Differences in the Vertical Ozone Distribution Deduced from Umkehr and Ozonesonde Data at Goose Bay

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ABSTRACT

This study is devoted to a comparison between the vertical ozone distribution profiles obtained using indirect Umkehr and direct ozonesonde methods. In the three year period 1963–1965, there were 17 days with simultaneous Umkehr and ozonesonde profiles at 53N, 60W, predominantly in the winter-spring season. The mean ozone profiles indicate that the greatest differences occur at or about the level of the ozone maximum. The ozonesonde profile shows two maxima with the predominant one at about 20 km and a secondary one between 13 and 14 km, whereas the Umkehr profile shows only one maximum near 22 km. The center of gravity of the Umkehr profile is close to 21 km, and is about 1 km above that of the mean ozonesonde profile. Generally, the vertical ozone distribution obtained by both methods shows an approximately similar percentage distribution of the ozone amount. Only within the 15–24 km layer in all cases do the sondes give 9 per cent (of the total amount) more ozone content than the Umkehr method. Above 24 km the ozone partial pressure given from Umkehr is higher than it is from sondes. In this region the Umkehr profile gives 6 per cent (of the total amount) more ozone than the sondes. The correlation between the simultaneous changes in the integrated ozone within a given layer, estimated by alternative sampling methods, is high (≥ 0.80) between 10 and 19 km. Little relationship is found between them in the troposphere and above 24 km. The study suggests that direct comparisons of profiles taken by Umkehr and ozonesonde methods cannot be useful for the study of short-period and small-scale features.

1. Introduction

In the 25-year period after Götz (1931) discovered a method for determining the vertical ozone distribution from variations in the ratio of intensities of selected spectral intervals in zenith skylight with changing solar zenith angle, the total number of profiles computed was under 200. Prior to the IGY, daily Umkehr observations were begun in Arosa and subsequently the number of profiles computed increased rapidly there and elsewhere. Thanks to the efforts of Dütsch (1959) and Dütsch and Mateer (1964), there are now over 4000 Umkehr-type vertical ozone distribution profiles available.

A knowledge of the vertical ozone distribution is highly pertinent for studies of the stratospheric radiation budget and the stratospheric circulation. Studies of the ozone distribution in relation to weather pattern features have been aided by the establishment of an ozonesonde network over North America (Hering 1964; Hering and Borden, 1965) within the past three years.

Until sampling by sondes becomes more general, we must determine how consistent are the profiles determined by environmental sampling and by the indirect Umkehr method. Attempts to compare the vertical ozone distributions obtained by different methods have been made by Brewer *et al.* (1960) in the summer of 1958 in Arosa. In this study, Dütsch made a comparison of nine ozone profiles. He found that the height of the ozone maximum from Umkehr determinations was about 2–2½ km higher than that found using the Brewer-type electrochemical sonde, and about 3½ km above that given by the infrared technique. The level of maximum concentration, as determined by Paetzold optical ozonesondes, was found to correspond quite closely with that given by Umkehr, especially when D wavelength measurements were used. In a recent study, Mateer and Dütsch (1964) mentioned that the direct soundings showed a much sharper maximum, with less ozone in adjacent layers [mainly the second (10–15 km) and the sixth (28–33 km), but also to some extent the third (15–19 km)], as compared to the Umkehr results.

The North American network run by the Air Force Cambridge Research Laboratories (AFCRL) uses the Regener chemiluminescent sensor, and so far there have been no statistical comparisons of the results with Umkehr profiles. This study is devoted to such a comparison using vertical distribution profiles obtained by both methods at Goose Bay, Labrador (53N, 60W).

2. Observations and preliminary comparison

In the three year period 1963–65, there were seventeen days with simultaneous Umkehr and ozonesonde

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profiles, most of which (14 of 17) occur in the winter-spring season, making the results of this study most applicable in the season with greatest day-to-day changes. As the sonde profiles are in general made at 1200 GMT, the time lag between these and the Umkehr-derived profiles is seldom greater than six hours. There were a few cases of profiles on consecutive days, which made it possible to study the short-period changes as well as to compare the average profiles.

The ozonesonde profiles must first be corrected for consistency with the total ozone. This was done by integrating the net ozone enclosed on the ozonogram (Godson, 1962), having first extrapolated the profile at constant mixing ratio from its ceiling (<20 mb) to the top of the atmosphere, then making a uniform proportional increase at all levels by multiplying by the ratio of the total (spectrophotometric) to the integrated ozone.

The Umkehr profiles are corrected to the total ozone amount determined from the AD absorption method rather than the customary value found with the Vigroux absorption coefficients for the C wavelengths (Dobson 1957, 1963). The profiles are then consistent with the scaled sonde profiles adjusted using the total ozone found from the former technique.

For every observed Umkehr curve, there is an infinity of vertical ozone distributions (most of them physically unacceptable) which will "fit" the observations. The conclusions reached in this paper are valid only in interpreting Umkehr profiles evaluated by the system developed and described by Mateer and Dütsch (1964), and now in use at the World Ozone Data Center in Toronto.

To facilitate the comparison with the Umkehr data, the sonde profiles were subdivided into nine layers identical to those used in the standard Umkehr evaluation with the profiles then being specified in terms of the mean ozone partial pressure within each layer.

Average profiles of ozone partial pressure $\bar{p}_3{}^n$ computed from the sonde and Umkehr profiles for successive layers, are shown in Table 1. The overbar indicates an average and the index, $n=$ I to IX, the layers bounded by the 500-, 250-, 125-, 62.5-, 31.2-, 15.6-, 7.8-, 3.9-, 1.95- and 0.98-mb surface, respectively. The ozone in each layer n is also expressed as a percentage $\bar{\pi}^n$ of the total ozone above 500 mb in Table 1.

The profiles are in broad agreement with the mean winter-spring seasonal profile for the same latitude given from Bojkov (1965), WS$\bar{\pi}^n$ in Table 1. The partial pressures in the region from 10–24 km as measured by the sondes exceed those determined by the Umkehr method, the difference being greatest in layers III and IV (15–24 km). Above 24 km, and in the troposphere, the discrepancy between the profiles is reversed in sign with partial pressures determined by environmental sampling being less than those defined by the Umkehr determination. The fractional ozone content in each layer, expressed as a percentage $\bar{\pi}^n$ of the total ozone, also shows similar inconsistencies, though smaller in magnitude, between the alternative profiles.

The mean ozone profiles in Fig. 1 indicate that the greatest differences occur close to the height of the ozone maximum. The ozonesonde profile shows two maxima with a predominant one at about 20 km and a secondary one between 13 and 14 km, whereas the Umkehr profile shows only one maximum near 22 km. It is well known (Mateer, 1965) that Umkehr observations contain no information about features with vertical scales smaller than about 5–10 km. Even if Umkehr evaluations could provide the ozone content of these 5-km layers with perfect precision, any secondary maximum would still be lost most of the time. In fact, when the ozonesonde profiles used are integrated to provide the ozone content of the 5-km layers, not one of the profiles indicates a secondary maximum.

The center of gravity of the Umkehr profile is close to 21 km, about 1 km above that for the mean ozonesonde profile.

Within the upper troposphere (layer I) the differences from Table 1 give an excess, in favor of the Umkehr determinations, of only 1 per cent of the total ozone on the average, but the excess is invariably 2–7 per cent greater whenever the tropopause is above 9 km. When the tropopause is very low (7–7.5 km), the ozonesonde ascent gives higher values in layer I than does the Umkehr determination. This is obviously

TABLE 1. The average characteristics of vertical ozone distribution from Umkehr U and ozonesonde O_s observations where $\bar{p}_3{}^n$ is ozone partial pressure (μ mb), $\bar{\pi}^n$, the percentage of total ozone above 500 mb and WS, the mean winter-spring seasonal profile (Bojkov, 1965).

	Layer no.								
	I	II	III	IV	V	VI	VII	VIII	IX
	Approximate boundaries (km)								
	5–10	10–15	15–19	19–24	24–28	28–33	33–37	37–43	43–48
U$\bar{p}_3{}^n$	45.4	108.0	132.5	144.2	124.7	80.3	40.7	18.2	7.1
$O_s\bar{p}_3{}^n$	38.2	116.4	156.6	176.8	104.5	51.5	25.3	12.2	5.1
U$\bar{\pi}^n$	6.5	15.4	18.9	20.6	17.8	11.4	5.8	2.6	1.0
$O_s\bar{\pi}^n$	5.6	17.0	22.8	25.7	15.2	7.5	3.7	1.8	0.7
$\bar{\pi}^n(U-O_s)$	0.9	−1.6	−3.9	−5.1	2.6	3.9	2.1	0.8	0.3
WS$\bar{\pi}^n$	6.4	13.3	17.4	21.3	18.8	11.8	6.4	2.8	1.8

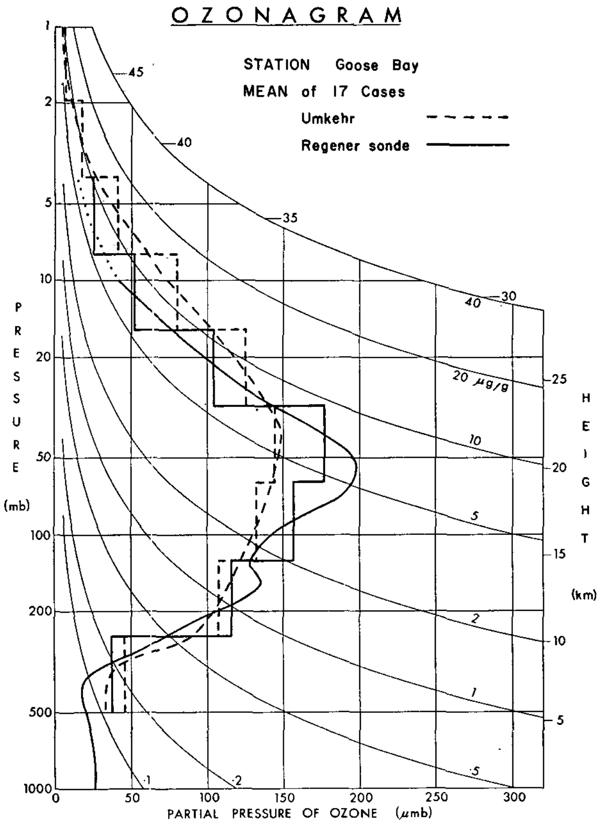

FIG. 1. The mean ozone vertical profiles and block diagrams for Goose Bay determined from 17 simultaneous Umkehr and ozonesonde observations.

related to the very rapid increase of ozone immediately above the tropopause to which the sonde responds much more effectively than the Umkehr with its lower resolution. When we compare the ozone content in the entire troposphere (not shown), we find that the amount from the Umkehr profile exceeds the ozonesonde profile value by 3 per cent (of the total ozone). The ratio between partial pressures determined by Umkehr and ozonesonde in this case is 1.31.

Study of the ratio of Umkehr- to sonde-determined partial pressures of ozone for successive layers, in Table 2, suggests that the ozone excess as determined by ozonesondes ranges between 7 and 18 per cent of its average value in the region between 10 and 24 km, but reverses in sign and increases to as much as 61 per cent in favor of the Umkehr profile above 24 km.

In relation to the fractional ozone content in different layers shown in Table 1, we can see that about 38 and 29 per cent of the net ozone content are recorded above the 24-km level by the Umkehr and sonde determinations, respectively. The corresponding fractional contents between 10 and 24 km are 54 and 65 per cent, respectively.

TABLE 2. Average ratio of Umkehr- to sonde-determined ozone partial pressure for various layers (from data of Table 1).

	Layer no.								
	I	II	III	IV	V	VI	VII	VIII	IX
$\dfrac{U\bar{p}_3^n}{O_s\bar{p}_3^n}$	1.19	0.93	0.85	0.82	1.19	1.56	1.61	1.49	1.39

TABLE 3. The average differences in simultaneous values of fractional ozone content $\Delta\bar{\pi}^n = U - O_s$ (as a percent of the total) estimated by Umkehr and ozonesonde methods for layers $n = $ I to IX for profiles in three ranges of total ozone content. Figures in parentheses show number of profiles in each range.

Total ozone amount (m atm-cm)	Layer no.								
	I	II	III	IV	V	VI	VII	VIII	IX
280–340 (5)	1.4	−0.8	−5.5	−4.9	2.1	4.0	2.6	1.0	0.2
341–400 (3)	1.7	−1.2	−5.2	−6.0	2.5	4.5	2.4	0.9	0.4
>400 (9)	0.6	−1.9	−2.8	−5.1	2.8	3.6	1.8	0.7	0.2

We next investigate the changes in the two profiles with variations in the total ozone amount. The ascents were divided into groups with 5, 3, and 9 cases each, whose total ozone fell within the limits 280–340, 340–400 and >400 m atm-cm, and the differences $\Delta\bar{\pi}^n$ between the fractional ozone contents of each layer as a percentage of the total evaluated for each group are shown in Table 3.

When the total ozone amount is below 400 m atm-cm we see from Table 3 that the difference in fractional ozone content is greatest between 15 and 24 km, but when the total ozone is greatest (>400 m atm-cm), the excess in the ozonesonde-determined profile extends down into layer II, reflecting the greater response of the sonde determination to changes in the lower stratosphere associated with the secondary maximum.

3. The correlation between total ozone and ozone within given layers

The sample is unfortunately small, but was nevertheless used to estimate the correlation coefficients between the departures from their respective mean values of total ozone and of the ozone contained in successive layers (as defined in Section 2). As the majority of profiles were made in the winter-spring season the results and inferences are particularly

TABLE 4. Average correlation coefficients between the variations in layer ozone contents and total ozone for 17 dual profiles (U, Umkehr; O_s, ozonesonde).

	Layer no.						
	I	II	III	IV	V	VI	VII+VIII+IX
U	0.46	0.88	0.88	0.88	0.73	0.50	0.16
O_s	0.47	0.83	0.71	0.88	0.38	0.24	0.15

TABLE 5. Average correlation coefficients between the variations in layers content determined by Umkehr and ozonesondes for 17 dual profiles.

	Layer no.				
	I	II	III	IV	V
$\rho(U, O_s)$	0.35	0.85	0.80	0.66	0.10

relevant to that period. The correlation coefficients, evaluated from both the Umkehr and ozonesonde profiles, are shown in Table 4.

We observe, in Table 4, that while the correlation coefficients are qualitatively similar (neither exhibiting the customary reversal in sign in the higher levels), the values are somewhat smaller in the 10–19 km region using ozonesonde data, and about half as much above 24 km, suggesting that the Umkehr determinations are more influenced by the total ozone amount. The correlations found agree quite satisfactorily with those computed for Arosa and for Japanese stations (Bojkov, 1965, 1966).

The correlation coefficients are most significant in the lower stratosphere where they have a value between 0.7 and 0.9 and a standard error of under 0.2. In the upper troposphere the standard error is about 0.2, and in the middle and upper stratosphere the standard error varies from 0.12 to 0.24.

It is also of interest to determine how simultaneous changes in the integrated ozone within a given layer, estimated by the alternative sampling methods, are related. The correlations between the simultaneous alternate estimates of the ozone content in each of the lower five layers are shown in Table 5.

We observe in Table 5 that the two estimates in the region between 10 and 24 km are highly correlated, but little relationship is found between them in the troposphere and above 24 km.

4. Changes on consecutive days

The profiles for 10 and 11 March 1964, determined by both methods, are shown in Fig. 2, and are representative examples for high total ozone amount. We note differences in the individual profiles in Fig. 2 similar to those already found in the averaged vertical distributions, the partial pressure from the Umkehr determinations being greater than that from ozonesondes above 24 km and less below. The ozone deficiency in the troposphere is consistent with the extremely low tropopause as noted in Section 2. The profiles are quite different with the ozonesonde ascents showing two distinct maxima apparently varying in height and the Umkehr determination showing only one maximum.

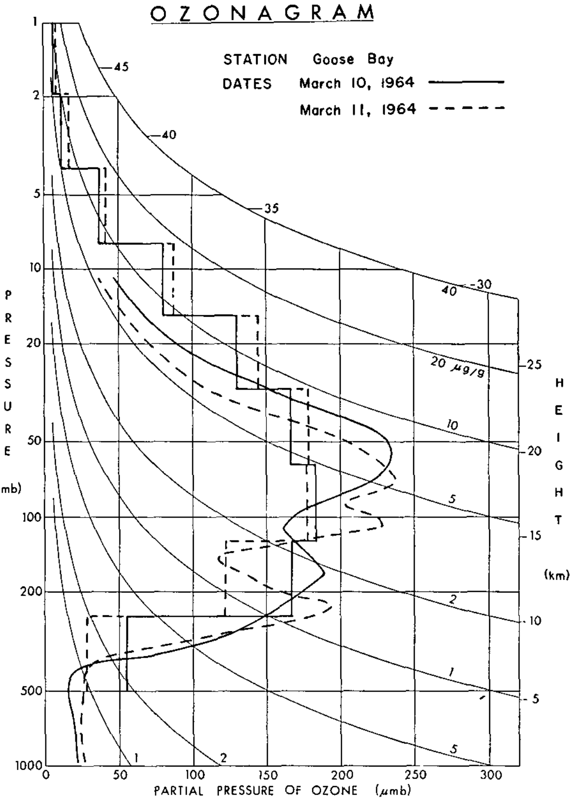

FIG. 2. Vertical ozone distribution for Goose Bay on 10 and 11 March 1964, shown with block diagrams for Umkehr and profiles for ozonesondes.

The total ozone amount for these days, as measured by the standard Dobson method, decreases from 489 to 452 m atm-cm. This change is accounted for, in the Umkehr determinations, by a decrease in the ozone below 19 km partly compensated by a corresponding increase at all levels above 19 km, whereas for the ozonesonde profile, there is a decrease at all levels from 19 km to the top of the flight. In the ozonesonde profiles the ozone fluctuates markedly below 19 km, with the two maxima on the profile apparently dropping by about 2 km, resulting in an increase in layer III but little net change below. The changes, expressed

TABLE 6. Percentage distribution of total ozone on 10 and 11 March 1964 (U, Umkehr; O_s, ozonesonde).

	Layer no.								
	I	II	III	IV	V	VI	VII	VIII	IX
$U\bar{\pi}^n$ 10 March	6.9	19.9	21.4	20.1	15.6	9.4	4.5	1.3	0.74
$U\bar{\pi}^n$ 11 March	3.7	15.4	21.9	22.1	18.2	10.7	5.1	2.2	0.78
$O_s\bar{\pi}^n$ 10 March	9.4	20.3	21.7	25.0	12.4	6.1	3.0	1.4	0.65
$O_s\bar{\pi}^n$ 11 March	10.0	20.1	28.0	23.3	10.2	4.5	2.3	1.0	0.40

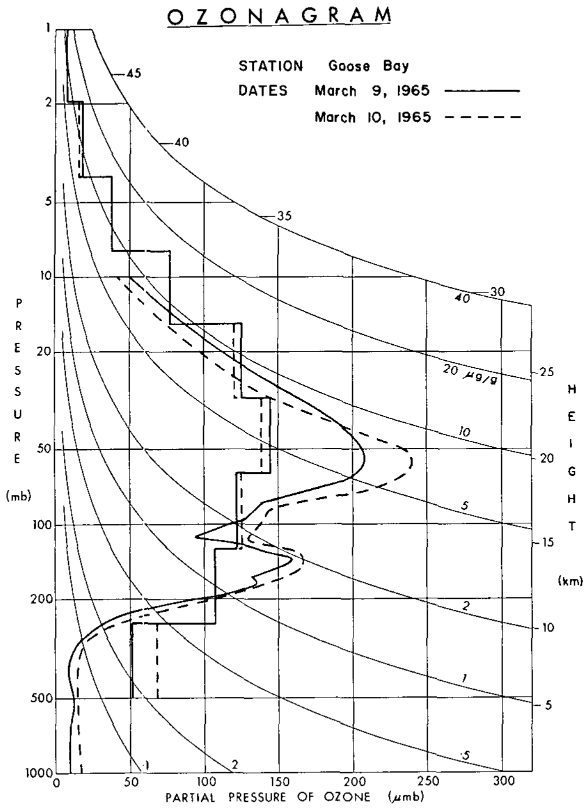

FIG. 3. Vertical ozone distribution for Goose Bay at 9 and 10 March 1965, shown with block diagrams for Umkehr and profiles for ozonesondes.

as fractional ozone content in successive layers as a percentage of the total, are shown in Table 6.

In Table 6 we observe that the net total ozone decrease is associated with contributions from different layers using the alternative methods. In brief, the short-period changes, even on a broad vertical scale, are in the opposite sense in this case.

A second case of consecutive days occurred on 9 and 10 March 1965, and was studied in a similar manner. The profiles are shown in Fig. 3. Again the ozonesondes show both primary and secondary maxima near 20 and 13 km, respectively, while the Umkehr determinations show only one at about 21–22 km.

The total ozone increases from 408 to 421 m atm-cm, and the increases in successive layers (Table 7) in this case are qualitatively similar. The net fractional content below 19 km, evaluated from Umkehr profiles, increases from 40 to 43 per cent, and from sonde profiles, from 39 to 43 per cent, between the 9th and the 10th.

These cases suggest that Umkehr and ozonesonde profiles are inconsistent as regards comparisons requiring vertical resolution of less than 5–10 km in the vertical, with the former profiles lacking the resolution to delineate even roughly the secondary maximum.

5. Conclusions

In spite of the inadequate representativeness of the sample considered, i.e., 17 cases predominantly in the winter-spring season at 53N, the study suggests that there are fairly characteristic differences between mean profiles determined by the two methods. The results presented in Section 1 suggest that seasonal profiles computed from one technique may be adjusted by a fractional correction which varies with successive layers, and is obtained by taking the ratio of the fractional ozone contents in given layers as derived from the two methods.

Above 24 km we have seen that the two curves are qualitatively similar, but the ozone partial pressure obtained from Umkehr data is larger than that from sondes. In this region the Umkehr profile gives 6 per cent (of the total amount) more ozone than the sondes. Here we must recall that above 28 km the ozonesonde data are extrapolated.

The most conspicuous difference remains in the position and number of the maxima. The analysis of consecutive profiles in Section 4 suggests that the Umkehr method is inadequate for studies of short-period changes even on a broad vertical scale.

Possible explanations for these differences are 1) the ozonesonde profile-adjustment method does not put enough ozone at high levels, and 2) Umkehr profiles are computed as minimum deviations from a smooth "standard profile" (Mateer and Dütsch, 1964), which does not permit an adequate peak in the derived profiles, and rarely if ever a secondary maximum.

Generally, the vertical ozone distributions obtained by both methods show approximately similar percentage distributions of the ozone amount. Only within the third and fourth (15–24 km) layers in all cases do the sondes give such more ozone content than the Umkehr technique. But when one knows (Dütsch 1963, 1965; Bojkov 1965) that the important total ozone variations result from changes in the lower and

TABLE 7. Percentage distribution of total ozone on 9 and 10 March 1965 (U, Umkehr; O_s, ozonesonde).

	Layer no.								
	I	II	III	IV	V	VI	VII	VIII	IX
$U\bar{\pi}^n$ 9 March	7.7	15.7	17.2	21.0	18.2	11.0	5.6	2.6	0.90
$U\bar{\pi}^n$ 10 March	10.2	15.4	17.4	20.0	17.2	10.8	5.5	2.4	0.88
$O_s\bar{\pi}^n$ 9 March	2.3	17.0	19.9	28.5	17.4	7.8	4.2	2.0	0.90
$O_s\bar{\pi}^n$ 10 March	2.7	17.6	22.7	28.9	15.4	6.8	3.5	1.7	0.77

middle stratosphere, it is evident that direct comparisons of profiles taken by Umkehr and ozonesonde methods cannot be useful for the study of short-period and small-scale features.

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REFERENCES

Bojkov, Rumen D., 1965: Vertical ozone distribution in the earth's atmosphere. *Meteor. Gydrol.* (Moskva), No. 10, 3–11.

——, 1966: The vertical distribution of atmospheric ozone and some relationship between its variations and the total ozone amount. *Z. Meteor.*, **19**, 10–12.

Brewer, A. W., H. U. Dütsch, J. R. Milford, M. Migeotte, H. K. Paetzold, F. Piscalar and E. Vigroux, 1960: Vertical ozone distribution—comparison of different methods. *Ann. Geophys.*, **16**, 1–27.

Dobson, G. M. B., 1957: Observers' handbook for the ozone spectrophotometer. *Ann. IGY*, **5**, 46–89.

——, 1963: Note on the measurement of ozone in the atmosphere. *Quart. J. R. Meteor. Soc.*, **89**, 409–411.

Dütsch, H. U., 1959: Vertical ozone distribution from Umkehr observations. *Arch. Meteor., Geophys. Bioklimatol.*, **A11**, 240–251.

——, 1963: Vertical ozone distribution over Arosa. Technical report No. 1, Grant No. AF-EDARDC 61–18, National Center for Atmospheric Research, Boulder, Colo., 26 pp.

——, 1965: Vertical ozone distribution over Arosa (August 1963–December 1964). Final report, Grant No. AF-EDAR 62-115, National Center for Atmospheric Research, Boulder, Colo., 34 pp.

——, and C. L. Mateer, 1964: Uniform evaluation of Umkehr observations from the world ozone network, Part II. National Center for Atmospheric Research, Boulder, Colo., 202 pp.

Godson, W. L., 1962: The representation and analysis of vertical distributions of ozone. *Quart. J. R. Meteor. Soc.*, **88**, 220–232.

Götz, F. W. P., 1931: Zum Strahlungsklima des Spitzbergen Sommers. *Beitr. Geophys.*, **31**, 119–154.

Hering, Wayne S., 1964: Ozonesonde observations over North America, Vols. 1 and 2. Air Force Cambridge Research Laboratories, Bedford, Mass.

——, and T. R. Borden, Jr., 1965: Ozonesonde observations over North America, Vol. 3. Air Force Cambridge Research Laboratories, Bedford Mass.

Mateer, C. L., 1965: On the information content of Umkehr observations. *J. Atmos. Sci.*, **22**, 370–381.

——, and H. U. Dütsch, 1964: Uniform evaluation of Umkehr observations from the world ozone network, Part I. National Center for Atmospheric Research, Boulder, Colo., 44 pp.