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THE DISCREPANCY BETWEEN STRATOSPHERIC OZONE PROFILES FROM BALLOON SOUNDINGS AND FROM OTHER TECHNIQUES: A POSSIBLE EXPLANATION

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ABSTRACT

Regular balloon ozone soundings with electrochemical sondes have been performed at Uccle (50°48'N, 4°21'E, 100 masl) since 1969. More than 450 ozone soundings between 1985 and 1989 were used to calculate the altitudes Zs from the VIZ radiosonde data and the altitudes Zr deduced from the tracking of the balloon train with a primary wind-finding radar. The values of Zs at fixed times appeared to be systematically too low as compared to Zr. The differences Zr-Zs increase with altitude; at 30 km the annual mean values of Zr-Zs (± standard deviation) vary between 590 ± 910 m and 1410 ± 1160 m, according to the pressure calibration of different manufacturing series of radiosondes. From these results it is found that around the 30 km level the ozone concentrations calculated from soundings with VIZ sondes are too low by 7.5 to 14 %, depending upon the manufacturing series of radiosondes. At least part of the discrepancy which has often been found between ozone profiles from balloon soundings and from other techniques such as rocket observations or Umkehr measurements may be explained by this effect. An altitude correction would have important consequences as to the climatology of ozone in the middle stratosphere as adopted at the moment. About half of the day-to-day variability of ozone observed from soundings with VIZ radiosondes above the 30 km level, is induced by the variability of Zr-Zs. The agreement between altitudes calculated from radar data and Vaisala radiosondes is much better; from 34 comparative soundings a mean difference (± standard deviation) of about -300 ± 180 m was found at 30 km.

1. INTRODUCTION

The systematic bias between average profiles from balloon soundings with electrochemical ozone sondes and profiles obtained with other techniques (the former being the lowest) is one of the major discrepancies among measurements of the ozone distribution in the stratosphere. *Dütsch and Ling* [1969] noticed that the ozone sondes indicated systematically lower ozone concentrations in the middle stratosphere as compared to the Umkehr data. *Mateer* [1981] mentioned a difference of 18% between rocket ozone profiles and balloon ozone sonde profiles near the 10 hPa level.

The present study gives a possible explanation for at least part of this discrepancy by proving that the ozone profiles derived from balloon soundings may suffer from a systematic distortion through erroneous pressure values obtained from the radiosonde data. Balloon profiles (at least in the middle stratosphere) are often used as first-guess profiles in the inversion of satellite data (such as SBUV ozone values); therefore ozone profiles from the latter data will be affected as well.

2. ALTITUDE CALCULATION

For a comparison with radar altitude data, the geopotential altitude H calculated from radiosoundings is converted to geometric altitude Z. This is done through the following equation:

$$Z = r_\phi H / (r_\phi g_\phi / g_s - H) \tag{1}$$

where
g_ϕ is the sea-level acceleration of gravity at latitude ϕ,
g_s is a standard value of acceleration of gravity,
r_ϕ is a fictitious quantity that takes into account the form of the earth and the effect of the centrifugal acceleration (see e.g. *Smithsonian Meteorological Tables* [1963]).

The geometric altitude of the balloon target is calculated from the slant range S and the elevation angle E provided by wind-finding radar data, as follows:

$$Z = h + S \sin E + C_1 + C_2 \tag{2}$$

where
h is the height of the radar above sea level,
C_1 denotes the correction for curvature of the earth,
C_2 denotes the correction for radio-wave refraction.

It may be readily calculated that

$$C_1 = [(r+h)^2 + S^2 + 2(r+h)S \sin E]^{1/2} - (r+h+S \sin E) \tag{3}$$

where r is the radius of earth curvature at the station and at sea level.

A good approximation of C_2 for wind-finding radar data in the region of Belgium is given by the following empirical equation:

$$C_2 \approx -0.34\, C_1^{0.86} \tag{4}$$

The absolute difference between the corrections calculated from this formula and climatological averages of the correction for radio-wave refraction at the location 51°08'N, 00°22'W (see *WMO* [1983], page 12.9) is smaller than 5 m for values of the earth curvature correction up to 3 km.

3. COMPARATIVE ALTITUDE MEASUREMENTS

Regular balloon ozone soundings with Brewer-Mast electrochemical sondes have been performed at Uccle since 1969. Up to 1989, VIZ radiosondes (model 1495) were used while from 1990 onwards, the ozonesondes are coupled to Vaisala radiosondes. From April 1985 through December 1989, the tracking of the balloon train was done with a primary wind-finding radar. This resulted in 455 ozone soundings for which two comparative altitude sets were available.

The geometric altitudes were calculated at one minute intervals for each of these 455 ozone soundings, by means of formula (1). The altitudes from wind-finding radar data were calculated at the same time intervals, through the equations (2), (3) and (4). From these two data sets, mean altitude differences were calculated as a function of the altitude calculated from the radar data. A list of the mean altitude differences at the 15 and 30 km level for the different years is given in Table 1.

Year	1985	1986	1987	1988	1989
15 km	830±450	870±560	680±350	80±360	180±170
30 km	1020±760	1410±1160	1360±780	590±910	850±920

Table 1. annual mean altitude differences (in m) (radar - radiosonde) at the 15 and 30 km levels, calculated from simultaneous wind-finding radar data and VIZ radiosonde data of ozone soundings at Uccle performed during 1985 through 1989.

The altitudes as calculated from wind-finding radar data are systematically higher than the altitudes calculated from the VIZ radiosondes. The mean difference increases with altitude. But in addition there appear to be year-to-year differences: from 1985 to 1987 the altitude differences were higher and increased much faster between the surface and the 15 km level than in 1988 and 1989. Figures 1 and 2 show the vertical distribution of the mean altitude differences and the corresponding standard deviation for these two time periods. It may be seen that also the standard deviation of the altitude differences increases rapidly with altitude: at the 30 km level it amounts for the first and second time period to 870 and 920 m respectively.

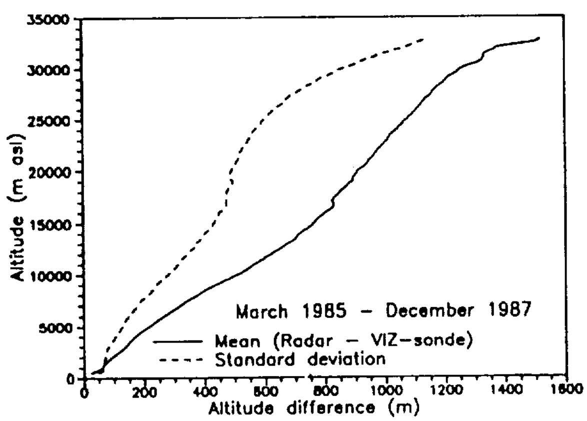

Fig. 1. Vertical distribution of mean altitude differences calculated from simultaneous wind-finding radar data and VIZ radiosonde data of ozone soundings at Uccle performed in 1985 through 1987 (full line). The dashed line represents the standard deviation at the corresponding altitude levels.

Taking into account that altitudes calculated from wind-finding radar data are much more accurate than altitudes deduced from radiosonde data, it may be assumed that the systematic bias between the two altitude sets is almost entirely due to the radiosonde and in particular to systematic errors in the pressure sensor data. The aneroid driven "baroswitch" that is used in the VIZ sondes consists of a mechanical arm assembly that drives a contact over a segmented commutator. Even a slight backlash of the mechanical arm assembly may cause an appreciable error in the pressure readings and consequently in the altitude calculations. This was verified as follows. From the baroswitch pressure calibration charts of the VIZ radiosondes used at the ozone soundings in 1988 and 1989, the mean pressure as a function of the segment number S was calculated. Through the relation of mean pressure vs. mean altitude Z, the value of $\Delta Z/\Delta S$ vs. Z was calculated. In Figure 2 the curve 0.7 $\Delta Z/\Delta S$ vs. Z is compared with the mean altitude differences. It may be seen that there is a striking similarity between the two curves up to an altitude of about 28 km. At higher altitudes the values of $\Delta Z/\Delta S$ are uncertain, due to irregularities in the mean curve of Z vs. S.

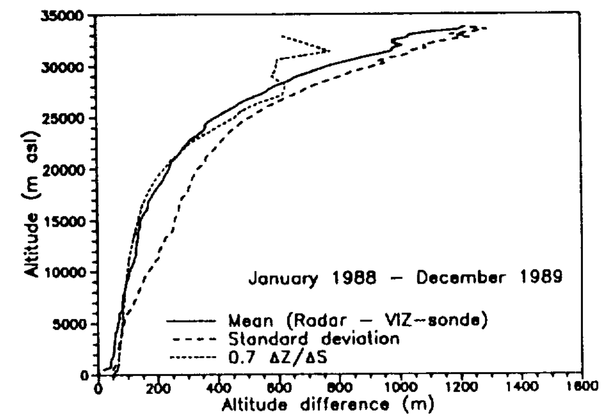

Fig. 2. As Figure 1, except that the data apply to the years 1988 and 1989. Short dashes: values of 0.7 $\Delta Z/\Delta S$ (see text).

The backlash of the arm assembly of VIZ sondes may be readily observed at the end of a sounding: due to the shock of the radiosonde at burst level, the position of the baroswitch arm is in most cases suddenly shifted to a higher commutator segment.

From the results shown in Figure 1 it appears that, beside the effect of backlash of the baroswitch arm, the VIZ radiosondes that were used in 1985 to 1987 suffered from a systematic calibration error of the pressure sensor. The number of commutator segments corresponding with this calibration error was calculated to amount to three at the 15 km level.

During an overlap period of four months (from September 1989 to December 1989), 34 ozone soundings were performed with a special balloon train that included a VIZ and a Vaisala radiosonde. The vertical distributions of the mean altitude differences between the radar data and both types of radiosondes are shown in Figure 3. Up to an altitude of 8 km there is virtually no difference between the altitudes calculated from radar data and from Vaisala sonde data; above that level the Vaisala sondes yield systematically too high altitudes. But the absolute value of the mean altitude difference is at nearly all levels less than half the corresponding mean difference calculated from radar data and the VIZ sondes. At 30 km the mean altitude difference between radar and Vaisala sonde data amounts to -300 ± 180 m. It is worthwhile to note that also the standard deviations of the mean altitude differences are much smaller in the case of Vaisala sondes as compared to the VIZ sondes. This means that pressure data from Vaisala sondes are considerably more accurate than corresponding measurements obtained from VIZ sondes, especially at stratospheric levels.

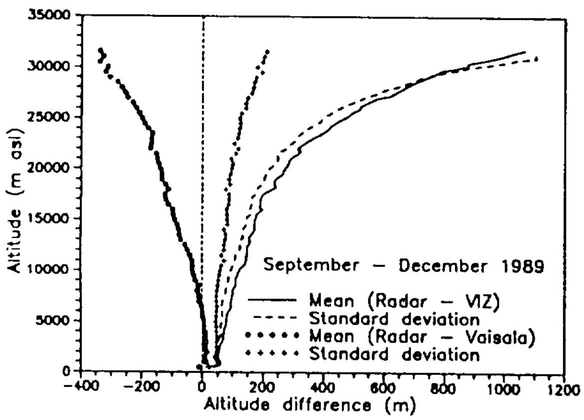

Fig. 3. Vertical distribution of the mean and standard deviation of altitude differences calculated from simultaneous wind-finding radar data and VIZ radiosonde data (full and dashed line) and calculated from wind-finding radar data and Vaisala radiosonde data (centred symbols). These data were obtained from special ozone soundings performed at Uccle between September and December 1989.

4. IMPLICATIONS FOR OZONE PROFILES

The accuracy of radiosonde pressure sensors is in general adequate for routine use. But at balloon ozone soundings the errors in stratospheric radiosonde pressure data may introduce appreciable errors in the calculated ozone profiles. Figure 4 shows a comparison of the mean vertical ozone distribution at Uccle for the three years period of 1985 through 1987, without and with altitude correction. The corrected profile was adjusted as to make the integrated total ozone amount the same as for the original profile; this resulted in a slightly lower ozone maximum. The corresponding percentage differences between the corrected and uncorrected mean profile amount to about -17% just above the tropopause and about 14% at 30 km. The percentage differences that correspond with the altitude correction for the period 1988-1989 (Figure 2) are smaller but certainly not negligible (about 7.5% at 30 km).

Other factors that contribute to a distortion of ozone profiles from balloon soundings such as the frequency response of the sensor and the variation of temperature of the sampled air [*De Muer*, 1985], may cause a systematic bias which partly cancels the effect of the altitude error above the ozone maximum. However the effect of the altitude error on the measured ozone profile, according to the radiosonde that is used, should on no account be neglected. Care should be taken in calculating stratospheric ozone trends from time series of soundings that were performed with different types of radiosondes. The percentage differences between the mean vertical ozone distribution during the period September through December 1989 as it was calculated using respectively the VIZ and Vaisala radiosonde data, amount to more than 10% around the 30 km level. This means that without altitude correction, switching from VIZ to Vaisala radiosondes would have induced a jump of that magnitude in the ozone values around 30 km. Consequently, a change in the type of radiosonde may induce a fictitious ozone trend, if the effect of the different type of pressure sensor is not taken into account.

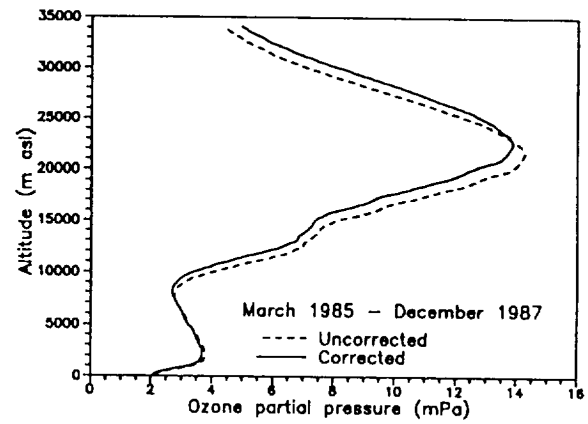

Fig. 4. Mean vertical distribution of the ozone partial pressure at Uccle during the period from 1985 through 1987, before (dashed line) and after (full line) correction for the mean error of the radiosonde pressure sensor.

From papers about ozone instrument intercomparison campaigns it is not always clear to what extent instrumental differences may be explained by errors in the pressure measurement. At the MAP/GLOBUS 1983 campaign [*Aimedieu et al.*, 1987] and BOIC [*Hilsenrath et al.*, 1986] all the ozone data were listed as a function of time and one pressure element was used to compare the ozone profiles as a function of pressure. But at the ozone profile intercomparison in Gap (southern France) in 1981 [*Aimedieu et al.*, 1983] atmospheric pressures were measured independently by each instrument, which means that differences between ozone profiles could be due to errors in both ozone and pressure measurements. At the intercomparison in Gap systematic differences of about 20% between stratospheric ozone profiles deduced from solar U.V. absorption and in situ techniques were found, while at BOIC the differences between those two techniques were only 5 to 10%. At least part of this different behaviour might be explained by errors in the pressure measurements at the intercomparison in Gap.

The standard deviations of the altitude differences shown in Figures 1 and 2 (denoted by D_1) result from the standard deviations of radar altitudes and radiosonde altitudes with respect to the true altitude values (denoted by D_2 and D_3 respectively): $D_1^2 = D_2^2+D_3^2$. Taking into account the angular precision of the wind-finding radar (0.1°) and a negligible range error, it may be verified that the variance D_2^2 was only about a fifth of the variance D_3^2. The values of D_3 may be calculated accordingly:

$D_3 = D_1/(1.2)^{1/2}$. By multiplying this value with the absolute value of the vertical ozone gradient, the corresponding ozone standard deviation due to the altitude error may be calculated. The result for the period 1985 through 1987 is depicted in Figure 5 (curve with the centred symbols). The same Figure also shows the stochastic standard deviation of ozone as calculated from the ozone soundings during the same period. It may be seen that below 25 km the variability of the altitude error has no significant effect on the total stochastic standard deviation of ozone, while above the 30 km level, about half of the observed day-to-day variability of ozone is induced by the altitude error. If the error bar is defined as an interval within which the true value can be expected with a probability of 95%, it may be calculated that the percentage error in individual ozone profiles induced by the altitude error amounts to more than 20 % above the ozone maximum. This is by far the largest error source in stratospheric ozone profiles obtained from balloon soundings [*De Muer et al.*, 1990].

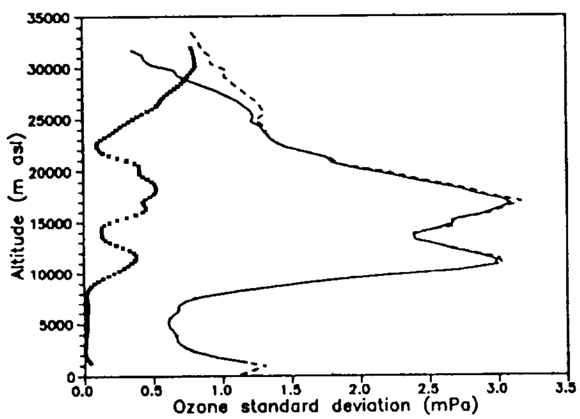

Fig. 5. Mean vertical distribution of the ozone standard deviation at Uccle calculated for the period 1985 through 1987:
- Total stochastic standard deviation (dashed line),
- standard deviation due to the variability of the altitude error (curve with centred symbols),
- stochastic standard deviation with the effect of the altitude error removed (full line).

5. CONCLUSIONS

(1) The altitude values calculated from VIZ radiosonde data are systematically lower than the altitudes calculated from the tracking of the balloon train with a primary wind-finding radar. The annual mean of the differences between the two altitude sets increases with altitude; at 30 km it varies between 590 and 1410 m.

(2) At least part of this systematic altitude error may be explained by a backlash of the aneroid driven "baroswitch" of the VIZ sondes. In addition certain manufacturing series of VIZ radiosondes apparently suffered from a systematic calibration error of the pressure sensor. The pressure data from Vaisala sondes appeared to be more accurate.

(3) At ozone soundings the pressure error of the VIZ radiosondes induces a bias in the ozone profile that varies between 7.5% to 14% at the 30 km level, depending upon the manufacturing series. At least part of the discrepancy which has been assessed at comparisons between stratospheric ozone profiles from balloon soundings and from other techniques may be explained by this bias.

(4) Above the 30 km level, about half of the stochastic standard deviation of ozone as inferred from ozone soundings with VIZ radiosondes is induced by the variability of the altitude error.

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