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DEPARTMENT OF COMMERCE
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THE SHORT UMKEHR METHOD, PART I:
STANDARD OZONE PROFILES FOR USE IN THE ESTIMATION OF OZONE PROFILES BY THE INVERSION OF SHORT UMKEHR OBSERVATIONS

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Air Resources Laboratories
Silver Spring, Maryland
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FOREWORD

In recent years there has been increasing concern about the possible reduction of atmospheric ozone due to photochemical reactions involving trace substances such as fluorochloromethanes, the concentrations of which are increasing because of human activities. Knowledge of the vertical ozone distribution is necessary for early detection of any trends in ozone variation. It is also essential in determining the radiative property of the stratosphere; understanding of major ozone changes may shed light on some important climatic fluctuations of the past.

The Umkehr effect is expressed as the ratio of the zenith sky light intensities of two wavelengths in the solar ultraviolet when the Sun is near the horizon. It was first noted by Dr. P. Götz in 1931. Observing the Umkehr effect and deducting therefrom the vertical ozone distribution is the most important means of using ground-based measurements for information on the ozone profile and its variations.

Ever since systematic observations began about 1930, the question of total ozone's precise vertical distribution has attracted atmospheric physicists. During the 1940's the existence of an ozone maximum at 20 to 30 km altitude was confirmed, but it was only during the IGY (1956/57) that a reliable uniform method for evaluation of Umkehr measurements, dividing the atmosphere into nine layers, became operational. During the last 20 years significantly improved evaluation techniques have been used by the World Ozone Data Center, operated on behalf of WMO by the Canadian Atmospheric Environment Service in Toronto. However, the total number of Umkehr profiles so far processed is below 20,000 and, more significantly, the number of observations made per year is steadily decreasing, the most frequently stated cause being the very long observing time required (3 to 7 hours!).

Therefore, the practical short-Umkehr method developed by Drs. C. L. Mateer and J. J. DeLuisi is a significant scientific achievement. The short-Umkehr method will increase dramatically the capability of Dobson stations to observe vertical ozone distribution, both systematically and more frequently. Not only will the observing time be decreased to 1-2 hours, but also the evaluation method outlined will allow delineation of average ozone partial pressure in up to 13 layers in the atmosphere.

It should be recalled that both the World Meteorological Organization and the Intergovernmental Meeting of Experts on the Ozone Layer identified a lack of sufficient data on vertical ozone distribution, which constituted a critical deficiency that prohibited assessing possible depletion of the ozone layer due to human activities and the consequences of such depletion.

It is expected that efforts will be made to give very wide application of the short-Umkehr method, which could substantially increase ozone profile information to interested scientists and thus be a major contribution to ozone science.

April 1980 Rumen D. Bojkov

PREFACE

This report is the first of a series that will describe the details of the development of the Short Umkehr Method. The Short Umkehr Method is being developed as an optional alternative to the conventional Umkehr method, for use when the time required for an observation is an important consideration. Whereas the time required for the conventional method is 2 to 3 hours, the short method will require only about 1/3 of this, namely the time while the Sun's zenith angle changes from 80° to 89°. The conventional method involves only the Dobson C-wavelength pair, while the short method involves the Dobson A-, C- and D- wavelength pairs. Available information on the ozone profile that is contained in the short method measurement is equivalent to the information contained in the conventional method measurement.

The development of the Short Umkehr Method can be separated into four phases. The first is the specification of a-priori statistical characteristics of the vertical ozone profile for inclusion in the measurement inversion system. For this, 5214 ozonesonde and 73 rocket observations were used. The second phase, which is the heart of the effort, is the development of the short measurement inversion system which will provide a best estimate of the ozone profile based on the information contained in the measurements and on the statistical constraints that were determined from the first phase. The efforts of the previous investigators who developed the Umkehr evaluation system currently in use at the World Ozone Data Center at Toronto enter significantly into this phase because it builds upon their work. The third phase is the determination of the error effects of haze on ozone profiles deduced by the Short Umkehr Method. Investigation of biasing errors due to the temperature dependence of ozone absorption is being postponed until newer determinations of ozone absorption become available. The fourth phase is the verification of the short method by comparing ozone profiles deduced by the short method with concurrent in-situ observations of ozone profiles obtained by ozonesonde and rocketsonde methods. At present, the data base for the fourth phase consists of only a few sets of concurrent observations. However, it is expected that this data base will be increased in the near future since a few stations in various countries have already begun obtaining concurrent observations, and it is hoped that others will follow.

Further work should be directed at the development of procedures to correct Short Umkehr Method ozone profiles for biases due to effects of stratospheric and tropospheric haze, and the temperature dependence of ozone absorption if they are needed. It would be desirable to build the correctional procedures into the inversion program; however, the feasibility of doing so has not yet been shown, and moreover, may require further experimental work to gather a sufficient body of data for evaluation.

Finally, the principal investigators wish to acknowledge their appreciation to the Canadian and U.S. governments for displaying a genuine willingness to promote a cooperative venture between the two countries. They also express their gratitude to Drs. Lester Machta and Donald Hunt who greatly encouraged the undertaking of the project at the time it was first proposed in the spring of 1978.

CONTENTS

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1. INTRODUCTION

In the development of the short or multi-wavelength Umkehr, we decided to use the optimum statistical inversion method (Rodgers, 1966; Strand and Westwater, 1968). Since this method presumes the availability of prior information about the ozone profile and its covariance matrix, we considered what information of a suitable nature was available. Standard ozone profiles (but not covariance matrices) had been generated for the evaluation of data from the Nimbus 4 Back-scattered Ultraviolet (BUV) experiment (Hilsenrath et al., 1977), but a considerable volume of additional direct balloon and rocket ozone sounding data had been generated since that time. Standard ozone profiles (again without covariance profiles) were generated by Hilsenrath and Dunn (1979) for the SBUV/TOMS experiment on Nimbus 7. However, in normalizing these profiles so that they integrated to the appropriate total ozone amount, a substantial correlation between upper stratospheric/mesospheric ozone and total ozone was introduced, for which there is no supporting theoretical or observational evidence. Accordingly, because the existing standard profiles were not entirely satisfactory and because no covariance matrices had been generated, we decided to proceed with the development of such information from the data available.

2. THE DATA BASE

The data base used in this study is essentially the same as that used by Hilsenrath and Dunn. Two magnetic tapes of ozonesonde data were obtained from them, the first consisting of ozonesonde data archived by the World Ozone Data Centre (WODC) and the second consisting of data from the U.S.A.F. special ozonesonde network operated primarily during the early 1960's. The stations contributing data are listed in Tables 1 and 2. Rocket ozonesonde data were provided by Krueger. (Locations are listed in Table 3.)

At best, these data provide a rather mixed bag of ozone profile information. The balloon ozone sounding data were obtained with several different instruments. The stations contributing data to the WODC tape used the Brewer-Mast ozonesonde, the Komhyr Carbon-Iodine (CI) sonde, and the Komhyr electrochemical concentration cell (ECC) sonde (or national versions thereof). The U.S.A.F. network used the Regener chemiluminescent ozonesonde. The raw ozone profiles obtained from these

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Table 1. Balloon sounding stations--World Ozone Data Centre tape

Station	Latitude (°)	Latitude Band	Instrument*
Kagoshima	31.6 N	M	CI
Tateno	36.0 N	M	CI
Wallops	37.5 N	M	ECC
Aspendale	38.0 S	M	M
Lisbon	38.8 N	M	M
Sterling	39.0 N	M	CI
Cagliari-Elmas	39.1 N	M	B
Bedford	42.5 N	M	M
Sapporo	43.0 N	M	CI
Biscarosse	44.4 N	M	M
Payerne	46.8 N	M	M
Hohenpeissenberg	47.8 N	M	M
Lindenberg	52.2 N	M	ECC
Berlin	52.5 N	M	B
Goose	53.3 N	M	M
Edmonton	53.6 N	M	M
Churchill	58.8 N	M	M
Fairbanks	64.8 N	H	CI
Syowa	69.0 S	H	CI
Base King Baudouin	70.4 S	H	M
Resolute	74.7 N	H	M
Byrd	80.0 N	H	CI

*CI - Carbon Iodine (national versions)
B - Brewer
M - Brewer-Mast
ECC - Electrochemical Concentration Cell

Table 2. Balloon sounding stations--U.S.A.F. tape

Station	Latitude (°)	Latitude Band
Canal Zone	9.0 N	L
La Paz	16.3 S	L
Grand Turk	21.5 N	L
Tallahassee	30.4 N	M
Pt. Mugu	34.1 N	M
Albuquerque	35.0 N	M
Wallops	37.5 N	M
Fort Collins	40.6 N	M
Bedford	42.5 N	M
Wisconsin	43.1 N	M
Seattle	47.4 N	N
Goose	53.3 N	M
Churchill	58.8 N	M
Fairbanks	64.8 N	H
Thule	76.5 N	H

Table 3. Locations of rocket ozonesondes

Station	Latitude	Latitude Band
Ship	4.0 N	L
Canal Zone	8.9 N	L
Peru	13.0 S	L
Antigua	16.9 N	L
Barking Sands	22.1 N	L
White Sands	32.2 N	M
Point Mugu	34.1 N	M
Wallops	37.8 N	M
Ship	47.0 S	M
Ship	52.0 S	M
Primrose Lake	55.0 N	M
Ship	58.0 S	H
Churchill	58.8 N	H

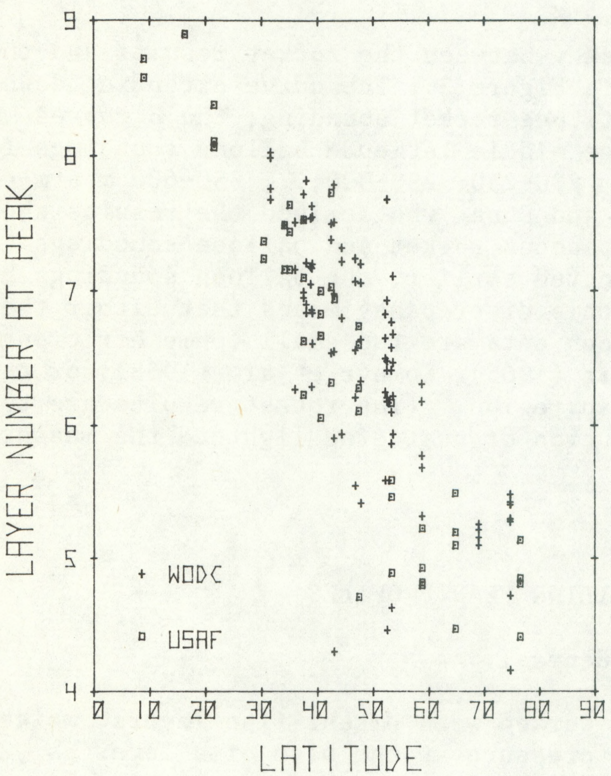

Figure 1. Layer number at main maximum of ozone profile as a function of latitude.

sondes (with the possible exception of the ECC sonde), must be normalized to the total ozone measured separately with a Dobson ozone spectrophotometer. The most serious discrepancy between the balloon sondes involves the Regener chemiluminescent ozonesonde which exhibited decreasing sensor sensitivity with time during many flights. Although considerable effort was expended to correct this deficiency during the data evaluation, there is a large-scale shape effect in the derived profiles such that there is relatively more ozone at lower levels, resulting in a lower center of gravity and a lower level of the main maximum (see Fig. 1). At least part of this effect is due, of course, to the very fast response time of the Regener instrument compared with the other sondes in use.

Table 4. Ratios between concurrent rocket and balloon ozonesonde measurements at various pressure levels*

Atmospheric Pressure (mb)	Rocket/Balloon Ratio
4	1.52
5	1.24
7	1.11
10	1.26
15	1.14
20	1.05
30	.99

*From Hilsenrath and Dunn (1979).

Finally, there is a serious discrepancy between the rocket results and the balloon soundings, which is illustrated in Figure 2. The curve extending downward from layer 16 is the mean middle latitude rocket sounding; the 8 curves extending upwards from layer 2 are average middle latitude balloon soundings for total ozone within the following ranges: 200-250; 250-300;...;550-600 m atm-cm. A similar effect was found by Hilsenrath and Dunn, who derived the results shown in Table 4 from a number of nearly simultaneous rocket and balloon soundings at Wallops Island, Virginia. Since, as noted earlier, the balloon soundings have already been normalized to total ozone, this discrepancy means that either the pump corrections applied to the raw balloon data are too small (pump efficiency decreases with pressure--Komhyr and Harris (1965), Komhyr et al. (1968)) or the rocket results are too high in the overlap region. (The rocket results are too low at low altitudes because the contribution of scattered light to the measurements becomes appreciable.)

3. METHOD OF COMPILING MEAN PROFILES

3.1 General

In compiling mean profiles, we have worked with Umkehr fine layers, which are defined as follows. The atmospheric pressure at the base of a layer is $\sqrt{2}$ times the atmospheric pressure at the top of the layer. The base of the lowest layer is taken to be 1.0 atmospheres (1013.25 mb), and the entire model contains 34 layers. The base of the 34th layer is at 1.08×10^{-5} atm (1.09×10^{-2} mb), and the uppermost layer therefore extends to the top of the atmosphere. For actual compilation purposes, the first four layers were lumped together as layer 1, as will be evident from an examination of Figures 2 et seq.

3.2 Balloon Profiles

Only soundings that reached at least the top of layer 8 (22.4 mb) were used in the compilation of our mean profiles. For all layers, the ozone content was calculated as the layer-mean partial pressure.

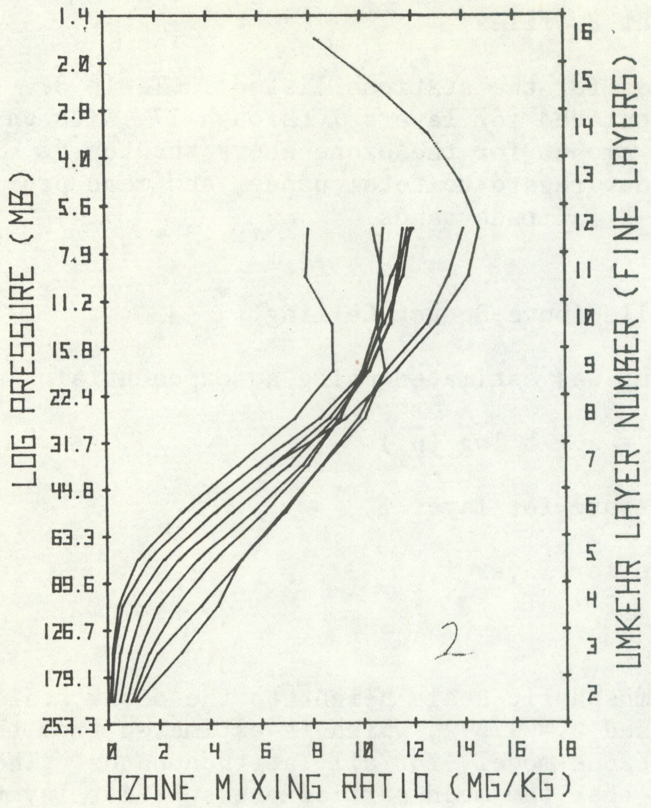

Figure 2. Average balloon and rocket ozone profiles for middle-latitude stations.

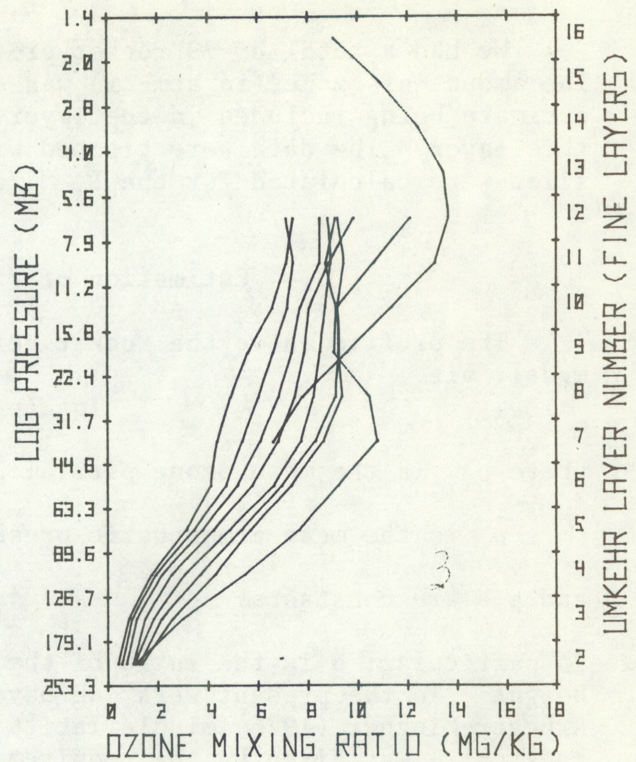

Figure 3. Average balloon and rocket ozone profiles for high-latitude stations.

$$\bar{p}_3 \text{ (nb)} = 3.654\ \Delta\Omega \text{ (m atm-cm)}$$

where $\Delta\Omega$ is the amount of ozone in the layer. For layer 1, the mean partial pressure for the layer from the actual surface pressure to 0.25 atm was considered to apply to the entire layer from 1.0 to 0.25 atm. At the top end of the sounding where, in general, there was always a part layer left, the layer was included if the balloon reached at least the midpoint of the layer. A constant mixing ratio was assumed, to estimate the ozone content of this layer above the balloon ceiling.

After all balloon profiles had been processed in the above manner, average profiles were calculated for each station within the total ozone ranges 200-250, 250-300; ....; 600-650 m atm-cm. The station results were then assigned to low (L), middle (M) or high (H) latitudes as indicated in Tables 1 and 2. Separate station averages were computed for stations on the WODC and U.S.A.F. tapes. At the same time, the layer number of the main maximum of each average profile was calculated; these are displayed in Fig. 1. Although there is a large amount of scatter, it is clear that the Regener sonde, as noted earlier, displays the main maximum at a lower level than the other sondes.

Finally, mean profiles were compiled for each latitude band and total ozone range. Figs. 2 and 3 contain examples of these for the middle latitude and high-latitude bands.

3.3 Rocket Profiles

We had a total of 73 rocket profiles for the stations listed in Table 3. The amount of ozone (in atm-cm) was calculated for layers 7 through 17, with an estimate being included in the layer 17 amount for the ozone above the top of this layer. The data were treated without regard to total ozone, and mean profiles were calculated for the L, M, and H latitude bands.

3.4 Estimation of Profile Above Rocket Ceiling

The profile above the rocket ceiling was estimated using an exponential model, viz.,

$$\log(\bar{p}_{3_i}) = a + b \log(\bar{p}_i)$$

where $\bar{p}_{3_i}$ is the mean ozone partial pressure for layer i,

$\bar{p}_i$ is the mean atmospheric pressure for layer i,

and a,b are constants.

In particular, b is the ratio of the atmospheric scale height to the ozone scale height. In the present work, we have used b = 1.872, which is estimated from the Krueger-Minzner (1976) middle latitude ozone model, for all latitude bands. The constant a was fixed by the requirement that the mean partial pressure for layer 16 should be 8.44 (nb) which was the overall mean for the 73 rocket profiles. The standard profiles are indicated for all latitude bands for all layers at and above layer 17.

4. MERGER OF BALLOON AND ROCKET PROFILES

This merger was necessarily somewhat arbitrary, and this arbitrariness increased with latitude.

For the low-latitude profiles, the mean profile corresponding to highest total ozone (.307 atm-cm) coincided with the rocket profile in layer 9, while the two remaining balloon profiles were very close. The rocket profile was used for the highest-total-ozone profile above layer 9 while the remaining two profiles were smoothly merged until, at layer 12, all three profiles were identical.

At middle latitudes, essentially the same procedure was followed. The highest-total-ozone mean profile was for .573 atm-cm. As can be seen in Fig. 2, the lowest-total-ozone profile (for .238 atm-cm) was significantly lower than the mean rocket profile, and the smooth progression over to the rocket profile began with layer 9.

The high-latitude situation is illustrated in Fig. 3. In this case, the highest-total-ozone profile was for .630 atm-cm and, again, the lowest-total-ozone profile (.285 atm-cm) is considerably below the mean rocket profile in layer 9. In this case, the smooth progression over to the rocket profile was begun with layer 7 and continued upwards to layer 15.

5. INTERPOLATION AND NORMALIZATION TO STANDARD TOTAL OZONE VALUES

The standard total ozone values selected for use in this application are as follows:

Low Latitudes: 0.2, 0.25, 0.3 atm-cm
Middle Latitudes: 0.2, 0.25, ... (0.05) ..., 0.55 atm-cm
High Latitudes: 0.2, 0.25, ... (0.05) ..., 0.65 atm-cm

Profiles for each of these total ozone values were interpolated/extrapolated from the mean profiles derived from the balloon-rocket merger process described above. It has to be emphasized that the total ozone value associated with each sounding has been used as the independent variable for interpolation and that no normalization of the profiles to this total ozone has been carried out up to this stage. Naturally, the normalization, which would have been present in the original balloon data, has been lost in the merging process.

The inconsistency between the rocket and balloon results at middle and high latitudes has been resolved somewhat arbitrarily in the merging process. In effect, the rocket data have been decreased while the balloon data have been increased over a broad transition zone. In the normalization to total ozone, we have adopted a procedure that leaves the rocket data unchanged in layers 13 and above, as follows.

We define

$$\Omega^1 = \sum_{i=1}^{12} C_i x_i$$

where x_i is the amount of ozone in layer i in the un-normalized profile, C(1) = C(2) = ... = C(6) = 1.0, and the values of C(7), ..., C(12) are as listed below.

Layer weights for normalization of profiles to total ozone

Layer	7	8	9	10	11	12
Weight	.8443	.6960	.5611	.4389	.3040	.1557

Further, we set $$\Omega = \sum_{i=1}^{34} x_i$$

If Ω_0 is the observed total ozone, then we may define a normalization factor

$$F = \frac{\Omega_0 - (\Omega - \Omega^1)}{\Omega^1}$$

such that the normalized profile is given by

$$x'_i = FC_i x_i + (1-C_i)x_i \qquad i= 1,2,\ldots,12$$

$$x'_i = x_i \qquad i= 13,14,\ldots,34$$

$$\text{and then} \quad \sum_{i=1}^{34} x'_i = \Omega_0 \quad \text{as required.}$$

Once again, the procedure is arbitrary, neither the balloon nor rocket results are considered to be correct. We have avoided inclusion of the high-level profile in the normalization process and, as a result, there is no correlation between the high-level profile and total zone.

6. TROPOSPHERIC PROFILE

As indicated earlier, the entire troposphere (and part of the winter lower stratosphere at high latitudes) was lumped together in layer 1 in the exercise just described. For purposes of inversion, this is quite satisfactory since the Umkehr method is incapable of resolving tropospheric structure. However, for purposes of pre-computing standard tables of multiple scattering effects this ozone must be distributed within the troposphere.

At low latitudes this was achieved very simply by downward extrapolation of trends clearly present in the higher layers. At middle and high latitudes, use was made of correlations, reported by Dütsch (1979), between total ozone and partial pressures from observations in Switzerland, as well as unpublished correlation and regression coefficients calculated for balloon soundings in Canada.

7. THE STANDARD PROFILES

The standard profiles are listed in Tables 5, 6, and 7. In these tables, the troposphere layer 1 has been subdivided into four layers, and all layers are renumbered accordingly. They are also shown graphically in three different formats in Figs. 4-12. The three formats are as follows; ozone partial pressure vs. log of atmospheric pressure; ozone mixing ratio vs. log of atmospheric pressure; and log of ozone partial pressure vs. log of atmospheric pressure. Each type of plot gives a somewhat different picture of the ozone profiles, and so all three have been included for completeness. Only the first-mentioned of these plots gives an equal area representation of the ozone profile; i.e., equal areas to the left of a curve represent equal amounts of ozone.

The additional profile on the low-latitude plots is for total ozone of 0.23 atm-cm. This was obtained by linear interpolation between the 0.2 and 0.25 profiles.

The weaknesses of these profiles center mainly around the inconsistency between the balloon and rocket profiles and the arbitrary methods used to resolve it. This procedure has the effect of lifting the center of gravity of the ozone profile. The overall effect is, of course, somewhat exaggerated when it is viewed on a mixing ratio plot as opposed to a partial pressure plot. An additional weakness arises from the lack of very-high-latitude rocket soundings and the fact that virtually all of the very-high-latitude balloon soundings are for a single location (Resolute). The lack of polar-night data is not, of course, a serious impediment for the present purpose, since Umkehr observations are impossible under such circumstances.

In all cases, the 0.2 atm-cm curve was obtained by extrapolation, as were the 0.25 and 0.65 atm-cm curves for high latitudes. In practice, we do not plan to use any of the 0.2 profiles. Our low-latitude series will probably start with the 0.23 atm-cm profile; the middle- and high-latitude ones will start with the 0.25 atm-cm profiles.

Table 5. Standard profiles for low latitudes

OZONE AMOUNTS IN VARIOUS LAYERS IN M ATM-CM

TOTAL OZONE (M ATM-CM)	200	230	250	300
LAYER				
1	.999E+00	.277E+01	.396E+01	.716E+01
2	.876E+00	.244E+01	.347E+01	.629E+01
3	.739E+00	.206E+01	.293E+01	.531E+01
4	.557E+00	.167E+01	.241E+01	.436E+01
5	.415E+00	.125E+01	.180E+01	.411E+01
6	.366E+00	.121E+01	.178E+01	.457E+01
7	.582E+00	.173E+01	.250E+01	.558E+01
8	.175E+01	.497E+01	.711E+01	.119E+02
9	.731E+01	.134E+02	.174E+02	.278E+02
10	.171E+02	.233E+02	.275E+02	.365E+02
11	.275E+02	.319E+02	.348E+02	.404E+02
12	.349E+02	.362E+02	.371E+02	.386E+02
13	.334E+02	.335E+02	.336E+02	.338E+02
14	.266E+02	.266E+02	.267E+02	.268E+02
15	.183E+02	.183E+02	.183E+02	.183E+02
16	.121E+02	.121E+02	.121E+02	.121E+02
17	.747E+01	.747E+01	.747E+01	.747E+01
18	.430E+01	.430E+01	.430E+01	.430E+01
19	.231E+01	.231E+01	.231E+01	.231E+01
20	.121E+01	.121E+01	.121E+01	.121E+01
21	.631E+00	.631E+00	.631E+00	.631E+00
22	.330E+00	.330E+00	.330E+00	.330E+00
23	.172E+00	.172E+00	.172E+00	.172E+00
24	.900E-01	.900E-01	.900E-01	.900E-01
25	.470E-01	.470E-01	.470E-01	.470E-01
26	.246E-01	.246E-01	.246E-01	.246E-01
27	.128E-01	.128E-01	.128E-01	.128E-01
28	.671E-02	.671E-02	.671E-02	.671E-02
29	.351E-02	.351E-02	.351E-02	.351E-02
30	.183E-02	.183E-02	.183E-02	.183E-02
31	.958E-03	.958E-03	.958E-03	.958E-03
32	.501E-03	.501E-03	.501E-03	.501E-03
33	.262E-03	.262E-03	.262E-03	.262E-03
34	.286E-03	.286E-03	.286E-03	.286E-03

Table 6. Standard profiles for middle latitudes

OZONE AMOUNTS IN VARIOUS LAYERS IN M ATM-CM

TOTAL OZONE (M ATM-CM) / LAYER	200	250	300	350
1	.287E+01	.521E+01	.707E+01	.719E+01
2	.253E+01	.457E+01	.619E+01	.630E+01
3	.213E+01	.386E+01	.522E+01	.631E+01
4	.175E+01	.317E+01	.430E+01	.712E+01
5	.188E+01	.350E+01	.611E+01	.127E+02
6	.204E+01	.445E+01	.849E+01	.165E+02
7	.341E+01	.735E+01	.129E+02	.209E+02
8	.708E+01	.144E+02	.225E+02	.306E+02
9	.155E+02	.241E+02	.323E+02	.394E+02
10	.219E+02	.301E+02	.370E+02	.417E+02
11	.244E+02	.314E+02	.366E+02	.383E+02
12	.260E+02	.286E+02	.314E+02	.324E+02
13	.252E+02	.256E+02	.261E+02	.265E+02
14	.206E+02	.209E+02	.211E+02	.213E+02
15	.161E+02	.161E+02	.161E+02	.161E+02
16	.108E+02	.108E+02	.108E+02	.108E+02
17	.697E+01	.697E+01	.697E+01	.697E+01
18	.414E+01	.414E+01	.414E+01	.414E+01
19	.228E+01	.228E+01	.228E+01	.228E+01
20	.121E+01	.121E+01	.121E+01	.121E+01
21	.631E+00	.631E+00	.631E+00	.631E+00
22	.330E+00	.330E+00	.330E+00	.330E+00
23	.172E+00	.172E+00	.172E+00	.172E+00
24	.900E-01	.900E-01	.900E-01	.900E-01
25	.470E-01	.470E-01	.470E-01	.470E-01
26	.246E-01	.246E-01	.246E-01	.246E-01
27	.128E-01	.128E-01	.128E-01	.128E-01
28	.671E-02	.671E-02	.671E-02	.671E-02
29	.351E-02	.351E-02	.351E-02	.351E-02
30	.183E-02	.183E-02	.183E-02	.183E-02
31	.958E-03	.958E-03	.958E-03	.958E-03
32	.501E-03	.501E-03	.501E-03	.501E-03
33	.262E-03	.262E-03	.262E-03	.262E-03
34	.286E-03	.286E-03	.286E-03	.286E-03

Table 6. Standard profiles for middle latitudes (continued)

TOTAL OZONE (M ATM-CM)	400	450	500	550
LAYER				
1	.719E+01	.719E+01	.719E+01	.719E+01
2	.676E+01	.698E+01	.707E+01	.708E+01
3	.724E+01	.805E+01	.823E+01	.809E+01
4	.889E+01	.117E+02	.129E+02	.133E+02
5	.212E+02	.288E+02	.341E+02	.389E+02
6	.254E+02	.348E+02	.431E+02	.589E+02
7	.297E+02	.409E+02	.549E+02	.685E+02
8	.389E+02	.474E+02	.579E+02	.640E+02
9	.459E+02	.510E+02	.563E+02	.599E+02
10	.452E+02	.472E+02	.497E+02	.516E+02
11	.393E+02	.403E+02	.414E+02	.435E+02
12	.332E+02	.339E+02	.347E+02	.360E+02
13	.270E+02	.274E+02	.279E+02	.283E+02
14	.215E+02	.218E+02	.220E+02	.222E+02
15	.161E+02	.161E+02	.161E+02	.161E+02
16	.108E+02	.108E+02	.108E+02	.108E+02
17	.697E+01	.697E+01	.697E+01	.697E+01
18	.414E+01	.414E+01	.414E+01	.414E+01
19	.228E+01	.228E+01	.228E+01	.228E+01
20	.121E+01	.121E+01	.121E+01	.121E+01
21	.631E+00	.631E+00	.631E+00	.631E+00
22	.330E+00	.330E+00	.330E+00	.330E+00
23	.172E+00	.172E+00	.172E+00	.172E+00
24	.900E-01	.900E-01	.900E-01	.900E-01
25	.470E-01	.470E-01	.470E-01	.470E-01
26	.246E-01	.246E-01	.246E-01	.246E-01
27	.128E-01	.128E-01	.128E-01	.128E-01
28	.671E-02	.671E-02	.671E-02	.671E-02
29	.351E-02	.351E-02	.351E-02	.351E-02
30	.183E-02	.183E-02	.183E-02	.183E-02
31	.958E-03	.958E-03	.958E-03	.958E-03
32	.501E-03	.501E-03	.501E-03	.501E-03
33	.262E-03	.262E-03	.262E-03	.262E-03
34	.286E-03	.286E-03	.286E-03	.286E-03

Table 7. Standard profiles for high latitudes

OZONE AMOUNTS IN VARIOUS LAYERS IN M ATM-CM

TOTAL OZONE (M ATM-CM) / LAYER	200	250	300	350	400
1	.543E+01	.626E+01	.662E+01	.666E+01	.684E+01
2	.537E+01	.619E+01	.654E+01	.708E+01	.740E+01
3	.491E+01	.612E+01	.646E+01	.771E+01	.897E+01
4	.430E+01	.604E+01	.712E+01	.976E+01	.153E+02
5	.485E+01	.973E+01	.165E+02	.236E+02	.314E+02
6	.126E+02	.174E+02	.219E+02	.267E+02	.331E+02
7	.216E+02	.268E+02	.313E+02	.361E+02	.415E+02
8	.271E+02	.337E+02	.394E+02	.447E+02	.494E+02
9	.225E+02	.298E+02	.373E+02	.435E+02	.479E+02
10	.157E+02	.209E+02	.290E+02	.357E+02	.400E+02
11	.124E+02	.167E+02	.209E+02	.249E+02	.287E+02
12	.114E+02	.141E+02	.167E+02	.192E+02	.214E+02
13	.111E+02	.129E+02	.145E+02	.161E+02	.176E+02
14	.982E+01	.112E+02	.124E+02	.136E+02	.147E+02
15	.862E+01	.940E+01	.101E+02	.109E+02	.115E+02
16	.734E+01	.769E+01	.803E+01	.838E+01	.873E+01
17	.598E+01	.608E+01	.618E+01	.627E+01	.637E+01
18	.425E+01	.425E+01	.425E+01	.425E+01	.425E+01
19	.243E+01	.243E+01	.243E+01	.243E+01	.243E+01
20	.121E+01	.121E+01	.121E+01	.121E+01	.121E+01
21	.631E+00	.631E+00	.631E+00	.631E+00	.631E+00
22	.330E+00	.330E+00	.330E+00	.330E+00	.330E+00
23	.172E+00	.172E+00	.172E+00	.172E+00	.172E+00
24	.900E-01	.900E-01	.900E-01	.900E-01	.900E-01
25	.470E-01	.470E-01	.470E-01	.470E-01	.470E-01
26	.246E-01	.246E-01	.246E-01	.246E-01	.246E-01
27	.128E-01	.128E-01	.128E-01	.128E-01	.128E-01
28	.671E-02	.671E-02	.671E-02	.671E-02	.671E-02
29	.351E-02	.351E-02	.351E-02	.351E-02	.351E-02
30	.183E-02	.183E-02	.183E-02	.183E-02	.183E-02
31	.958E-03	.958E-03	.958E-03	.958E-03	.958E-03
32	.501E-03	.501E-03	.501E-03	.501E-03	.501E-03
33	.262E-03	.262E-03	.262E-03	.262E-03	.262E-03
34	.286E-03	.286E-03	.286E-03	.286E-03	.286E-03

Table 7. Standard profiles for high latitudes (continued)

TOTAL OZONE (M ATM-CM)	450	500	550	600	650
LAYER					
1	.684E+01	.684E+01	.684E+01	.684E+01	.684E+01
2	.740E+01	.740E+01	.740E+01	.740E+01	.740E+01
3	.946E+01	.987E+01	.106E+02	.104E+02	.100E+02
4	.177E+02	.198E+02	.235E+02	.223E+02	.206E+02
5	.366E+02	.411E+02	.462E+02	.448E+02	.429E+02
6	.412E+02	.491E+02	.587E+02	.661E+02	.704E+02
7	.490E+02	.586E+02	.694E+02	.818E+02	.935E+02
8	.557E+02	.624E+02	.674E+02	.791E+02	.934E+02
9	.538E+02	.587E+02	.617E+02	.692E+02	.783E+02
10	.448E+02	.492E+02	.518E+02	.579E+02	.658E+02
11	.322E+02	.359E+02	.395E+02	.423E+02	.446E+02
12	.236E+02	.259E+02	.281E+02	.298E+02	.313E+02
13	.190E+02	.204E+02	.218E+02	.229E+02	.239E+02
14	.158E+02	.169E+02	.180E+02	.190E+02	.198E+02
15	.122E+02	.129E+02	.136E+02	.142E+02	.148E+02
16	.908E+01	.943E+01	.978E+01	.101E+02	.105E+02
17	.647E+01	.657E+01	.666E+01	.676E+01	.686E+01
18	.425E+01	.425E+01	.425E+01	.425E+01	.425E+01
19	.243E+01	.243E+01	.243E+01	.243E+01	.243E+01
20	.121E+01	.121E+01	.121E+01	.121E+01	.121E+01
21	.631E+00	.631E+00	.631E+00	.631E+00	.631E+00
22	.330E+00	.330E+00	.330E+00	.330E+00	.330E+00
23	.172E+00	.172E+00	.172E+00	.172E+00	.172E+00
24	.900E-01	.900E-01	.900E-01	.900E-01	.900E-01
25	.470E-01	.470E-01	.470E-01	.470E-01	.470E-01
26	.246E-01	.246E-01	.246E-01	.246E-01	.246E-01
27	.128E-01	.128E-01	.128E-01	.128E-01	.128E-01
28	.671E-02	.671E-02	.671E-02	.671E-02	.671E-02
29	.351E-02	.351E-02	.351E-02	.351E-02	.351E-02
30	.183E-02	.183E-02	.183E-02	.183E-02	.183E-02
31	.958E-03	.958E-03	.958E-03	.958E-03	.958E-03
32	.501E-03	.501E-03	.501E-03	.501E-03	.501E-03
33	.262E-03	.262E-03	.262E-03	.262E-03	.262E-03
34	.286E-03	.286E-03	.286E-03	.286E-03	.286E-03

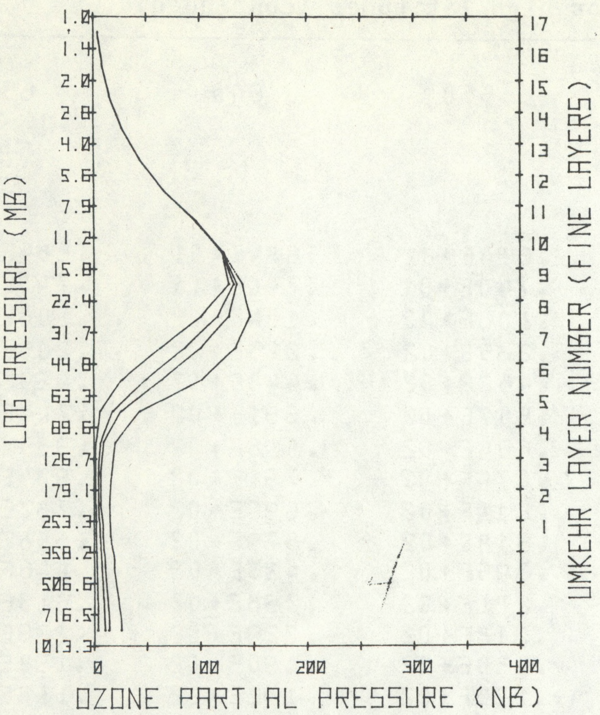

Figure 4. Low-latitude standard ozone profiles for total ozone .20, .23, .25, and .30 atm-cm.

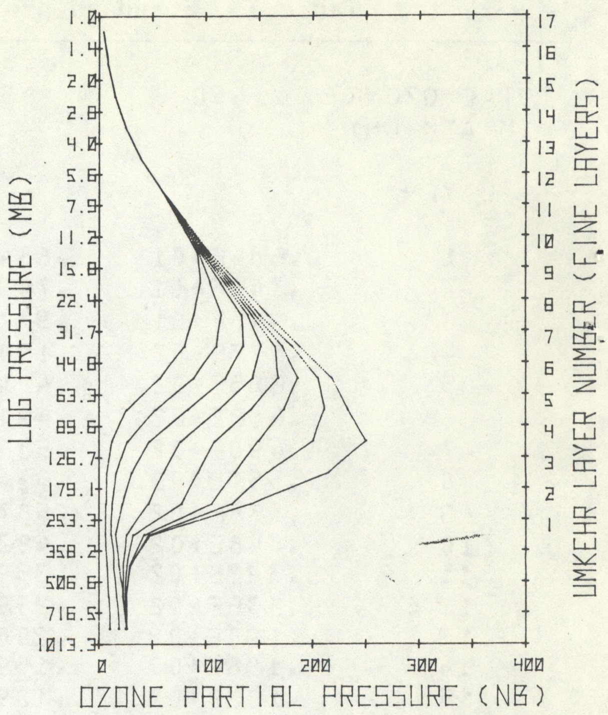

Figure 5. Middle-latitude standard ozone profiles for total ozone .20, .25,..., .55 atm-cm.

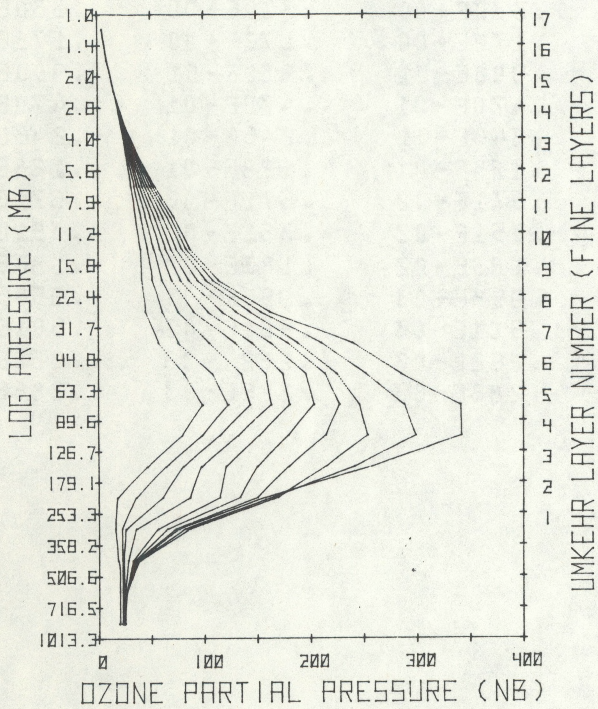

Figure 6. High-latitude standard ozone profiles for total ozone .20, .25,..., .65 atm-cm.

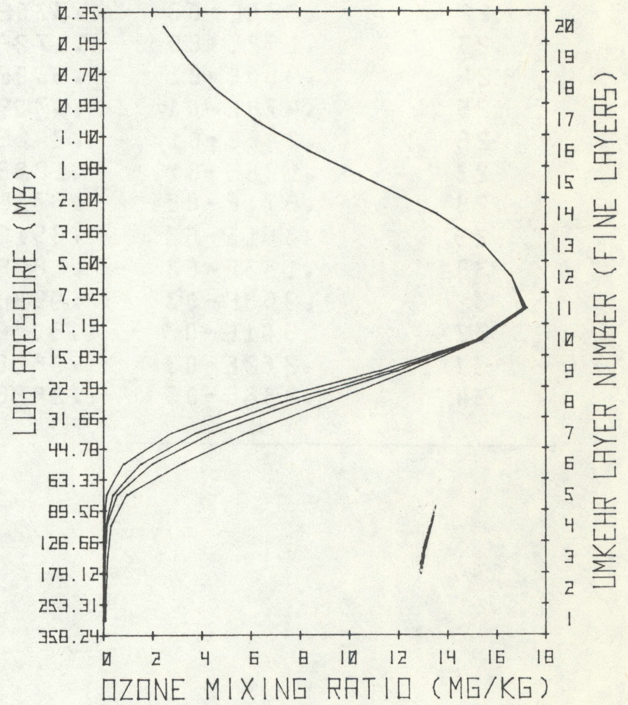

Figure 7. Low-latitude standard ozone profiles for total ozone .20, .23, .25, and .30 atm-cm.

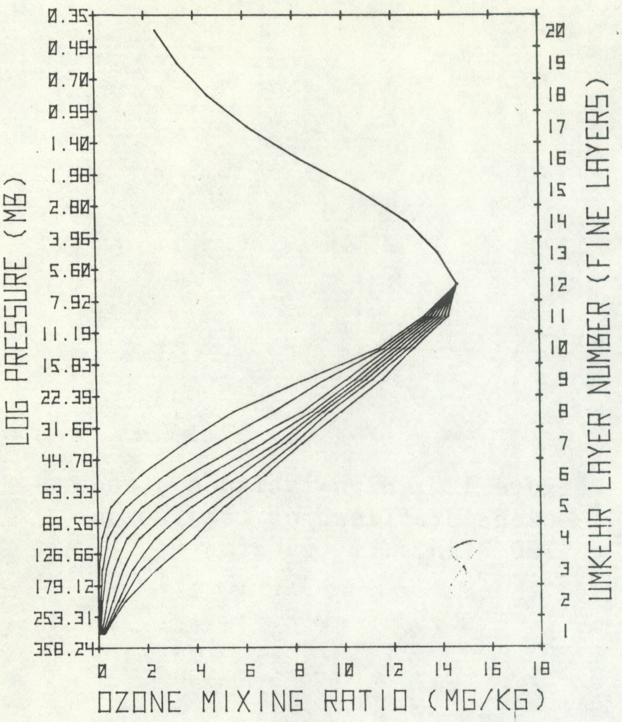

Figure 8. Middle-latitude standard ozone profiles for total ozone .20, .25,..., .55 atm-cm.

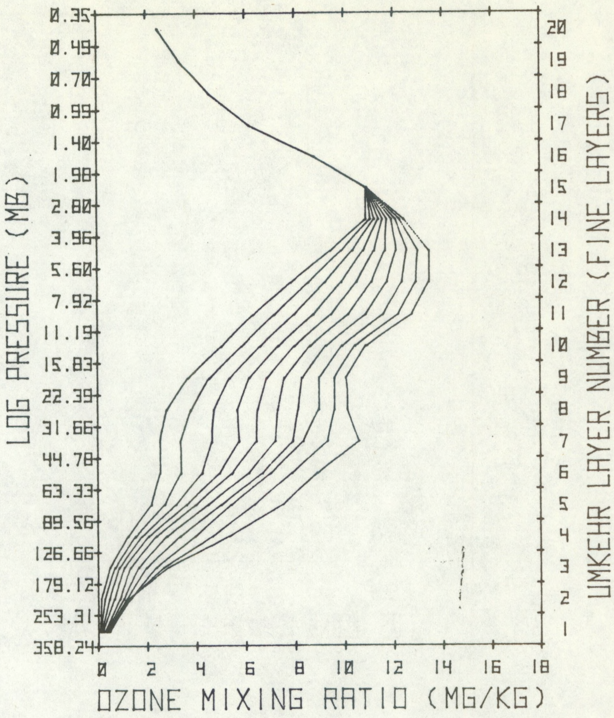

Figure 9. High-latitude standard ozone profiles for total ozone .20, .25,..., .65 atm-cm.

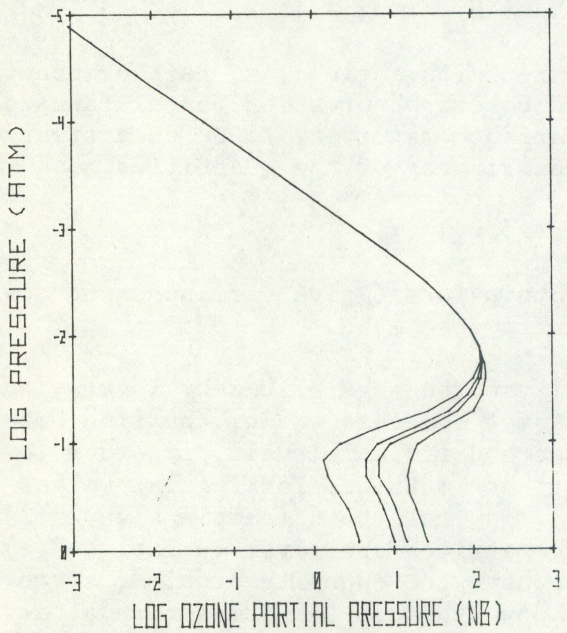

Figure 10. Low-latitude standard ozone profiles for total ozone .20, .23, .25, and .30 atm-cm.

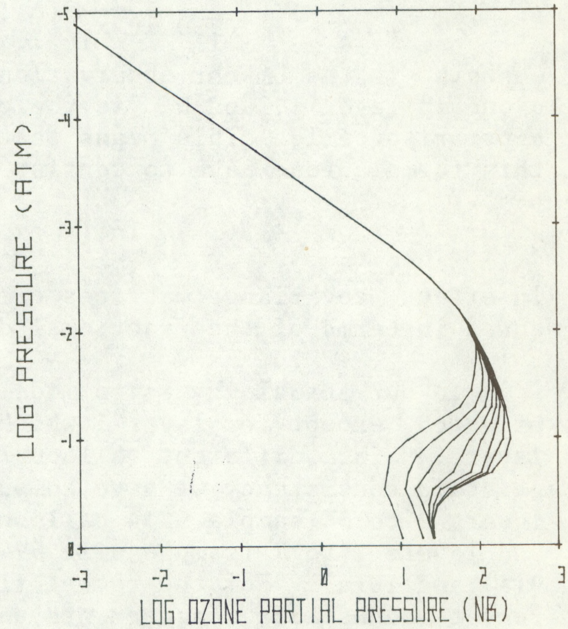

Figure 11. Middle-latitude standard ozone profiles for total ozone .20, .25,..., .55 atm-cm.

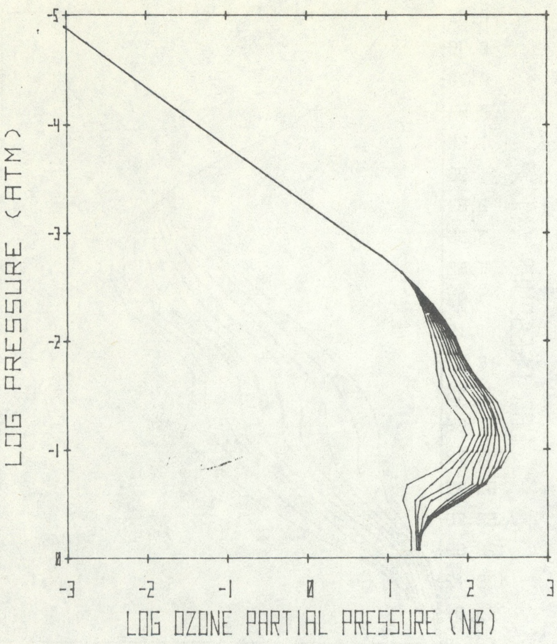

Figure 12. High-latitude standard ozone profiles for total ozone .20, .25,..., .65 atm-cm.

8. THE COVARIANCE MATRICES

The Umkehr inversion problem takes the following form (see Dütsch, 1959; Mateer and Dütsch, 1964):

$$\sum_i \frac{\partial N_j}{\partial \ln x_i} (\Delta \ln x_i) = N_j - N_{sj} \qquad j = 1, 2, \ldots$$

where N_j is the Umkehr observation for solar zenith angle j, x_i is the amount of ozone in layer i, and N_{sj} is the calculated Umkehr observation for a standard or a-priori profile. This means that our covariance matrices, to be consistent with this formulation, have to consist of the covariances of the quantities

$$\ln (x_i/\bar{x}_i) \text{ and } \ln (x_j/\bar{x}_j) .$$

In effect, covariance matrices computed in this format give variances and covariances in terms of the fractional departure from the mean.

In our actual inversion model we shall use the regular Umkehr layers, each of which, except for layer 1 which is the same, combines two of the fine Umkehr layers. Since different balloon flights reach different levels, in order to maintain consistency we have computed covariance matrices for regular Umkehr layers 1 to 5 (sample 5214 balloon flights), layers 1 to 6 (sample size 2912), and layers 1 to 7 (sample size 594). These matrices are given in Tables 8(a), 9(a) and 10(a). For the rocket flights, we have the opposite problem, since the rocket sondes take measurements on the way down through the atmosphere after deployment near rocket apogee. That is to say, different flights penetrate down to different levels. Accordingly, we have computed covariance matrices for regular Umkehr layers 9 to 6 (sample size 69), layers 9 to 5 (sample size 66), and layers 9 to 4 (sample size 53). These matrices are listed in Tables 11, 12, and 13.

Table 8. Covariance matrix for layers 1 to 5 (sample size 5214)

(a) Unadjusted

	1	2	3	4	5
1	.165	.160	.071	.015	-.011
2	.160	.690	.385	.103	-.035
3	.071	.385	.303	.081	-.023
4	.015	.103	.081	.042	.006
5	-.011	-.035	-.023	.006	.024

(b) Adjusted for Total Ozone Correlation

Correlation	.308	.548	.497	.517	.108
1	.149	.103	.036	.002	-.013
2	.103	.482	.260	.055	-.043
3	.036	.260	.228	.052	-.028
4	.002	.055	.052	.031	.004
5	-.013	-.043	-.028	.004	.024

Table 9. Covariance matrix for layers 1 to 6 (sample size 2912)

(a) Unadjusted

	1	2	3	4	5	6
1	.157	.146	.061	.014	-.009	-.009
2	.146	.674	.357	.101	-.026	-.059
3	.061	.357	.279	.077	-.017	-.044
4	.014	.101	.077	.041	.006	-.008
5	-.009	-.026	-.017	.006	.020	.017
6	-.009	-.059	-.044	-.008	.017	.037

(b) Adjusted for Total Ozone Correlation

Correlation	.337	.623	.579	.589	.142	.024
1	.139	.078	.021	-.001	-.012	-.010
2	.078	.413	.201	.040	-.036	-.061
3	.021	.201	.186	.040	-.023	-.046
4	-.001	.040	.040	.026	.004	-.008
5	-.012	-.036	-.023	.004	.020	.017
6	-.010	-.061	-.046	-.008	.017	.037

Table 10. Covariance matrix for layers 1 to 7 (sample size 594)

(a) Unadjusted

	1	2	3	4	5	6	7
1	.123	.116	.026	.013	.001	.004	-.001
2	.116	.614	.217	.069	-.010	-.035	-.030
3	.026	.217	.143	.042	-.003	-.022	-.018
4	.013	.069	.042	.032	.007	-.006	-.008
5	.001	-.010	-.003	.007	.011	.008	.003
6	.004	-.035	-.022	-.006	.008	.025	.024
7	-.001	-.030	-.018	-.008	.003	.024	.038

(b) Adjusted for total ozone correlation

	1	2	3	4	5	6	7
Correlation	.442	.770	.749	.691	.248	.038	.109
1	.099	.022	-.018	-.006	-.003	.002	-.004
2	.022	.250	.046	-.006	-.025	-.039	-.042
3	-.018	.046	.063	.006	-.010	-.024	-.024
4	-.006	-.006	.006	.017	.004	-.007	-.011
5	-.003	-.025	-.010	.004	.010	.008	.003
6	.002	-.039	-.024	-.007	.008	.025	.024
7	-.004	-.042	-.024	-.011	.003	.024	.038

Table 11. Covariance matrix for layers 6 to 9 (sample size 69)

	6	7	8	9
6	.029	.020	.004	-.002
7	.020	.024	.019	.012
8	.004	.019	.039	.034
9	-.002	.012	.034	.058

Table 12. Covariance matrix for layers 5 to 9 (sample size 66)

	5	6	7	8	9
5	.018	.014	.008	.000	-.003
6	.014	.028	.020	.005	-.002
7	.008	.020	.025	.020	.013
8	.000	.005	.020	.040	.035
9	-.003	-.002	.013	.035	.060

Table 13. Covariance matrix for layers 4 to 9 (sample size 53)

	4	5	6	7	8	9
4	.104	.009	.001	-.002	-.009	-.024
5	.009	.017	.014	.008	.004	-.000
6	.001	.014	.030	.021	.006	-.003
7	-.002	.008	.021	.024	.017	.010
8	-.009	.004	.006	.017	.032	.029
9	-.024	-.000	-.003	.010	.029	.060

Finally, we shall be using total ozone in our inversion procedure as a predictor for selecting the prior information or first guess ozone profile. In other words, given total ozone we shall interpolate linearly between the appropriate standard profiles to obtain our prior information profile. The covariance matrices have to be adjusted to allow for this selection procedure; the covariance between total ozone and the partial pressure in each layer must be removed from the covariance matrices (see Westwater and Strand, 1968). These adjusted covariance matrices are given in Tables 8(b), 9(b) and 10(b) for the balloon soundings. It was not possible to do this for the rocket soundings because total ozone measurements were not available for many of them. In any event, the correlation with total ozone is small in the uppermost layers where we use the rocket results to estimate the covariance. The merging and actual use of these covariance matrices in the short Umkehr inversion will be discussed in a subsequent report on the development of the short Umkehr inversion system.

9. ACKNOWLEDGMENTS

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10. REFERENCES

Dütsch, H.U., 1959: Vertical ozone distribution from Umkehr observations. Arch. Met. Geophys. Biol. A, 11, 240-251.

Dütsch, H.U., 1979: Regular ozone soundings at the aerological station of the Swiss Meteorological Office at Payerne, Switzerland, 1972-1976. Lab. für Atmosphärenphysik. ETH, Zurich, LAPETH-16, 239 pp.

Hilsenrath, E., P.J. Dunn, and C.L. Mateer, 1977: Standard ozone profiles from balloon and rocket data for satellite and theoretical model input. Presented at IAGA/IAMAP Joint Assembly, Seattle, August 1977.

Hilsenrath, E., and P.J. Dunn, 1979: Standard profiles for total ozone retrievals. Unpublished manuscript.

Komhyr, W.D. and T.B. Harris, 1965: Note on flow rate measurements made on Brewer-Mast ozone sensor pumps. Mon. Wea. Rev., 93, 267-268.

Komhyr, W.D., R.D. Grass and R.A. Proulx, 1968: Ozonesonde intercomparison tests. Tech. Rep. ERL 85-APCL 4, ESSA Res. Labs., Boulder, Colo., 74 pp.

Krueger, A.J., and R.A. Minzner, 1976: A mid-latitude ozone model for the 1976 U.S. Standard Atmosphere. J. Geophys. Res., 81, 4477-4481.

Mateer, C.L. and H.U. Dütsch, 1964: Uniform evaluation of Umkehr observations from the world ozone network, Part I. National Center for Atmospheric Research, Boulder, Colo., 105 pp.

Rodgers, C.D., 1966: Satellite infrared radiometer--a discussion of inversion methods. Clarendon Lab., University of Oxford, Memo No. 66.13, 25 pp.

Strand, O.N. and E.R. Westwater, 1968. The statistical estimation of the numerical solution of a Fredholm integral equation of the first kind. J. Assoc. Comp. Mach., 15, 104-114.

Westwater, E.R., and O.N. Strand, 1968: Statistical information content of radiation measurements used in indirect sensing. J. Atm. Sci., 25, 750-758.