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Intercomparison of Umkehr and differential absorption lidar stratospheric ozone measurements

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Abstract. A comparison of stratospheric ozone measurements using the Umkehr and differential absorption lidar (DIAL) techniques is presented. The ozone observations were made in Toronto, Canada (43.8°N, 79.5°W), using a Brewer ozone spectrophotometer and a DIAL co-owned by York University, the Institute for Space and Terrestrial Science, and the Atmospheric Environment Service. DIAL and Umkehr comparisons were made between January 1, 1991, and November 30, 1993. Our measurements show that under conditions of low aerosol loading, the Umkehr and DIAL ozone measurements overlap within their respective confidence intervals. After the Mount Pinatubo eruption the presence of aerosol affects both measurement techniques. The Umkehr retrievals are 20–40% lower than corresponding DIAL data at altitudes of 28 km and above. Below 28 km the DIAL data are ~35% lower than the Umkehr measurements. We apply aerosol corrections to the Umkehr data and observe overlap between DIAL and Umkehr measurements for altitudes greater than 28 km to within their respective error intervals throughout the entire period of observation.

Introduction

The need to monitor ozone depletion in the stratosphere has resulted in efforts to improve ozone remote sensing. The Umkehr technique, first developed by *Götz* [1931] and *Götz et al.* [1934], provides the longest useful database for ozone profiles in the stratosphere. This technique has limitations, for example, low vertical resolution, the nonuniqueness of the retrieved profiles, and a response to the presence of stratospheric (and to a lesser degree tropospheric) aerosols [*World Meteorological Organization* (*WMO*), 1988]. Some of these concerns have been overstated, however, and recent developments in the Umkehr retrieval have addressed some of the problems with promising results [*Mateer and DeLuisi*, 1992; *Lacoste et al.*, 1992]. For instance, given the total ozone, the retrieval is robust if the ozone absorption coefficients are accurately known. Also, many stations are already in place, with good ozone measurement records extending back some 30 years, together with good records of instrument properties. Future Umkehr measurements made using the Brewer ozone spectrophotometer should be better, quicker, and much greater in number than earlier Umkehr measurements, since it is an automated instrument capable of taking unattended ozone measurements almost anywhere in the world.

Like the Umkehr, the differential absorption lidar (DIAL) technique uses the differential absorption of light by ozone to infer the ozone concentration profile. It has a number of advantages, for example, improved vertical resolution, higher accuracy at altitudes up to 40 km, and effectiveness at high latitudes in winter [*Uchino et al.*, 1978; *Werner et al.*, 1983; *Mégie et al.*, 1985; *McDermid et al.*, 1990; *Carswell et al.*, 1993]. These advantages are accompanied currently by limitations such as the relatively high expense of equipment, maintenance, and operation [*Godin et al.*, 1989; *Steinbrecht and Carswell*, 1995]. The presence of aerosol in the atmosphere also provides serious interference to DIAL ozone measurements, but this particular problem may be circumvented with the use of a Raman DIAL [*McGee*, 1993]. The DIAL data in this report, however, were not collected in this way.

It is evident that the Umkehr and DIAL measurement techniques complement one another and require intercomparisons to assure consistency in measured ozone levels. Moreover, given the long time span of accumulated Umkehr data, it is sensible to make intercomparisons over a prolonged time period in order to assure continuity in time series and trend analysis for the two measurement techniques.

The results we present here represent the first comparison of the Umkehr data collected with the Brewer ozone spectrophotometer located at the Atmospheric Environment Service (AES) in Toronto, Canada, and DIAL data collected with the DIAL located at the Institute of Space and Terrestrial Science (ISTS) on the main campus of York University (YU), also in Toronto. The Umkehr and DIAL instruments are in close proximity to one another (~2 km). The data were collected over a period of time which extends from January 1, 1991, before the Mount Pinatubo eruption of June 15–16, 1991, to the end of 1993. The two periods of different stratospheric aerosol conditions offer an opportunity to study the circumstances in which the two techniques provide accurate ozone measurements.

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Umkehr Measurements

The Umkehr data presented here were collected with the Brewer ozone spectrophotometer 015, located at AES headquarters in Toronto. The Brewer instrument and retrieval algorithm are described more fully elsewhere [*Evans et al.*, 1987; *Mateer and DeLuisi*, 1992], but a brief description follows here. When making Umkehr observations, the instrument measures the intensity of the ultraviolet radiation from the zenith sky at three wavelength pairs, each roughly 20 nm apart (306.3 and 323.2 nm; 310.0 and 326.4 nm; and 313.4 and 329.5 nm), and over a large number of solar zenith angles (SZAs). The intensity ratio data ($100 \times \log_{10}$ of the ratio of the intensity of the longer wavelength to that of the shorter; hereinafter called "N" units) are processed using an algorithm which is essentially the same as the Mateer-DeLuisi "short" algorithm [*Mateer and DeLuisi*, 1992] and which can be used over the full 60°–90° solar zenith angle range or over a shorter range (e.g., 80°–89°). It differs from the earlier short retrieval algorithm in that better a priori profiles are used, the inversion method and error analysis of *Rodgers* [1976, 1990] is employed, and the effect of atmospheric optical depth on retrieved profiles has been better accounted for [*DeLuisi et al.*, 1989].

The retrieved amount of ozone in any layer is to some degree correlated to the amount of ozone found in adjacent layers. These correlations occur for two reasons. The first is that the Umkehr vertical sampling function has a finite width. The second is that correlations exist in the retrieved data because they are present in the real ozone profiles. A covariance matrix is used to quantify the expected correlation of ozone between Umkehr layers in retrieval calculations. It is essentially a smoothing constraint on the retrieved ozone profile. There are two versions of the covariance matrix: the climatological and the uniform. The climatological covariance matrix includes correlations which exist between layers, as evidenced in the observed ozone climatology determined through other profiling techniques (e.g., ozonesondes, rocketsondes, etc.). The uniform covariance matrix comprises small uniform correlations assumed between layers without consideration of climatology. Because no climatology is present in the uniform covariance matrix, it is used in long-term trend analyses where the relevance of past climatology to change in the ozone profiles is uncertain [*Mateer and DeLuisi*, 1992]. Both matrices smooth the ozone profile between layers and help stabilize the solution.

The Umkehr retrieval and the specification of the forward model organize the atmosphere into 16 layers. Layers 4 through 8, corresponding to altitudes of roughly 20–45 km, are the layers which the Umkehr technique is best able to represent [*Mateer and DeLuisi*, 1992] and are the center of discussion in this paper.

Umkehr measurements can be made twice a day, at sunrise and sunset. Measurements from a minimum range of SZAs starting at 80° or less and ending between 89° and 90° are required. An experimental error of 2% is assumed. Acceptable solution ozone profiles are found in no more than three iterations of the processing program, with less than 0.75% rms discrepancy between the observed and modeled data. Given these restrictions on data acceptance, we have collected 341 climatological and 310 uniform ozone profiles for the period spanning 1991 through 1993.

Table 1. ISTS/AES DIAL Specifications

Component	Specification
Transmitter	
Laser	Lumonics EX 600
Pulse repetition, length	300 Hz, 13 ns
Pulse energy	100 mJ at 308 nm, 10 mJ at 353 nm
Beam expansion	×3
Beam divergence after expansion (containing 66% of pulse energy)	0.2 mrad
Receiver	
Telescope	1-m-diameter Newtonian
Focal length	2.5 m
Maximum field of view	1 mrad
Detectors	
Photomultipliers	Thorn EMI 9893 B/100
Signal Processing	
Amplifier	Philips 770 (×10)
Discriminator	Philips 704
Multichannel counter	Optech PC plug-in board, version I

Lidar Measurements

Lidar measurements of the ozone profile, through the use of the DIAL technique, were made at the Institute for Space and Terrestrial Science located on the main campus of York University in metropolitan Toronto. A list of the equipment and important operating specifications is shown in Table 1. A complete description of the YU/ISTS/AES DIAL is available elsewhere [*Carswell et al.*, 1991]. We include a cursory description here. The DIAL transmitter comprises a XeCl laser and a hydrogen Raman shifter so that light at 308 and 353 nm is launched. The receiver system comprises a 1-m-diameter (f/2.5) Newtonian reflector, two photomultiplier tubes (PMTs) to collect the light backscattered at the "on" (308 nm) and "off" (353 nm) absorption wavelengths, and supporting electronics for data capture.

DIAL measurements were shown to match Stratospheric Aerosol and Gas Experiment II (SAGE II) measurements to within 3–6% at altitudes of 30–40 km and to within 10% for altitudes of 20–30 km. The precision is better than 3% for a 2-km binwidth, for altitudes below 45 km, and during the new moon. During the full moon the precision was degraded to 11% for the same binwidth and altitude range [*Steinbrecht*, 1994]. The DIAL resolution was degraded to match the Umkehr resolution. Comparatively local effects, such as those due to the presence of aerosols, have therefore been averaged into entire Umkehr layers.

A detailed description of the effects of stratospheric aerosol on ozone DIAL measurements, including an analysis of the errors in the differential extinction and backscatter terms, has been published [*Steinbrecht and Carswell*, 1995]. It has been found that neglecting the differential extinction error does not greatly affect the measured amount of ozone (<10% and more usually <2%). In contrast, neglecting the differential backscatter term can lead to errors of 100% under conditions of high aerosol loading. The differential backscatter term's dependence on spatial variation leads to overestimation of the ozone level at the bottom of the aerosol layer and underestimation of the ozone level at the top of the layer. Differential extinction and backscatter are negligible for the Toronto location for data collected before November 1, 1991, peak for data collected early in 1992, and decrease steadily for data collected thereafter, as shown in Figures 1a–1e.

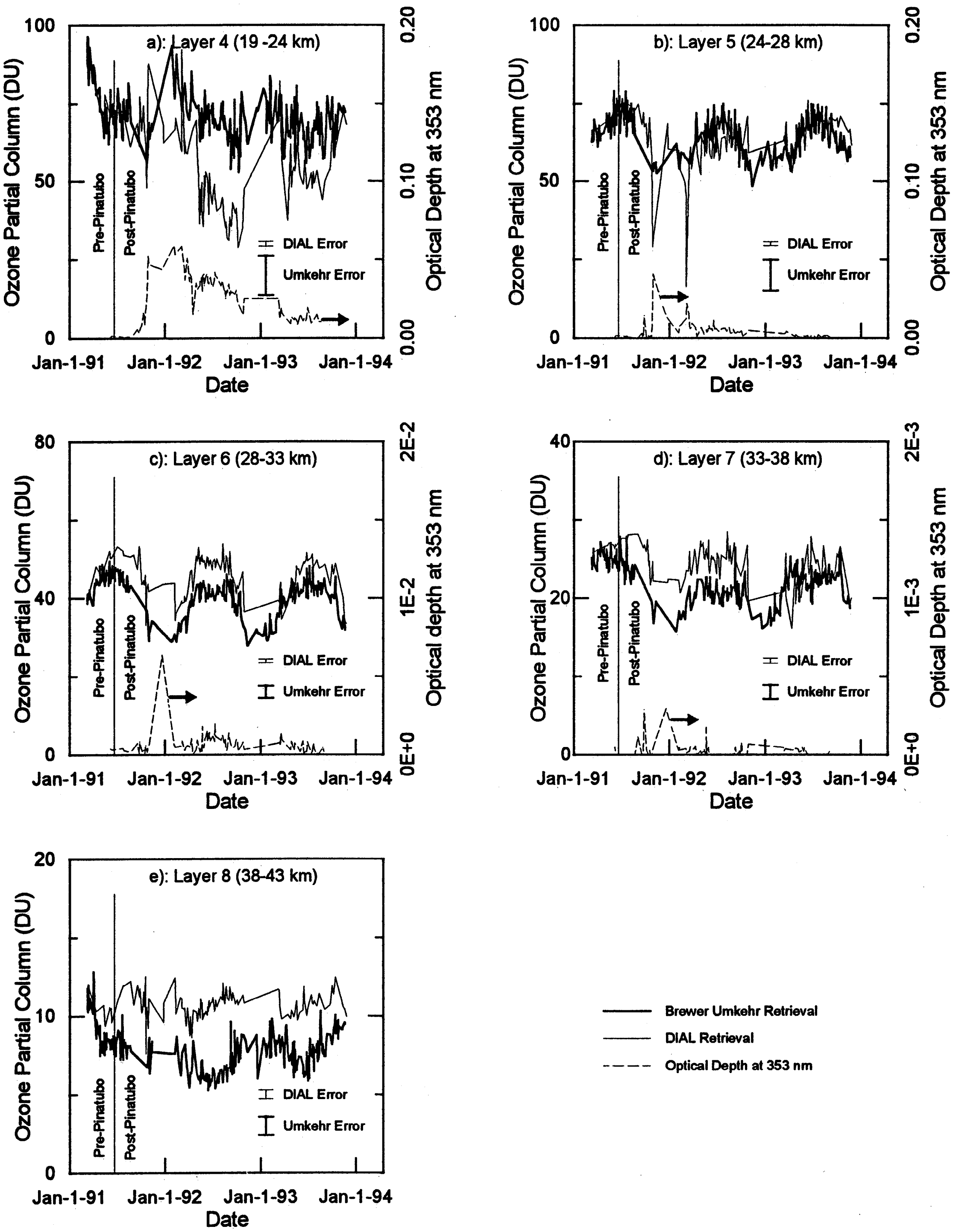

Figure 1. Time series values of DIAL and Umkehr ozone retrievals. The aerosol optical depth at 353 nm within each Umkehr layer is shown at the bottom of each panel, with its value shown on the right-hand axis.

The DIAL measurements are necessarily made during the night, typically between 2100 and 0400 LT. Measurements are made under clear conditions. During the period of study, 123 ozone profiles were collected with the DIAL.

Data Comparison

A time series comparison of the DIAL and Umkehr measurements for Umkehr layers 4 through 8 is shown in Figures 1a–1e, respectively, starting with January 1, 1991. The curves are unsmoothed. The period of the Mount Pinatubo eruption (June 15 and 16, 1991) is represented by the heavy vertical line. The aerosol optical depth is also shown and was determined from the lidar measurements at 353 nm using the techniques described by *Steinbrecht and Carswell* [1995] and *Russell et al.* [1979]. The error bars displayed represent confidence intervals of plus or minus one standard deviation for the respective data sets. The confidence intervals vary over the period depicted:

Table 2a. Monthly Stratospheric Optical Depth Averages at 353 nm

Month	Total, $\times 10^{-2}$	Layer 3, $\times 10^{-2}$	Layer 4, $\times 10^{-2}$	Layer 5, $\times 10^{-3}$	Layer 6, $\times 10^{-4}$	Layer 7, $\times 10^{-5}$
June 1991	0.36	0.10	0.11	1.13	3.51	2.49
July 1991	0.64	0.45	7.03	0.87	3.36	0.00
Aug. 1991	2.14	2.00	0.12	0.00	1.67	0.00
Sep. 1991	2.80	1.88	0.40	4.46	5.09	10.02
Oct. 1991	5.19	1.83	2.45	8.53	3.67	1.49
Dec. 1991	12.77	6.31	4.37	14.03	63.55	29.38
Feb. 1992	12.51	6.27	5.55	6.15	5.47	3.68
March 1992	12.02	5.94	4.81	12.03	5.21	2.94
April 1992	9.98	6.02	3.28	6.09	5.52	2.89
May 1992	8.93	4.85	3.54	4.63	5.92	3.08
June 1992	9.87	5.41	3.67	6.49	11.80	0.00
July 1992	8.76	4.34	3.80	4.89	11.92	0.00
Aug. 1992	9.70	5.96	3.16	4.84	8.27	0.00
Sep. 1992	8.45	5.06	2.93	3.83	6.47	1.24
Oct. 1992	7.11	4.59	2.13	3.29	5.56	3.79
March 1993	6.55	4.38	1.74	3.21	8.84	3.48
April 1993	4.78	3.44	1.12	1.47	5.63	3.33
May 1993	5.27	3.93	1.20	0.86	4.29	3.00
June 1993	5.21	3.77	1.28	1.17	3.64	9.76
July 1993	3.77	2.52	1.10	1.08	3.36	0.00
Aug. 1993	4.46	3.15	1.18	1.00	1.75	0.00
Sep. 1993	3.81	2.81	0.93	0.58	0.33	1.58

The Umkehr confidence intervals vary less than 10%, and the DIAL intervals become 4 times larger than the sample interval toward the end of the comparison period in layers 4–6. DIAL errors in layers 7 and 8 remain close to the average throughout the comparison period.

Umkehr layers are defined in terms of pressure but are labeled here in terms of the corresponding altitude range in kilometers. The Umkehr ozone retrieval variation, due to the effect of day-to-day or seasonal pressure profile variation, is within the error interval.

The Mount Pinatubo eruption very conveniently provides us with two distinct periods for comparison: the period of time preceding the arrival of the Mount Pinatubo aerosol cloud, when the stratosphere is clean, and the period of time following the arrival of the Mount Pinatubo aerosol cloud (after November 1, 1991), when the stratosphere is heavily laden with aerosol. The arrival of the aerosol cloud in the Toronto area can be easily seen from the lidar-derived optical depth curves shown at the bottoms of Figures 1a–1d. The DIAL- and Umkehr-measured ozone time series match each other to within their respective confidence intervals before the arrival of the aerosol cloud at Toronto latitudes. After the arrival of the aerosol cloud at Toronto, the DIAL and Umkehr results diverge. At altitudes below 28 km, where the bulk of the aerosol resides, the DIAL measures lower levels of ozone than the Umkehr retrieves. Above 28 km, however, the Umkehr-measured ozone levels are 10–35% lower than the corresponding DIAL measurements.

The behavior of the data in Figure 1 is consistent with earlier work concerning the effect of aerosol loading upon DIAL and Umkehr measurements [*Steinbrecht and Carswell*, 1995; *Browell*, 1989; *Dave et al.*, 1979; *DeLuisi et al.*, 1989]. The presence of aerosol causes the DIAL ozone concentration to be in error at a given altitude owing to the aerosol differential backscatter contribution. The nature of the DIAL measurement technique limits the measurement error to altitudes at which the aerosol is actually present, which are 19–28 km and are shown in Figures 1a and 1b [*Steinbrecht and Carswell*, 1995; *Deshler et al.*, 1993]. The DIAL ozone data shown in Figures 1c–1e are representive of an aerosol-free sky. These data were found to correspond well to SAGE II data [*Steinbrecht*, 1994].

In contrast, the nature of the Umkehr technique results in the ozone measurement error due to conditions of high aerosol loading being distributed among all the Umkehr layers. In practice, this results in Umkehr ozone values being overestimated by ~2% at altitudes of 19 to 28 km and being underestimated by 10–50% at altitudes of 28 km and above [*DeLuisi et al.*, 1989]. Corrections for the error in the Umkehr ozone data, defined as the percent difference between the calculated Umkehr with stratospheric aerosol and the corresponding one without stratospheric aerosol, can be made when the stratospheric optical depth is known [*WMO*, 1988; *DeLuisi*, 1979; *DeLuisi et al.*, 1989]. The optical depths shown in Figures 1a–1e can be summed in order to calculate corrections to the Umkehr data on the basis of tabulated percent error per value of 0.01 stratospheric optical depth [*DeLuisi et al.*, 1989; C. Mateer, private communication, 1994]. The monthly averages for the aerosol optical depth at 353 nm and the aerosol correction factors for each Umkehr layer are presented in Tables 2a and b, respectively. The results of the correction on the Umkehr time series are shown in Figures 2a–2e.

The corrections for aerosol optical depth were applied by smoothing the optical depth data obtained with the 353-nm wavelength from the DIAL, multiplying the optical depth val-

Table 2b. Umkehr Profile Aerosol Correction

Layer	Value
4	0.1
5	0.2
6	−0.9
7	−3.2
8	−6.3

Percent per 0.01 total optical depth (C. Mateer, private communication, 1994).

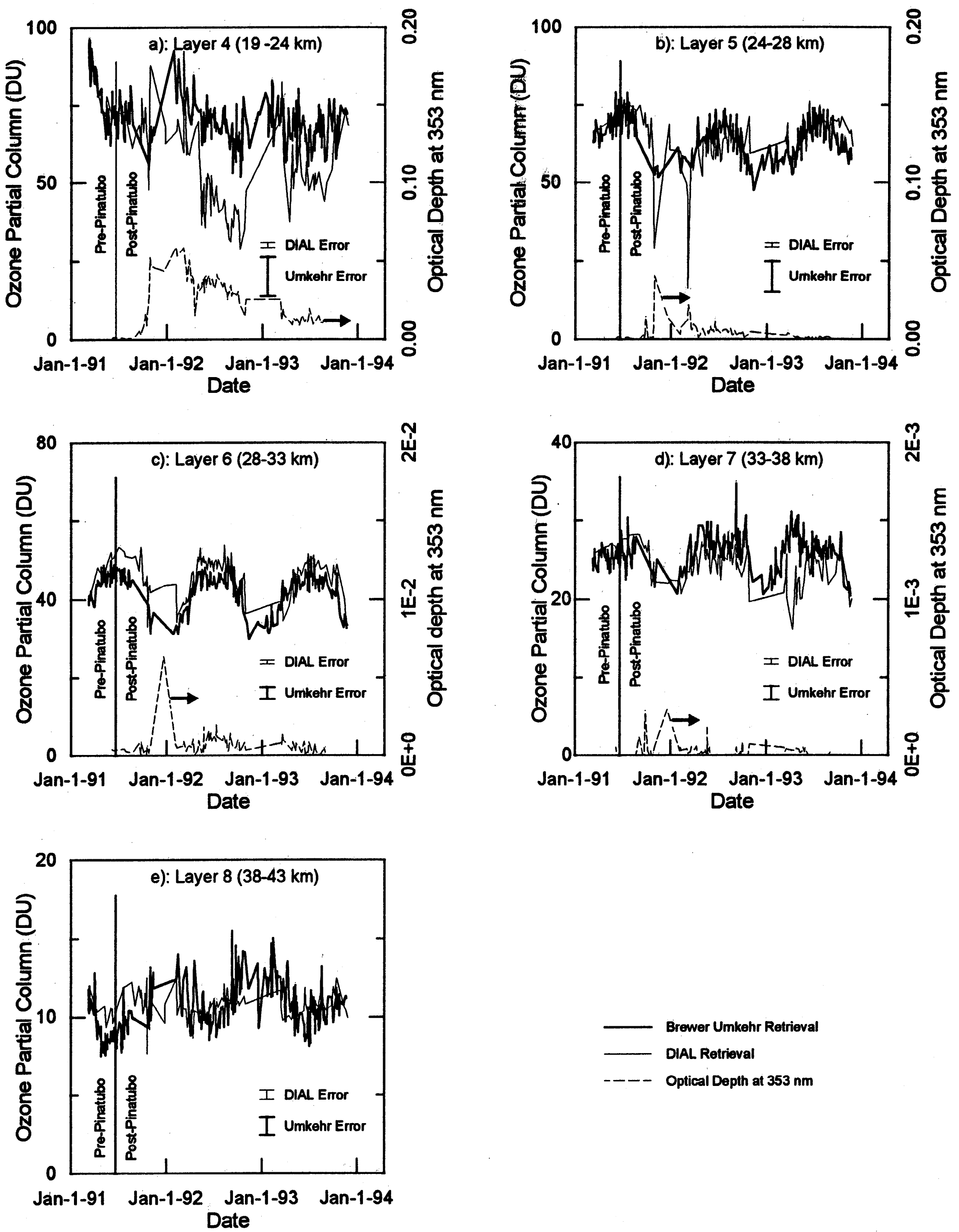

Figure 2. Time series values of DIAL and aerosol-corrected Umkehr ozone retrievals. The lidar-obtained aerosol optical depth at 353 nm within each Umkehr layer is shown at the bottom of each panel, with its value shown on the right-hand axis.

ues by the correction factor for each Umkehr layer as found in Table 2 and the ozone value for each Umkehr layer, and finally, adding the product to the original ozone value.

Figures 2a and 2b are substantially the same as their counterparts in Figure 1. The aerosol corrections to the Umkehr ozone values are small. The difference between the DIAL and Umkehr ozone values in the 19- to 24-km altitude range is nearly constant throughout most of the period following the arrival of the aerosol cloud in this latitude. This is a result of the uncorrected differential backscatter contribution to the DIAL ozone concentration.

In the 24- to 28-km range the Umkehr and DIAL ozone results now agree to within their respective error intervals throughout the entire period of the comparison, except for two large negative deflections. The two instances correspond to spikes in the aerosol optical depth, which indicate that the top of the aerosol cloud is in this altitude range. The large negative deflection is consequently due to the differential contribution

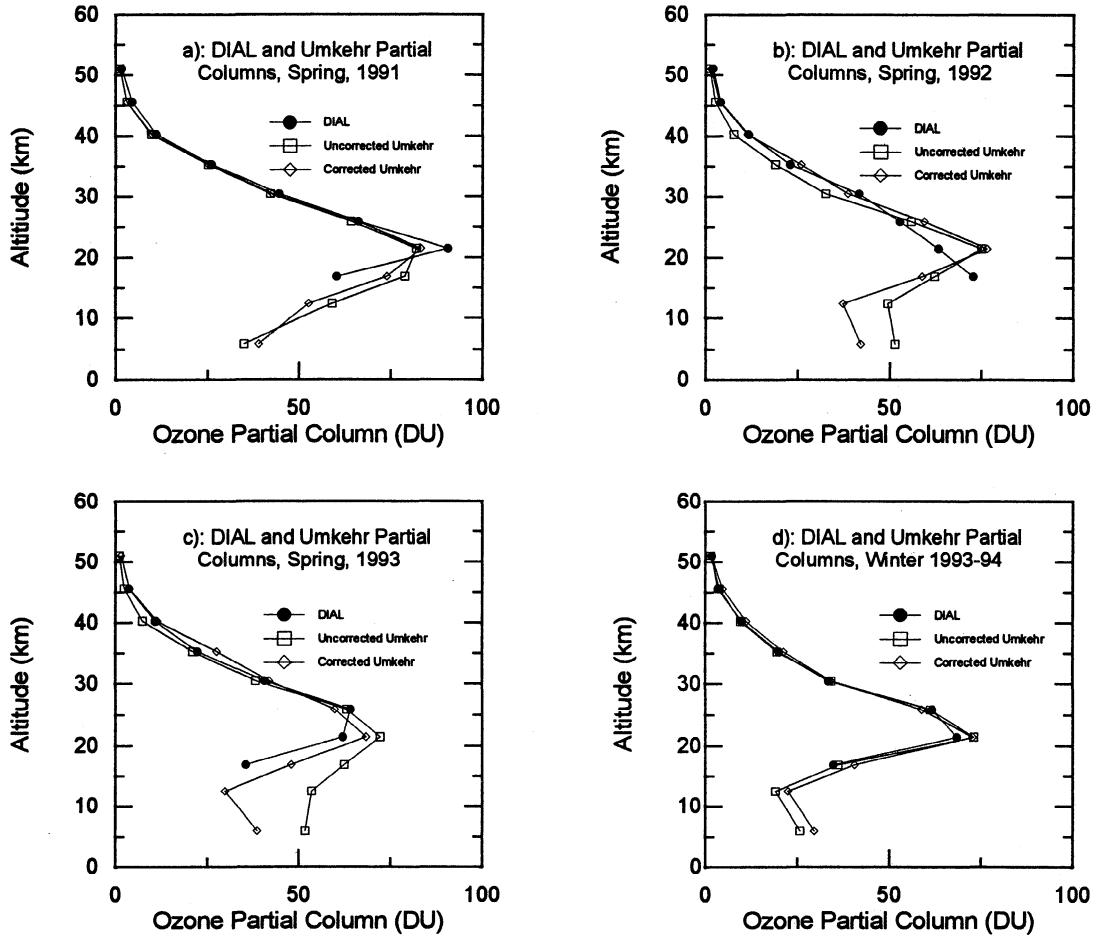

Figure 3. DIAL, Umkehr, and aerosol-corrected Umkehr ozone partial column retrievals for the springs of 1991–1993 and winter of 1993–1994. The results are for periods of low, high, moderate, and return to relatively low optical depths.

to the differential backscattering error. Smaller negative spikes occur in the DIAL data during the summer of 1992, but the DIAL and Umkehr results still overlap to within their respective confidence intervals.

Figures 3a–3d compare the vertical distribution of the DIAL and Umkehr ozone values, integrated over Umkehr layers 1–10, individually, for the springs of 1991, 1992, 1993, and the winter of 1993–1994, respectively. These time periods represent low, high, moderate, and a return to relatively low aerosol loading, respectively.

There is a close match between aerosol-corrected and -uncorrected Umkehr results during periods of low aerosol loading in Umkehr layer 4 and above (over 19 km). Below 19 km the corrected and uncorrected Umkehr values disagree by no more than ~10%. Both Umkehr versions agree closely with the DIAL results for Umkehr layers 5 and above (over 24 km), where the vertical resolution of the two techniques becomes comparable. Agreement at layer 4 is not as good, where there is a discrepancy between the DIAL and Umkehr results by ~5–12%. Below 19 km the DIAL and Umkehr results both become less certain. The Umkehr results at lower altitudes respond to real ozone changes in other Umkehr layers, and DIAL results at lower altitudes are more susceptible to aerosol loading effects.

The results from the springs of 1992 and 1993 show the effects of the Umkehr correction. The corrected Umkehr results match the DIAL results to within 8% or better at the higher altitudes (33 km and above) with the single exception of layer 7 from the spring of 1993, which shows a 22% difference between the two ozone values. These results compare favorably to the errors of 10–25% seen generally for the uncorrected data. At lower altitudes, there is greater disagreement between the corrected Umkehr and the DIAL results, but this is expected due to the differential backscatter error that the DIAL encounters there.

In layer 3 at an altitude of 20 km, DIAL results vary widely (25–50%) between the three years. Umkehr results also vary: 1992 and 1993 are about 25% lower than the clean year of 1991. The Umkehr results of layer 1 vary upward for 1992 and 1993, a result of the negative covariance of the solution with layer 3. This also demonstrates the Umkehr technique's diminished capabilities at lower altitudes, in that the ozone values in layers 1–3 partially result from real ozone values in higher layers [*Mateer and DeLuisi*, 1992].

The DIAL and Umkehr data from the winter of 1993–1994 match well, differing by no more than 12% in layer 4 at 20 kms. This suggests that the atmosphere is returning to its pre-Pinatubo condition, although aerosol effects are still seen in layer 4. Umkehr measurements are not appreciably affected by aerosol at this time.

The discrepancy between DIAL and Umkehr results in Umkehr layer 4 (19–24 km) is important to understand, since

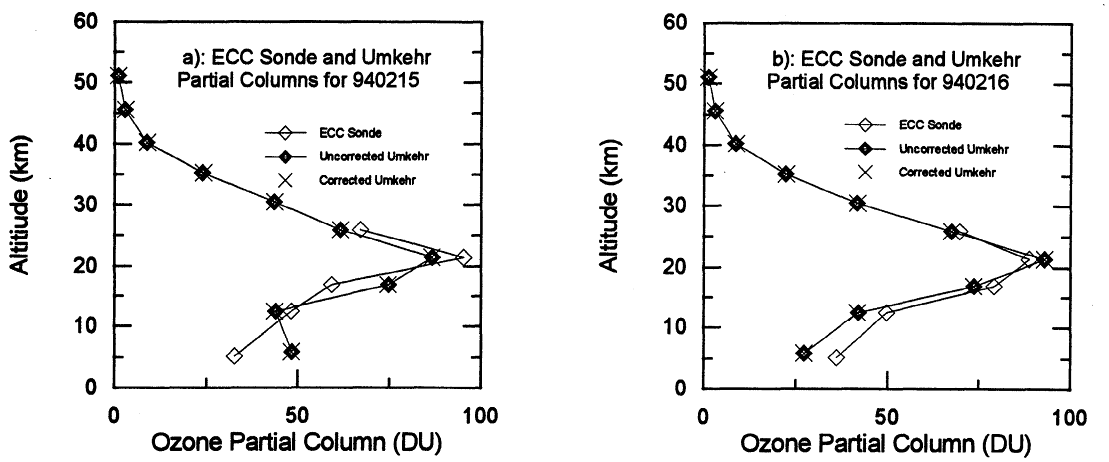

Figure 4. Ozonesonde, Umkehr, and aerosol-corrected Umkehr partial columns for March 15 and 16, 1994.

layer 4 accounts for the greatest concentration of ozone. We have already noted the good agreement between DIAL and SAGE II results at altitudes above 24 km. But DIAL results in layer 4 are affected by the presence of the volcanic aerosol and differ from the Umkehr retrieval. In order to better understand the discrepancy, Figures 4a and 4b compare Umkehr and ozonesonde results from the low aerosol period of February 15 and 16, 1994, respectively. The sondes were released from AES headquarters and reached a maximum altitude of just under 32 km. The results represent worst- and best-case scenarios for such a comparison. Figure 4a compares results from an Umkehr retrieval which, based upon the diagnostics (i.e., the number of iterations required for convergence to within 0.75% of a suitable climatological profile), would not normally have been accepted. The differences between the sonde and Umkehr results in layers 4 and 5 are ~5% and ~9%, respectively. At lower altitudes, there is considerable disagreement between the two measurements.

Figure 4b compares accepted Umkehr retrieval results to ozonesonde measurements. Above 15 km the two measurements compare to within 2–4%, and at lower altitudes the two measurements agree to within 9%. By previous argument, we suppose that the discrepancy at lower altitudes is due in part to the Umkehr retrieval's mixing of actual ozone levels at this altitude with those of higher altitudes.

Consequently, we are confident that the Umkehr technique retrieves useful ozone data between 19 and 28 km and differs pessimistically by less than 9% and more likely less than 4% from sonde data. The Umkehr retrievals in this altitude range might be used as benchmarks for other techniques, including the DIAL.

In cases where two techniques have the same response to the measured quantity, they will vary in a 1:1 ratio with respect to one another. The DIAL and Umkehr techniques, however, evaluate ozone levels differently when the aerosol optical depth is large, as evidenced in the earlier figures. In Figures 5a–5e we have scatterplots of percent differences of concurrent (i.e., within 6 hours of one another) DIAL and Umkehr measurements from their respective clean seasonal averages, i.e., the average amount of ozone measured by the respective instruments in each Umkehr layer during the periods of lowest aerosol loading (<0.04 optical density (OD)). The effect of the aerosol upon the two measurements can then be seen better. For clean air seasonal averages we use data from the spring, summer, and autumn (before November 1) of 1991, before the arrival of the Mount Pinatubo aerosol cloud above Toronto. The data from the winter of 1993–1994 provides the clean air, winter average ozone values.

Figure 5a compares DIAL and Umkehr data from Umkehr layer 4, occurring between 19 and 24 km. The data align along the 1:1 reference line for the reference periods, but during periods of heavy aerosol loading the data are displaced negatively along the ordinate while still exhibiting the 1:1 variation. Since we know that the DIAL is sensitive to the differential backscatter error and that the Umkehr is relatively insensitive to aerosol in this layer, the displacement of the data can be attributed to the effect of the aerosol upon the DIAL's response.

Figure 5b compares DIAL and Umkehr retrievals from layer 5 (24–28 km). The data are roughly evenly distributed about the origin, although they are arranged in an elongated pattern along the ordinate. There is no systematic error as seen for layer 4, but there is an increase in the variability of the DIAL data. It is reasonably certain that it is the DIAL data which are overvariable instead of the Umkehr retrieval being underresponsive because this altitude region is the one in which the upper boundary of the aerosol cloud is found. The boundary effects of the differential backscatter error can cause large negative errors at the upper boundary of the aerosol cloud, which appears borne out by the data from summer and spring of 1992. The reference datum from spring 1991 appears anomalously high.

Figure 5c compares DIAL and Umkehr results from Umkehr layer 6 (28–33 km). The data are negatively displaced along the abscissa. Because the aerosol in this layer is much smaller than the lower layers, the differential backscatter error is negligible for the DIAL. The distributed nature of the aerosol error for the Umkehr retrieval, however, assures that the ozone measurements are affected, even in layers where there is no aerosol actually present. This is seen as a negative excursion from clean air values by the Umkehr retrieval, consistent with earlier observations [*DeLuisi*, 1979]. Similarly, for layers 7 (33–38 km) and 8 (38–43 km), seen in Figures 5d and 5e, respectively, the Umkehr retrievals are negatively displaced from their clean air values, while the DIAL results are roughly evenly distributed about the origin.

Figures 6a–6e compare the DIAL and aerosol-corrected Umkehr retrievals for Umkehr layers 4–8, respectively. In

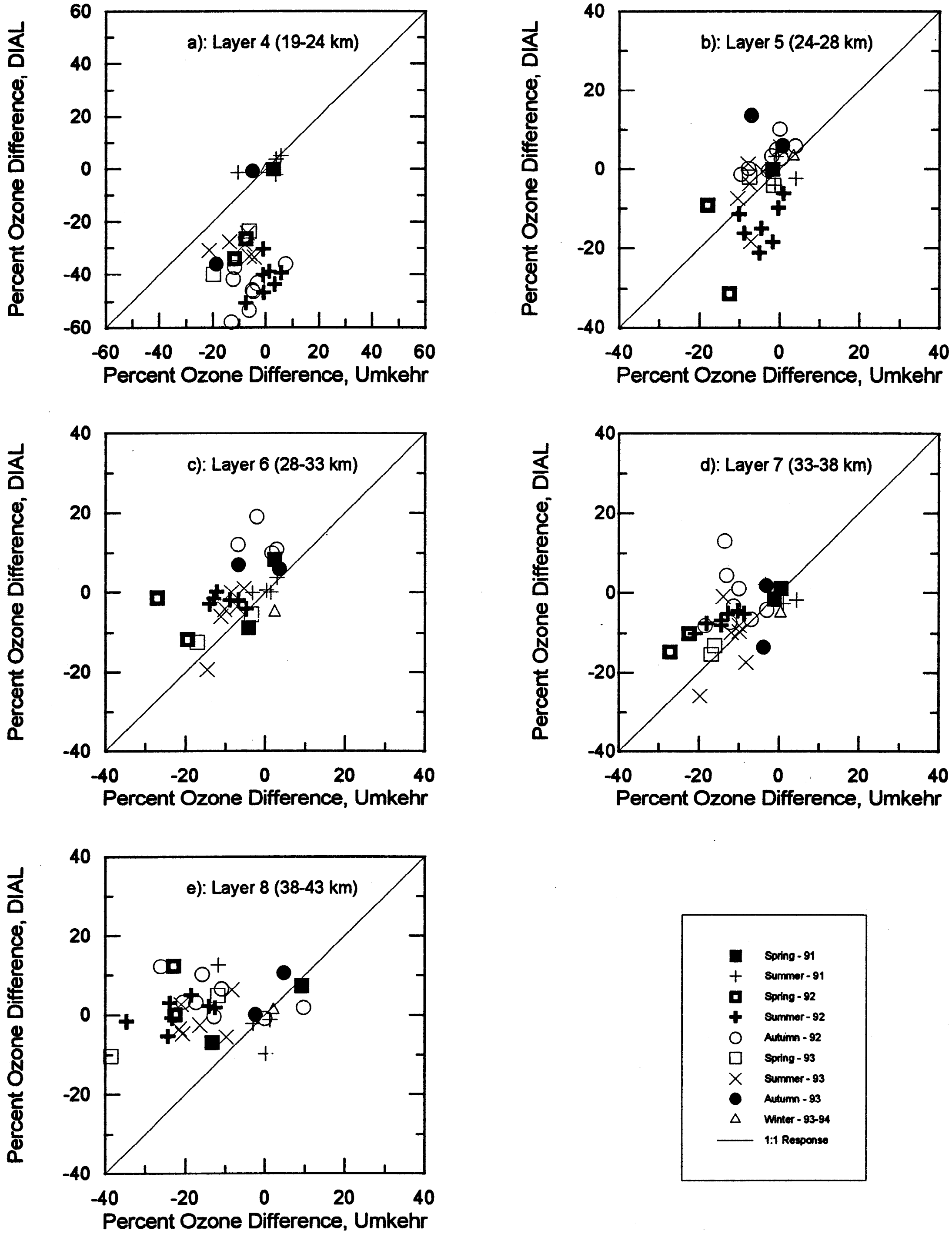

Figure 5. Scatterplots of DIAL versus Umkehr-measured ozone partial columns, percent difference from seasonal averages during periods of lowest aerosol loading (≤0.05), for spring 1991, summer 1991, autumn 1991 (before November 1), and winter 1993–1994.

layers 4 and 5 (19–24 and 24–28 km, respectively) the aerosol correction is nearly superfluous. Umkehr retrievals at these altitudes are not greatly affected by the presence of atmospheric aerosols. After the aerosol correction in layers 6 and 7 (28–33 and 33–38 km, respectively) the Umkehr data are evenly distributed about the origin. The results for layer 8 (38–43 km) are not so dramatically improved as the results for layers 6 and 7, but there is a 50% increase in the number of data points occurring within a 10% radius of the origin after the aerosol correction. The positive displacement of the remaining data points is possibly the result of a systematic error between the DIAL and Umkehr retrievals unrelated to the aerosol. Although the Umkehr shows greater variability at this altitude than the DIAL measurements, the measurements are still comparable. This is a result of the general stability of the stratosphere and the use of climatology to provide the a priori ozone profiles in the Umkehr retrieval algorithm.

Figures 7a–7d demonstrate how the full Umkehr retrieval

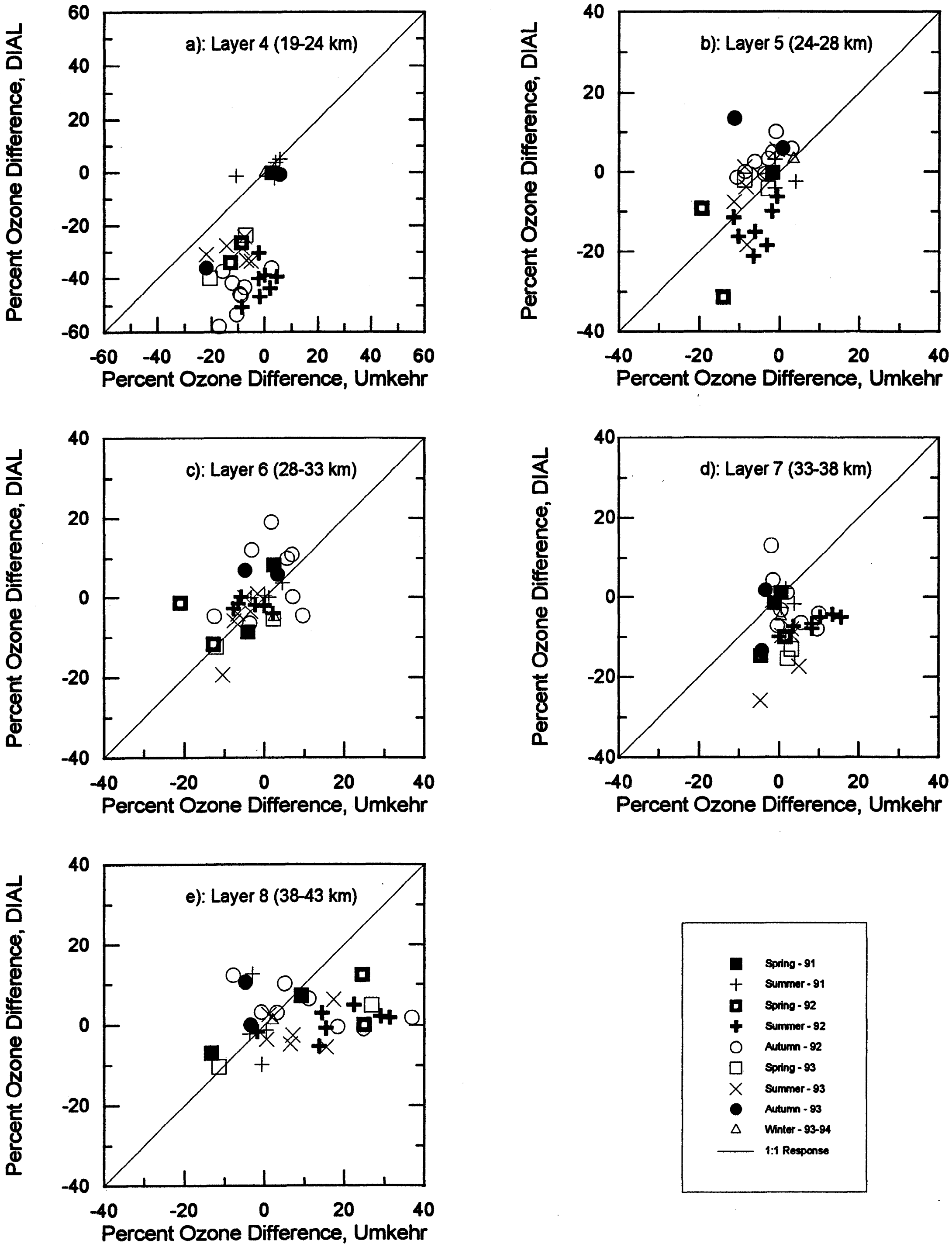

Figure 6. Scatterplots of DIAL versus aerosol-corrected Umkehr-measured ozone partial columns, percent difference from seasonal averages during periods of lowest aerosol depth (≤0.05), for spring 1991, summer 1991, autumn 1991 (before November 1), and winter 1993–1994.

provides additional information over the a priori ozone climatology. The respective DIAL/full Umkehr retrieval and DIAL/climatology ozone rms difference values are compared. These comparisons occur over two different time intervals. The first time interval comprises the entire period of the study, thus including periods of clean air and and periods of heavily aerosol laden air. The second interval comprises only those periods when the air is clean, i.e., the optical depth ≤0.04. The full Umkehr retrieval in these figures includes aerosol corrections. The comparisons take place between concurrent DIAL and Umkehr measurements. The data for Figures 7a–7d are presented in Tables 3a and 3b for the full time series and for the low optical depth data sets, respectively.

Figure 7a presents the rms differences between the DIAL/full Umkehr retrieval and DIAL/climatology for the entire data set, from 1991 through 1993. The rms values are plotted

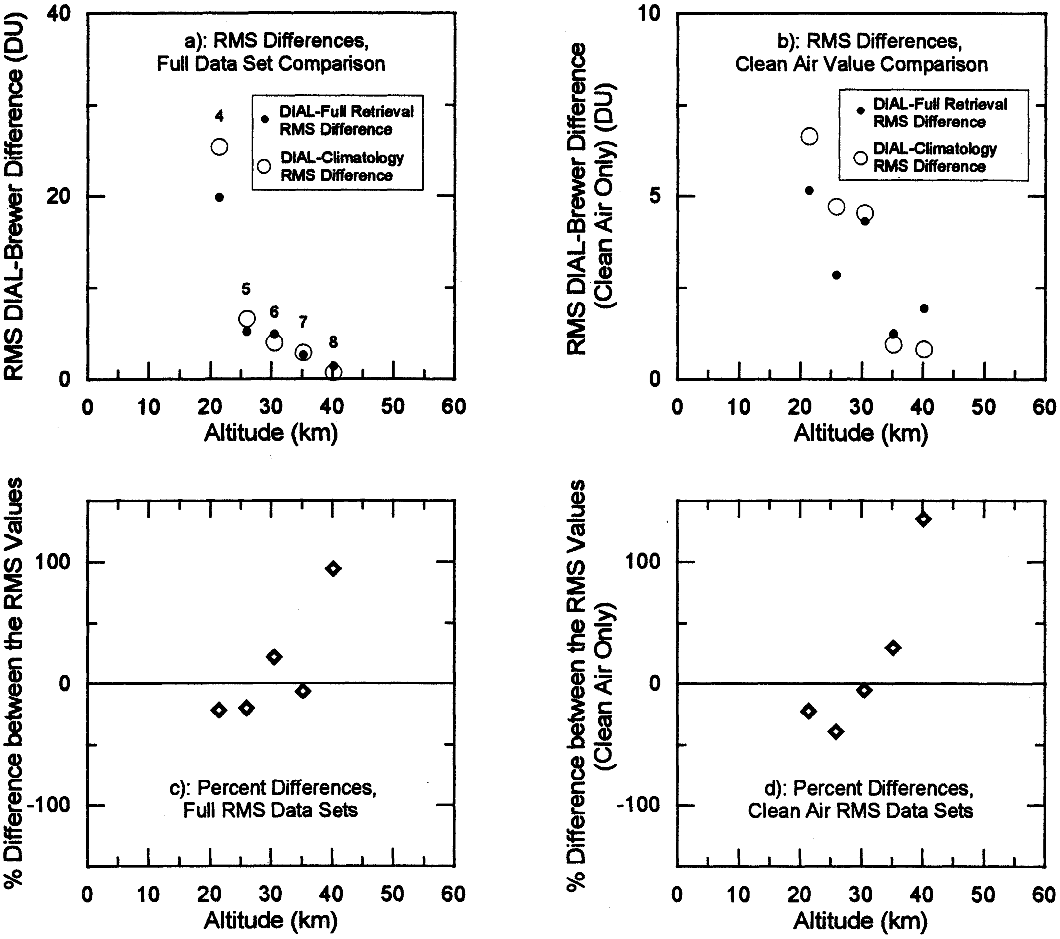

Figure 7. (a) Respective rms values of DIAL/climatology and DIAL/Umkehr differences over entire time series. (b) Same as Figure 7a, only taken over periods of total optical depth less than 0.05. (c) Percent difference per Umkehr layer between the DIAL/climatology and DIAL/Umkehr difference rms values over the entire time series. (d) Same as Figure 7c, only taken over periods of total optical depth less than 0.05.

against the midrange altitude of each Umkehr layer to which they correspond. The data points in Figure 7a are labeled with the corresponding Umkehr layer numbers to clarify this. Figure 7b presents the same information as Figure 7a, but for the clean air periods. Figure 7c is the percent difference between the two sets of rms values found in Figure 7a. A negative percent difference indicates better agreement between the DIAL and the full Umkehr retrieval results. A positive percent difference indicates better agreement between the DIAL and the Umkehr's a priori ozone values. Figure 7d provides the same information for Figure 7b.

In both Figures 7a and 7b the DIAL/climatology rms difference decreases monotonically as altitude increases. This is a result of the decreasing variation in ozone levels with altitude. Climatology has shown that the ozone levels in layers 7 and 8 do not vary greatly, which is corroborated by the DIAL measurements. At lower altitudes the ozone levels vary much more, and the first-guess approximation of the ozone level based upon climatology can be substantially different from the actual value. This is best seen in Figure 7b, because the DIAL measurements are dependable throughout the period with low aerosol loading. The DIAL results in layers 4 and 5, shown in Figure 7a, are not dependable owing to the large differential backscatter error. This results in even larger values for the

Table 3a. DIAL/Brewer rms Ozone Differences, Full Data Set

Layer	DIAL/Umkehr rms, DU	DIAL/Climatology rms, DU	Difference between rms Values, %
8	1.44	0.74	94.6
7	2.70	2.89	−6.6
6	4.93	4.04	22.0
5	5.22	6.56	−20.4
4	19.86	25.45	−22.0

DU, Dobson unit.

Table 3b. DIAL/Brewer rms Ozone Differences, Low Optical Depth Data Set

Layer	DIAL/Umkehr rms, DU	DIAL/Climatology rms, DU	Difference between rms Values, %
8	1.94	0.82	136.6
7	1.25	0.96	30.2
6	4.31	4.54	−5.1
5	2.86	4.71	−39.2
4	5.15	6.64	−22.4

DU, Dobson Unit.

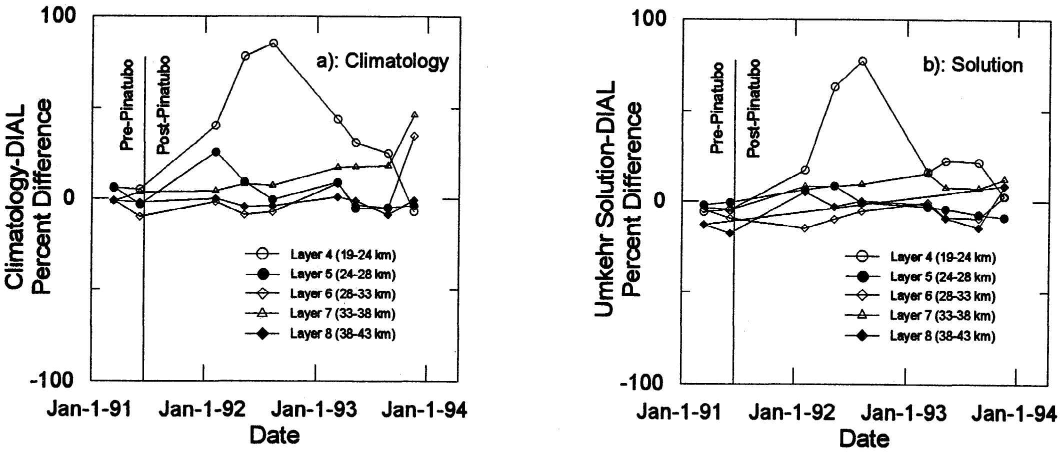

Figure 8. (a) Percent difference between seasonally averaged, concurrent climatology and DIAL ozone values, January 1, 1991, through November, 1993. (b) Same as Figure 8a, with aerosol-corrected, full Umkehr solution values used instead of climatology values.

DIAL/climatology rms differences, as the DIAL measurements are displaced widely from expected climatological ozone levels.

Both DIAL/climatology and DIAL/full Umkehr rms ozone differences in layer 4 differ by a factor of 4 between the full data set and the clean air data set. However, in both cases the DIAL/full Umkehr rms ozone difference is 22% less than the corresponding DIAL/climatology value. Even with large aerosol loading, the full Umkehr retrieval performs consistently at this altitude.

Because the retrieval algorithm distributes ozone into the Umkehr layers in a manner consistent with both the total measured ozone and the characteristics of the forward model, the DIAL/full Umkehr rms ozone difference does not necessarily decrease monotonically with height. The full Umkehr retrieval assesses the ozone level with the additional information, and the a priori ozone level is modified accordingly. In Figure 7b this is clearly seen in layers 4, 5, and 8. In layers 4 and 5, there is a large, negative change in absolute units between the respective DIAL/climatological rms ozone differences and the corresponding DIAL/full Umkehr values, with a large increase between those values in layer 8. In layers 6 and 7, the two rms difference values compare closely. The difference between the rms values in absolute units for layer 4 is even larger in Figure 7a but is offset by smaller differences in layers 5–8.

Figures 7c and 7d show the relative differences between the rms values plotted in Figures 7a and 7b, respectively. In layer 4 the relative difference between the rms values remains the same when the full comparison period and the clean air period are considered. Aerosol error corrections decrease the sensitivity of Umkehr returns to the presence of aerosol at this altitude. The relative difference between the rms values in layers 5 and 6 is about 40% lower during the clean air period than during the full comparison period. The apparent coupling between layers 5 and 6 results from the increased return in ozone information from the full Umkehr retrieval when the atmosphere is clean. The relative difference between the rms values in layers 7 and 8 is nearly 100% greater during the clean air period than during the full comparison period. The loss in information from the full Umkehr retrieval at higher altitudes is the subject of ongoing investigation.

The differences which develop in time between the DIAL and Umkehr retrievals are shown in Figures 8a and 8b. Figure 8a shows the percent difference between the seasonally averaged, concurrent climatological and DIAL ozone values. There is small difference between the DIAL and climatological ozone values in early 1991. After the arrival of the Pinatubo aerosol in the Toronto area, the difference between DIAL and climatology becomes quite large and positive in layers 4 and 5. There is less difference between the other layers until the end of the comparison period, where layers 6 and 7 show a difference of ~15% and ~20%, respectively.

Figure 8b shows the difference between the full aerosol-corrected Umkehr solution and DIAL for concurrent measurements, averaged seasonally. The overall difference in layer 4 is reduced by nearly 10% during the period of peak aerosol loading. Toward the end of the comparison period, the differences between the Umkehr and DIAL measurements are converging back to their pre-Pinatubo values.

The raw data used to derive the curves in Figure 8 are presented in Tables 4a and 4b. The largest differences are seen in layers 4 and 8 (50 and 70%, respectively) about a year after the Pinatubo eruption. Layer 5 appears the least perturbed of the five layers shown, with less than 20% difference between the measurements and more generally less than 15%. The last entries in the table indicate that pre-Pinatubo conditions are being restored throughout the entire altitude range.

Discussion

The time over which this comparison concerns itself corresponds to the initiation of the YU/ISTS/AES DIAL as an

Table 4a. Seasonally Averaged DIAL/Climatological Percent Differences

Season	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8
Spring 1991	6.14	6.57	−0.83	−1.16	−1.00
Summer 1991	5.09	−3.19	−9.82	3.71	−1.81
Spring 1992	40.03	25.70	−1.72	4.41	0.33
Summer 1992	78.52	9.45	−8.62	8.14	−4.10
Autumn 1992	89.58	−0.53	−6.71	7.35	−3.11
Spring 1993	43.60	9.08	8.56	16.96	0.95
Summer 1993	31.07	−5.29	−3.27	17.48	−0.96
Autumn 1993	25.18	−4.75	−5.15	17.94	−8.87
Winter 1993–1994	−3.72	−9.16	15.16	24.47	8.63

Table 4b. Seasonally Averaged DIAL/Umkehr Retrieval Percent Differences

Season	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8
Spring 1991	−5.79	−1.91	−4.70	−3.44	−12.80
Summer 1991	−4.50	−0.39	−9.20	−4.52	−17.57
Spring 1992	17.30	6.71	−14.58	8.56	5.45
Summer 1992	63.39	8.68	−9.61	8.53	−2.69
Autumn 1992	77.56	−0.34	−5.13	9.67	0.59
Spring 1993	16.13	−2.86	−0.45	15.69	−1.71
Summer 1993	22.42	−3.94	−8.63	7.89	−8.94
Autumn 1993	21.39	−7.22	−9.41	7.33	−14.32
Winter 1993–1994	2.99	−8.87	2.98	12.36	8.38

active system and to the intense aerosol loading in the stratosphere following the Pinatubo eruption. This is an interesting set of circumstances in that for a short time the instruments are compared under "clean" atmospheric conditions. This is followed by the aerosol loading. It is clear that, in general, the measurements follow one another well, qualitatively. Systematic differences between DIAL and Umkehr measurements can be accounted for by aerosol loading.

Recovery from the aerosol loading is seen to occur at about the same rate for layers 6–8. Layers 4 and 5, where most of the aerosol is deposited, indicate that the maximum disagreement between the two techniques occurs somewhat later than for the other layers, perhaps owing to the change in the aerosol layer's optical properties with time. The large differential backscattering error renders the DIAL data in layers 4 and 5 suspect, in absolute terms, for most of the period following Pinatubo. The use of nitrogen Raman backscattering is planned for the DIAL [*McGee et al.*, 1993]. The Raman DIAL is expected to markedly improve ozone measurements under aerosol-laden conditions.

It is an artifact of the Umkehr retrieval that it distributes the error brought about by the presence of aerosol among all of the Umkehr layers. This problem was addressed before and following the El Chichon eruption of 1983 [*Dave et al.*, 1979; *DeLuisi et al.*, 1989]. Umkehr curves were collected throughout that time period, and the differences between the clear and aerosol-laden retrievals were tabulated to provide a correction in times when such loading reoccured, when stratospheric optical depth is known. We have applied the technique with success here, making use of the lidar-provided data on optical depth. Ideally, optical depth data should be collected on each day that the Umkehr data are collected, instead of averaged on a weekly basis as seen here.

Summary

We have begun a period of intercomparison between the YU/ISTS/AES DIAL and the AES Umkehr ozone measurement systems. Initial results show agreement to within the respective error intervals of the measured ozone values. Differences which occur later owing to the presence of aerosol affect the comparison most in the layers actually carrying the aerosol: layer 4 (19–23 km). The Umkehr and DIAL measurements at higher altitudes differ by constant or slowly varying amounts. If the known aerosol effects are accounted for in the Umkehr results, the DIAL and Umkehr results again agree to within their respective error intervals.

A comparison of the DIAL- and Brewer-derived ozone profiles is necessary over a prolonged period in order to ensure consistency in the retrieved ozone values. This comparison will continue as the effects of the Mount Pinatubo eruption diminish with time. Concurrent Umkehr and DIAL measurements at stratospheric observing sites are especially important due to the complementary relationship between the instruments. While it is clear that the DIAL technique offers the advantages of improved vertical resolution, higher accuracy up to 40 km, and an operation independent of geographical location, the Brewer ozone spectrophotometer provides a robust method of measuring the ozone under a variety of conditions and with greater observation frequency. It is also a fully automated system, and it is less costly than DIAL systems.

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