New Pump Correction for the Brewer–Mast Ozone Sonde: Determination from Experiment and Instrument Intercomparisons

W. STEINBRECHT, R. SCHWARZ, AND H. CLAUDE

Meteorological Observatory Hohenpeissenberg, German Weather Service, Hohenpeissenberg, Germany

(Manuscript received 6 May 1996, in final form 1 May 1997)

ABSTRACT

Pump efficiency of the Brewer–Mast (B–M) ozone sonde deteriorates significantly at altitudes above 22 km (pressures below 50 hPa). The correction currently used as the WMO standard does not sufficiently account for the efficiency decrease. It is based on laboratory measurements made in 1965. The authors have redetermined pump efficiency for the B–M sonde and found that a much higher pump correction is appropriate. The net effect of the new pump correction, after Dobson normalization to integrated ozone, is a substantial increase of ozone values above 28 km (15 hPa) and a small decrease below. At 6 hPa (34–35 km) ozone values need to be increased by 20%. From 22 to 28 km (50–15 hPa) net corrections are smaller than 4%. Below 16 km (100 hPa) ozone values decrease by 5%–7%. Using the new pump correction, agreement of better than 2%–5% is found with lidar, SAGE II, electrochemical concentration cell (ECC) sondes, and HALOE (Halogen Occultation Experiment) for the entire altitude range from 16 to 35 km (100–6 hPa). The pump correction currently used in the WMO standard procedure should be updated. Mixing ratio profiles at Hohenpeissenberg indicate that pump efficiency of the B–M sonde has probably not changed over the last 30 years. However, the evidence is not conclusive and this question will have to be addressed in the future. Even if pump efficiency should have changed, negative trends reported by B–M sondes in the lower stratosphere would remain valid and increase by approximately −5% per 20 years. Large positive trends reported in the troposphere would become smaller by the same amount.

1. Introduction

The electrochemical Brewer–Mast (B–M) ozone sonde, commercially produced since the late 1960s by the Mast Development Company, Iowa, has been one of the workhorses of vertical ozone profiling for almost 30 years (Angell and Korshover 1983; Tiao et al. 1986; Logan 1994). Newer and more sophisticated instruments have since been developed, such as the satelliteborne SBUV (solar backscattered ultraviolet, Heath et al. 1975; Frederick et al. 1986) and SAGE (Mauldin et al. 1985) in the late 1970s, or ground-based differential absorption lidars (Werner et al. 1983; Mégie et al. 1985; McDermid 1987; Carswell et al. 1991) in the 1980s. Nevertheless, the Brewer–Mast sondes as well as the improved electrochemical concentration cell (ECC) sondes (Komhyr 1969) are still important instruments for stratospheric ozone measurements (e.g., von der Gathen et al. 1995), and they are also the major source of routine ozone data for the free troposphere.

An important goal of the ozone research community has been to establish a broad database of precise and internally consistent ozone data that extends as far back into the past as possible. Efforts in this direction are the WMO Global Ozone Observing System GOS, the World Ozone Data Center at AES, Toronto, (WMO 1988, 1989, 1991, 1995) and several instrument intercomparisons (e.g., Attmannspacher and Dütsch 1970, 1981; Hilsenrath et al. 1986; Kerr et al. 1994; Margitan et al. 1995; Veiga et al. 1995). For total ozone, this goal has already been achieved by the combination of the ground-based Dobson network and the TOMS (total ozone mapping spectrometer) instruments (Bojkov et al. 1988; WMO 1994).

For vertical ozone profiles, several inconsistencies have yet to be resolved. The change from B–M sondes to ECC sondes has resulted in discontinuities in time series at several stations, for example, the Canadian sites (Tarasick et al. 1995). This has made reliable estimation of ozone trends at those stations very difficult. For this reason a few stations (in Europe: Hohenpeissenberg, Payerne, and Uccle) are still using the B–M sonde today. Intercomparisons with ECC sondes (Kerr et al. 1994), SAGE (Attmannspacher et al. 1989; Veiga et al. 1995), HALOE (Brühl et al. 1996), and ongoing comparison with the DIAL system at Hohenpeissenberg have shown that the B–M sonde gives systematically too low ozone values (by 10% or more) at altitudes above about 28 km (15 hPa). An inadequate correction for decreasing
pump efficiency has been mentioned as one possible cause for these discrepancies (e.g., Veiga et al. 1995). The pump efficiency correction applied at altitudes above 13 km (pressures below 150 hPa) in the current WMO standard evaluation procedure for B–M sondes (Dütsch 1966; Claude et al. 1987) is based on 30-yr-old laboratory measurements by Komhyr and Harris (1965).

We have now redetermined the pump efficiency correction for the B–M sonde and found that higher values are appropriate. After a brief introduction of the operating principle of the B–M sonde, the first part of the paper reports on the experimental determination of B–M sonde pump efficiency in a vacuum chamber. In the second part, the pump correction is derived from recent intercomparisons between B–M sondes and other ozone profiling instruments.

2. Principle of the B–M sonde

The commercial B–M sonde evolved from ozone sondes developed at Oxford, United Kingdom, by Brewer and Milford (1960). It employs the chemical reduction of ozone in an electrochemical cell consisting of an alkaline buffered potassium iodide solution with a silver anode and a platinum cathode. Theoretically, two electrons are released when one ozone molecule enters the solution (for details see Brewer and Milford 1960; Claude et al. 1987). Constantly pumping outside air containing ozone at partial pressure through the solution results in a current \( I \) that is measured. The current \( I \) (\( \mu A \)) is proportional to ozone partial pressure \( p_0 \) (nbar) (e.g., Claude et al. 1987):

\[
I = \alpha \frac{T}{F} \text{(nbar} \mu \text{A K s}^{-1})
\]

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 \( \alpha = 4.307 \times 10^{-3} \text{nbar ml} \) is the proportionality constant.

In the B–M sonde the flow rate \( F \) is measured only before launch at the ground (pressure \( p_o \), e.g., 1000 hPa). It remains fairly constant during flight to a pressure of about 150 hPa but is known to decrease when ambient pressure \( p \) falls below 150 hPa. In WMO standard procedure (Claude et al. 1987) a pump correction \( K(p) \) is used to account for this decrease. Here, \( K(p) \) is given by the ratio of flow rate \( F(p) \) at ground pressure \( p_o \) (e.g., 1000 hPa) to that at pressure \( p \).

\[
K(p) = \frac{F(p_o)}{F(p)}
\]

Measurements by Komhyr and Harris (1965) form the basis for the pump correction developed by Dütsch (1966), which is still in use today in the WMO standard procedure for the evaluation of B–M sondes.

The B–M sonde uses a piston pump, driven by a commercially available constant-speed motor (e.g., Densitron Corporation, P/N DTCN-12G, as used in commercial tape recorders). According to the manufacturer’s specifications, motor speed does not vary by more than 1%. Figure 1 shows the B–M sonde assembly. The pump works in two strokes.

1) In the first stroke (intake) the pump cylinder (total volume \( V_o \), typically 115 mm\(^3\)) is filled by ambient air at pressure \( p \).
2) In the second stroke (exhaust) the air is pushed through the reaction cell, usually against an additional back pressure \( p_b \). At the end of the exhaust stroke, the pump dead volume \( V_d \) (typically 23 mm\(^3\)) remains filled with air at the enhanced pressure \( p_b \) plus \( p \) of the exhaust tract.

This air will already be inside the pump cylinder at the next intake stroke. Therefore, fresh ambient air at pressure \( p \) cannot fill the entire pump volume \( V_o \), only a certain fraction \( V \) of it. Only the amount of air corresponding to \( V \) is actually pumped through. Using the ideal gas law and assuming a perfect pump (no losses around piston or at valve slits), the correction factor \( K(p) = V(p)/V(p) \) is given by

Fig. 1. Photograph of the B–M sonde. The pump assembly is on top at the left. The silver rod is the pump piston; the pump cylinder is the transparent piece to the left. The white hose on the left is the intake line; the pump exhaust line goes straight down into the Plexiglas bubbler (cylinder at the bottom).
FIG. 2. Theoretical pump correction as a function of ambient pressure for the B±M sonde and for back pressures between 2 and 15 hPa. Dotted curves are for isothermal compression; dashed curves are for adiabatic compression. Labels denote the back pressure (hPa); italicized labels are used for the adiabatic curves.

Here, \( \gamma \approx 1.4 \) is the adiabatic exponent, if compression in the pump is assumed to be adiabatic. For isothermal compression, set \( \gamma = 1 \) in Eq. (3) (cf. Kobayashi et al. 1966).

At this point, discussion of the physical processes leading to the back pressure \( p_b \) is appropriate. In the B±M sonde, air is pumped to the bottom of the reaction cell ("bubbler") filled with a 0.1% solution of potassium iodide in water to a depth of about 2 cm. To produce air bubbles, which then rise through the solution, the pressure in the pump’s exhaust tract has to be high enough to overcome the surface tension of the bubbles (pressure enhancement of 1.5, 3, and 6 hPa for bubbles of 2-, 1-, and 0.5-mm diameter) and the hydrostatic pressure of the solution column (typically 2 hPa). Therefore, pump back pressure \( p_b \) must be of the order of 5 hPa.

For a real pump, additional effects, such as flow impedance by orifices and tubing or viscosity resisting the displacement of solution during the creation of air bubbles, will result in a less than perfect pump performance. In the B±M pump, a thin film of oil serves to seal piston and valve slits quite effectively, but some air leakage has to be expected as well. If it is assumed that air leakage is proportional to \( p_b \) (the difference between pressure in the exhaust tract and ambient pressure) and that the other effects lead to a net increase of the back pressure, then Eq. (3) still describes the change of pump efficiency with ambient pressure. However, a higher value of \( p_b \) will be required. In any case, the theoretical results derived for an ideal pump [Eq. (3) with a back pressure of 2–5 hPa] give a lower limit for the pump correction of a real B±M pump.

Vapor pressure from the solution (6.1, 12.3, and 23.4 hPa at 0°, 10°, and 20°C) is comparable to ambient pressure above 26 km (20 hPa). However, it does not contribute to the static back pressure in the pump’s exhaust tract. Nevertheless, small effects from a net stream of evaporated water diffusing toward the pump cylinder cannot be excluded.

Figure 2 shows the theoretical pump correction \( K \) for back pressures \( p_b \) ranging from 2 to 15 hPa. Depending on effective back pressure \( p_{eb} \), the theoretically expected pump correction \( K \) at 100 hPa is of the order of 1 to 1.04, at 30 hPa it ranges from 1.02 to 1.15, at 10 hPa from 1.03 to 1.6, and at 5 hPa from 1.02 to over 2. Applying a pump correction increases raw ozone values measured by the B±M sonde substantially and has a significant effect on results obtained at high altitudes (low ambient pressures).

In the experiments forming the basis of the WMO standard pump correction, Komhyr and Harris (1965) were not measuring against a bubbler filled with solution, but against a 3-cm column of Apiezon A oil. This simulates the right hydrostatic pressure, but other contributions to back pressure, for example, surface tension in bubbles and viscosity of the fluid displaced by the bubbles, are different. We were not able to use Apiezon A oil, but when pumping against a 3-cm column of vacuum pump oil, we found a quite unrealistic pump correction (very high, \( \approx 1.6 \) at 10 hPa, \( \approx 2.0 \) at 7 hPa).

3. Experimental determination of pump efficiency

a. Setup

For our experimental determination we followed an approach used by Komhyr et al. (1995) for measuring the pump correction of ECC sondes. The idea is to use two pumps, as shown in Fig. 3. The first pump (2 in the figure) is the B±M pump to be tested, the other pump (1 in the figure) is coupled to a variable speed motor and used as a flow meter. The speed of the flow meter pump is adjusted so that pressure at its exhaust is the same as at its intake. The flow meter pump does not work against back pressure. It just transfers air at ambient pressure \( p \) to pump 2, which is being tested. The tested pump 2, on the other hand, has to work against back pressure of the bubbler with solution, as under actual flight conditions.

The difference between ambient pressure and pressure at the exhaust of pump 1 (equalling the intake of pump 2) is monitored by a manometer (filled with vac-
uum pump oil) and the speed $s$ of pump 1 is regulated so that this pressure difference is always zero. The whole setup is in a pressure chamber (3). Because it is operating without enhanced back pressure [$p_b = 0$ in Eq. (3)], it is assumed that the pump rate of pump 1 is proportional only to motor speed and volume of the cylinder, independent of ambient pressure. Whatever air is transported by pump 1 must be pumped through the bubbler by pump 2, otherwise the pressure in the line between the two pumps would fall below or rise above ambient pressure. The pump rate of both pumps must then be identical and the correction factor $K(p)$ is given by comparing the motor speed $s(p)$ of pump 1 at pressure $p$ with its speed at ground pressure $p_o$.

$$K(p) = \frac{s(p_o)}{s(p)}.$$  

The assumption that the pump rate of the flowmeter pump 1 is proportional only to motor speed is critical. Although pump 1 (flowmeter) is not working against a static back pressure, its pump efficiency might decrease with ambient pressure, for example, due to air leakage or flow restrictions. If this is the case, it will have to be run faster and the measured pump correction value $K(p)$ for pump 2 would be too low.

To check the assumption, we compared results obtained with a B–M pump as flowmeter to those obtained with an ECC-4A pump as flowmeter. The geometry of these two pumps is quite different, and the loss of pump efficiency at low ambient pressure is much smaller for the ECC pump (compare Fig. 4). Nevertheless, almost identical pump corrections $K(p)$ were obtained. Therefore, efficiency of the flowmeter pump does not seem to decrease substantially at low ambient pressure, and the assumption that the pump rate of pump 1 is proportional only to motor speed seems to hold. Finally, the good agreement found between the pump correction measured using the flowmeter pump and the pump correction derived from the instrument intercomparisons (compare Fig. 4) also indicates that pump efficiency loss for the flowmeter pump is small.

Motor speed was measured to within about 1% using a light barrier coupled to a frequency counter (Yokogawa Electric, Model 3632 pocket tachometer). The pressure in the chamber was monitored by a high-precision barometer (Diptron 3, Pennwalt, Wallac & Tierman). Several tests showed that connecting hoses and pipes had no influence on the results.

b. Single runs

For each test the pressure chamber was evacuated from 900 to 5 hPa in about 40 min. This is half the time (90 min) that B–M sonde flights at Hohenpeissenberg take to reach the 5-hPa level in the atmosphere. The speed of the flowmeter pump was regulated and measured at regular pressure intervals. After reaching the 5-hPa level, in many cases the chamber was slowly refilled to 900 hPa, again within about 40 min. For each test the pump correction was calculated at the different pressure levels. If speed readings were taken during pump-down and fill-up, the mean of the two was used. No systematic difference was found between the speeds taken at the same pressure during pump-down or fill-up.

At pressures below 15-hPa regulation of the flowmeter pump speed was difficult and values scattered
c. Experimental pump correction

To reduce the high single run uncertainty and to minimize the effects of manufacturing and assembly differences, a representative pump correction was determined by averaging over several test runs. Only results obtained with two B–M pumps and one ECC-4A pump as flowmeters were included in the average. These pumps gave essentially the same results. As mentioned above, the widely scattered and significantly different results obtained using a third B–M pump as the flowmeter were not used. This pump eventually broke down and probably was damaged before.

Figure 4 and Table 2 show the average pump correction determined from 16 single tests with eight different pumps. The pump correction derived from the instrument intercomparisons is discussed later, but it has been included in Fig. 4 and Table 2. Also included are the WMO standard B–M pump correction in use now (Dütsch 1966; Claude et al. 1987) and a pump correction for ECC sondes (Komhyr et al. 1995). The error bars give the estimated uncertainty (2σ) of each pump correction. For the chamber experiments we used the standard deviation of single runs from the mean, divided by the square root of the number of runs minus one (σ_{clean} = σ_{single}/\sqrt{n - 1}). The number of runs was 14 for all pressures except 7.5–5 hPa, where it was 9.

The pump corrections from the chamber experiments and the one determined from the instrument intercomparisons (see below) agree within better than 2%, except between 15 and 7.5 hPa where the pump correction from the intercomparisons is up to 10% higher. Both are significantly higher than the WMO standard correction currently in use. Recently De Backer et al. (1996) reported a pump correction for the B–M sonde that is almost identical to our results between 70 and 20 hPa, but substantially lower at pressures smaller than 10 hPa. In their experiments the B–M pumps were operating against a static back pressure of about 2 hPa, and flow rate was measured using a Brooks volume calibrator. Substantially higher pump correction values are reported by Görsdorf et al. (1990) for a slightly different ozone sonde pump (GDR-OSE). They used a weight, giving a fixed static back pressure (magnitude is not reported). Our pump correction is in good agreement with work by Kobayashi et al. (1966), who had his pump (type is unknown) work against solution.

Note that the pump correction for the B–M sonde is much higher than for the ECC sonde. This can be explained by the much smaller dead volume of the ECC pump (3% of total pump volume for the ECC-4A, compared to 20% for the B–M pump).
TABLE 2. Comparison between current WMO standard B-M pump correction (Dütsch 1966) (second column) and the two pump corrections from this work. Columns 3 to 5 give the results from the chamber experiments; columns 6 to 8 show the results from the instrument intercomparisons. The standard deviations give the estimated uncertainty (1σ) of the mean pump correction.

<table>
<thead>
<tr>
<th>Pressure (hPa)</th>
<th>Dütsch (1966)</th>
<th>Chamber experiments</th>
<th>Intercomparisons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>K</td>
<td>1σ absolute</td>
</tr>
<tr>
<td>900</td>
<td>1.000</td>
<td>1.000</td>
<td>0.0</td>
</tr>
<tr>
<td>850</td>
<td>1.000</td>
<td>1.002</td>
<td>0.001</td>
</tr>
<tr>
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<td>1.000</td>
<td>1.006</td>
<td>0.001</td>
</tr>
<tr>
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<td>0.002</td>
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<tr>
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<td>0.004</td>
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<tr>
<td>70</td>
<td>1.022</td>
<td>1.052</td>
<td>0.005</td>
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<tr>
<td>60</td>
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<tr>
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<tr>
<td>6</td>
<td>1.26</td>
<td>1.65</td>
<td>0.22</td>
</tr>
</tbody>
</table>

4. Effect of pump corrections on the ozone profile

The “Dobson correction” applied in WMO standard evaluation procedure (e.g., Claude et al. 1987) requires that total column ozone, obtained by integrating ozone from the balloonsonde with altitude, has to be consistent with a ground-based total ozone measurement, usually from a Dobson spectrophotometer. To achieve this, the entire ozone profile is multiplied by a constant factor called the Dobson correction factor (Claude et al. 1987). A change of the pump correction has to leave total ozone from the sounding unchanged. Since the new pump corrections increase ozone values at high altitudes, this has to be compensated by reduced ozone values at low altitudes. A higher pump correction results in a smaller Dobson correction factor.

At Hohenpeissenberg from 1987 to 1995 the increase in integrated ozone when switching from the WMO standard pump correction to the one from the chamber experiments is about 4.0% ± 0.3% on average, or 5.0% ± 0.3%, for the pump correction derived from the instrument intercomparisons (described later in the paper). Values for the latter are shown in brackets hereafter.

Since B-M ozone sondes operate properly only up to 30 or 35 km, the residual part of the total ozone column has to be estimated. WMO standard procedure assumes a constant ozone mixing ratio above the last data point of the sonde launch. This assumption is unrealistic, but a discussion of the effect on residual ozone and the Dobson normalization is beyond the scope of this paper. At high altitudes (low pressures) the new pump correction (from the chamber experiments) results in a large increase of raw ozone values, of the order of 10%–30%. Consequently, estimated residual ozone increases substantially, by 20% ± 5% [26% ± 5%]. The ratio of residual ozone to total column ozone increased from 11% to 13% [14%].

When the new pump correction is used, the Dobson correction factor decreases by 5.5% ± 0.6% [7.2% ± 0.6%]. At altitudes where the new pump correction is smaller than about 1.05 (below 21 km or 50 hPa), the decreased Dobson correction results in smaller ozone values. The combined effect of using the new pump correction and applying the Dobson correction is shown in Fig. 5 and summarized in Table 3. Essentially, the Dobson correction shifts the pump correction curve to the left. Higher ozone values (0%–20%) above 28 km (15 hPa) are compensated by reduced values at lower altitudes. Below 12 km (200 hPa) ozone values are re-

Fig. 5. Relative change of ozone concentration after Dobson correction when using the new pump correction from the chamber experiments and from the instrument intercomparison instead of the WMO standard pump correction.
duced by 5.5% [7.2%]. Between 18 and 27 km (80 to 15 hPa) net changes are smaller than 5%.

Apart from the uncertainty of the pump correction itself, the Dobson correction introduces additional uncertainty into the net ozone change profile from Fig. 5 or Table 3. This uncertainty is caused by the shape of the ozone profile, because the effect of the new pump correction on total ozone, and thus the Dobson correction factor, depends on the shape of the ozone profile. Based on Hohenpeissenberg ozone profiles from 1987 to 1995, we estimate that this uncertainty is usually smaller than 2%.

5. Pump correction derived from instrument intercomparisons

An independent way for determining the pump efficiency of the B–M sonde is to use the results of several instrument intercomparisons performed over the last couple of years. In these intercomparisons, ozone profiles measured by the B–M sonde were compared with those measured by a variety of other instruments.

a. Altitude dependence of pump temperature

When comparing ozone profiles from the B–M sonde to those from other instruments, an additional effect of similar size as the pump correction at altitudes below 28 km (15 hPa) has to be considered. Different from the standard WMO procedure, where a fixed value of 300 K is used for the pump temperature $T$ in Eq. (1), such comparisons require that the change of pump temperature $T$ with altitude is taken into account. Unfortunately, pump temperature is not routinely monitored in the B–M sonde. However, during about 15 sonde flights between April and September 1995 at Hohenpeissenberg, pump temperature was recorded.

Figure 6 shows the resulting average pump temperature profile, along with the single profile standard deviation. Pump temperature decreases from about 292 K at the ground to 275 K at 32 km (9 hPa), with a typical cooling rate of 5 K per 10 km. Standard deviation increases from $\pm 2.4$ K (1σ) at the ground to $\pm 8.4$ K near the tropopause (200 hPa). After entering the stratosphere, standard deviation is reduced and drops to $\pm 2.4$ K at 9 hPa (32 km).

For comparison, a few other pump temperature measurements from the B–M sonde (Dütsch 1966), a Japanese sonde (Kobayashi et al. 1966), and the GDR-OSE (Görsdorf et al. 1990) have been included in Fig. 6. Temperatures from these measurements differ substantially, but with the exception of Dütsch (1966), they all show a temperature decrease of typically 20 K during flight. Very similar to our results, Attmannspacher (1968) reported a temperature decrease from 295 to 271 K for the B–M sonde during flight.

The net effect of applying the different pump temperature profiles instead of using $T = 300$ K in Eq. (1) and after performing the Dobson correction is shown in Fig. 7 and Table 4. All four temperature profiles result in nearly the same ozone change. Because of the Dobson correction, ozone values near the concentration maximum (20–25 km, 60–25 hPa) are virtually unchanged.

![Figure 6. Average pump temperature derived from 15 B–M sondes launched throughout 1995 at Hohenpeissenberg (solid circles). The error bars give the standard deviation of the individual measurements. For comparison, pump temperatures measured in single flights for the B–M sonde by Dütsch (1966) (solid squares), by Görsdorf et al. (1990) for the GDR-OSE (gray triangles), and by Kobayashi (1966) (gray diamonds) for the Japanese sonde are included.](image-url)
no matter what pump temperature profile is used. The absolute value of the pump temperature is compensated by the Dobson correction, and only the vertical temperature change leads to a change of the ozone values. Below 22 km (40 hPa) ozone values have to be increased, by up to 5% at the ground. Above 24 km (30 hPa) ozone values have to be reduced, by up to −3% at 34 km (6 hPa). It is important to note that at altitudes above about 28 km (15 hPa) the pump efficiency correction dominates. Here, the effect of pump temperature correction (−2% to −3%) is small compared to the pump efficiency correction (up to +20%).

As the true pump temperature profiles for all the instrument intercomparisons reported below are not available, we applied the average pump temperature profile to each intercomparison. As mentioned, the effective ozone change is usually small. The major source of uncertainty comes from a possibly different shape of the true temperature profile, affecting the raw ozone profile. A minor source is the shape of the ozone profile, which affects the Dobson correction. We estimate that the error made by using our mean pump temperature profile, instead of the actual one, is well below 2% in most cases (compare Fig. 7).

b. Comparison with lidar, SAGE, ECC sondes, and HALOE

At Hohenpeissenberg a laser radar (lidar) for measuring stratospheric ozone has been in routine operation since October 1987 (about seven nights each month). The system uses the differential optical absorption technique (in the ultraviolet) to measure ozone in the stratosphere and is estimated to have an accuracy better than 2% for the altitude range between 20 and 35 km (Claude and Wege 1989; Claude et al. 1989). Other instruments that can be used for intercomparison are the satellite-borne SAGE I (since 1979) and SAGE II instruments (since 1984). Here, limb scanning and differential optical extinction in the visible are used to measure the ozone profile. For SAGE II an accuracy of 7% is reported in the altitude range of 20–60 km (Cunnold et al. 1989; Veiga et al. 1995).

Figure 8 shows the average difference between ozone profiles measured by B–M sondes and lidar at Hohenpeissenberg (monthly mean profiles from October 1987 to December 1995) and between Hohenpeissenberg B–M sondes and SAGE II profiles measured within 6–15° latitude and ±15° longitude of Hohenpeissenberg (monthly mean profiles from October 1987 to May 1993). The SAGE II data were obtained from the NASA Langley Research Center EOSDIS DAAC. Altitude regions and time periods where the lidar or SAGE data are contaminated by high stratospheric aerosol loading after the Pinatubo eruption were excluded.

Results from the WMO ozone sonde intercomparison held in Vanskoy, Canada, in 1991 (Kerr et al. 1994) are shown in Fig. 9. For the WMO intercomparison in Vanskoy, B–M and ECC sonde data from 10 balloon flights were compared. As mentioned, the pump correction for ECC sondes is substantially smaller than for B–M sondes, and superior performance of the ECC is expected, especially at high altitudes. Except for a systematic shift by −5% (B–M is lower), virtually the identical curve as in Vanskoy is obtained for a 2-yr comparison of B–M sondes launched in Uccle, Belgium, with ECC sondes launched at DeBilt, the Netherlands (DeBacker and DeMuer 1995, personal communication). However, while results from the Vanskoy and Uccle/De Bilt in-

Table 4. Relative ozone change after Dobson correction when using the average pump temperature from 15 B–M sondes launched in 1995 at Hohenpeissenberg, instead of a fixed value of 300 K.

<table>
<thead>
<tr>
<th>Pressure (hPa)</th>
<th>Net O₃ change after Dobson correction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>+4.3</td>
</tr>
<tr>
<td>850</td>
<td>+4.1</td>
</tr>
<tr>
<td>200</td>
<td>+2.2</td>
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<td>40</td>
<td>−0.15</td>
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<tr>
<td>30</td>
<td>−0.4</td>
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<tr>
<td>20</td>
<td>−0.8</td>
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<tr>
<td>15</td>
<td>−0.9</td>
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<tr>
<td>10</td>
<td>−1.7</td>
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<tr>
<td>7.5</td>
<td>−2.2</td>
</tr>
<tr>
<td>6</td>
<td>−2.9</td>
</tr>
</tbody>
</table>

Fig. 7. Net ozone change after Dobson correction when the pump temperature profiles from Fig. 6 are used, instead of a fixed value of 300 K.

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tercomparisons agree well, they are inconsistent with the findings of the WMO ozone sonde intercomparison (BOIC) in Palestine, Texas, in 1983 (Hilsenrath et al. 1986). The cause of this disagreement is not known, but we think that the ECC and B–M intercomparison from BOIC should be treated with suspicion.

Figure 9 also includes the comparison between the Halogen Occultation Experiment (HALOE) onboard the UARS satellite and the Hohenpeissenberg B–M sondes, reported in a detailed HALOE validation paper by Brühl et al. (1996). About 30 ozone profiles from April 1991 to April 1994 were included in the comparison. HALOE uses the solar occultation technique in the 9.6-μm band to measure ozone profiles between 0.01 and 100 hPa. HALOE’s maximum accuracy of 6% is reached at 0.4 hPa (about 55 km), accuracy decreases to 12% at 10 hPa (31 km) and 30% at 100 hPa (17 km) for a single profile. HALOE has been operational on the UARS satellite since October 1991.

The B–M sonde data in Figs. 8 and 9 were processed using the standard WMO pump correction, the pump temperature correction described above, and the Dobson normalization. For Fig. 9 [the Vanskoy intercomparison (Kerr et al. 1994) and the HALOE validation campaign (Brühl et al. 1996)] only the pump temperature correction had to be applied to the original results. All intercomparisons in Figs. 8 and 9 show very similar differences. Between 17 and 24 km (90 and 30 hPa) SAGE and B–M sonde agree very well, while the lidar reports about 5% lower ozone values than the B–M sonde. In the same altitude range (between 16 and 26 km, 100 to 20 hPa) the B–M sonde also tends to give somewhat higher ozone values (up to 5%) than ECC sondes or HALOE. Above 27 km (20 hPa) the picture changes dramatically. Ozone values from the B–M sonde drop off substantially compared to all other instruments. They are about 10% lower at 31 km (10 hPa) and 15%–20% lower at 33 km (7.5 hPa). The fact that above 26 km (20 hPa) four independent instruments report significantly higher ozone values than the B–M sonde with standard WMO pump correction is a strong indication that this pump correction is too small—at least above 26 km (20 hPa).

**c. Pump correction deduced from intercomparisons**

The intercomparisons can be used to deduce a new pump efficiency correction by postulating that with the new pump efficiency correction the differences between the B–M sonde and the other instruments should become minimal. Above 17 km (90 hPa), the average difference profile obtained from the four instrument intercomparisons was minimized. Below 17 km (90 hPa), B–M sonde data are not very sensitive to the pump correction and, in addition, the results from the intercomparisons differ widely. Therefore, it was postulated that below 17 km (90 hPa) the pump correction derived from the instrument intercomparison should be identical to the one from the chamber experiments. The pump correction resulting from this minimization has already been

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**Fig. 8.** Relative ozone difference between B–M sondes and lidar or SAGE II at Hohenpeissenberg when using the standard WMO pump correction. The comparison is based on monthly means between November 1987 and November 1995 (May 1993 for SAGE II). For SAGE all measurements with a footpoint within ±7.5° latitude and ±15° longitude of Hohenpeissenberg were included. The B–M data were corrected for pump temperature as described in the text.

**Fig. 9.** Relative ozone difference between B–M and ECC sondes during the WMO ozone sonde intercomparison in Vanskoy, Canada, 1991, after Kerr et al. (1994), and between HALOE (version 17 data) and B–M sondes at Hohenpeissenberg, after Brühl et al. (1996). The B–M sonde data were processed using the WMO standard pump correction. The differences were corrected for pump temperature as described in the text.
shown in Fig. 4 and was also included in Table 2. To estimate the uncertainty of this pump correction, the standard deviation of the differences from the four instrument intercomparisons was used. Above 22 km (50 hPa) the precision of the pump correction derived from the instrument intercomparisons should be better than 2%–3% (1σ).

As mentioned in the discussion of Fig. 4 and Table 2, the pump correction from the chamber experiments and the one deduced from the instrument comparisons are very similar. Around 10 hPa the correction from the instrument intercomparisons is about 10% higher. At 20 and 6 hPa both are identical. The differences are within the 2σ uncertainty margins of both pump corrections. Because the chamber measurements are increasingly inaccurate for pressures lower than 20 hPa, the pump correction derived from the instrument intercomparisons should be much more accurate there. We suggest that it should be considered for replacing the standard WMO pump correction (Komhyr and Harris 1965; Dütsch 1966; Claude et al. 1987).

The effect of applying the pump correction from the instrument intercomparisons (with Dobson correction and temperature correction from above) is shown in Figs. 10 and 11. The substantially improved agreement between the B–M sonde and the four other instruments above 26 km (20 hPa) is obvious. Differences are now less than 5% at all altitudes between 16 and 35 km (100 and 6 hPa). When the pump correction from the chamber experiments is used, very similar good agreement is found with the exception of a dip around 30–33 km (12–7 hPa). There the B–M sonde consistently shows 5%–10% lower ozone values. This dip appears in all the instrument intercomparisons and seems to be caused by too low a value measured in the chamber.

6. Has the pump of the B–M sonde changed?

If Komhyr and Harris’s (1965) pump efficiency measurements were correct then and the ones reported in this paper are correct now, the pump efficiency of the B–M sonde must have changed over the last 30 years. However, no obvious change in design and geometry of the B–M pump has occurred since 1965. If one believes that pump efficiency did change, then other changes, for example, in manufacturing tolerances or pump preparation, have to be considered. They could have led to higher air leakage or increased flow impedance. According to the theoretical curves in Fig. 2, an increase of the effective back pressure by about 5 hPa would lead to the observed differences between the WMO standard pump correction and the new pump corrections.

There is no clear evidence indicating that a change in sonde interior temperature has occurred or that such a change has an effect on pump efficiency. When testing B–M pump assemblies cooled by an ice package, we were not able to find a temperature dependance of B–M pump efficiency, contrary to DeBacker et al. (1996), who reported a slight decrease in pump efficiency with temperature. The B–M pump temperature as reported for 1995 in Fig. 6 is about 15 K colder than found by Dütsch (1966) but very similar to the results of Attmannspacher (1968).

An indirect check of Komhyr and Harris’s results is presented in Figs. 12 and 13, showing representative annual mean mixing ratio profiles from B–M ozone
Figure 12. Annual mean ozone mixing ratio profiles from B–M soundings at Hohenpeissenberg for 1968, 1971, and 1993 were processed using the standard WMO pump correction. For 1993 the annual mean mixing ratio from lidar measurements at Hohenpeissenberg is shown as well. Also included are climatological profiles based on rocket soundings, primarily from 1968 to 1970 (Krüger and Minzner 1976), and based on data from SBUV, LIMS (both on Nimbus-7), and SAGE I (on ERBS) from 1979 to 1982 (Keating and Pitts 1990).

Figure 13. Same as Fig. 12 except that the new pump correction (from the chamber experiments) was applied to the B–M sonde data.

The important feature in Figs. 12 and 13 is the gradient of mixing ratio with respect to altitude above 30 km. As expected from climatology, the 1993 lidar data show increasing ozone mixing [\(\approx 0.2 \text{ ppmV km}^{-1}\)] up to a maximum of about 7 ppmv at 35 km (5 hPa). In contrast, the mixing ratio measured in 1968, 1971, and 1993 by the B–M sondes with standard WMO pump correction (Fig. 12) is almost constant above 30 km (12 hPa), and gradients are smaller than 0.03 ppmv km\(^{-1}\).

At 33 km (7 hPa) the mixing ratio profile measured by the B–M sonde in 1968 or 1971 lies almost as much below the Krüger and Minzner climatology as the 1993 mixing ratio profile lies below the lidar data. This seems to indicate that the WMO standard pump correction was too weak in 1968 and 1971, just as it is too weak now. Already before 1981 Attmannspacher and Dütsch (1981) noted that “...above 20 to 15 mbar the balloon sondes produce lower values than the (optical or chemoluminescent) rocket instruments ... which may be due to pump problems at low pressure.” In contrast, when the new pump correction (from the chamber experiments) is used as shown in Fig. 13, ozone values increase by 5%–20% above 30 km (12 hPa), and much better agreement is found between B–M sonde and lidar or climatology in 1968, 1971, and 1993. These are indications that the WMO standard pump correction was not correct already in 1968 and 1971.

However, the evidence presented in Figs. 12 and 13 must be treated with caution. First of all, it is very critical that Krüger and Minzner’s climatological model represents the true mixing ratio gradient at Hohenpeissenberg in 1968. It may have been increasing less steep than expected from the Krüger and Minzner climatology. As very few reliable ozone profile data are avail-
able above 25 km from that time, this could not be tested in the paper. Second, inspection of all annual mean profiles from 1967 to 1996 (with WMO pump correction) shows several profiles, in the early years but also in the late 1980s, where the mixing ratio increases between 30 and 33 km by more than 0.2 ppmV. Nevertheless, when the standard WMO pump correction is used, there is only 1 year (1976) where it increases by 0.6 ppmV as expected from climatology and lidar profiles. Third, unless new experiments with the original Apiezon A oil are performed, there is no convincing reason to believe that Komhyr and Harris’s (1965) measurements were not correct.

Because of the above-mentioned uncertainties, we feel that extensive further investigation, exceeding the scope of this paper, is needed to resolve the question whether the pump correction of the B–M sonde has changed over the last 30 years.

If one believes that the B–M pump correction has indeed changed, an important question is, how such a change would affect long-term ozone trends derived from B–M sonde data that were processed with the standard WMO pump correction. Several studies based on B–M sonde data (Dobson corrected) report a long-term ozone decrease of about −0.5% to −1% per year below 24 km (30 hPa) in the lower stratosphere (e.g., Angell and Korshover 1983; Tiao et al. 1986; Logan 1994). In the troposphere for many B–M stations a long-term ozone increase of up to 1% or 2% per year is reported (e.g., Logan 1994; Claude et al. 1996). If the standard WMO pump correction should be correct in the first years and the new pump correction from this paper should be correct in the last years, then, in combination with the Dobson correction, this would result in typically 5% lower ozone values below about 26 km (20 hPa) in the last years of these time series (cf. Fig. 5). In this case, the negative ozone trends reported in the lower stratosphere would be enhanced, roughly by −5% per 20 years. As mentioned above, tropospheric ozone data from Dobson-corrected B–M sonde data have to be treated with caution. Nevertheless, the observed long-term increase of tropospheric ozone (1%–2% per year) would become smaller by roughly 5% per 20 years. This means that ozone trends reported by B–M sondes over the last 30 years would not be affected substantially, even if the pump efficiency of the B–M sonde should have changed.

7. Conclusions

Pump efficiency of the B–M sonde deteriorates significantly at pressures less than 100 hPa. The pump correction used in current WMO standard evaluation procedure does not properly account for this deterioration. Experimental investigations in the laboratory and instrument intercomparisons in the atmosphere show that a higher pump correction is required. With the new pump correction, considerably better agreement is found between ozone profiles from B–M sondes and profiles from lidar, SAGE II, HALOE, and ECC sondes, especially above 27 km (20 hPa). Remaining systematic differences are smaller than 5% up to altitudes of 35 km (6 hPa).

The Dobson normalization spreads out local changes, for example, due to a different pump efficiency correction, over the entire ozone profile. Therefore, errors introduced by the Dobson correction and errors arising from the assumption of constant mixing ratio for the determination of residual ozone should be addressed in the future.

Our results indicate that the 30-yr-old pump correction currently used in the WMO standard evaluation of B–M sondes should be updated. Mixing ratio profiles at Hohenpeissenberg indicate that the WMO standard pump correction may have been too low already in 1968 and 1971. However, this evidence is not conclusive, and further investigations are needed to resolve the question whether B–M pump efficiency has changed since 1965. In any case, the main trend results derived from B–M sonde data below 26 km (20 hPa) are not affected by a possible change of pump efficiency and would remain valid.

Acknowledgments. The 4000 ozone sonde launches and over 700 nights of lidar measurements were only possible through the hard work of many people at the Observatory Hohenpeissenberg. Representative for all of them we would like to thank F. Schönenborn, S. Steiner, and W. Vandersee. W. Steinbrecht greatly appreciates financial support by the German Federal Ministry of Education and Research, Grant 01LO9106/8. Valuable comments from one reviewer pointed out a serious error in the initial manuscript and helped to improve the paper considerably. The SAGE data were obtained from the NASA Langley EOSDIS Distributed Active Archive Center.

REFERENCES


