
Intercomparison of ozone profiles by radiosoundings over Payerne and microwave measurements in Bern: updated report

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Preliminary Remarks

This report is an updated version of the Research Report n° 97-4, *Intercomparison of Ozone profiles by radiosonde soundings over Payerne and microwave measurements in Bern*, completed in April 97.

Its content is, in what concerns the introduction and data reduction (sections **1 and 2**) essentially identical to the previous report version. A new point was brought to the comparison of the ozone profiles (section **3**), where we added a comparison of the microwave and radiosonde measurements to lidar data. Some changes occurred also in the comparison of the column ozone distributions (section **5**), where the atmospheric comparison regions were redefined, and the level above which the constant Volume Mixing Ratio (VMR) extrapolation was assumed for the radiosondes profiles was systematically set at 17 hPa instead of the former 20 hPa.

Moreover the data set was updated, for the microwave as well as for the radiosonde measurements. A new algorithm was used for the microwave data retrieval, allowing to take into account and estimate a possible offset occurring in the spectra, between the intensities measured by two different filter arrays of the detection system. The new retrieval version also includes a two-parameters fit for the calculation of the measurement covariance matrix, which we adapted not only to the transmission of the troposphere as in the previous version, but also to the noise temperature of the system. The whole data set (corresponding to a measurement period between November 1994 and June 1997) was reprocessed, leading to a new homogenized data set over this time period. The new radiosonde data consist of a subset of Payerne ozone sounding data which have been transferred to the SPARC/IOC database. This database has been created for the needs of the Ozone Trend Assessment (OTA) working groups. Their final report will contain a general description of the data processing and quality control.

Some new sections were added to the study: the influence of the a-priori data on the microwave retrieved profiles (section **8**), and the effects of the folding of the radiosonde profiles with the microwave averaging kernel matrixes on the results of the comparison (section **7**), were examined in more details. A comparison of the microwave climatology to SBUV climatological tables was moreover performed (sec-

tion **10**). The details of the derivation of the standard formula for the computation of the residual ozone amounts equivalent to constant VMR profiles are given in Appendix **A**. Appendix **B** contains a conversion plot for altitude levels expressed in [km] into atmospheric pressure levels in [hPa].

1 Introduction

In order to ensure their consistency, atmospheric ozone profiles obtained by balloon-borne radiosoundings have to be scaled to coincident total ozone measurements, as performed by Dobson- or Brewer-Spectrophotometers [WMO]. This is done, for each measured profile, by computing the value of the corresponding column ozone amount and comparing it to the total ozone measurements. Since the radiosoundings are limited in height by the balloon-burst altitude (typ. 35 km), an extrapolation of the measured profile is needed to determine the column ozone amount above this level (residual ozone).

The standard method consists of assuming a constant ozone mixing ratio above the balloon-burst altitude (according to [Dütsch, 1970], the balloon should have reached at least the 17 hPa level). The value of the residual ozone can then be calculated by integrating the constant Volume Mixing Ratio (VMR) profile up to infinity, which leads to the formula (see Appendix A):

$$O_{3,Res} [DU] = 0.79 \cdot p_{o3} \quad (1)$$

where p_{o3} is the last measured ozone partial pressure value [*nbar*]. The total ozone is then obtained by adding $O_{3,Res}$ to the column ozone amount computed by integration of the measured profile up to the balloon-burst altitude. A scaling factor for the radiosonde profiles can thus be defined:

$$f = \frac{\text{Tot. } O_3 \text{ from the total ozone measurements}}{\text{Tot. } O_3 \text{ corresponding to the radiosonde profile}} \quad (2)$$

and the scaling is performed by multiplying the whole radiosonde profile with f (f being usually greater than 1).

The goal of this study is first to investigate the influence of the constant ozone mixing ratio assumption on the scaling of the radiosonde profile, and second to show to which extent actual ozone profiles obtained by simultaneous millimeter-wave radiometric measurements could be used to improve the extrapolation of the radiosondes profiles above the balloon-burst altitude. Due to the subsequent scaling of the profiles to the total ozone measurements, an erroneous assumption for the

constant volume mixing ratio value above balloon-burst could indeed lead to a distortion of the whole profile, by balancing a too high or too low estimated residual ozone value with a too low or too high scaling of the ozone values below the burst altitude respectively. Ozone profiles obtained by coincident millimeter-wave radiometric measurements could therefore be very useful to complement the radiosonde profiles above the balloon-burst altitude and to improve their scaling to a total ozone value.

To investigate these issues, we compared the ozone profiles obtained by balloon-borne measurements using Brewer-Mast ozonesondes at the Swiss Aerological Station in Payerne ($46.80^{\circ}\text{N}/6.95^{\circ}\text{E}$) with coincident profiles computed from observations with the GROUND-based Millimeter-wave Ozone Spectrometer GROMOS between November 1994 and June 1997 in Bern ($46.95^{\circ}\text{N}/7.45^{\circ}\text{E}$, 40 km from Payerne). Continuous measurements of ozone profiles using the GROMOS instrument are performed at the Institute of Applied Physics of the University of Bern since November 1994. The overall bandwidth and resolution of this radiometer allows to determine ozone profiles with an altitude resolution of 10 to 15 km and a time resolution of 1 to 2 hours in the altitude range between 12 and 80 km. The retrieval of ozone profiles from radiometric measurements is limited in the altitude range because of extreme pressure broadening at low altitudes (< 12 km) and by vanishing pressure broadening of the measured emission line at high altitudes (> 85 km). Actual NMC temperature and pressure profiles with 500 meter resolution are used for the retrieval of ozone profiles from the millimeter-wave measurements. The NMC data were chosen rather than the Payerne measurements for the microwave retrieval because they provide temperature and pressure values up to 45 km, with daily operational access; these profiles correspond indeed in general quite well to the Payerne measurements. For a review of the microwave technique for atmospheric remote sensing see [Kämpfer, 1995], and for a description of the instrument, see for example [Lobsiger and Künzi, 1986], [Peter and Kämpfer, 1995] and [Peter et al., 1996]. The retrieval of the ozone profiles from the microwave observations was performed according to the Optimal Estimation Method [Rodgers, 1976].

2 Data Reduction

The main difficulty in comparing ozone profiles measured with different monitoring methods is to adjust their different altitude resolution. Ozone profiles obtained by balloon-borne radiosoundings have an altitude resolution reaching 50 meters (corresponding to the measurement points), whereas profiles of independent information obtained by microwave observations have a typical altitude resolution of 10 km in the same altitude range.

The ozone profiles retrieved from microwave measurements are indeed characterized by values calculated inside defined atmospheric layers (called “retrieval layers”). Inside each retrieval layer, the ozone value is assumed to be constant.

The retrieval layers cover the entire altitude range of the retrieved ozone profiles. The set of retrieval layers used for the inversion of the measured microwave spectra form the “retrieval grid”. For the retrieval of ozone profiles from the GROMOS measurements, the width of these layers was selected between 2 and 3 km in the altitude range 12 to 78 km. The retrieved profiles are hence characterized by 25 values over the altitude range. (N.B.: the width of the retrieval layers is not representative for the altitude resolution of the microwave profiles. The resolution of the profiles is determined by the overall system characteristics and is lower than the retrieval layers width).

In order to compare the data obtained with the two different measurement methods, the high altitude-resolution radiosonde profiles have to be reduced to the microwave retrieval grid. This is done by calculating, for each microwave retrieval layer, the equivalent ozone mixing ratio inside the layer for the radiosonde profiles using the Curtis-Godson relation (see [Kuntz, 1996]):

$$\overline{VMR} = \frac{\sum_{n=i}^{j-1} \left(\frac{vmr(n) * P(n)}{T(n)} \right)}{\sum_{n=i}^{j-1} \frac{P(n)}{T(n)}} \quad (3)$$

This weighted-mean preserves the column ozone amounts inside each retrieval layer. \overline{VMR} [ppm] is the equivalent ozone volume mixing ratio value for the considered retrieval layer, $vmr(n)$ [ppm] is the volume mixing ratio measured by the radiosonde at the altitude level n inside the layer, and $P(n)$ and $T(n)$ are the pressure [Pa] and

temperature $[K]$ measured by the sonde at the same level, respectively. The indices i and j correspond to the bounding altitudes of the retrieval layer.

In this way, we can produce an equivalent "step-profile" to each ozone profile measured by the radiosondes, the step-profiles being characterized by the same number of values as the retrieved microwave profiles. These profiles were then used to perform the comparison. Figure 1 shows an example of coincident microwave and radiosonde step-profiles: inside each retrieval layer, the ozone VMR values are represented constant, as the same value is applying to the whole layer. Above the balloon-burst altitude, the radiosonde profile is extended as a constant VMR profile, according to the standard assumption (section 1).

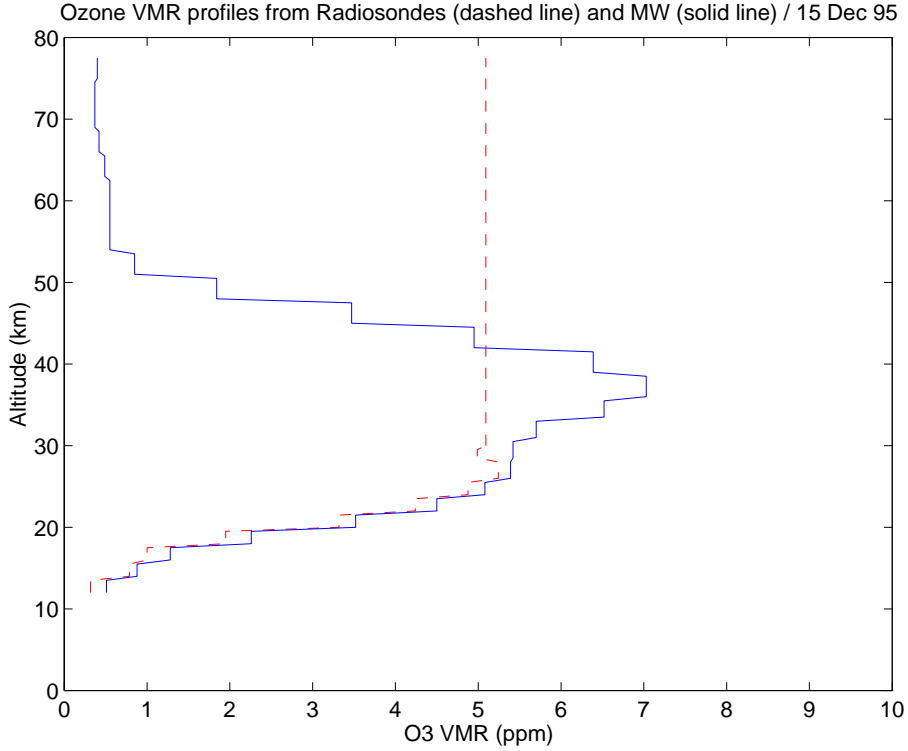


Figure 1: Coincident ozone step-profiles obtained from radiosondes (dashed line) and microwave (solid line) measurements. The radiosonde profile has been reduced to the microwave retrieval grid, and extrapolated into a constant VMR profile above the balloon-burst altitude (according to the standard assumption).

3 Ozone Profiles Comparison

3.1 Comparison Method

We first compared the microwave and radiosonde profiles (transformed into step-profiles as described in the previous section) in a direct way, by computing for each day of coincident measurements the difference between the corresponding ozone VMR values at each retrieval layer.

To ensure a good temporal coincidence with the radiosonde measurements, which are performed in Payerne three times a week at noon (12:00 UT), only the midday ($12:00 \text{ UT} \pm 2 \text{ hours}$) microwave profiles for the matching measurement days were selected and taken into account for the comparison. In the best cases, 3 microwave ozone profiles were selected for each radiosonde measurement, from which the mean value was used. The four hours time span, corresponding to the 3 microwave ozone profiles, allow to attenuate the possible differences between the Bern and Payerne measurements due to the fact that both instruments do not observe the same atmospheric air volume at the same time.

For the time period between November 1994 and June 1997, about 310 matching measurement days were available. The mean difference profile over the two and a half years was computed, providing general information about the characteristics of the results obtained with one measurement method with respect to the other.

3.2 Results

The comparison showed a good overall agreement between the ozone profiles obtained with the two different monitoring methods. For example, the ozone profiles obtained by the microwave and radiosonde measurements on January 31 and February 5, 1997 are shown in Figure 2. The radiosonde and microwave profiles reproduce well the same features up to about 27 km ($\sim 20 \text{ hPa}$), taking into account the different altitude resolution obtained with the two monitoring methods (the microwave profile, with much lower altitude resolution than the radiosonde measurement, appears to be "smoothed" in comparison to the radiosounding). Below 27 km ($\sim 20 \text{ hPa}$), the mean absolute difference, expressed in VMR, between the respective profiles

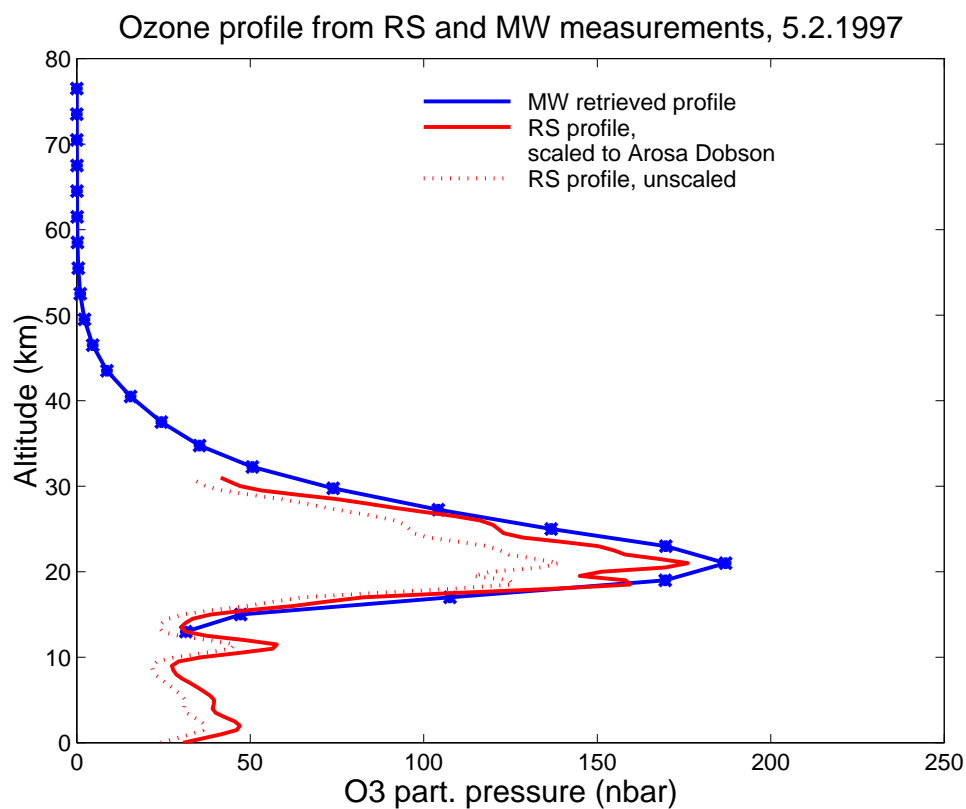
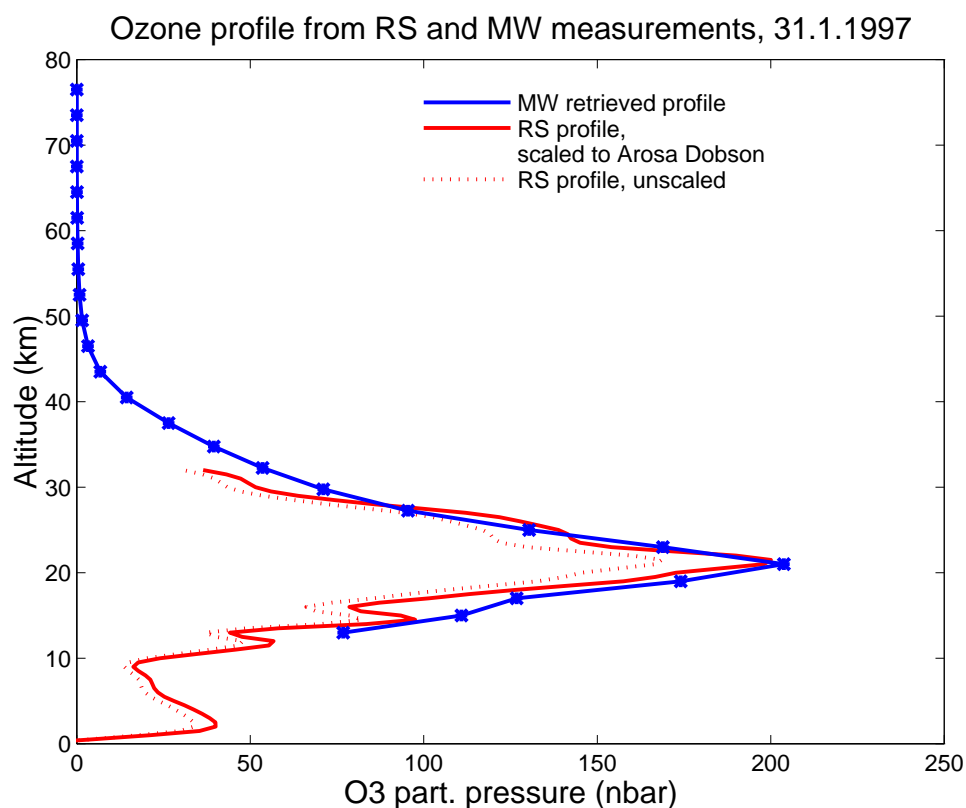


Figure 2: Ozone profiles as computed from radiosonde and microwave measurements, for January 31 and February 5, 1997. The ozone quantities are represented here in nbar (ozone partial pressure) which shifts the ozone maximum to lower altitudes in comparison to the profiles represented in ppm (ozone volume mixing ratio).

during the whole comparison period does not exceed 0.2 ppm (Figure 3). Above this altitude, the ozone values measured with the two instruments start however to deviate from each other and the absolute difference between the coincident measurements increases rapidly with altitude. This increasing difference with altitude is also to be seen in the representation of the relative difference between the mean respective profiles (see Figure 12), reaching 10 % disagreement between the ozone values measured by the two methods at 30 km (~ 15 hPa).

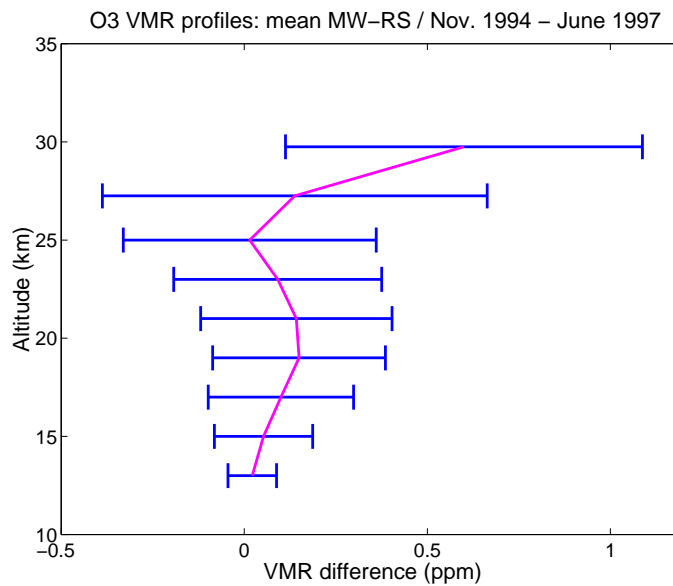


Figure 3: Mean difference [ppm] between the coincident radiosonde and microwave ozone profiles, over the time period Nov. 1994 - June 1997. The error bars are given by $\pm \sigma$ of the values at each altitude.

A priori, this discrepancy could as well be attributed to a microwave retrieval artifact as to an underestimation of the ozone amounts by the radiosoundings above a certain altitude level. The freezing of the Brewer-Mast chemical solution (KI) in the sonde (see [Stübi et al., 1996]), or a too low correction factor for the sonde pump efficiency above a certain altitude (see [Steinbrecht, 1997] and [De Backer et al., 1996]) could account for it. In order to find out to which of the two measurement methods this discrepancy should be attributed, we performed a further comparison between the respective radiosonde and microwave measurements and the Hohenpeissenberg (47.80°N/11.07°E) and Observatoire de Haute-Provence (43.55°N/5.45°E) ozone lidar data. For a description of the Haute-Provence DIAL lidar measurement system,

see [Godin et al., 1989], and for results obtained during the SESAME campaign, see [Godin et al., 1995]. For a description of the DIAL lidar system at the Meteorological Observatory Hohenpeissenberg see [Claude and Wege, 1989].

For each radiosounding, the lidar data were selected as close as possible to the time of the sounding, that is, around 20:00 UT ($20:00 \text{ UT} \pm 4 \text{ hours}$) on the radiosounding day. Considering lidar measurements and radiosoundings, exact simultaneous ozone measurements can indeed not be found since the latter are performed around noon and the lidar measurements take place at night. The mean values of the selected lidar profiles for each radiosounding were computed and taken into account in the comparison. Using this procedure, 95 measurements coinciding with radiosounding days were found for the Hohenpeissenberg lidar, and 100 for the Observatoire de Haute-Provence lidar. The results are shown in Figure 4.

Figure 4 (upper part) shows the mean difference between the radiosonde profiles (RS), and the Hohenpeissenberg (HO) and Observatoire de Haute-Provence (OHP) lidar data over different comparison periods. The HO lidar data span between November 1994 and April 1996; the OHP lidar data between November 1994 and December 1996. The mean difference between the coincident radiosondes and microwave ozone profiles between November 1994 and June 1997 from Figure 3 is given for comparison. Even though they were not calculated for the same time period, the mean differences between the radiosonde measurements and the lidar HO and OHP ozone profiles both diverge above 25 km. The discrepancy increasing with altitude above a certain level is hence not only a characteristic of the comparison with the microwave data, indicating a probable tendency of the radiosonde measurements to underestimate the ozone values above this level.

This feature is on the contrary not reproduced in Figure 4 (lower part), where the mean difference between the microwave data, and the Hohenpeissenberg and Observatoire de Haute-Provence lidar measurements is represented (the data selected for each instrument are the same as in the Figure 4 (upper part)). The comparison with both lidar instruments shows negative values of the difference between 25 and 30 km, indicating rather a tendency of the microwave measurements to underestimate the ozone values at those altitudes. However, a tendency of the microwave

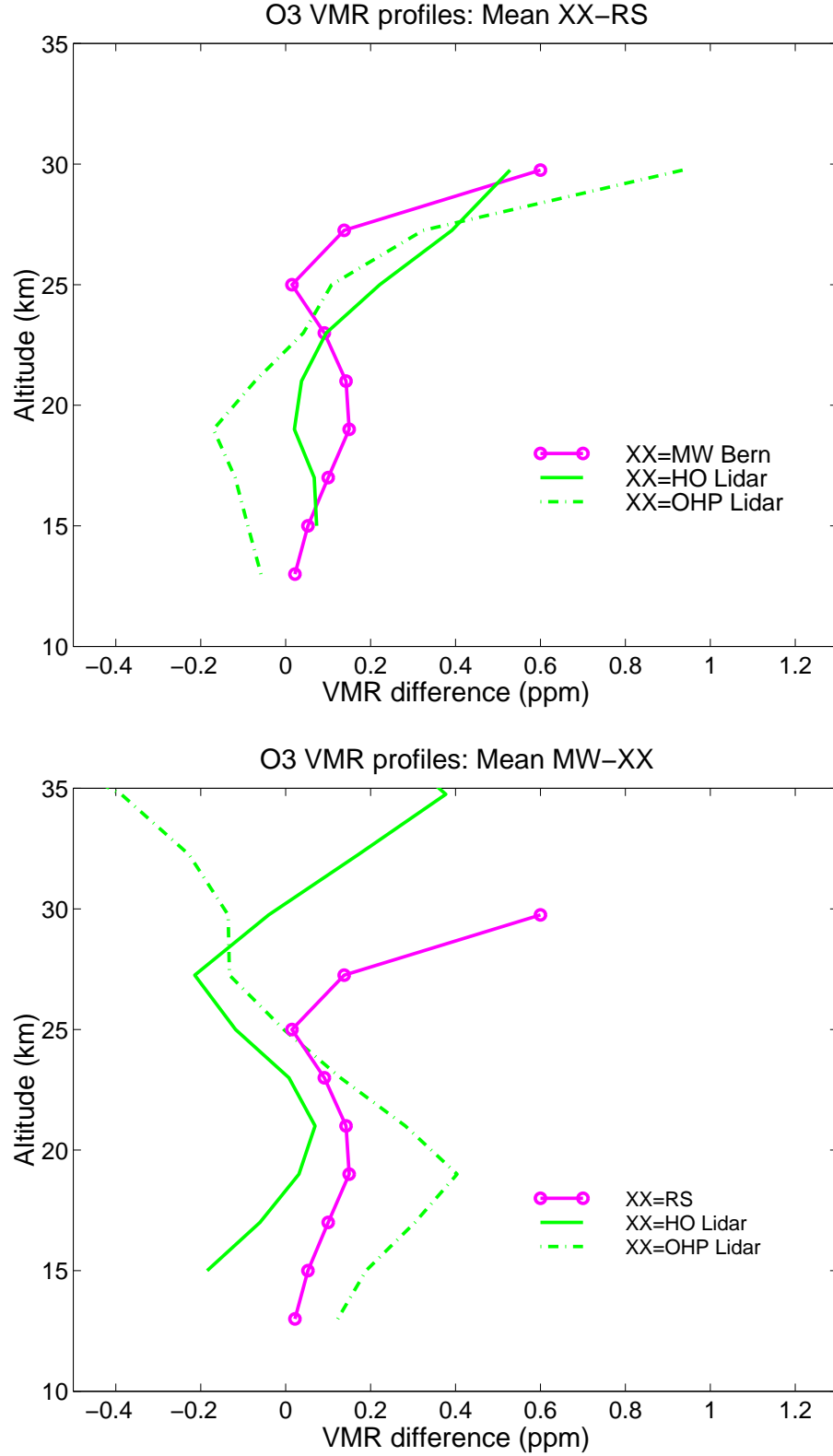


Figure 4: Mean difference [ppm] between (upper part) the Payerne radiosonde (RS) measurements, and the Hohenpeissenberg (HO) and Observatoire de Haute-Provence (OHP) lidar ozone profiles, and (lower part) the Bern microwave (MW) measurement and the same lidar data, respectively. The altitude range of the comparison with the Payerne radiosoundings is limited by the altitude range of the soundings themselves.

measurements to overestimate the ozone amounts between 17 and 22 km is revealed.

Considering this, we conclude that the discrepancy increasing with altitude observed between the microwave and the radiosonde data above 27 km is rather due to a systematic underestimation of the ozone values by the radiosoundings above this altitude than to a microwave retrieval artifact. These results are consistent with other studies (see [De Backer et al., 1996]), which showed that the standard correction applied to the ozone profiles measured with Brewer-Mast sondes underestimates the loss of pump efficiency at high altitudes. Insufficient correction for loss of pump efficiency can lead to ozone values up to 10 % too low at 10 hPa (~ 31 km) (De Backer, private communication, 1997; see also [De Backer et al., 1996]). For a further comparison between the Hohenpeissenberg lidar data and Brewer-Mast radiosonde ozone profiles see [Claude and Wege, 1989], and for another comparison between microwave measurements and lidar data, see [Tsou et al., 1995].

4 Total Ozone Comparison

4.1 Comparison Method

In a second step, we compared the total ozone amounts corresponding to the ozone profiles measured with the two monitoring methods to the coinciding total ozone measurements with the Arosa-Dobson Spectrophotometer. Since the radiosonde profiles used in this study have been previously scaled to the Arosa total ozone measurements, the total ozone value computed by integration of the corresponding step-profiles should indeed give a very close value to the Arosa results. We used this property to check our calculations of the column ozone values corresponding to the measured profiles.

The calculation of the column ozone values was performed as following:

the radiosonde step-profiles were integrated up to the 17 hPa level, which we set as a systematic upper-limit for the integration:

$$O_{3,RS} = \frac{T_o}{P_o} \cdot 10^5 \int_{h(\text{ground})}^{h(17\text{hPa})} vmr_{RS}(h) \cdot \frac{P(h)}{T(h)} dh = -\frac{T_o}{\rho_o g} \cdot 10^5 \int_{P(\text{ground})}^{17\text{hPa}} vmr_{RS}(P) \cdot \frac{1}{T(P)} dP \quad (4)$$

where the barometric equivalence was used to change dh into dP (see Appendix A). T_o and P_o are the standard temperature (273 [K]) and pressure ($1.013 \cdot 10^5$ [Pa]), respectively; $vmr_{RS}(h)$ [ppm $\cdot 10^{-6}$] is the ozone volume mixing ratio measured by the sonde at the altitude h , and $P(h)$ [Pa] and $T(h)$ [K] are the atmospheric pressure and temperature measured by the sonde at the same altitude. $h(17hPa)$ is the altitude of the 17 hPa pressure level; $h(ground)$ is the launching site altitude (491 m. a.s.l. for Payerne) and $P(ground)$ is the ground atmospheric pressure at the launching site.

The residual ozone was then calculated using

$$O_{3,Res} = 0.79 \cdot p_{o3}(17 hPa) \quad (5)$$

where $p_{o3}(17 hPa)$ is the ozone partial pressure measured at 17 hPa and expressed in [mbar] (see Appendix A).

For each radiosonde profile, the total ozone value is then given by the sum of $O_{3,RS}$ and $O_{3,Res}$:

$$O_{3,Tot} = O_{3,RS} + O_{3,Res} \quad (\text{Radiosonde profiles}) \quad (6)$$

For the microwave profiles, the total ozone was calculated by integrating the step-profiles up to 78 km:

$$O_{3,MW} = \frac{T_o}{P_o} \cdot 10^5 \int_{12km}^{78km} vmr_{MW}(h) \cdot \frac{P(h)}{T(h)} dh \quad (7)$$

$vmr_{MW}(h)$ is here the ozone volume mixing ratio profile resulting from the inversion of a microwave spectra; and $P(h)$ and $T(h)$ are the NMC pressure and temperature profiles over Bern for the corresponding day. The ozone amount below 12 km was calculated using the value corresponding to the coincident radiosonde profile:

$$O_{3,<12km} = \frac{T_o}{P_o} \cdot 10^5 \int_{h_o}^{12km} vmr_{RS}(h) \cdot \frac{P(h)}{T(h)} dh \quad (8)$$

The total ozone corresponding to the each microwave profile was then defined as

$$O_{3,Tot} = O_{3,MW} + O_{3,<12km} \quad (\text{Microwave profiles}) \quad (9)$$

These values were then compared to the Arosa total ozone measurements.

N.B.: For the numerical application, the integrals in (4), (7) and (8) were replaced by sums. The radiosonde temperature and pressure profiles were interpolated to 500 m. intervals; the NMC temperature and pressure profiles were the same as those used for the retrieval of the ozone profiles from the measured microwave spectra and are also interpolated to 500 m. The ozone profiles for both microwave and radiosonde measurements were kept as step-profiles (see section 2) and a constant volume mixing ratio value was assumed within each retrieval layer (many points with the same vmr value, with 500 m. intervals between the points, were then considered inside each layer). dh was then replaced with Δh , with $\Delta h = 500$ m.

4.2 Results

The comparison of the radiosonde- and microwave-profiles equivalent total ozone amounts to the Arosa values showed slight differences between the results obtained with the two methods. Figure 5 shows the relative difference between the total ozone values computed from the respective profiles and the Arosa value for each day of coincident measurements, represented as a function of time.

The total ozone values corresponding to the radiosonde profiles show a good general agreement with the coincident Arosa measurements. The mean difference between the calculated and measured values is less than 1 %, with a spread of ± 5 % which could be due to the reshaping of the measured radiosonde profiles into step-profiles. Some single values for the radiosonde total ozone are however more than 5 % lower than the Arosa values, indicating that for those profiles the altitude above which the radiosonde profile was assumed constant (this altitude was systematically taken at the 17 hPa level in this study) was set too high. For those profiles, the ozone value measured by the radiosonde was indeed too low at 17 hPa, which led to an underestimation of the residual ozone and hence to a too low total ozone value when the systematic procedure for the total ozone calculation was used. This is not the case for the calculation of the total ozone as it is performed during the operational scaling procedure of the soundings at the Swiss Meteorological Institute. There, the real shape of the profile is taken into account and the level above which the residual ozone is calculated is adjusted according to the measured VMR values. This shows

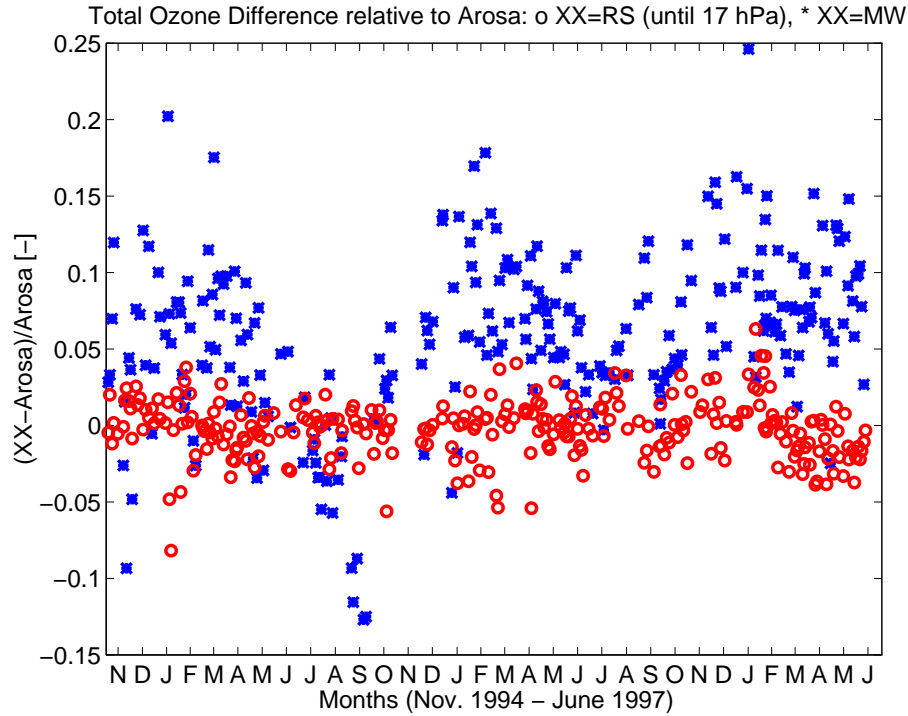


Figure 5: Deviation of the calculated total ozone values relative to the Arosa measurements, between November 1994 and June 1997. The mean difference between the calculated radiosonde total ozone values and the corresponding measurements at Arosa is -0.2 % (Arosa > Payerne), whereas the microwave total ozone amounts are on the mean 5.8 % higher than the Arosa values.

however the importance of the choice of the appropriate level for the calculation of the residual ozone and its influence on the corresponding total column ozone values.

Figure 5 also shows that the total ozone amounts calculated from the microwave profiles are on the mean by 5.8 % higher than the total ozone values measured at Arosa over the comparison period. This difference is mainly due to an overestimation of the ozone values by the microwave retrieval between 17 and 22 km (in the next chapter, we will show that the mean difference in column ozone between the radiosonde and the microwave profiles in the altitude range 12 - 24 km is 8 DU, which corresponds to 4.8 % difference between the two methods in this altitude range). A critical period appears in the late summer 1995, where the total ozone values measured by the microwave instrument are much too low in comparison to the Arosa values. The altitude difference between Arosa and Payerne and between Arosa and Bern was not taken into account in this calculation, what should account for a slight shift between the calculated total column ozone and the Arosa value.

The column ozone difference between the Arosa and Payerne measurements due to the altitude difference of the two sites is between 2.5 and 6.5 DU (estimated from the radiosonde measurements) depending on the season, which corresponds to 1 to 2 % relative difference. This difference is not to be seen in Figure 5 between the Arosa and the Payerne, since this effect is counterbalanced by the underestimation of the residual ozone for some profiles due to the too low integration limit at 17 hPa. This effect is estimated to account for 1.8 % underestimation of the total ozone values in comparison to the results obtained by integrating the radiosondes profiles up to the balloon-burst level.

5 Comparison of the Column Ozone Distribution Over the Altitude Range

5.1 Comparison Method

In order to compare the distribution of the column ozone amounts over the altitude range covered by the radiosonde and microwave measurements, we divided the atmosphere between 12 and 78 km into 4 different regions within each of them the respective partial column ozone amounts were computed and compared.

The upper (4th) region was defined as the altitude range in which the constant VMR extrapolation was assumed for the radiosonde measurements, i.e., the atmospheric region corresponding to the residual ozone. Its lower bounding limit was hence set at the 17 hPa level (~ 28 km), and its upper boundary at infinity. There, the partial column ozone (residual ozone) value was calculated according to (5) for the radiosonde profiles, whereas the microwave profiles were integrated between 17 hPa and 78 km to compute the equivalent value, using (10).

The atmosphere lower down was further divided into 3 other regions:

Region 1: 12 km (194 hPa) to 19.5 km (60 hPa),

Region 2: 19.5 km (60 hPa) to 24 km (30 hPa), and

Region 3: 24 km (30 hPa) to 28 km (17 hPa).

The regions boundaries correspond to standard aerological levels. Inside each

of these regions, the value of the partial column ozone corresponding to both radiosonde and microwave measurements was computed using:

$$O_{3,Part} [DU] = 10^5 \cdot \frac{T_o}{P_o} \cdot \sum_{n=i}^{j-1} \frac{vmr(n)P(n)}{T(n)} \cdot \Delta h \quad (10)$$

where i and j are the indices corresponding to the bounding altitudes of the considered comparison region. The other symbols are defined as in section 4.1; $vmr(n)$ (in $[ppm] \cdot 10^{-6}$) is the volume mixing ratio value at the point n of the radiosonde or microwave step-profile, n situated inside the considered comparison region, and $P(n) [Pa]$ and $T(n) [K]$ are the pressure and temperature at the same altitude. Δh represents the vertical distance separating two characteristic points of the considered profiles ($\Delta h = 500$ m.).

5.2 Results

Figure 6 shows the relative differences obtained between the radiosonde and microwave partial column ozone values inside each comparison region, as a function of time between November 1994 and June 1997. The mean results are given in Table I, where the mean relative differences between the radiosonde and microwave partial column ozone amounts calculated inside the different comparison regions, and the corresponding mean standard deviations over the comparison period are represented. The mean values (in Dobson Units) inside each region and for each measurement method are also given. Below 12 km, the partial ozone values can be calculated only for the radiosonde profiles (41.0 ± 10.1 DU on the mean).

The best agreement between the partial column ozone amounts corresponding to the coincident microwave and radiosonde measurements is found between 24 and 28 km, where the mean difference is less than 1 %. The agreement is also very good between 19.5 and 24 km, where the mean difference is about 2 % over the whole comparison period. Below 19.5 km, the disagreement between the millimeter-wave and radiosonde partial column ozone values increases, probably due to the overestimation of the ozone amounts by the microwave retrieval between 17 and 22 km (see

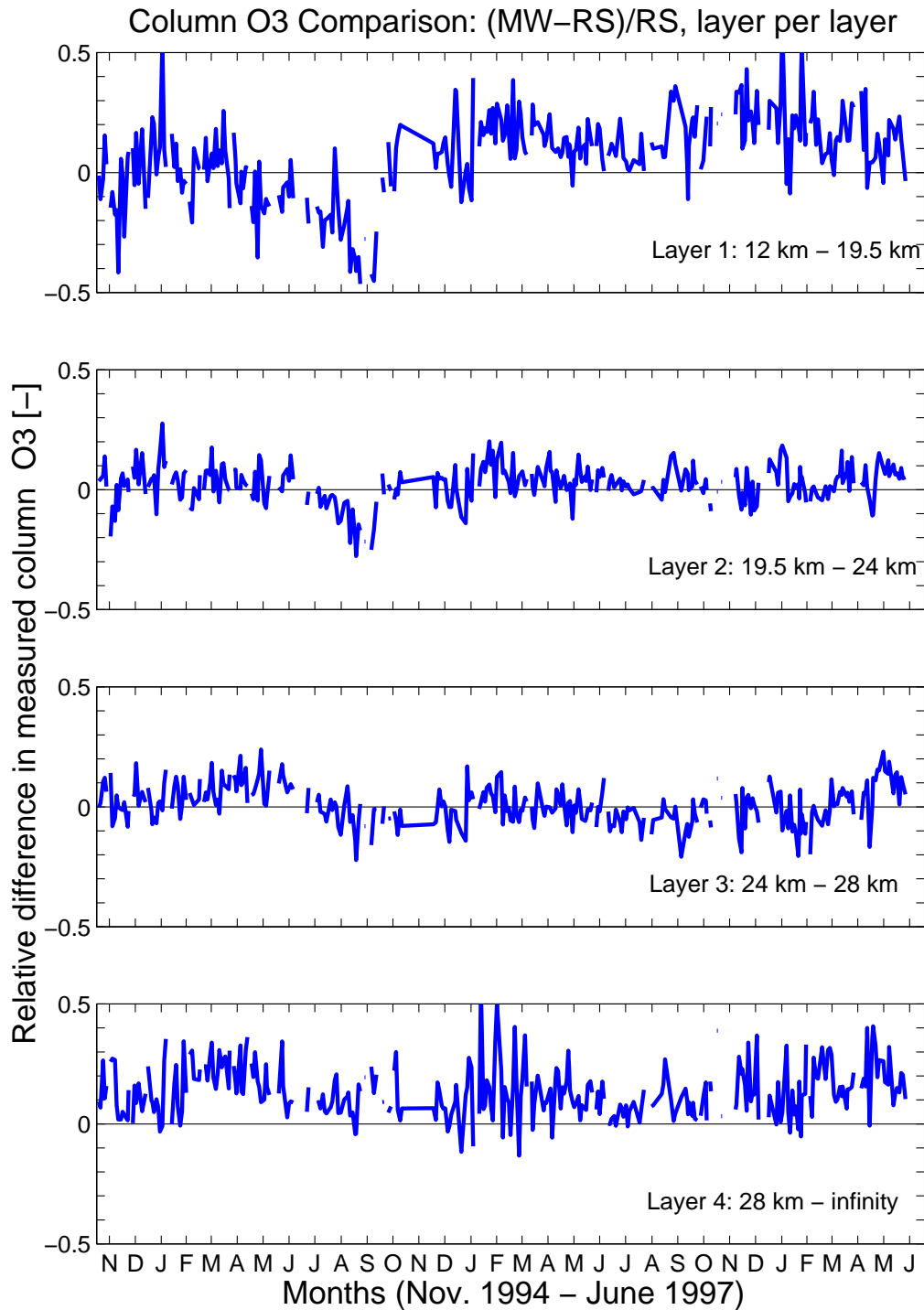


Figure 6: Comparison of the results obtained by the radiosonde and microwave instruments, represented for each comparison region and for the two and a half years of the comparison (Nov. 1994 to June 1997). Above 17 hPa, the radiosonde values for residual ozone are on the mean by 11 % lower than the microwave values. The best agreement between the two measurement methods is found between 24 km and 28 km, where the difference between the respective partial ozone values is on the mean less than 1 %.

<i>Comparison Region</i>	<i>Region 1:</i> 12 - 19.5 km (194-60 hPa)	<i>Region 2:</i> 19.5 - 24 km (60 - 30 hPa)	<i>Region 3:</i> 24 - 28 km (30 - 17 hPa)	<i>Region 4:</i> 28 - 78 km (17 - 0 hPa)	<i>Total</i> 12 - 78 km (194 - 0 hPa)
$\frac{mean(mw-rs)}{mean(mw)}$	+7.2 %	+2.2 %	+0.7 %	+11.3 %	+6.1 %
$\frac{std(mw-rs)}{mean(mw)}$	15.7 %	7.4 %	8.0 %	8.3 %	6.9 %
$mean(mw)$	90.0 DU	74.6 DU	43.5 DU	82.6 DU	290.8 DU
$mean(rs)$	83.6 DU	73.0 DU	43.2 DU	73.3 DU	273.0 DU

Table I: Mean differences between the radiosonde and microwave partial column ozone amounts inside the different comparison regions.

section 3). Considering the relative difference, this overestimation is less important in region 2 than in region 1, where the absolute column ozone amounts are lower; this explains why the difference between radiosonde and microwave measurements is decreased in the second region (see also Figure 12).

The most interesting point of this comparison are the results obtained in the last (fourth) comparison region, which corresponds to the residual ozone region. There, the constant VMR assumption was used for the radiosonde profiles, while for the microwave instrument the retrieved ozone profiles were integrated up to 78 km. The comparison of the partial column ozone amounts in this layer provide thus information about the validity of the constant VMR assumption used to calculate the residual ozone for the radiosonde profiles.

The results show more than 10 % mean difference between the radiosonde and microwave partial column ozone calculated above 17 hPa. Now, we showed in section 3 that the radiosonde profiles tend to underestimate the ozone values above 27 km (~ 20 hPa). The question arising here is then: is this disagreement due to the underestimation of the ozone values by the radiosonde profiles above 27 km, or is it due to the different methods used to calculate the residual ozone values for the

radiosonde and microwave profiles (use of a constant vmr approximation according to (5) for the radiosonde profiles, and integration of the retrieved profile according to (10) for the microwave measurements) ?

Further investigations using standard temperature, pressure and ozone profiles as the CIRA'86 profiles for all months of the year showed that the relative differences between the ozone amounts integrated from the standard profiles between 17 hPa and 110 km, and the residual ozone amounts calculated for the same profiles using the constant VMR assumption and Eq. (5), oscillate between +10 and +13.5 %, as seen in Figure 7 (with more residual ozone for the integrated profiles than for the calculated values). Two standard ozone profiles were used, one for the winter (October to March) and one for the summer (April to September). These two standard profiles are shown in Figure 8, together with the constant VMR profiles above 17 hPa.

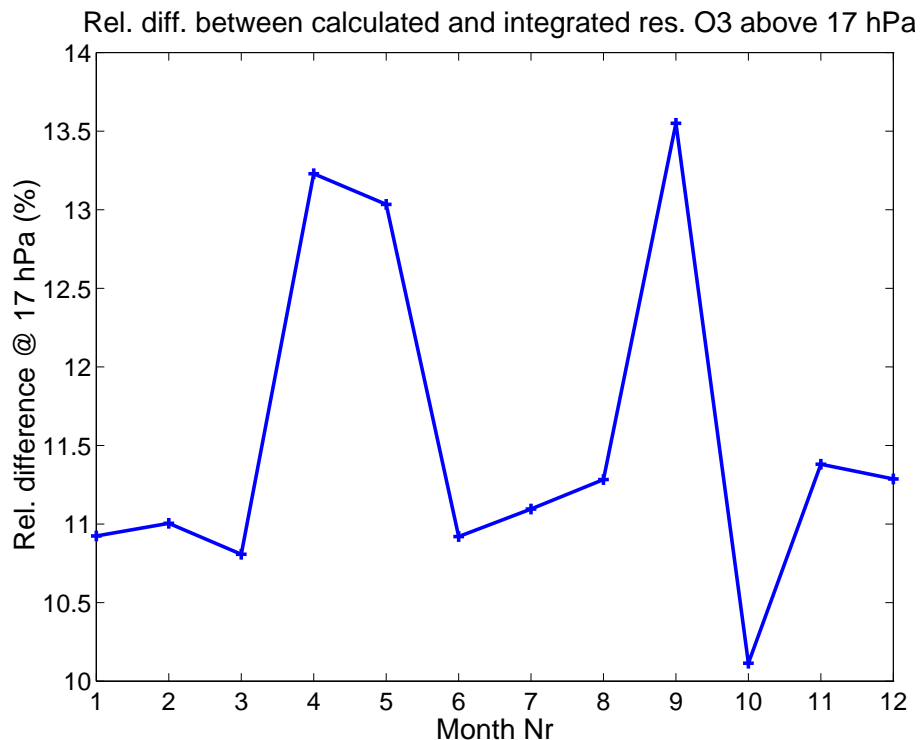


Figure 7: Relative difference between calculated (using (5)) and integrated (using (10)) residual ozone above 17 hPa, from standard ozone, temperature and pressure profiles.

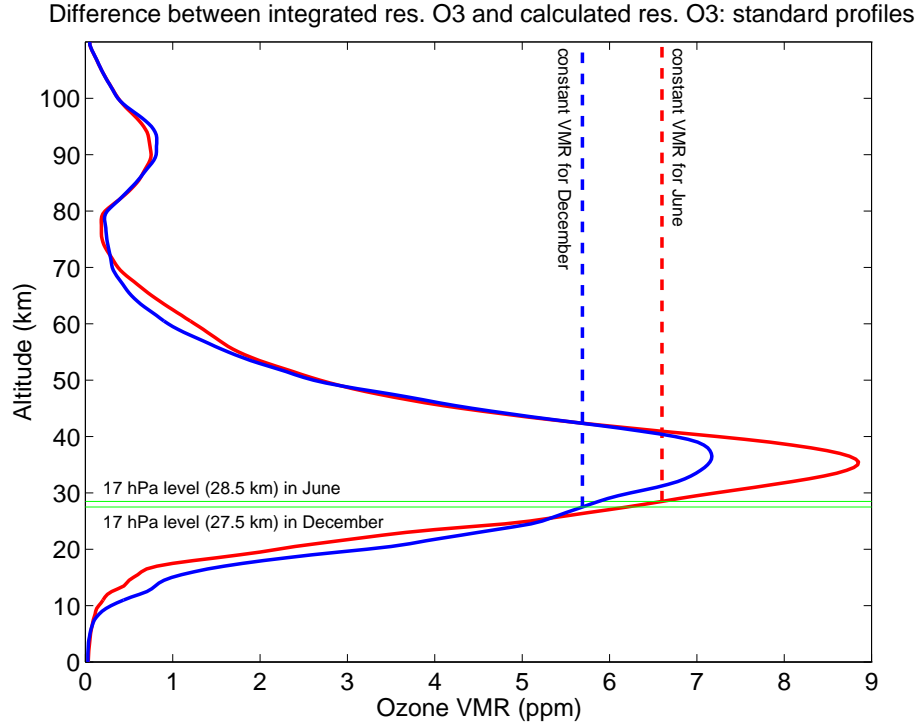


Figure 8: Standard ozone VMR profiles, represented with the constant VMR profiles extrapolated above 17 hPa. More residual ozone is obtained by integrating the true profile (solid curve) between 17 hPa and 110 km than by integrating the constant VMR extrapolation (dashed curve) between 17 hPa and infinity (the last being equivalent to using Formula (5)). The first method was used in this study to compute the residual ozone from the microwave measurements; the second ozone was used for the radiosonde profiles.

We conclude from this that the large difference obtained between the respective microwave and radiosonde residual ozone amounts above 17 hPa is due to the different methods used to compute this value, namely, to the constant VMR approximation used above 17 hPa for the radiosoundings. By looking at Figure 9, one can see that when the standard profiles are considered, this difference diminishes when the residual ozone limit is raised towards higher altitudes (i.e. towards the ozone maximum), up to about 10 hPa (~ 31 km).

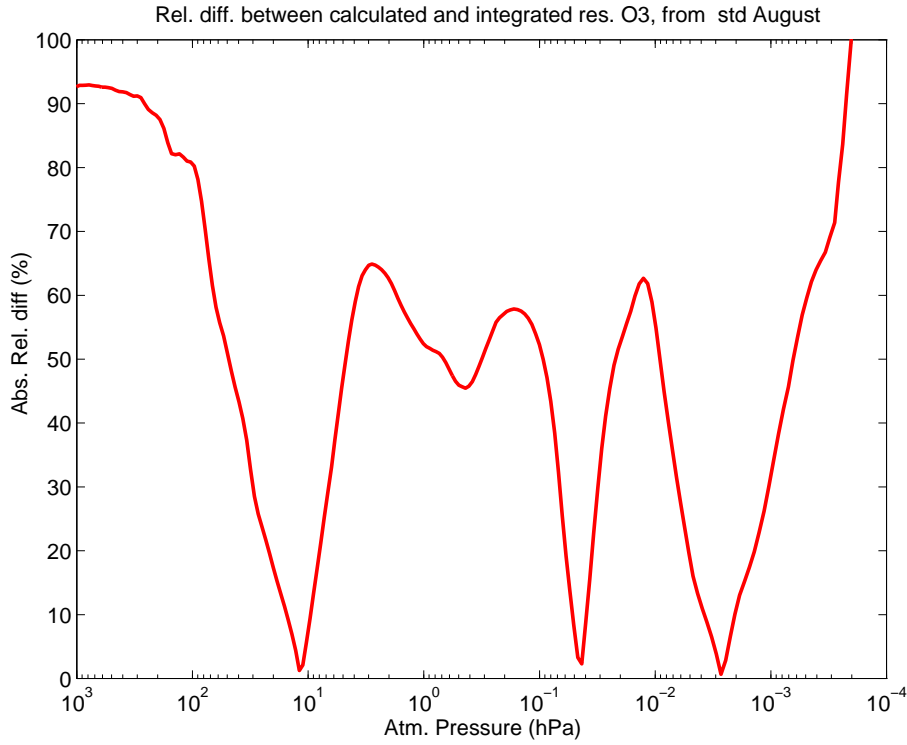


Figure 9: Absolute relative difference between calculated and integrated residual ozone, calculated using standard August temperature, pressure, and ozone profiles, as a function of the altitude (here the corresponding atm. pressure) above which the residual ozone was integrated. The difference is less than 10 % between 17 and 8 hPa; the altitude of the minimum difference oscillates between 9 and 12 hPa (30-31 km) depending on the season.

Two critical points show up for the application of these considerations to the real radiosonde profiles:

- Not all the radiosoundings reach the 10 hPa level;
- The radiosonde profiles underestimate the ozone amounts above 27 km (20 hPa) due to the too low pump corrections factors applied to the profiles at these altitudes. Indeed, the profiles VMR values increase too slowly with altitude or even reach a maximum value well below the end of the sounding. To raise the altitude above which the residual ozone is calculated doesn't help much then, since the VMR values do not increase (or increase too slowly) with altitude, preventing the raising of the residual ozone values which would be expected. The minimum which is obtained in the difference using the standard profiles around 10 hPa (Figure 9) is then not reproduced in the real case.

Indeed, raising the limit level above which the residual ozone was calculated (up to the last measurement point of each radiosonde profile) produced a mean difference of 11.7 % with the microwave equivalent values for the residual ozone, which is no improvement in comparison to what was obtained with the limit at 17 hPa. Moreover, according to the results obtained using standard profiles (Figure 9), the sign of the difference between the results obtained with the two calculation methods should change if the integration limit for the residual ozone is moved towards higher altitudes (higher than 31 km), which was not observed when the real radiosonde profiles were used. This shows that no improvement is to be expected in the estimation of the residual ozone for the radiosonde profiles (using (5)) by raising the altitude above which it is calculated.

To resume, we showed that:

1. The residual ozone calculated for the radiosonde profiles according to (5) above 17 hPa is on the mean about 11 % lower than the equivalent value computed by integrating the microwave ozone profiles.
2. This difference is mainly due to the different methods used for the calculation of the residual ozone for the profiles gained with the two instruments.
3. According to the results obtained with standard profiles, it would be possible to lower this difference down to a few percents if the residual ozone is calculated (with constant VMR approximation) above the 10 hPa level instead of above 17 hPa. This was not the case when the Payerne radiosonde profiles were used: raising the integration limit of the residual ozone up to the last sounding level of each profile resulted in very similar results to those obtained with a limit at 17 hPa.
4. The improvement of the estimation of the residual ozone by raising the integration limit is not possible because of the underestimation of the ozone values above 20 hPa (27 km) by the Payerne radiosoundings.
5. The underestimation of the ozone values by the radiosoundings above 20 hPa is due to a too low correction of the measured profiles for the loss of the pump efficiency of the Brewer-Mast ozonesondes above this altitude.

Another computation method than the use of the constant VMR approximation has then to be found if a better estimation of the residual ozone for the radiosoundings is needed. 11 % underestimation of the residual ozone leads to about 3 % underestimation of the total column ozone; this in turn results in an overscaling of the whole profile by about 3 %. (Those values apply to the raw radiosonde measurements too, since the shape of the profile and therefore the relative quantities are conserved by the scaling). In the next section, we will show in which way the microwave measurements could be used to improve this estimation, and consequently to improve the scaling of the radiosonde profiles to the total ozone measurements. We will also try to estimate the main changes that would affect the results if another scaling method than the standard scaling to the total ozone measurements was used.

6 How to Improve the Scaling of the Radiosonde Profiles using the Microwave Measurements

Two possibilities arise to improve the scaling of the radiosonde profiles: the first one consists of improving the estimation of the residual ozone itself, and then to perform the scaling to the total ozone measurements as usual; the second one is to find another method allowing to perform the scaling without need of a calculation of the total ozone values. Ozone profiles gained by coincident microwave radiometric measurements could indeed be extremely useful both to complement the radiosoundings and to perform their scaling, as they provide real-time measurement data up to altitudes well above the balloon-burst. If performed close enough in space and time, microwave and radiosonde measurements refer to the same actual atmospheric ozone distribution and can consequently be directly compared to each other.

In the previous sections, we showed that a good agreement is generally found between the Payerne radiosoundings and the corresponding microwave ozone measurements in Bern at altitudes between 60 hPa (19.5 km) and 17 hPa (28 km). A tendency of the microwave results to overestimate the ozone amounts between 17 and 22 km was also found, as well as an underestimation of the residual ozone (above 17 hPa) for the radiosonde profiles due to the constant VMR approximation.

How could then the Bern microwave profiles be used to complement the Payerne soundings ?

We tested 3 different possibilities.

6.1 Different Scaling Methods

6.1.1 Replacing the constant VMR extrapolation above 17 hPa by the microwave profile

We first simply tried to replace the constant VMR assumption for the radiosonde profiles above 17 hPa by the corresponding microwave profile up to 78 km. The microwave profile was rescaled to the unscaled radiosonde profile by dividing the profile VMR values by the radiosonde scaling factor. (The unscaled radiosonde profiles are the profiles obtained by dividing the scaled radiosonde profiles by the scaling factor. The scaling factor of the Payerne radiosoundings is defined as in (2), with the Arosa Dobson measurements for the measured total ozone values). The sum of the integrated unscaled radiosonde profiles below 17 hPa and the microwave rescaled residual ozone was then computed, giving a value for the unscaled radiosonde total ozone. This value was then compared to the corresponding Arosa total ozone value, in order to perform the scaling of the radiosonde profile to the total ozone measurements as in the standard procedure.

6.1.2 Replacing the constant VMR extrapolation above 17 hPa by the microwave profile and scaling to the microwave total ozone

As a second attempt, we used the corresponding microwave profiles to compute the residual ozone values as above, but this time performing the scaling of the radiosonde profiles to the microwave total ozone values themselves.

6.1.3 Scaling to the microwave profile using the comparison region 3

Finally, avoiding the calculation of the total ozone values, we performed the scaling of the raw radiosonde measurements to the microwave profiles taking the comparison region 3 (see Table I) as only reference. This is indeed the atmospheric region in

which the radiosonde and microwave ozone profiles showed the best agreement with each other (see Section 5). The partial column ozone value corresponding to the unscaled radiosonde profiles was calculated, and directly compared to the equivalent microwave value to compute the scaling factor. There is, in this way, no absolute need for the estimation of the residual ozone values.

N.B.: The "shape" of the measured radiosonde profiles remains in each case unchanged by the scaling, since the whole ozone profile is multiplied with the same scaling factor.

6.2 Results

In order to visualize the effects of the different scaling methods proposed above on the ozone amounts distribution, we represented the results in a bar chart: inside each comparison region (defined in Section 5.2, Table I), we computed the partial column ozone amounts corresponding to the different scaling methods, and compared them to each other. These results, mean values over the comparison period (Nov. 1994 - June 1997), are represented in Figure 10. The interesting points are, for each scaling method, the relation between the residual ozone amounts (when calculated) and the ozone amounts distributed in the corresponding profiles (layers 1 to 3), and the differences obtained in each layer with the different scaling methods. The mean values of the partial column ozone obtained in each comparison region and for each scaling method for the radiosonde profiles, over the two and a half years comparison period, are given in Table II.

As we can see in Figure 10 (dash-dotted curve), replacing the constant VMR extrapolation for the radiosoundings above 17 hPa by the corresponding microwave profiles reduced on the mean the scaling factor to the total ozone measurements. This resulted in ozone values on the mean 3 % lower than the original scaling in the regions 1 to 3. These lower values of the integrated column ozone below 17 hPa are in turn compensated by higher residual ozone amounts (+ 11 % on the mean) in comparison to the results obtained with the constant VMR assumption, as the total ozone value measured at Arosa has to be reproduced. The 11 % difference corresponds essentially to the difference between the integrated microwave residual

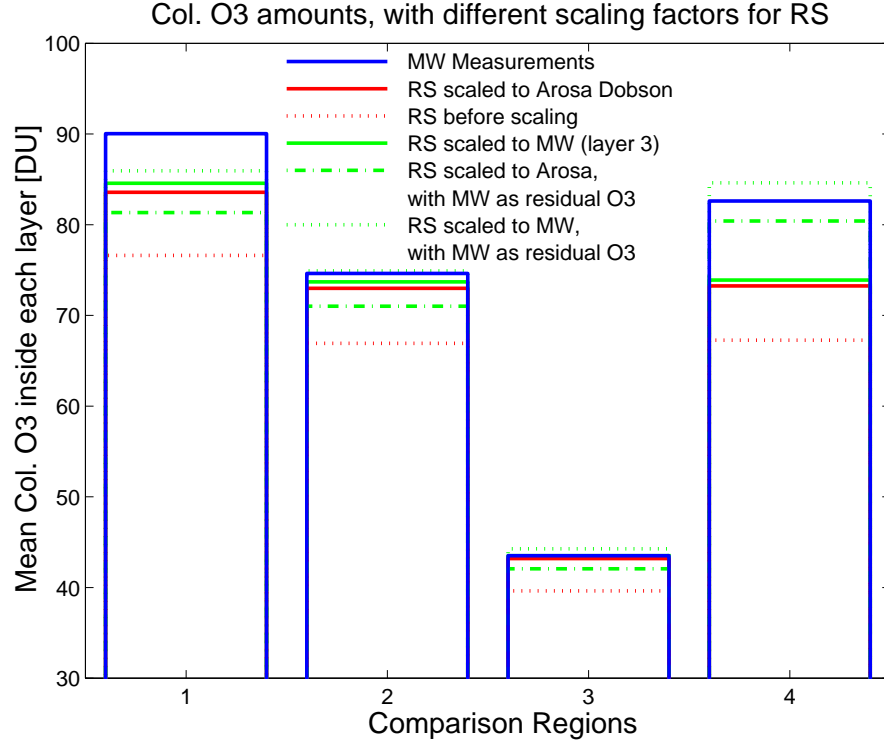


Figure 10: Mean values, over the comparison period November 1994 - June 1997, of the partial column ozone values obtained inside each comparison region (defined in Section 5.2, Table I) corresponding to the radiosonde profiles scaled according to the different methods proposed in this section. The values corresponding to microwave profiles, as well as to the raw (unscaled) and scaled (to Arosa) radiosonde profiles are also given (see text for details).

ozone and the equivalent radiosonde residual ozone (see Section 5.2, Table I).

Still using the microwave profiles to complement the radiosoundings above 17 hPa, but scaling the radiosonde profiles to the microwave total ozone values themselves this time (dotted curve in Figure 10), raised all the results obtained with the preceding method by another 6 %. Due to the fact that the microwave total ozone values are on the mean 6 % higher than the Arosa values, the radiosonde profiles have indeed to be brought to higher ozone values by a higher scaling factor.

Finally, using the comparison region 3 as only reference for the scaling of the radiosonde profiles produced ozone values on the mean less than 1 % higher than the values obtained with the standard scaling in all comparison regions (plain curve). (There, we represented the residual ozone as calculated using the constant VMR approximation again; this value is however of no importance for the result of the scaling).

<i>Region No.</i>	1 (12- 19.5 km)	2 (19.5- 24 km)	3 (24-28 km)	4 (28-78 km)	Σ (12-78 km)
<i>RS scaled to Arosa</i>	83.57	72.99	43.20	73.26	273.02
<i>RS before scaling</i>	76.61	66.92	39.63	67.26	250.42
<i>RS scaled to Arosa, with MW as res. O_3</i>	81.34	71.02	42.07	80.41	274.84
<i>RS scaled to MW, with MW as res. O_3</i>	85.96	74.91	44.26	84.62	289.75
<i>RS scaled to MW (layer 3 only)</i>	84.57	73.70	43.51	73.90	275.68
<i>MW meas.</i>	90.05	74.63	43.51	82.62	290.81

Table II: Mean partial column ozone values [DU], in each comparison region as in Table I, obtained using the different scaling methods described in the text. The values corresponding to the radiosonde profiles originally scaled to Arosa, as well as the values corresponding to the radiosonde profiles before scaling and the microwave measurements, are given for comparison.

These results show first the large influence of the estimation of the residual ozone amounts on the scaling of the whole radiosonde profiles, and second how simultaneous microwave measurements could be used to perform the scaling of the radiosonde profiles with (method 1)) or without (method 3)) estimation of the total ozone amounts. It should however be pointed out that the use of the comparison region 3 as only reference for the scaling of the radiosonde profiles (method 3)) presupposes a good agreement between the radiosonde and the microwave results in this region. This, in turn, depends on the way in which the previous scaling of the radiosonde profiles was performed; the fact that the results obtained with this scaling method reproduce the results obtained with the scaling to Arosa does not

confirm the accuracy of the scaling to Arosa. Other scaling regions should indeed be defined, depending on the goal that is pursued: whether to reproduce the Arosa scaling, or to perform a scaling independent of any total ozone measurement (giving for example the best agreement with the microwave measurements inside all regions).

The relative differences between the total ozone amounts obtained with the different scaling methods and the corresponding Arosa values, represented as a function of time over the comparison period, are shown in Figure 11.

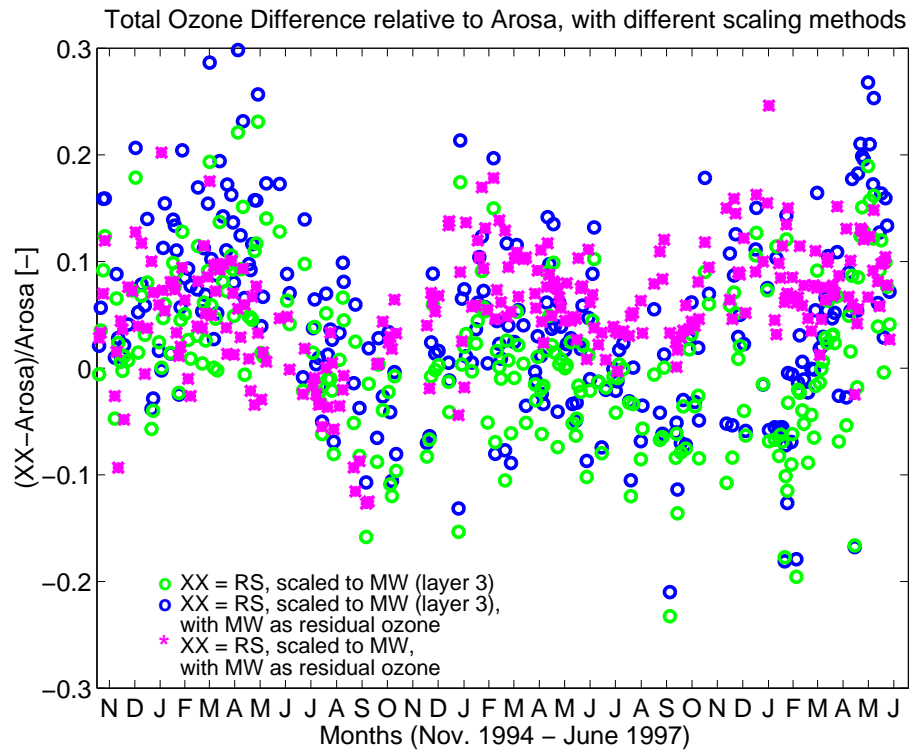


Figure 11: Relative difference between the total ozone amounts, obtained from the radiosonde profiles scaled according to the three different methods described in Section 6, and the Arosa total ozone measurements, as a function of time between November 1994 and June 1997.

7 Convolution of the Radiosonde Profiles with the Microwave Averaging Kernel Matrix

In Section 2, we presented the method used in this study to reduce the number of characteristic points of the high altitude-resolution radiosonde profiles to the number of characteristic points of a retrieved microwave ozone profile. This procedure is actually the minimal manipulation required to perform a comparison between the two different measurement methods at all. It does however not take into account the effect of the different instruments resolution and a-priori data contribution on the respective measured profiles and hence on the results of the comparison. For this purpose, the high altitude resolution of the radiosonde profiles has to be reduced to the effective, lower, microwave altitude resolution. This is realized by folding each radiosonde ozone profile with the corresponding microwave averaging kernel matrix, as described in [Tsou et al., 1995].

The convolved radiosonde profile is expressed as:

$$\mathbf{x}_{\mathbf{rs},\mathbf{c}} = \mathbf{x}_{\mathbf{a}} + A \cdot (\mathbf{x}_{\mathbf{rs}} - \mathbf{x}_{\mathbf{a}}) \quad (11)$$

where $\mathbf{x}_{\mathbf{rs},\mathbf{c}}$ is the convolved radiosonde profile, $\mathbf{x}_{\mathbf{rs}}$ is the measured radiosonde profile interpolated to the microwave retrieval layers of 2 to 3 km thickness, (see Section 2), $\mathbf{x}_{\mathbf{a}}$ is the a-priori profile used for the microwave retrieval and A is the matrix of microwave averaging kernels.

We obtain in this way radiosonde ozone profiles equivalent to the microwave's, in this way that their artificially degraded altitude resolution makes them correspond to the profiles that would have been obtained if the microwave instrument and retrieval method had been used for the radiosonde measurement. The convolved radiosonde and equivalent microwave profiles can then be directly compared to each other, without bias due to the different instruments resolution or a priori data contribution since those components have already been integrated to the radiosonde results by the convolution.

One main problem was encountered for the convolution of the Payerne radiosonde data with the Bern microwave averaging kernel matrix: that is, that the a-priori profiles used to retrieve ozone profiles from the Bern microwave spectra are precisely the

Payerne radiosonde profiles ! The folding of these profiles with the microwave averaging kernel matrix, with themselves as a-priori, would then reproduce exactly the same if the microwave inversion didn't imply many iterations. In fact, 3 iterations of the retrieval are used to compute the definitive microwave profiles, using as a-priori for each iteration the ozone profile retrieved during the previous stage. Hence, the last a-priori profile used in the microwave inversion is not the pure original Payerne radiosonde profile, and can therefore be used for its convolution. Each radiosonde profile is moreover complemented above the balloon-burst altitude, up to the last microwave retrieval layer, using standard ozone profiles scaled to the radiosondes in order to obtain a smooth transition from one to the other.

The effect of the convolution of the measured radiosonde profiles with the microwave averaging kernel matrixes can be evaluated by comparing Figures 12 and 13, where the mean difference between the microwave measurements on the one hand and the radiosonde, Hohenpeissenberg lidar, and Observatoire de Haute-Provence lidar ozone profiles on the other hand, folded and unfolded respectively, are represented. The mean microwave ozone profile that was compared to the lidar and radiosonde measurements being the same from one plot to the other, the changes in the results are only due to the changes in the radiosonde or lidar profiles brought by the convolution.

One can see that the major effect of the folding is to smooth the differences, erasing particularly the structures in the lidar and radiosonde profiles below 20 km altitude. This reflects the fact that the confidence in the microwave measurements is at its best only above 20 km, as shown by the higher standard deviations values below this altitude (Figures 12 and 13, see also [Peter, 1998]). In a general way, the agreement with the microwave measurements is improved by the folding between 20 and 25 km, while the behavior above 25 km remains nearly unchanged. Below 20 km, the effect of the convolution is to lower the VMR values of the radiosonde and lidar profiles, resulting in much larger difference with the microwave profiles.

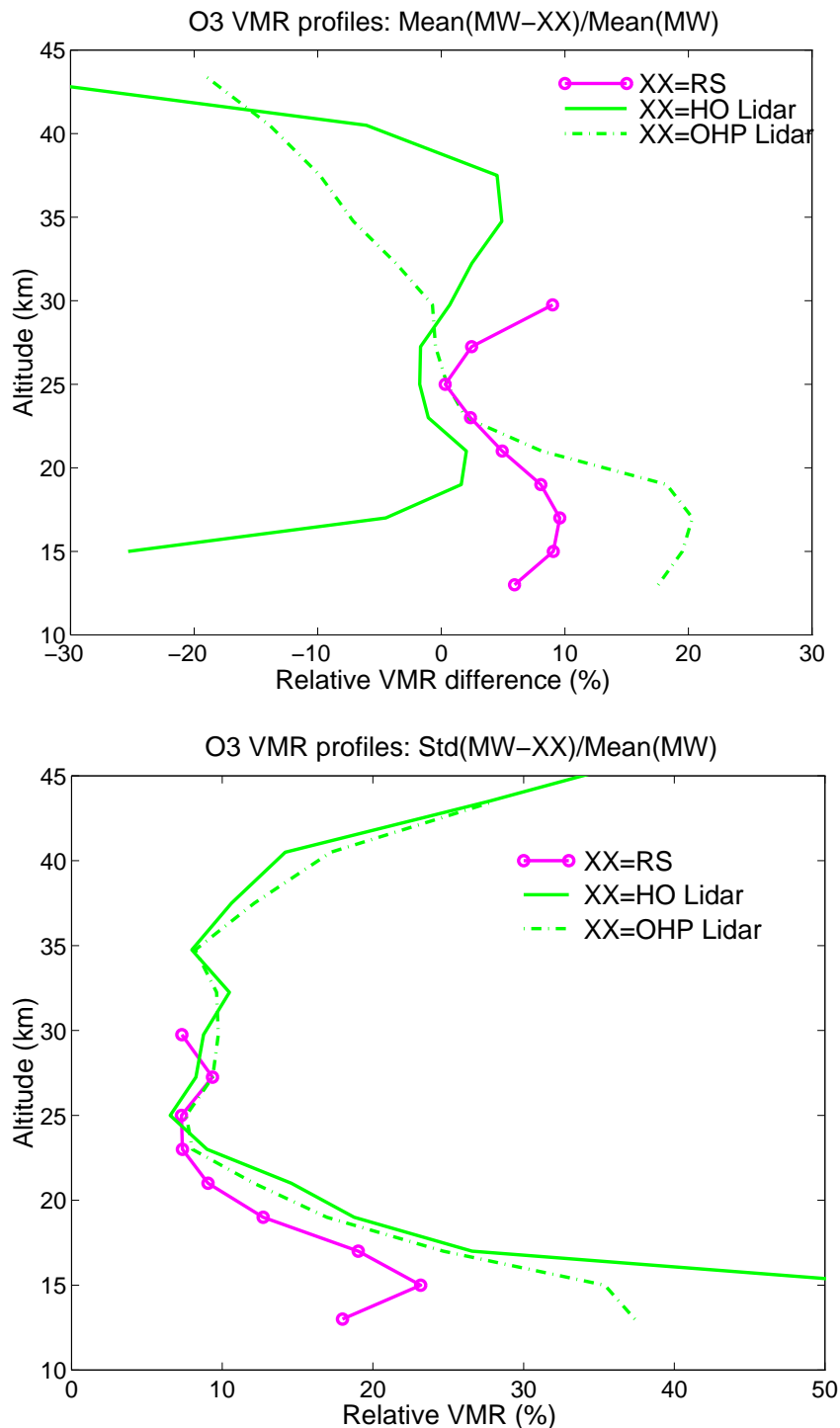


Figure 12: Relative mean difference, at each retrieval layer, between the measured microwave (MW) ozone profiles and the corresponding radiosonde (RS), Hohenpeissenberg lidar (HO), and Observatoire de Haute-Provence (OHP) lidar measurements (unfolded). As for Figure 4, the HO-lidar data correspond to measurements between November 1994 and April 1996, and the OHP-lidar data to measurements between November 1994 and December 1996. For the radiosondes, the measurements were performed between November 1994 and June 1997, as in the rest of the study. The lower plot shows the relative standard deviation of the difference, at each altitude, between the individual data sets.

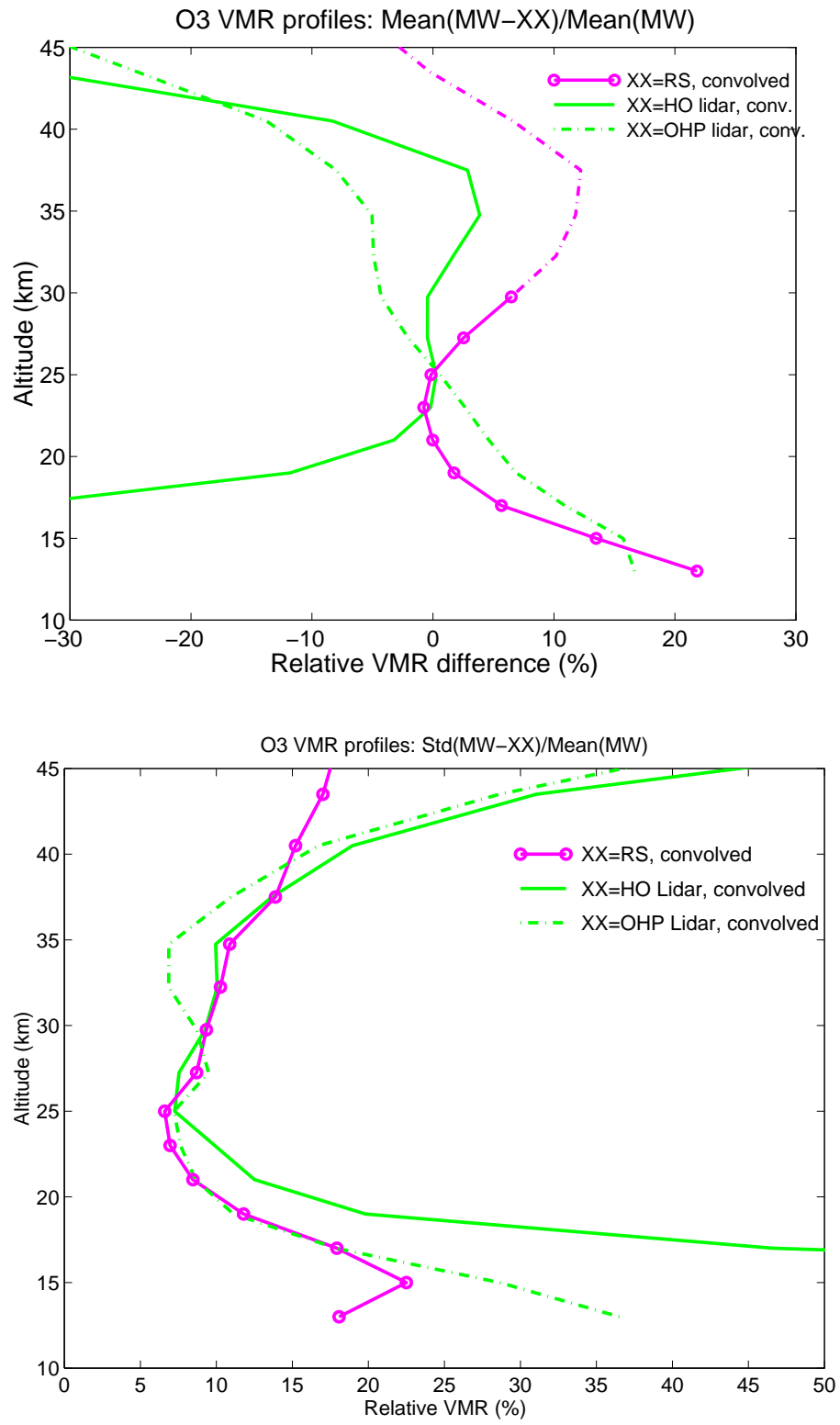


Figure 13: Same representation as Figure 12, but using this time the convolved radiosonde, Hohenpeissenberg, and Observatoire de Haute-Provence lidar data.

8 Influence of the a-priori Information on the Microwave Retrieval

An other important point to be taken into account in the comparison is precisely the influence of the a-priori data on the results of the microwave retrieval. This point is of particular importance in this study, since the (first) a-priori profiles used for the inversion of the Bern millimeter-wave spectra are precisely the Payerne profiles below ~ 25 km (above this altitude, the radiosonde profiles used for the microwave inversion are complemented by standard ozone profiles).

According to [Connor et al., 1995] (see also [Rodgers, 1990]), an estimation of a-priori contribution to the retrieved ozone profile can be gained by rewriting Eq. (11)

$$\hat{\mathbf{x}} = \mathbf{x}_a + A \cdot (\mathbf{x} - \mathbf{x}_a) = A \cdot \mathbf{x} + (I - A) \cdot \mathbf{x}_a \quad (12)$$

where $\hat{\mathbf{x}}$ is the retrieved ozone profile, \mathbf{x} is the true atmospheric ozone profile (the one we want to measure), and \mathbf{x}_a is the a-priori profile. According to this relation, the retrieved profile is then composed of a sum of contributions from the true profile and the a-priori profile. Normalizing to 1, the contribution of the a-priori to the ozone profile at the retrieval layer j is given by:

$$(I - A)_j \cdot \frac{\mathbf{x}_a}{\hat{x}_j} \quad (13)$$

where I is the identity matrix, A is the matrix of the microwave averaging kernels, $(I - A)_j$ is the j -th row of $(I - A)$, \mathbf{x}_a is the a-priori profile and \hat{x}_j is the j -th component of the retrieved profile.

We performed this calculation to compute the contribution of the a-priori data to the profiles retrieved from the Bern microwave measurements: these quantities are represented, as a function of the altitude and as mean values for different months, in Figure 14.

The influence of the a-priori appears to be less than 20 % (monthly mean) in the altitude range 25 to 70 km, and less than 30 % between 18 and 25 km. Below 18 km and above 70 km, the contribution of the a-priori profiles to the retrieval increases drastically: there, the a-priori profiles have a significant impact on the solution of

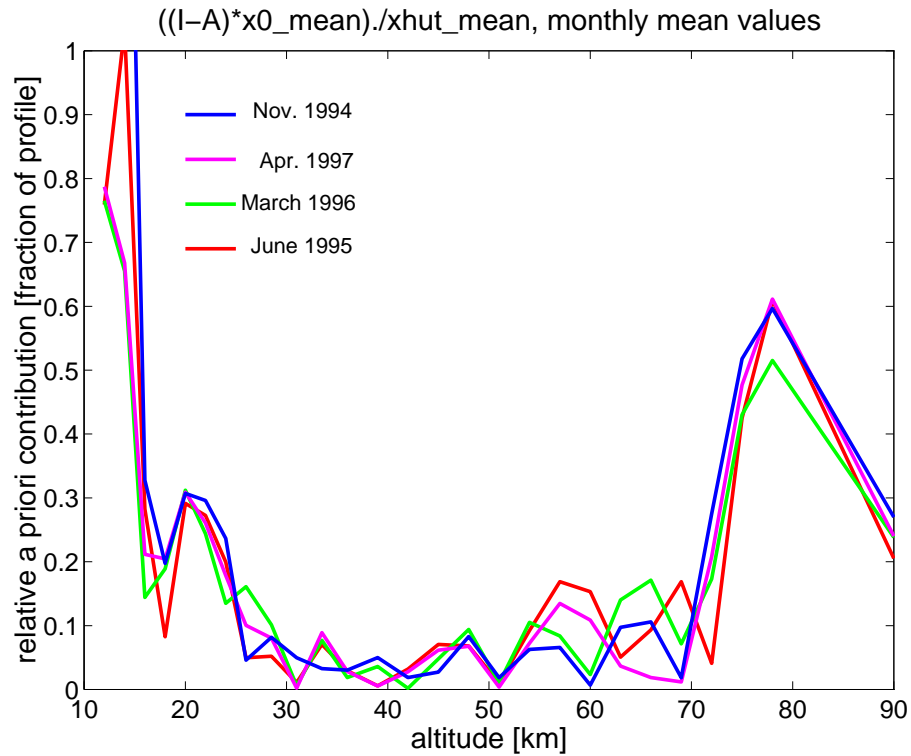


Figure 14: Mean contribution of the a-priori data to the microwave retrieved profile, represented as a function of the altitude of the retrieval layer for different months. This quantity is normalized to 1: 1 meaning full a-priori information, 0 no a-priori contribution.

the microwave retrieval, which should be kept in mind when considering the results of the comparison.

9 Climatology

Under normal conditions, about 12 ozone profiles per day are retrieved from the microwave measurements using GROMOS. This allows to produce a climatology of the ozone concentrations over the months, by computing the average of the total of the ozone profiles measured with the radiometer in one month. This has been done for each month, starting from November 1994 to June 1997. The resulting profiles could be a useful help for the scaling of the radiosondes measurements in case of no total ozone measurements at the Arosa station. As an example, the averaged profile obtained during February 1996 is shown in Figure 15, with the associated standard deviation and maximum deviation from the mean profile measured during

the month.

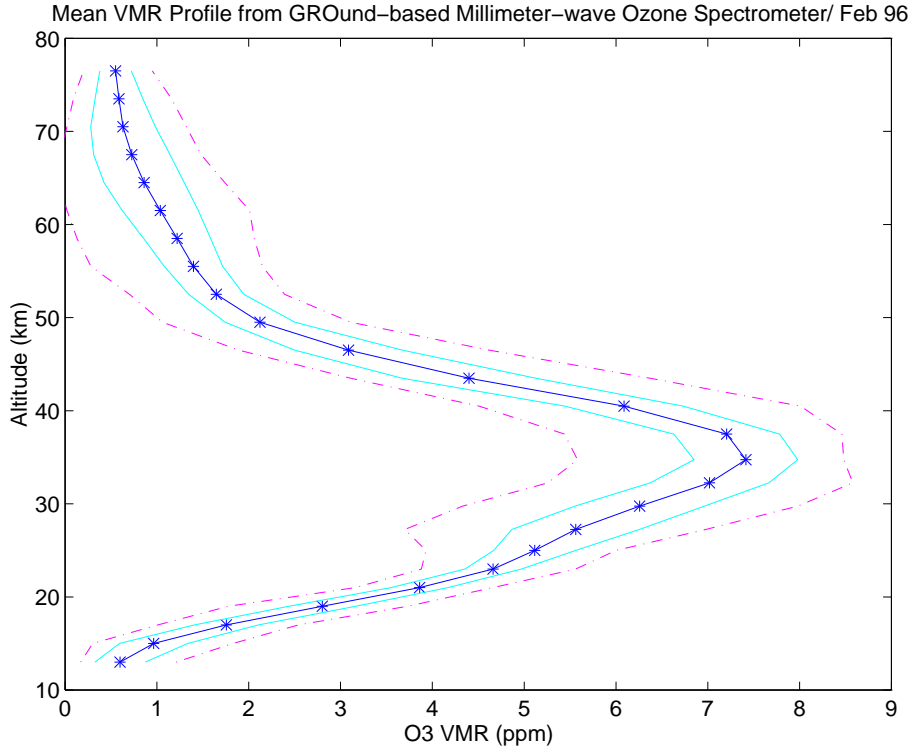


Figure 15: Mean ozone profile obtained by continuous microwave measurements, in February 1996. Represented are the monthly mean profile (*), the standard deviation (solid line), and the maximal deviation at each altitude (dash-dot line).

10 Comparison to SBUV Climatological Tables

SBUV (Solar Backscattered Ultraviolet) climatological tables can be used to improve the calculation of the total column ozone from balloon-borne radiosonde measurements (see [McPeters et al., 1996]). They consist of column ozone values, calculated above 30 distinct pressure levels in the middle and upper atmosphere (from 1 through 30 hPa), for each month and 10 degree latitude zones. Those values are calculated using a monthly average ozone climatology, based on ozone profile measurements with the SBUV instrument on the Nimbus-7 satellite. The appropriate residual ozone quantities taken from the table can hence be directly added to the ozone values integrated from the measured balloon profiles, in order to reduce the uncertainty

in the column ozone estimate of the soundings.

The same calculation is of course possible with the microwave ozone profiles: by integrating the profiles above the same 30 pressure levels, and taking the corresponding mean value for each month, we could provide residual ozone data fully comparable to the SBUV climatological tables.

The results of the comparison are shown in Figures 16 and 17. For each month, the residual ozone values $O_{3,Res}(P^*)$ above the pressure levels P^* indicated on the y-axis were calculated from the Bern microwave-climatology according to:

$$\begin{aligned} O_{3,Res}(P^*) &= \frac{T_o}{P_o} \cdot 10^5 \int_{h(P^*)}^{80km} vmr(h) \cdot \frac{P(h)}{T(h)} dh \\ &= -\frac{T_o}{\rho_o g} \cdot 10^5 \int_{P^*}^0 vmr(P) \cdot \frac{1}{T(P)} dP \end{aligned} \quad (14)$$

(see Appendix A, and Eq. (4) for a definition of the symbols).

The residual ozone values from the SBUV-climatology are the values given in [McPeters et al., 1996]) for the latitude zone 40°-50°N, within which Bern is located.

On the mean, the SBUV and millimeter-wave results coincide very well for the residual ozone values integrated above 20 hPa (i.e., for limiting pressure levels between 20 and 1 hPa). The absolute difference obtained between the SBUV and microwave results above those pressure levels is mostly less than ± 5 DU (i.e., less than 5 % of the measured ozone quantity), with an exception in December (see Figure 16). The relative difference between the results obtained with the two instruments increases up to 10 % for individual months at low pressures levels, due to the rapid decrease of the estimated residual ozone values (see Figure 17). For the residual ozone values corresponding to higher pressure levels (30 to 20 hPa) (i.e., the residual ozone values integrated above lower altitude levels), the SBUV results tend to indicate higher values than the millimeter-wave instrument. The agreement is however particularly good for the summer months (April to August), where the residual ozone values based on the two instruments measurements above the defined pressure levels differ by less than 5 DU (5 %) for almost all pressure levels.

Above 15 to 3 hPa, the microwave results tend to show higher values of residual

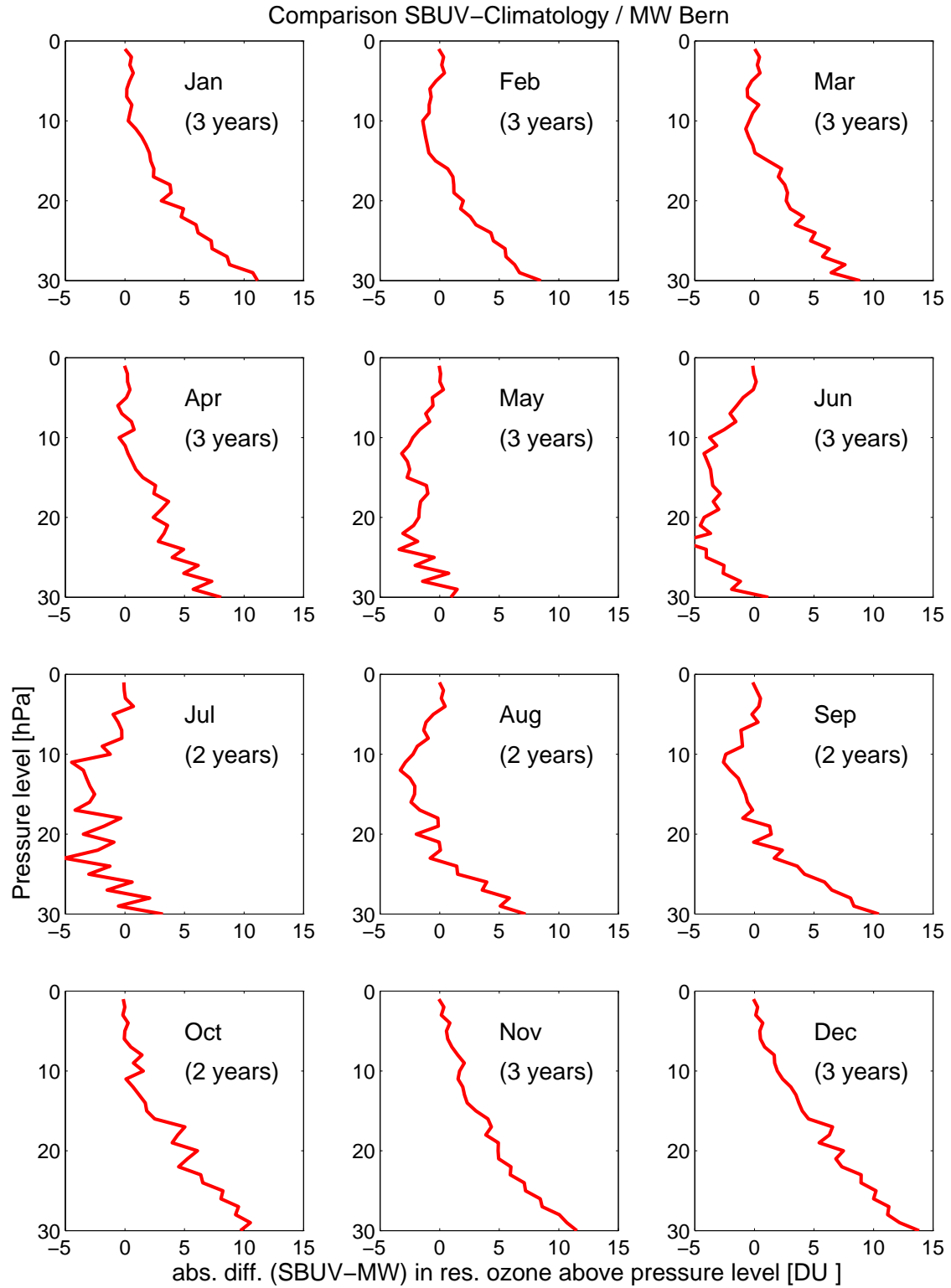


Figure 16: Absolute difference [DU], for each month, between the residual ozone values from SBUV and microwave climatologies above the pressure levels P^* represented on the y-axis.

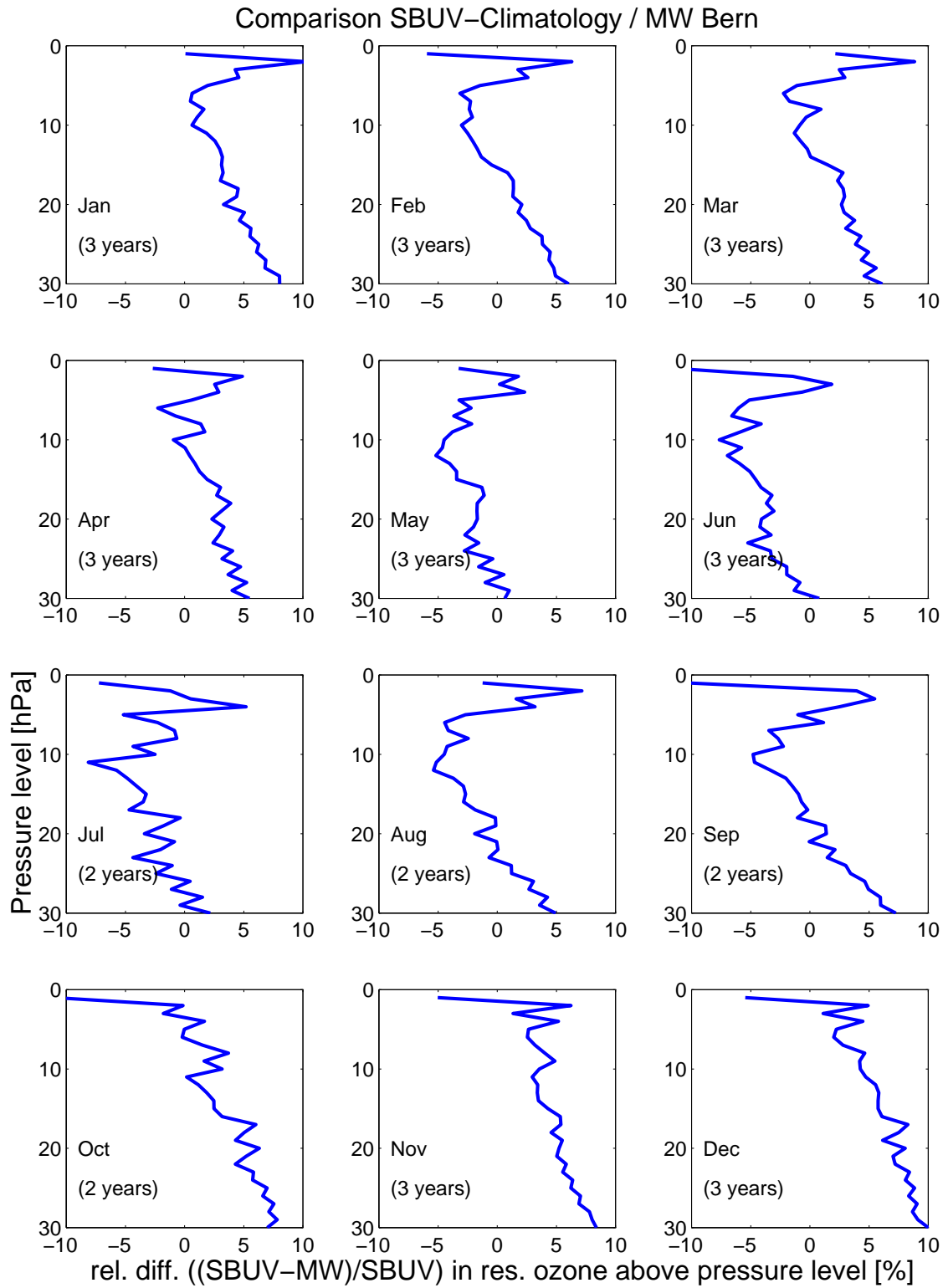


Figure 17: Relative difference [%], for each month, between the residual ozone values from SBUV and microwave climatologies above the pressure levels P^* represented on the y-axis.

ozone than the SBUV tables (up to 8 % more residual ozone for July !). This difference reduces however to max. -1.4% mean value for all months over the same altitude range, and reaches +1.9% for the residual ozone taken above the 17 hPa level. This doesn't account for the larger difference obtained with the radiosonde residual ozone quantities calculated using the constant VMR extrapolation above the same pressure level. The mean relative differences in the residual ozone values, calculated above the different pressure levels for the microwave measurements and the SBUV climatology, taken over all months, are given in Table III.

P^* [hPa]	1	2	3	4	5
$\frac{SBUV-MW}{SBUV} [\%]$	-5.1	+4.3	+1.6	+3.0	-0.8
P^* [hPa]	6	7	8	9	10
$\frac{SBUV-MW}{SBUV} [\%]$	-1.3	-1.1	+0.4	-0.4	-1.2
P^* [hPa]	11	12	13	14	15
$\frac{SBUV-MW}{SBUV} [\%]$	-1.4	-1.0	-0.3	+0.2	+0.7
P^* [hPa]	16	17	18	19	20
$\frac{SBUV-MW}{SBUV} [\%]$	+1.4	+1.9	+2.2	+2.1	+1.9
P^* [hPa]	21	22	23	24	25
$\frac{SBUV-MW}{SBUV} [\%]$	+2.1	+2.3	+2.1	+3.0	+3.3
P^* [hPa]	26	27	28	29	30
$\frac{SBUV-MW}{SBUV} [\%]$	+4.0	+4.1	+4.7	+4.7	+5.6

Table III: Relative residual ozone difference [%] between the values obtained from the SBUV climatological tables and the corresponding microwave (MW) climatology, above each limiting pressure level P^* (see Formula (14)) and averaged over all months.

11 Summary

The main results obtained during this intercomparison study can be listed as following:

- The ozone VMR profiles obtained by coincident radiosonde and microwave measurements between November 1994 and June 1997 show in general a good agreement with each other, particularly below 20 hPa (~ 27 km).
- Above 20 hPa, the mean difference obtained between the respective profiles increases rapidly with altitude to a maximum of 10 % at 30 km. The radiosonde measurements show lower ozone values than the microwave measurements at these altitudes.
- Comparison of the Payerne ozone profiles with coincident Hohenpeissenberg- and Observatoire de Haute-Provence lidar data confirmed the results obtained with the microwave data, namely, a tendency of the ozone profiles measured by balloon-borne radiosoundings to underestimate the ozone amounts above 20 hPa (~ 27 km). This underestimation reaches about 10 % on the mean at 15 hPa (~ 30 km).
- The total ozone values computed by integrating the radiosonde ozone profiles up to 17 hPa, and using the constant VMR approximation above this level, showed a very good agreement with the coinciding Arosa total ozone measurements (less than 1 % difference on the mean). However, these results showed a large dependency on the actual shape of the measured profile, that is, profiles showing too low ozone values at 17 hPa should be cut at lower altitudes and another estimation method for the residual ozone value should be used.
- The total ozone amounts obtained by integrating the microwave profiles showed on the mean 6 % higher values than the corresponding Arosa measurements, mainly due to an overestimation of the ozone amounts by the microwave retrieval between 17 and 22 km.
- The best agreement between the partial column ozone amounts calculated from both radiosondes and microwave profiles was found in the comparison

region 24 to 28 km (~ 30 to 17 hPa), where the mean differences between the respective results over the comparison period was less than 1 %. The agreement is also very good for the partial column ozone values calculated between 19.5 and 24 km (~ 60 to 30 hPa), with 2 % mean difference.

- Concerning the residual ozone values (column ozone above 17 hPa), a large difference between the results corresponding to the two measurement methods was found (more than 10 % mean discrepancy over the comparison period). Investigations using standard profiles showed however that this difference is mainly due to the different methods used to calculate the residual ozone for the two instruments, that is, the integration of a constant VMR ozone profile above 17 hPa results in 10 to 14 % less column ozone as when the true standard profile is integrated above the same level.
- Raising the lower integration limit for the residual ozone doesn't help to diminish the difference obtained between the two calculation methods (using the constant VMR approximation for the radiosonde profiles), since the radiosonde ozone VMR values do not increase or increase too slowly with altitude above 17 hPa. In the former version of this report, we showed indeed that the residual ozone amounts were still underestimated by more than 10 % if this value was calculated above the last measurement point of the sounding instead of the 17 hPa level.
- Replacing the constant VMR approximation for the radiosonde ozone profiles above 17 hPa by the corresponding microwave profile above the same level resulted on the mean in 3 % lowering of the scaling factor to the Arosa measurements, which in turn resulted in 3 % less ozone for the radiosonde profiles below this level. This lowering of the ozone amounts below 17 hPa balances the mean 11 % increase of the residual ozone amounts due to the replacement of the constant VMR approximation by the microwave profile.
- Scaling the radiosonde profiles to the corresponding microwave column ozone values between 24 and 28 km (30 to 17 hPa) resulted in values within 1 % from the original scaling to the Arosa total ozone measurements.

- Comparison of the microwave data to SBUV climatological tables showed a very good agreement between the two methods for the residual ozone values calculated above the 20 hPa level, mostly within 5 % agreement; below 20 hPa and down to the 30 hPa level, the residual ozone values given by the SBUV tables are up to 10 % higher than the corresponding microwave values.

12 Conclusion

The intercomparison showed that ozone profiles obtained by balloon-borne radiosoundings over Payerne and coincident microwave measurements in Berne are generally in good agreement with each other, reproducing particularly the same features of the profiles below about 27 km (20 hPa). Above this altitude, the respective profiles part from each other and the ozone values measured during the radiosoundings are too low.

Since the ozone values estimated from the radiosoundings are generally too low above 20 hPa, the estimated residual ozone values obtained by integrating the constant VMR extrapolation above this altitude (and in particular above 17 hPa) are also too low, leading to an underestimation of the radiosonde residual ozone amounts and consequently of the corresponding total ozone amounts. Raising the integration level for the residual ozone estimation to higher altitudes doesn't help, since the ozone VMR values measured by the radiosoundings above 20 hPa generally increase too slowly with altitude. This prevents from reaching the point where the overestimation of the ozone values at high altitudes by the constant VMR extrapolation compensates the loss of residual ozone which is due to the truncation of the ozone profile maximum by this same extrapolation.

To perform an accurate scaling of the ozone profiles, one should either improve the correction of the radiosonde measurements above 20 hPa, in order to obtain the correct ozone values for the constant VMR extrapolation, or use another estimation method for the residual ozone amounts. In the first case, a correction factor for the pump efficiency varying with altitude and taking into account the performance of the individual pumps should be used, as for example in [De Backer et al., 1996]. In

the other case, one should give up the use of the constant VMR extrapolation for the computation of the residual ozone. The scaling of the radiosonde profiles could then be performed with the help of coincident microwave measurements. Ground-based microwave radiometry constitutes indeed a very suitable mean to complement the individual balloon-borne radiosoundings, since this remote-sensing technique is hardly affected by weather conditions and does not require sun illumination, allowing to retrieve ozone profiles up to high altitudes in a continuous operation mode. The residual ozone value corresponding to each radiosounding can be computed by integrating the coincident ozone profile from the microwave measurements; this value can be used to perform the scaling of the radiosonde profile either to a total ozone measurement as in the standard method, or to the microwave total ozone value itself (in both cases, the radiosonde ozone profile should however be truncated below 20 hPa). Another method consists of performing the scaling without the computation of any equivalent total ozone value for the radiosoundings, by comparing directly the radiosonde and microwave ozone profiles or partial column ozone values in an altitude range where both measurement methods are accurate. In this study, the original scaling of the radiosonde profiles to the Arosa total ozone measurements could be reproduced within 1 % on the mean when only the partial column ozone values between 24 and 28 km (30 and 17 hPa) from both measurement methods were compared to compute the radiosonde scaling factor.

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$$O_{3,Res} [DU] = 0.79 \cdot p_{o3}(h_o) = O_{3,Res} [millicm]$$

The 0.79 factor consists only of standard atmospheric constants and conversion factors, and is therefore totally independent of the altitude h_o above which the residual ozone is calculated.

B Appendix: Pressure-Altitude Equivalence

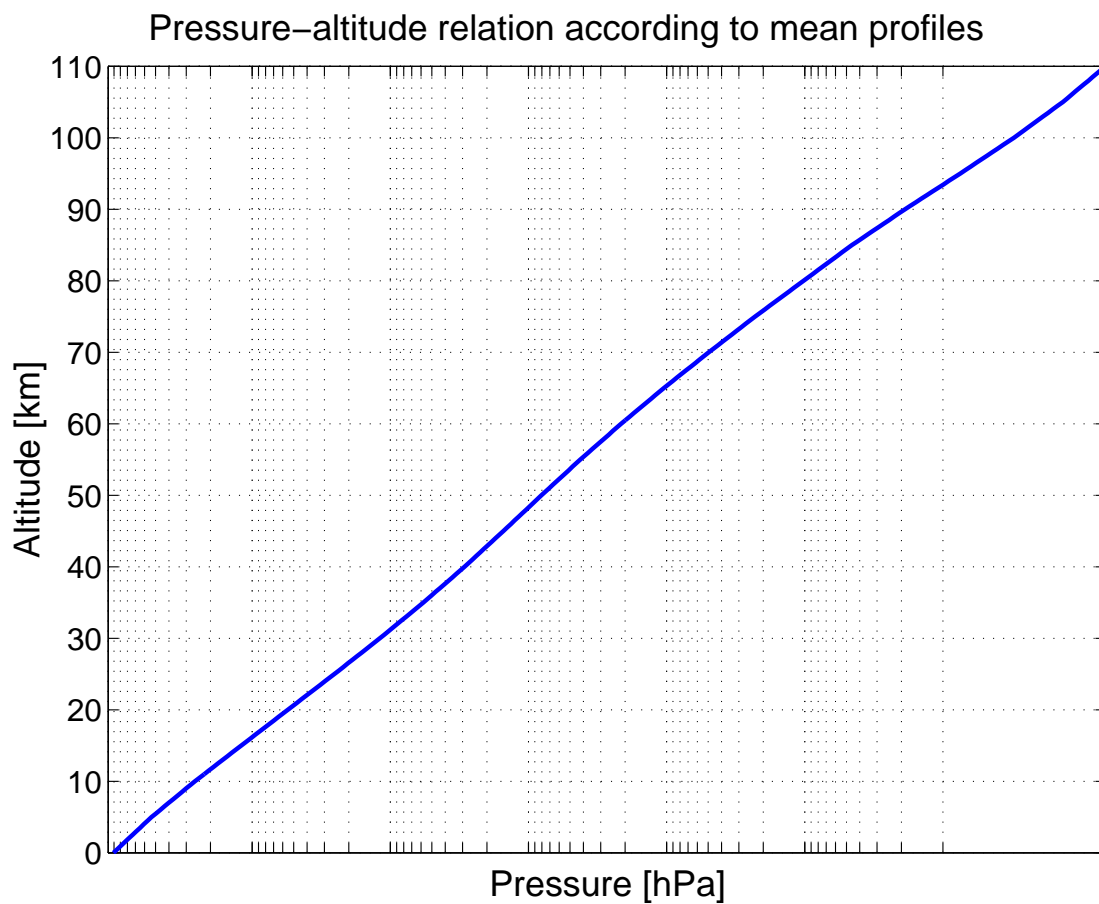


Figure 18: Relation between altitude and pressure levels, as from standard pressure profiles.

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