison in Fig. 3(b). For the Dütsch case in Fig. 3(a), any curvature in the distribution over the same pressure range is comparatively small. It is the appraisal of the significance of the departure in Fig. 3(b) at pressures below about 12 hPa that differentiates the two methods as appropriate corrections for the Laverton BM ozonesonde.

Fig. 2 **Plots of the variance (solid) of the average fractional difference between the ozone partial pressures of profile pairs of BM ozonesonde and SAGE II measurements, over the pressure range 5-12 hPa, and the number of profile pairs that occur closer than 2 days, as a function of maximum distance between Laverton and the SAGE II effective measurement point. The optimal maximum separation distance between Laverton and the SAGE, and the associated sample size, has been indicated by the dotted lines.**

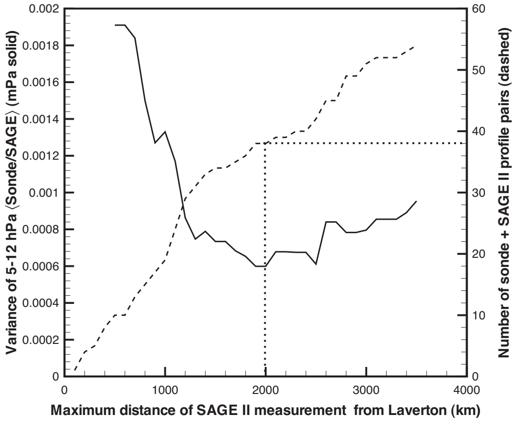
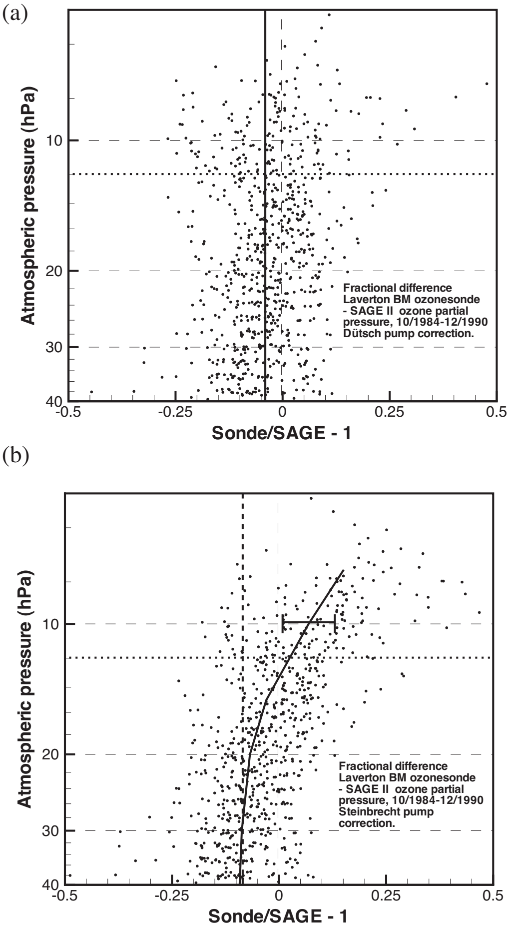


Fig. 3 **Scatter plots of (a) the fractional difference between Laverton BM ozonsonde and the SAGE II ozone partial pressures for the period 10 October 1984 - 31 December 1990, for the Dütsch pump correction, and (b) for the Steinbrecht pump correction. For comparison, the solid curve in (b) shows the result of the Steinbrecht correction if the scatter plot in (a) were the straight vertical line through the means indicated in (a). The heavy vertical dashed line indicates the 20-40 hPa mean fractional difference against which the 95% error bars (uncertainty of the 5-12 hPa mean fractional difference) are referenced. The horizontal dotted lines in both (a) and (b) depict the 12 hPa upper pressure limit for the statistical analysis.**



It was found that outliers in Figs 3(a) and 3(b) were removed by reducing the maximum acceptable Dobson correction factor (ratio of the Dobson total ozone measurement to the integrated ozonesonde profile; Claude et al. 1987) in the BM ozone profiles. However, lowering this factor reduced the sample size and therefore the number of degrees of freedom of the analysis. Rejecting BM profiles with Dobson correction factors that exceeded 1.3 removed most apparent outliers and was consequently adopted. This is a slightly more conservative approach than recommended by the World Meteorological Organization (Claude et al. 1987), in which correction factors greater than 1.35 are generally regarded as unacceptable.

Using the optimal estimates of $D^* = 2000$ km (Fig. 2), and $\tau^* = 2$ days, mean ozone fractional differences were computed for the pressure ranges $5 \le p \le 12$ hPa and $20 \le p \le 40$ hPa. The associated 95 per cent uncertainties of the difference between the ozone fractional difference means of these two ranges were computed for both Dütsch and Steinbrecht corrections. The uncertainty estimates associated with the SAGE II Version 6.0 ozone profile have been included in the data set by NASA Langley Research Center (Zawodny et al. 2000). Being at least an order of magnitude less than the uncertainty associated with the variability of $\overline{\Delta}_{p'-p}$ at all atmospheric pressure levels considered, the SAGE ozone profile uncertainty was neglected in this analysis. One source of systematic uncertainty associated with the BM ozonesonde is in the pressure measurements. This was included in the uncertainty analysis as ±4 hPa at the 95 per cent confidence level (Young, 1989). The resultant differences between the means of the two pressure ranges and associated 95 per cent confidence limits were:

$$\overline{\Delta}_{5-12\,\mathrm{hPa}} - \overline{\Delta}_{20-40\,\mathrm{hPa}}\Big|_{\mathrm{Dütch}} = -0.015 \pm 0.046\ \mathrm{mPa} \qquad ...6$$

and

$$\overline{\Delta}_{5-12\,\mathrm{hPa}} - \overline{\Delta}_{20-40\,\mathrm{hPa}}\Big|_{\mathrm{Steinbrecht}} = -0.150 \pm 0.061\ \mathrm{mPa} \qquad ...7$$

It is evident that the Steinbrecht BM ozonesonde pump correction produces fractional differences that are on average significantly different from zero between the atmospheric pressure ranges $5 \le p \le 12$ and $20 \le p \le 40$ at the 95 per cent confidence level. In the case of the Dütsch correction, however, the mean difference between the same pressure ranges is not significantly different from zero, and therefore it can be argued to be a more satisfactory pump correction for the Australian BM ozonesonde for the approximate period October 1984 - December 1990.

Discussion

There has been a number of investigations of the pump efficiency carried out since the original Komhyr and Harris correction of 1965. In 1983 the Hohenpeissenberg Observatory found good agreement with the original correction (Claude et al. 1987). In 1996 a new pump correction was derived (De Backer 1998) that was consistently slightly higher than the original 1965 Komhyr and Harris correction. The Steinbrecht pump efficiency correction is significantly larger than previous estimates, particularly for pressures less than 10hPa where pump inefficiencies become large.

Compounding the concern of significantly different derived corrections in the past are the differences between the methods of derivation used. These factors could explain why the differences in the results are more than 5-10 per cent at 5hPa (Harris et al. 1998). Harris et al. (1998) suggest that the pump inefficiencies may have changed when the BM factory was relocated in 1989, after which a noticeable decrease in BM ozonesonde quality was reported. Also, a common concern with BM pump inefficiencies was the high degree of variability between these pumps. For example, Komhyr and Harris (1965) found the efficiencies to be very dependent on the length of time a pump had been running and the degree of lubrication. There are investigations currently being carried out at the Environmental Simulation Facility in Jülich, Germany, (World Calibration Center for Ozone Sondes), to address these issues.

The Steinbrecht correction was derived using a later series of pumps which were cleaned by the Claude et al. (1987) procedures. Here the pumps were disassembled, cleaned, reassembled and relubricated. Unfortunately the instructions for these procedures were not well documented for this delicate process. It is therefore possible that the cleaning process has degraded the original factory product, resulting in higher inefficiencies.

Results of independent comparisons with lidar and satellite confirm the magnitude of the Steinbrecht corrections. However, all data used for the Steinbrecht corrections and the independent comparisons were obtained using BM ozonesondes that were probably produced later than 1989 after the factory change and were prepared using the Claude et al. (1987) ozonesonde cleaning procedures.

Until December 1990, the Australian Bureau of Meteorology ozonesondes were routinely prepared by the BM (Mueller) procedures, where the pumps were used in the condition supplied by the Mast Development Company. After 1988 the Bureau become aware of the existence of the revised Claude et al. procedures. Aspects of these procedures were not incorporated until after December 1990.

Bureau records indicate that the quality of the BM ozonesondes had evidently deteriorated in the batches manufactured after 1989, and coupled with poor flight performances, poor resolution, and procedures that were manpower intensive, the Bureau ceased BM ozonesonde measurements in 1991. Alternative sensors and systems were sought and evaluated, and a new program began in 1992 using ECC type ozonesondes.

All of the Laverton flights for the present analysis utilised sondes produced prior to the year of the BM factory change in 1989 and no changes in preparation procedures were recorded by the Bureau for these flights. It is probable that the Steinbrecht corrections derived in 1998 were determined from data acquired using later more inefficient BM ozonesondes and they were certainly prepared using procedures that differed from the 1976 Mueller method.

The discrepancy (~0.03) evident between the mean BM ozonesonde and the SAGE II ozone profiles in Fig. 3(a), as indicated by the separation between the vertical zero line and the vertical distribution mean line, is an absolute calibration issue and of no concern to this study.

Conclusion

The Australian BM ozonesonde data was corrected for systematic errors in the pump efficiency using the Dütsch and Steinbrecht correction profiles for the period October 1985 – December 1990, and a statistical analysis was carried out to compare both against SAGE II Version 6.0 satellite ozone profile data. The results indicate that the use of the Steinbrecht correction produces significant discrepancies when compared with the SAGE ozone data, while the Dütsch correction does not. Thus the Dütsch correction is in better quantitative agreement with the reference SAGE II satellite data at atmospheric pressures less than about 12 hPa.

It is suggested here that the difference between the Dütsch and Steinbrecht BM pump corrections may have been caused by different cleaning procedures used for the chemical cells as well as the possibility that they were determined on BM pumps that had different physical characteristics.

Acknowledgments

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