JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 101, NO. D11, PAGES 16,779–16,787, JULY 20, 1996

Influence of a priori profiles on trend calculations from Umkehr data

C. L. Mateer
Scarborough, Ontario, Canada

H. U. Dütsch and J. Staehelin
Laboratory for Atmospheric Physics, ETH Hönggerberg, Zürich, Switzerland

J. J. DeLuisi
NOAA Environmental Research Laboratories, Boulder, Colorado

Abstract. Although the new (1992) ozone profile retrieval algorithm for Umkehr measurements provides much better agreement with ozone sounding results than the old (1964) algorithm, considerable discrepancies remain with respect to ozone trends at different levels in the atmosphere. These discrepancies have been found by the comparison of long-term trends obtained from the Umkehr measurements at Arosa and the ozone balloon soundings at Payerne (Switzerland). It is investigated here whether these obvious discrepancies can be removed by using time-dependent a priori profiles. This procedure is successful only in the lowest part of the atmosphere, below about 19 km. To further explore this problem, synthetic Umkehr observations are calculated from the ozonesonde profiles. Trends are calculated for both the synthetic and actual Umkehr observations. The difference pattern between these Umkehr observation trends is compared with the difference in ozone profile retrieval trends from the synthetic and actual observations. The distinctive difference patterns strongly indicate an inherent disagreement between the Umkehr observations and the ozonesonde profiles. The application of corrections for stratospheric aerosol effects to the Umkehr profiles reduces, but does not eliminate, a discrepancy above 32 km. It is concluded that the discrepancies are due to the constant mixing ratio assumption used in computing the residual ozone above balloon burst level and to the fair-weather bias of Umkehr observations (there are Umkehr observations at Arosa on fewer than 20% of the sonde observation days at Payerne). This sampling difference influences the results for the lower stratosphere. The study furthermore indicates that the ozone trends derived from Umkehr measurements for altitudes above about 32 km are robust for time-dependent changes in the a priori profiles at lower altitudes. Based on the results of this study, we conclude with revised recommendations as to which atmospheric layers should be used for Umkehr trend studies.

1. Introduction

The Umkehr technique provided the first indirect observations of the vertical ozone profile [*Götz et al.*, 1934], as well as the first regular ozone profile observations (dating back to the midfifties) and also provided information on the ozone content of the upper stratosphere. However, Umkehr observations are possible only when the sky, especially near the zenith, is free of clouds. On the other hand, regular balloon soundings, starting in the sixties and yielding much more profile detail, reach only into the middle stratosphere, but are possible in most weather conditions and therefore do not suffer from the fair-weather bias of the Umkehr method.

In the Umkehr method the Dobson spectrophotometer is used to measure the intensity ratio of two ultraviolet wavelengths in the zenith skylight between 60° and 90° solar zenith angle. For each wavelength, the main contribution to this scattered light comes from different altitudes as the solar zenith angle changes. Because ozone absorbs one wavelength more strongly than the other, the sequence of observations provides a vertical scanning effect and therefore contains information on the ozone profile.

The Umkehr is an indirect profiling method and, as is often the case with such methods, the profiles retrieved from the observations are not unique and depend on the details of the retrieval method. The first computer-based Umkehr algorithm was developed by *Dütsch* [1959a, b]. The second such algorithm [*Mateer and Dütsch*, 1964] has been applied routinely to all Umkehr observations from the world network at the World Ozone Data Center (WODC) at Toronto through December 31, 1991. Because of the introduction of new ozone absorption coefficients and to correct obvious discrepancies between sonde and Umkehr profile statistics, a third algorithm [*Mateer and DeLuisi*, 1992] (hereinafter MD92) was introduced at the WODC beginning with the data from January 1, 1992.

Using this new algorithm, *Dütsch and Staehelin* [1992] re-

Copyright 1996 by the American Geophysical Union.

Paper number 95JD03794.
0148-0227/96/95JD-03794$09.00

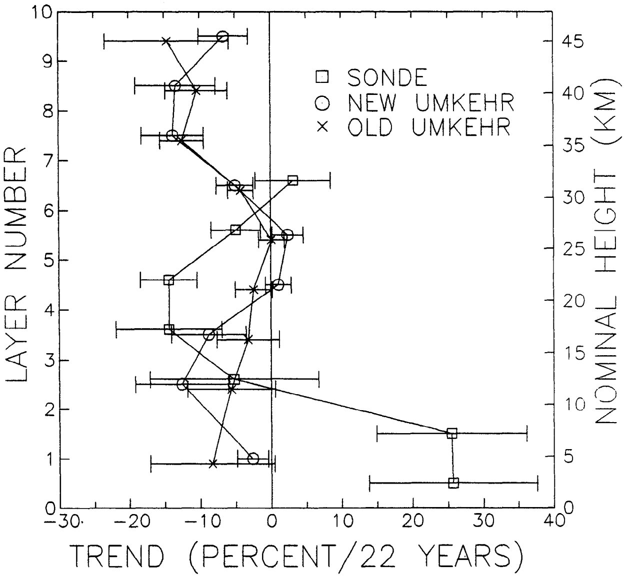

Figure 1. Ozone profile trends from *Dütsch and Staehelin* [1992, Table 7] for sondes (squares), 1964 Umkehr algorithm (crosses), and 1992 Umkehr algorithm (circles). Error bars are for 2σ.

computed the over 30-year-long Umkehr record for Arosa, Switzerland, comprising 3775 profiles obtained from clear sky and 3925 profiles from partially cloudy sky measurements. They compared these results with those from the 1964 algorithm and also with those for the ozone sounding data set collected from 1967 to 1989 at Payerne, Switzerland, about 200 km west of Arosa. It was found that, for this latter period of parallel measurements, the overall annual mean profile obtained from the 1992 algorithm agreed much better with the mean ozonesonde profile than was the case for the mean profile from the 1964 algorithm. The agreement with respect to the seasonal variation was not equally good, but still fair. For a small comparison sample of simultaneous sonde and Umkehr observations, the agreement of average layer amounts was not as good [see *Dütsch and Staehelin*, 1992, Tables 3 and 5]. However, there remained considerable discrepancies between the trends at different levels calculated from the new and 1964 Umkehr retrievals and the sounding data, as illustrated in Figure 1 [from *Dütsch and Staehelin*, 1992, Table 7]. In layer 1, both Umkehr retrievals fail to reproduce the large positive trend from the sondes. In layer 4, both Umkehr trends are small compared to the large negative sonde trend. Because the trend error bars are correlated (due to common interannual variations in the sonde and Umkehr measurements), it is not possible to infer the statistical significance of trend differences directly from the trend error bars. It will suffice here to state that all trend differences between the sonde and the new Umkehr are significant, except in layer 2, using the method described in section 3.2. The trends in Figure 1 are for the entire period 1967–1989 and include the results for the 1982–1985 period when the Umkehr results were strongly affected by the stratospheric aerosols from the El Chichon volcanic eruption. The pressures and heights for the Umkehr layer boundaries are listed in Table 1.

The differences between these sonde and Umkehr trends provided the impetus for this paper. We investigate the differences, especially with the aim to confirm the reliability of the Umkehr trend results for the upper stratosphere, for which no long-term soundings are available, and where the Umkehr record provides the only information for an extended period covering three solar cycles.

To better understand the reasons for the differences, we carry out two diagnostic studies. First, *Dütsch and Staehelin* [1992] argued that the differences could be a consequence of a considerable influence of the a priori profiles on the final Umkehr retrieval. To examine this possibility, we obtain Umkehr retrievals using time-dependent a priori profiles, which mimic the sonde trends in the lower layers (below 24 km). In the second study, we calculate synthetic Umkehr observations for the series of annual average sonde profiles, obtain Umkehr ozone profile retrievals from these observations, and calculate profile trends from the retrievals. Recognizing that an ozone profile retrieval trend difference must be produced by an Umkehr observation trend difference, we examine the difference between the trend of the synthetic Umkehr observation curves and the trend of the annual average actual Arosa Umkehr observation curves. We then compare these observation trend differences with the retrieval trend differences produced by them.

Finally, we introduce corrections for the effect of stratospheric aerosols on the Umkehr observations [e.g., *DeLuisi*, 1969, 1979] for the period following the El Chichon volcanic eruption.

2. Possible Reasons for Differences

2.1. Umkehr Profiles

The limitations of the Umkehr method are well known [*World Meteorological Organization* (WMO), 1988; MD92]. These are well illustrated by the averaging kernels [*Rodgers*, 1990], which describe the mapping of the difference between the true ozone profile and the a priori profile into the difference between the retrieved profile and the a priori profile. For the Umkehr retrievals, the profile resolution is poor, with the half width of the averaging kernels (Figure 2) being at least two layers (about 10 km). In Figure 2, layer 1 (a double layer) extends from ordinates zero to 2, layer 2 from ordinates 2 to 3, and so on. Layer 1 has a relatively weak uniform response from the Earth's surface up to the base of layer 4. Layers 2 and 3 have their peak response near the base of layer 4 and retain a weak but not insignificant response down to the Earth's surface. It is evident that real ozone changes (from the a priori

Table 1. Layers Used for Umkehr Ozone Profile Retrievals

Layer	Layer-Base Pressure, atm	Layer-Base Height, km
1A	1.00E+0	0.0
1B	5.00E−1	5.5
2	2.50E−1	10.3
3	1.25E−1	14.7
4	6.25E−2	19.1
5	3.12E−2	23.5
6	1.56E−2	28.0
7	7.81E−3	32.6
8	3.91E−3	37.5
9	1.95E−3	42.6
10	9.77E−4	47.9

Layer 1 is a double layer. Layer 10 extends to the top of the atmosphere. Read 1.00E+0 as 1.00×10^0.

profile) in layers 1 through 4 will appear, in the retrieval, as ozone changes in all four layers. If, as in the Payerne ozonesondes, there is a large positive trend in layer 1, and negative trends in 2–4, with a sharp peak in layer 4, these changes will be averaged out in the retrievals for these layers.

At the upper end, layers 8, 9, and 10 have their peaks at the same level, with the peaks decreasing in amplitude for the higher layers. The only real difference in relative response is the layer 8 response to ozone changes in layer 7 and the upper part of layer 6.

Based on these averaging kernels, the Ozone Trends Panel [*WMO*, 1988] recommended that Umkehr trends be calculated only for layers 4–8.

The most significant error in Umkehr retrievals is the sensitivity to scattering by aerosols (generally of volcanic origin) in the stratosphere [*DeLuisi*, 1969, 1979]. An example of the effect of aerosols for the current algorithm has been given in MD92 (see Figures 15 and 16 in that reference). For the present study, the El Chichon eruption had a very strong effect on Umkehr observations at Arosa from June 1982 through October 1984. After that, the retrievals are amenable to the usual correction techniques.

Other than the Forward (Physical) Model for the algorithm, already discussed in MD92, the remaining possible impact on Umkehr trends lies with the instrument alignment and calibration.

2.2. Sonde Profiles

The uncertainties of the Payerne sonde data record (the Payerne record includes ascents launched from Thalwil near Zürich during 1967–1969) have been discussed by *Dütsch and Staehelin* [1989a, 1992] and by *Staehelin and Schmid* [1991]. In the first of these papers, the net effect of changing the pressure element from the old baroswitch to the newer hypsometer, is found to be a sharp increase in the amount of ozone in layer 6. The pressure element was changed at the end of 1980, and the layer 6 annual mean increased by almost 10% from 1980 to 1981.

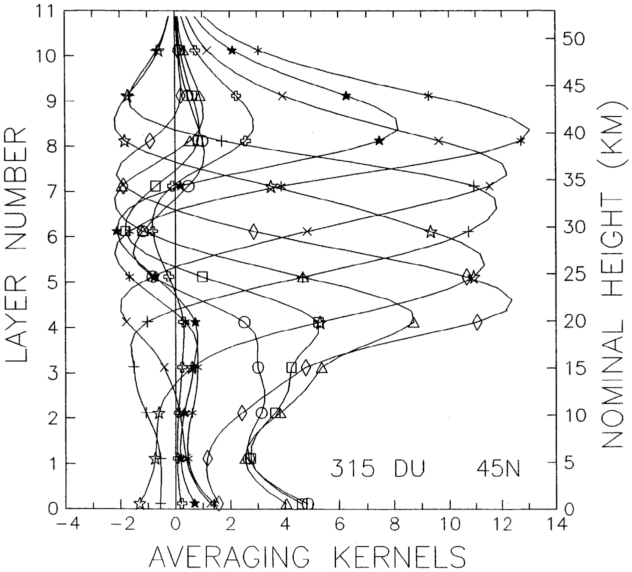

Figure 2. Averaging kernels for 1992 Umkehr algorithm for total ozone 315 DU at 45N for layers 1 (circles), 2 (squares), 3 (triangles), 4 (diamonds), 5 (open stars), 6 (plus signs), 7 (crosses), 8 (asterisks), 9 (solid stars), and 10 (open plus signs). Averaging kernel units are 100 [log(retrieval/a priori)]/[log(true/a priori)].

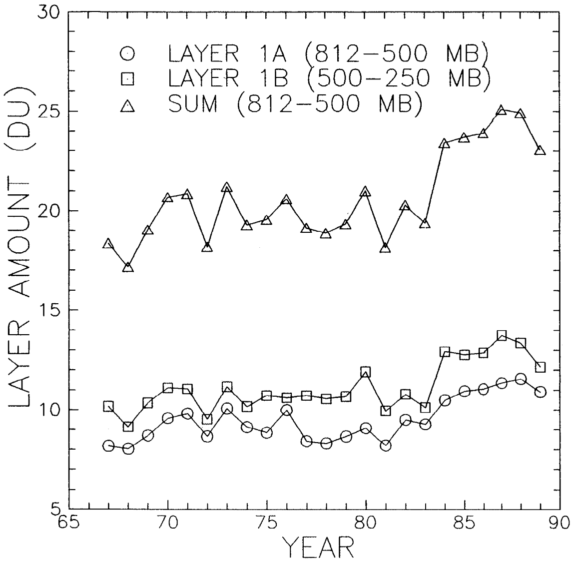

Figure 3. Ozonesonde ozone amounts (DU) for layers 1A (circles), 1B (squares), and 1A+1B (triangles) for 1967–1989.

In the third of these papers, by Staehelin and Schmid, the authors discuss the effect of changing balloon release times on the ozone mixing ratios measured at 900, 800, and 700 mbar. These changes arose because the sonde is then sampling a different portion of the diurnal ozone variation in the lower troposphere [see also *Logan*, 1985]. In this paper, we are concerned with ozone trends above 812 mbar, the surface pressure at Arosa. Since these diurnal changes at Payerne die out very rapidly above 800 mbar and are not found at 700 mbar, we have not attempted to account for them in the present work.

Near the end of 1983, an improved preflight protocol was adopted at Payerne. This was followed by a decrease in the correction factor (CF) used to adjust the entire sounding below balloon burst level to the separately observed total ozone [see *Staehelin and Schmid*, 1991, Figure 1]. At the same time, there was a sharp increase in the integrated ozone amounts in layer 1, as illustrated in Figure 3.

Apart from layer 1, the largest sonde-Umkehr trend discrepancy is in layer 4. In Figure 4, we show the annual average layer 4 amounts for Umkehr and sonde from 1967 through 1989. The sonde shows a larger and more clear-cut quasi-biennial oscillation than the Umkehr and a rapid decrease beginning in the late 1970s. On the other hand, the Umkehr record suggests a slow increase beginning in the early 1970s.

The CF for a sonde ascent is not the sole parameter for assessing the quality of the ascent. Preflight laboratory calibrations of individual sondes have been performed routinely at Payerne since 1984. Recent ongoing studies using these calibrations suggest that the data (both before and after 1984) used in this paper may overestimate ozone concentrations in the upper troposphere and above about 30 km, and slightly underestimate ozone concentrations near the ozone maximum, as a result of a dark current in the sonde's electrochemical cell. Results of these studies will be reported separately.

Finally, because of the method of estimating the CF, i.e., assuming a constant mixing ratio of ozone to exist from balloon

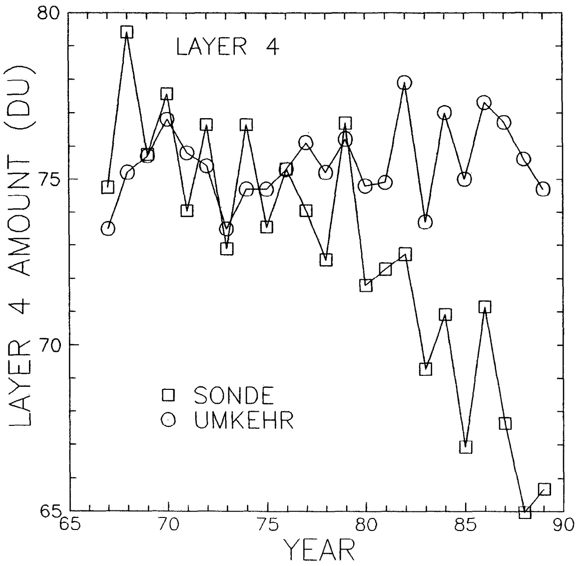

Figure 4. Ozonesonde (squares) and Umkehr (circles) layer 4 ozone amounts (DU) for 1967–1989.

burst level to the top of the atmosphere, any negative (or positive) trend which may exist entirely above that level will be included in the total ozone trend. However, it will be "invisible" to the sonde and will lead to incorrect trend values for sonde layer 7+ (see below) and, in compensation, to small trend errors with reversed sign in layers 1–6.

2.3. Sampling Differences

The Umkehr data record has a clear good-weather bias, whereas the sonde program operates in both good and bad weather, even when total ozone amounts have to be estimated because of the bad weather. The following remarks, while somewhat speculative, are based nevertheless on several decades of close examination of weather patterns, Umkehr observations and retrievals, and ozonesonde flight results [*Dütsch and Staehelin*, 1989b].

For all sounding days, the average total ozone is 319.0 Dobson unit (DU) (1 DU = 1 m atm cm of ozone), but only 312.2 DU for Umkehr observation days. This means that the well-known ozone-weather relationship may have an influence on the trend. High total ozone values are normally linked to the advection of ozone-rich air from higher latitudes, and/or cyclonic conditions, with prevailing descending motion in the lowest part of the stratosphere; on the other hand, small total ozone amounts go along with rising motion in the region above the tropopause. This suggests that trend differences between sonde and Umkehr, arising out of the sampling differences, should show up in the lower stratosphere (layers 2–4).

The increasing polar ozone depletion caused by surface reactions on polar stratospheric cloud particles presumably decreases the ozone content of air advected from higher latitudes in the winter/spring season, which provides the main contribution to the annual mean ozone trend. Thus the bad weather situations at Arosa caused by the uphill flow of northerly winds, which are not sampled by the fair-weather Umkehr method but are sampled by the Payerne soundings, will be linked to a stronger negative trend than the fair weather days with Umkehr observations. The resulting trend differences will be confined to the lower stratosphere, layers 2–4, where the flow pattern is influenced from below. As the vertical motion contribution to the ozone increase in such bad weather situations may dwindle more rapidly upward above the tropopause than the advective part, the advective part of the above-discussed trend differences could be larger in layer 4 than below.

3. Diagnostic Studies

3.1. Common Aspects of These Studies

As in the work of *Dütsch and Staehelin* [1992], we restrict ourselves to the period 1967–1989, inclusive. Moreover, we further restrict the data samples to annual averages of sonde profiles, Umkehr observations, and the Umkehr profiles retrieved from these. We have therefore 23 profiles in each series. In order to avoid El Chichon aerosol effects on the Umkehr observations, we delete the years 1982–1985, inclusive, from the studies. In addition, there are 4 months missing from the 1969 Umkehr record, and the 1969 mean data are also excluded. For comparison purposes, we degrade the sonde profiles by combining layers 1A and 1B into the single layer 1. The Umkehr profiles are also degraded by lumping all layers above layer 6 into layer 7+. In addition, we introduce an "implied" sonde layer 7+, as the difference between the total ozone and the sum of sonde layers 1–6. As the small difference between two relatively larger numbers, we recognize that the ozone amount for sonde layer 7+ will have a relatively large error. Nevertheless, it exists as a number which has been used in the adjustment of the sonde profile to the observed total ozone and we choose not to ignore it. Again, for comparison purposes, the sonde profiles as used here start at 812 mbar, the average surface pressure at Arosa. Finally, since we are using annual averages, it was considered appropriate to "turn off" the seasonal cycle in the Umkehr algorithm a priori profiles for layers 6 and up. The a priori profiles for the lower layers retain the usual dependence on observed total ozone. All trends presented in this paper are computed by simple least squares. For more sophisticated trend calculation methods, the reader may refer, for example, to the work by *Miller et al.* [1995].

Finally, we wish to emphasize that the sonde data use here are the original data, uncorrected for any of the problems discussed in section 2.2 above. This paper is primarily concerned with the capabilities of the Umkehr method, and the conclusions are not affected by the known deficiencies of the uncorrected sonde record. In addition, most studies of sonde trends ignore layer 7+, since it is not a direct measurement and its implied trend, if any, has relatively little impact on trend results for layers 1–6.

3.2. Study 1: Use of Time-Dependent A Priori Profiles

In this study we investigate the influence of the a priori profile on the Umkehr retrievals. To do this, we use time-dependent a priori profiles which mimic the observed sonde trends. The a priori profiles in the 1992 algorithm are consistent with the observed total ozone (the a priori ozone amounts for layers 1–3 are quadratic functions of total ozone, and the sum of all layer amounts adds up to the observed total ozone; see MD92 for more detail). Since there is a negative trend in the total ozone at Arosa, it follows that the standard a priori profiles will also have a negative trend (Table 2, first row). If we subtract this a priori trend from the Payerne ozonesonde trend (second row), the trend difference (third row), when added up over all atmospheric layers, will have a nearly zero

Table 2. Calculation for Time-Dependent A Priori Profile

	Layer							
	1	2	3	4	5	6	7+	Sum
A priori	−0.5	−2.9	−4.3	−3.6	−1.1	−0.3	0.	−12.7
Sonde	5.7	−0.6	−6.5	−10.8	−3.5	1.4	1.5	−12.8
Difference*	6.2	2.3	−2.2	−7.2	−2.4	1.7	1.5	−0.1
Used	6.2	2.3	−2.2	−6.3	0.	0.	0.	0.

Values are in units of DU/22 years.

*Difference is equal to sonde trend minus a priori trend.

effect on total ozone. Therefore the time-dependent a priori profiles consist of the sum of the regular a priori profile plus a time-dependent fraction of the trend difference. The fourth row adjusts the third row slightly so that the sum for the first four layers is zero.

The restriction of the time-dependent adjustment to the a priori profile to the lowest four layers is consistent with the discussion of the averaging kernels in section 2.1 above, where departures of the true profile from the a priori profile in these layers contribute to the retrievals for all four layers. The time-dependent part of the a priori is given by fx', where

$$f = (Y - 78.5)/22$$

$$Y = (\text{year}) + (\text{Julian day})/365$$

and the x' are the values in the fourth row of Table 2.

The trends for Umkehr retrievals using the time-dependent a priori profiles are shown in Figure 5, along with the sonde trends and the trends from the standard Umkehr retrievals. For layers 1–3, the time-dependent retrieval trends are now in general agreement with the sonde trends. For layer 4 the time-dependent retrieval trend is about halfway between the standard Umkehr trend and the sonde trend, and appears not to be significantly different from the sonde trend. In layer 5, however, the time-dependent retrieval trend is even more positive than the standard retrieval trend, and does appear to be significantly different from the sonde trend.

In Figures 1 and 5, as pointed out by a reviewer, the statistical "significance" of the trend differences cannot be assessed directly from the individual trend error bars because these are correlated owing to common interannual variations in ozone (see Figure 4). To get around this problem, we have calculated (as suggested by the reviewer) trends for the time series of the layer differences (sonde − Umkehr [regular a priori]) and (sonde − Umkehr [time-dependent a priori]). These are shown in Figure 6. Since we are using simple least squares, the trend of the difference is identical to the difference of the trends. However, the statistical significance suggested by the error bars has changed somewhat. Trends for both the regular and time-dependent a priori profile retrievals are now significantly different from the sonde trends for layers 4 and up, and for the regular a priori, they are also significantly different for layers 1 and 3.

There are a few conclusions to be taken from these results. First, for layers 1–3, it appears that the Umkehr retrieval trend can be "tuned," through the a priori profile, to agree with any (reasonable) trend profile. It is clear that the implied trend in the standard a priori profiles, arising out of the total ozone trend, is not the correct "tuning" for the present situation. Consider that the Umkehr retrieval partitions the total ozone

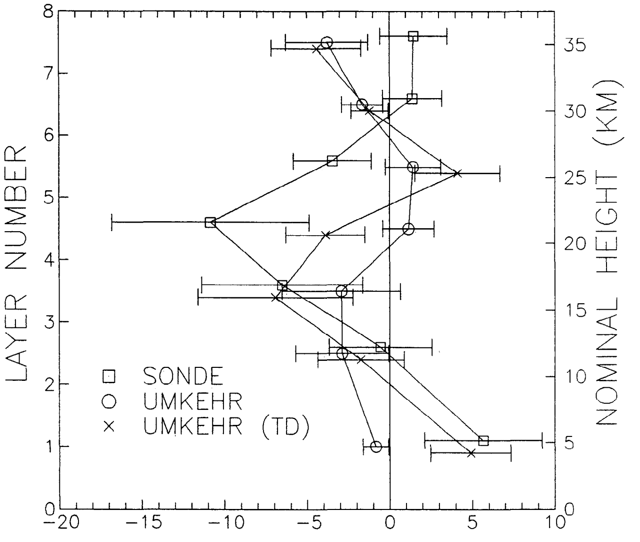

Figure 5. Ozone profile trends for sonde (squares), Umkehr with standard a priori profiles (circles), and Umkehr with time-dependent a priori profiles (crosses). Error bars are for 2σ.

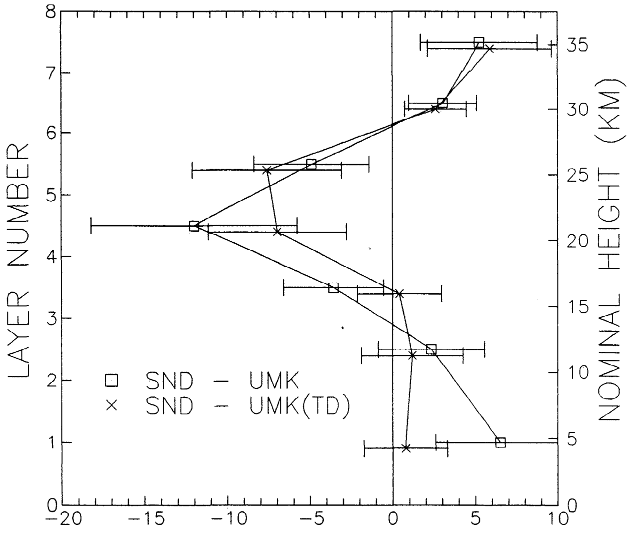

Figure 6. Ozone profile trend differences for sonde − regular Umkehr (squares) and sonde − Umkehr with time-dependent a priori profiles (crosses). Error bars are for 2σ.

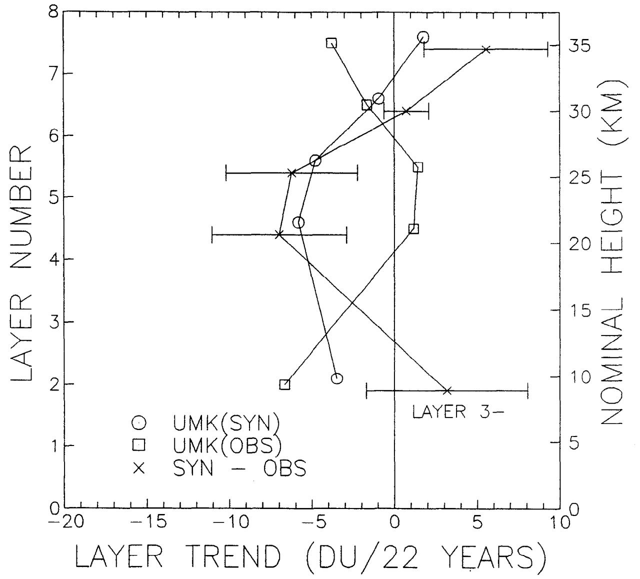

Figure 7. Ozone profile trends for synthetic Umkehr (circles) and observed Umkehr (squares) and profile trend difference synthetic − observed (crosses). Bottom layer is layer 3− (see text). Error bars are for 2σ.

(and its trend) into the various layers. The strong sensitivity of the lower layer trends to the a priori profile demonstrates that Umkehr observations do not contain the information necessary to correctly distribute ozone within these layers. Consequently, for trend calculations, it would be more appropriate to combine layers 1-3 into a single broad layer. For the remainder of this paper, we refer to this layer as 3− and show only trends for layers 3−, 4, 5, 6, and 7+.

Second, as suggested earlier, the sonde fails to capture the negative trend above layer 6, thereby reinforcing the negative trends at lower levels. The corollary to this result is that the application of the correction factor to normalize the sonde profile to the total ozone may not always produce the best results for trend calculations [see *Miller et al.*, 1995]. If there should exist a strong negative trend in layer 7+, as indicated by the Umkehr results, the true residual ozone will decrease with time compared to that calculated by the present correction method. This means that the CFs become increasingly too small, leading to too negative trends for layers 1–6 (relatively, a small effect) and a too positive implied trend for layer 7+. Finally, there appears to be a significant difference between Umkehr and sonde for layer 4, and possibly for layer 5. It is clear from this study that the Umkehr trends for layers 6 and 7+ remain essentially unaffected by the use of the time-dependent a priori profiles. An important additional conclusion is that attempts to improve the a priori profile in the lower atmosphere (layers 1–4) will not really help to improve trends for the upper levels.

3.3. Study 2: Retrievals and Trends From Calculated Umkehr Observations

In order to calculate synthetic Umkehr observations from the annual average sonde retrievals, it is necessary to add a profile "shape" for the residual ozone above layer 6, the uppermost layer for which a layer amount is given explicitly in the sonde data. The residual upper level ozone (layer 7+), as noted earlier, is determined by subtracting the sum of layers 1 through 6 from the total ozone. We have used an average stratosphere and aerosol gas experiment (SAGE II) profile for 30N to 60N (P. K. Bhartia, personal communication, 1992) for layers 7 and up (total 38.3 DU) and multiplied it by the appropriate factor to make it equal to the sonde layer 7+ ozone value. The synthetic Umkehrs were then calculated using the same radiative transfer code as used to calculate the multiple scattering corrections for the 1992 algorithm (MD92). Retrievals were obtained from these synthetic Umkehr observations using the standard a priori profiles, but with two differences. First, since these are annual average observations, as noted earlier, it was considered appropriate to remove the sinusoidal seasonal variation in the a priori profiles for layers 6–10. Second, the usual refraction corrections (quite small, see MD92, Figure 2) were not applied to the synthetic observations because they were not included in the physical model used to calculate the synthetic observations.

The trends for the synthetic Umkehr observations are plotted in Figure 7, along with the trends for the actual Umkehr observations, and the trends of the difference (synthetic − observed). The trends of the differences are plotted with error bars. The synthetic and observed trends are significantly different in layers 4, 5, and 7+.

In the next step, we examine the trend and trend difference patterns for the synthetic Umkehr and the Arosa Umkehr observations. We then compare these observation trend difference patterns to the corresponding retrieval trend difference patterns.

The Umkehr observation is generally quoted in *N* units, which is 100 times the common log of the ratio of the intensities of the strongly and weakly absorbed wavelengths of the Dobson C wavelength pair (viz., 311.45 and 332.4 nm). The measurement is really a relative logarithmic attenuation because the tables which convert the Dobson dial reading to *N* units include the extraterrestrial log ratio for the wavelength pair. Figure 8 shows the trends at each of the standard solar zenith angles of observation. The two curves on the left (without error bars) show the trends for the Arosa Umkehr observations and for the synthetic Umkehr observations. The negative trends in the 60°–70° range correspond to the total ozone trend, since observations in this zenith angle range are primarily total ozone measurements. The Arosa Umkehr observations display a monotonically increasing negative trend up to the slight reversal from 89° to 90°. The synthetic observation trends, however, start to reverse after 80°. This earlier reversal, and the sharp decrease in negative trend as the Sun approaches the horizon, are related to the switchover from the negative ozone trends in layers 3− through 5 to positive trends in layer 7+.

The third curve, with error bars, displays the observation trend differences: synthetic − observed. These observation trend differences are related to the retrieval trend differences shown in Figure 7. The linear weighting functions for the Umkehr, plotted in Figure 9, provide some insight into the trend differences. Although the positive retrieval trend difference for layer 7+ is nearly as large in magnitude as the negative trend difference in layers 4 and 5, the Umkehr observation is much more sensitive at the larger zenith angles to the upper level ozone changes. This effect dominates the observation trend difference pattern. The much smaller negative observation trend differences at zenith angles 74°, 77°, and 80° are related to the large negative retrieval trend difference in layers 4 and 5, where the sensitivity to ozone changes is much less. It

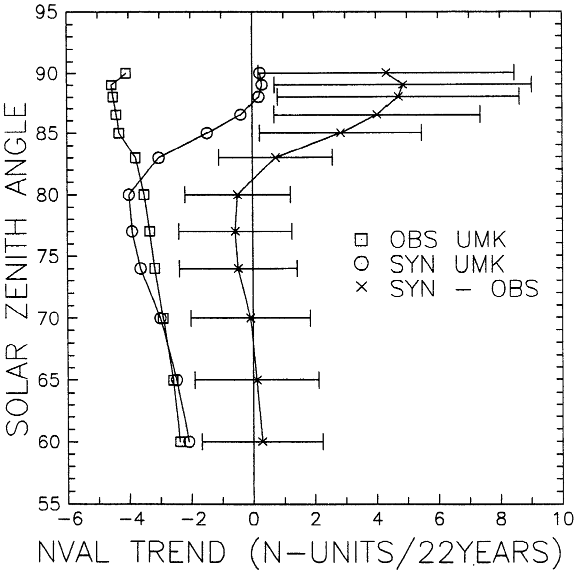

Figure 8. Same as in Figure 7, except these are Umkehr observation trends (synthetic and observed) at the various solar zenith angles of observation. Error bars are for 2σ.

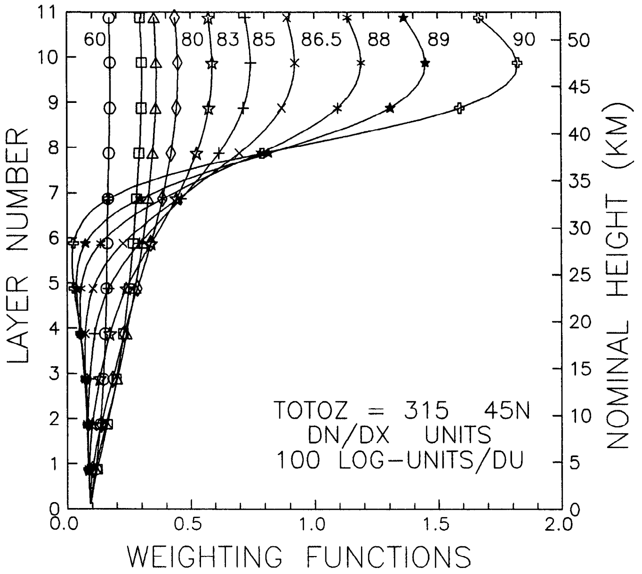

Figure 9. Linear Umkehr weighting functions ($\partial N/\partial X_i$), where N is the observation in 100 log-units and X_i is the ozone amount (DU) in layer i, for various solar zenith angles as labeled on figure, except 74° (squares), 77° (triangles). Curves for zenith angles 65° and 70° are not shown.

is interesting to note that although the observation trend differences are not significantly different from zero for 60°–83°, the trend differences in Figure 7 for layers 4 and 5 are significantly different from zero. In summary, the Arosa Umkehr observations are quite clearly inconsistent with the synthetic Umkehr observations computed from the Payerne sonde profiles.

4. Effects of Stratospheric Aerosols on Umkehr Trends

The chief remaining question concerns the effects of stratospheric aerosols on the Umkehr observations during the post El Chichon period. Corrections have been calculated for 40N for most months for the period November 1984 through 1989. For application in this study, the monthly corrections have been averaged to obtain an annual average correction for each Umkehr layer. In Figure 10, we show a plot of the corrected and uncorrected ozone amounts for layer 7+. Two facts are immediately evident from the plots. First, there is no discernible ozone trend for this combined layer from 1967 through 1981. Second, there appears to have been a downward level shift for the post El Chichon period, which is only partially compensated for by the application of the aerosol corrections. It follows that the overall negative trend for layer 7+, as determined by the Arosa Umkehr record, is produced solely by the lower ozone amounts in this post El Chichon period.

It appears that this level shift is real; it is also seen by SBUV and at other Umkehr stations [*DeLuisi et al.*, 1994]. Figure 11 displays the Umkehr trends with and without haze corrections. Without the corrections, only the trends for layers 6 and 7+ are significant (Figure 5). With the corrections, the trends for layers 3−, 6, and 7+ are significant. In addition, the Umkehr trends with corrections are significantly different from the sonde trends in all layers except 3−. This was also the case for the Umkehr trends without corrections, where the trend difference (sonde − Umkehr) for layer 3− was 5.3 ± 6.7 DU/22 years (not shown in Figure 6).

For the interested reader, additional details re the effects of the aerosol corrections for the uppermost layers are given in Table 3. In terms of layer differences and trends, the effects are quite substantial for what is generally regarded as a relatively "low" aerosol period (low, at least when compared with the very large effects for 1982 and 1983, as illustrated in Figure 10).

5. Conclusions and Further Remarks

Time-dependent a priori profiles can be used to effectively "tune" the Umkehr retrievals to match any reasonable trend profile for layers 1–3. In terms of "information content," it follows that the Umkehr is unable to partition ozone changes

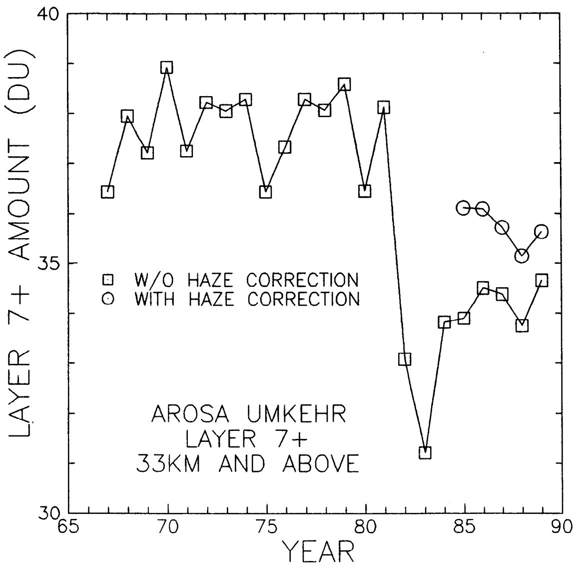

Figure 10. Umkehr ozone amount (DU) for layer 7+ for 1967–1989, with haze correction (circles) and without (squares).

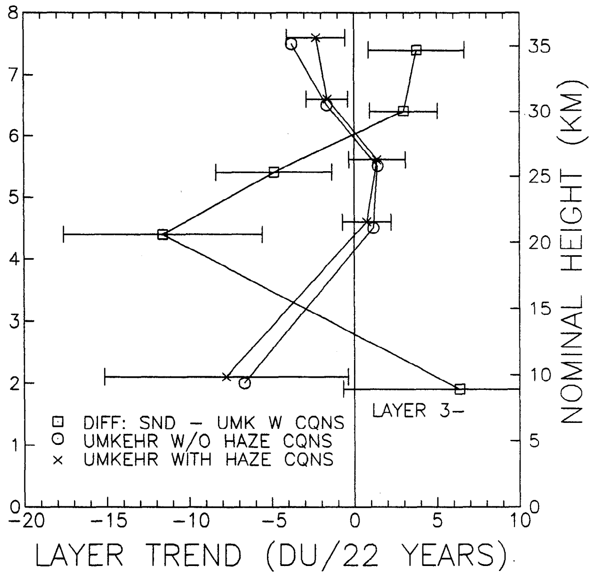

Figure 11. Umkehr ozone profile trends without haze corrections (circles) and with haze correction (crosses), and trend differences (sonde with haze corrections (squares)). Error bars are for 2σ.

between these three layers, although trends for the combined layer 3− may be reasonably good. The time-dependent a priori profiles exert some influence on layer 4 trends, but cannot overcome the inherent information in the Umkehr observations for this layer.

The second study, involving the use of synthetic Umkehr observations, identifies a significant difference between the Umkehr observations at Arosa and the sonde profiles at Payerne. There are four possible contributing factors here. First, there is the sampling difference, where there are Umkehr observations on fewer than 20% of the sonde observation days. This sampling difference has been discussed in section 2.3 above. Second, there is the inability of the sonde to "see" any real ozone trend above the top of layer 6 (see section 2.2). Third, there is the possibility that the Forward (Physical) Model part of the algorithm, essentially the multiple scattering corrections, is incorrect. Fourth, there is some possibility of a slow change in the Dobson instrument in use at Arosa for the Umkehr measurements. While all four of these may contribute to the difference, we believe that the first is the major contributor to the discrepancy in layer 4, and the second to that in layer 7+. The remaining factors cannot be completely ruled out.

The original overall aim of this paper, to confirm the reliability of the Umkehr trend results for the upper stratospheric layers, has been accomplished. However, as we knew from the beginning, the original trends are too great in magnitude because of the stratospheric aerosol effects. The final aerosol-corrected trend for the combined layer 7+, the atmosphere above about 32 km, is not quite 60% of the uncorrected value.

The results from these studies suggest some further remarks on the utility of trends calculated from Umkehr profiles [see also *DeLuisi et al.*, 1994]. As discussed earlier, the Umkehr partitions the total ozone trend into the various layer trends. This is inherent in the Umkehr observations. It has been known for 60 years that the level of the Umkehr curve depends mainly on the total ozone [*Götz et al.*, 1934; *Mateer*, 1965]. However, because of the very broad averaging kernels (Figure 2), this partitioning leaves much to be desired, especially for the lowest four layers and the uppermost three layers (i.e., 8, 9, and 10). It has been recommended [*WMO*, 1988; MD92] that only layers 4–8 should be used for trend analysis. Based on the results of this study, we suggest that the recommendations be extended to include layer 3−, the combined layer 1 + 2 + 3. Considering the averaging kernels (Figure 2), we further suggest that the upper layers (8 + 9 + 10) be combined as layer 8+. This layer system (layers 3−, 4, 5, 6, 7, and 8+) would cover the entire atmosphere and account fully for the total ozone trend.

Whichever layer system is used for Umkehr trends, the broadness of the averaging kernels must always be kept in mind when drawing conclusions or comparing with trends from more direct higher-resolution measurement methods.

Since this study is limited to data from only two stations, one sonde station and one Umkehr station, we prefer not to state general conclusions concerning the relative reliability of sonde versus Umkehr profiles and their trends as a function of height. For a more comprehensive study involving several sonde and Umkehr stations, the reader should refer to *Miller et al.* [1995]. It may be useful to note here, however, that our Figures 1 and 5 are remarkably similar to their Figure 9 (left).

Acknowledgment. One of us (J.J.D.) wishes to acknowledge partial support from the Department of Energy through contract DOE-A102-94ER61878.

Table 3. Effect of Haze Corrections on Upper Level Trends and Layer Averages

	Period									
	1967–1981 (1969 Excluded; No Haze Corrections)		1985–1989 (No Haze Correction)		1985–1989 (Haze Correction)		1967–1989 (1969, 1982–1984 Excluded; No Haze Correction)		1967–1989 (1969, 1982–1984 Excluded; Haze Correction)	
Layer	Trend	Average	Average	Difference	Average	Difference	Trend	Average	Trend	Average
10	0.03	1.36	1.33	−0.03	1.35	−0.01	−0.02	1.35	0.00	1.35
9	0.17	3.40	3.20	−0.20	3.34	−0.06	−0.19	3.35	−0.04	3.39
8	0.56	9.89	8.86	−1.0	9.43	−0.46	−1.1	9.62	−0.40	9.77
7	−0.47	23.1	20.8	−2.3	21.6	−1.5	−2.8	22.5	−1.9	22.7
7+	0.28	37.7	34.2	−3.5	35.7	−2.0	−4.1	36.8	−2.4	37.2

Units are trends, DU/22 years; averages and differences, DU; differences = Average (1985–1989) − Average (1967–1981).

References

DeLuisi, J. J., A study of the effect of haze upon Umkehr measurements, *Q. J. R. Meteorol. Soc.*, *95*, 181–187, 1969.

DeLuisi, J. J., Umkehr vertical ozone profile errors caused by the presence of stratospheric aerosols, *J. Geophys. Res.*, *84*, 1766–1770, 1979.

DeLuisi, J. J., C. L. Mateer, D. Theisen, P. K. Bhartia, D. Longenecker, and B. Chu, Northern middle-latitude ozone profile features and trends observed by SBUV and Umkehr, 1979–1990, *J. Geophys. Res.*, *99*(D9), 18,901–18,908, 1994.

Dütsch, H. U., Vertical ozone distribution over Arosa, Final report, Ozone and General Circulation in the Stratosphere, Lichtklimatisches Observ., Arosa, 1959a.

Dütsch, H. U., Vertical ozone distribution from Umkehr observations, *Arch. Meteorol. Geophys. Bioklimatol.*, *Ser. A*, *11*, 240–251, 1959b.

Dütsch, H. U., and J. Staehelin, How much information on anthropogenic influences on the ozone layer can be obtained from a set of one-station observations, in *Ozone in the Atmosphere*: *Proceedings of the Quadrennial Ozone Symposium 1988 and Tropospheric Ozone Workshop*, *Göttingen*, *Germany*, pp. 76–79, A. Deepak, Hampton, Va. 1989a.

Dütsch, H. U., and J. Staehelin, Discussion of the 60 year total ozone record at Arosa based on measurements of the vertical distribution and a meteorological parameter, *Planet. Space Sci.*, *37*(12), 1587–1599, 1989b.

Dütsch, H. U., and J. Staehelin, Results of the new and old Umkehr algorithm compared with ozone soundings, *J. Atmos. Terr. Phys.*, *54*, 557–569, 1992.

Götz, F. W. P., A. R. Meetham, and G. M. B. Dobson, The vertical distribution of ozone in the atmosphere, *Proc. R. Soc. London A*, *45*, 416–446, 1934.

Logan, J. A., Tropospheric ozone: Seasonal behavior, trends, and anthropogenic influence, *J. Geophys. Res.*, *90*, 10,463–10,482, 1985.

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

Mateer, C. L., and J. J. DeLuisi, A new Umkehr inversion algorithm, *J. Atmos. Terr. Phys.*, *54*, 537–556, 1992.

Mateer, C. L., and H. U. Dütsch, Uniform evaluation of Umkehr observations from the World Ozone Network, Part I, Proposed standard evaluation technique, 105 pp., Natl. Cent. for Atmos. Res., Boulder, Colo., 1964.

Miller, A. J., G. C. Tiao, G. C. Reinsel, D. Wuebbles, L. Bishop, J. Kerr, R. M. Nagatani, J. J. DeLuisi, and C. L. Mateer, Comparisons of observed ozone trends in the stratosphere through examination of Umkehr and balloon ozonesonde data, *J. Geophys. Res.*, *100*(D6), 11,209–11,217, 1995.

Rodgers, C. D., Characterization and error analysis of profiles retrieved from remote sounding measurements, *J. Geophys. Res.*, *95*(D5), 5587–5595, 1990.

Staehelin, J., and W. Schmid, Trend analysis of tropospheric ozone concentrations utilizing the 20-year data set of ozone balloon soundings over Payerne (Switzerland), *Atmos. Environ.*, *25A*(9), 1739–1749, 1991.

World Meteorological Organization, Report of the International Ozone Trends Panel, WMO Global Ozone Research and Monitoring Project, *Rep. 18*, Geneva, 1988.

J. J. DeLuisi, NOAA Environmental Research Laboratories, Boulder, CO 80803-3328.

H. U. Dütsch and J. Staehelin, Laboratory for Atmospheric Physics, ETH Hönggerberg, CH 8093 Zürich, Switzerland.

C. L. Mateer, 1210-255 Bamburgh Circle, Scarborough, ON M1W 3T6, Canada.

(Received June 29, 1995; revised November 24, 1995;
accepted November 24, 1995.)