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Stratospheric Aerosol and Gas Experiment II–Umkehr ozone profile comparisons

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Abstract. This study compares 1789 pairs of ozone profiles derived from 1384 Umkehr observations at 14 different stations and 1163 Stratospheric Aerosol and Gas Experiment (SAGE) II profiles coincident within 1000 km and 14 hours between October 1984 and April 1989. The comparison indicates the following significant percentage differences (SAGE II–Umkehr)/Umkehr with 2 × standard errors of the mean: Umkehr layer 4, (18.3 ± 0.8)%; layer 5, (−1.6 ± 0.4)%; layer 6, (−6.2 ± 0.5)%; layer 7, (0.8 ± 0.6)%; layer 8, (7.7 ± 0.6)%; and layer 9, (12.0 ± 1.1)%. Differences in layers 4 and 6 are due, at least in part, to inaccurate Umkehr climatologies. Average SAGE II/Umkehr differences in layers 5 through 9 at individual stations are generally less than 10%. While the Umkehr retrievals are known to be sensitive to aerosol interference, the mean layer 8 correction during the period of this study is estimated to be only 2% with large station-to-station variability. The correction in lower layers is smaller. We have chosen to ignore the small Umkehr aerosol correction in this study. The mean difference would decrease if Umkehr profiles were corrected for a priori profile effects calculated by DeLuisi et al. (1989a). However, using the newer Bass and Paur (1985) ozone absorption cross sections would tend to increase the differences at most levels. The profile of mean differences is similar to previously observed differences between Umkehr and solar backscattered ultraviolet (SBUV) observations. Comparing SAGE II/Umkehr differences to SAGE I/Umkehr differences at seven common stations shows a bias of −4% at the ozone peak (layer 4). This bias increases with altitude to 8% in layer 8 and 15% in layer 9, with SAGE II ozone partial pressures higher than or equal to those of SAGE I (version 6.1) relative to Umkehr in all layers above 4. A systematic upward reference-altitude shift between 0.25 and 0.50 km for SAGE I, similar to the quoted uncertainty, would increase SAGE I ozone 4% to 8% in layer 8 and would result in similar SAGE and Umkehr ozone trends during the 1980s. Cross correlations of numerous variables associated with the Umkehr and SAGE II data sets show a minimum correlation between SAGE II and Umkehr ozone partial pressures in layers 5, 8, and 9. This correlation is a result similar to the one previously noted in other comparisons against Umkehr data. We discuss these minimum correlations in relationship to the seasonal cycle in ozone and synoptic scale variations at midlatitudes based on model results. Substantial differences between SAGE II and Umkehr exist in both the mean and the variability of ozone in layers 8 and 9. Substantial differences also exist in layer 6 where the Umkehr algorithm does not retrieve the low ozone values periodically observed by SAGE II during winter.

Introduction

Stratospheric Aerosol and Gas Experiment (SAGE) I and II and Umkehr measurements provide time series for ozone trend evaluation [*World Meteorological Organization* (*WMO*), 1988; *McCormick et al.*, 1992; *Reinsel et al.*, 1989; *DeLuisi et al.*, 1989b]. Because stratospheric photochemical models predict that the altitude with the greatest percentage of ozone decrease is near 40 km, a good deal of effort has been focused on determining the actual ozone trend in this region. While the ozone trends report [*WMO*, 1988] presented a number of comparisons of various ozone profile measurement systems and comparisons of both SAGE and Umkehr measurements, a site-by-site study of SAGE II/Umkehr ozone profile comparisons has not previously been made.

The SAGE instrument obtains vertical profiles of ozone and aerosols in the solar occultation mode using a visible and near-infrared wavelength spectrometer [*McCormick and Trepte*, 1987; *Cunnold et al.*, 1989; *Chu et al.*, 1989]. Because both solar occultation and Umkehr measurements occur at the terminator, these two instruments often sample the same atmospheric volume under the same solar conditions. The Umkehr method uses the ground-based Dobson spectrophotometer measuring ultraviolet solar radiation

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scattered downward from the zenith sky over a period of a few hours around sunrise or sunset [*Dobson*, 1931]. The ratio of the scattered radiance at two ultraviolet wavelengths as a function of zenith angle is sensitive to the vertical distribution of stratospheric ozone [*Gotz et al.*, 1934]. Both the SAGE instrument and the Dobson instrument (when operated in Umkehr mode) are most sensitive to stratospheric ozone (Umkehr layers 4 through 9), and it is those layers that we study here.

In a comparison of SAGE I (version 5.5) and Umkehr profiles, *Newchurch et al.* [1987] found SAGE I ozone partial pressures to be lower than Umkehr ozone partial pressures in layers 8 and 9. That study is updated here by using data obtained from the newer version (6.1) of the SAGE II algorithm. In the current study, we find that average SAGE II ozone amounts are significantly higher than Umkehr ozone amounts in layers 8 and 9 in northern midlatitudes. However, among the 14 Umkehr stations studied here, significant variation exists in the SAGE II/Umkehr differences.

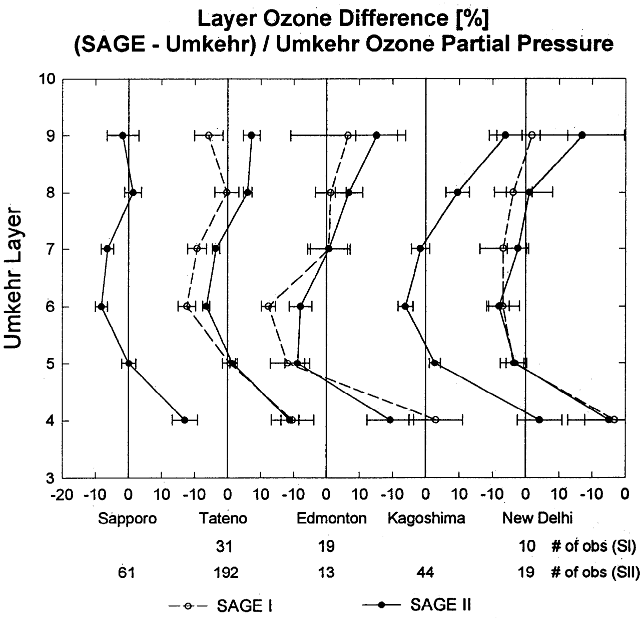

Figure 1. Layer ozone partial pressure differences between SAGE II and Umkehr (solid lines) and between SAGE I (version 6.1) and Umkehr (dashed lines) at Tateno, Edmonton, and New Delhi (SAGE II and I) and at Sapporo and Kagoshima (SAGE II only). Differences are ±2 standard errors of the mean (SEM). Number of coincidences (<1000 km and <14 hours) indicated below station name.

SAGE II and Umkehr Error Budgets

A thorough study of the SAGE II error budget reported by *WMO* [1988], *Cunnold et al.* [1989], and *Attmannspacher et al.* [1989] indicates that at 1-km resolution, the SAGE II ozone profile precision appears to be 5% between 24 and 36 km (Umkehr layers 5–7) and decreases monotonically to 7% at 48 km (Umkehr layer 10). The procedure for obtaining SAGE II error bars, described by *Chu et al.* [1989], is based on the variance of the radiances from approximately six solar disk scans at the same tangent altitude. Variance in the measured radiances results primarily from variability in the ozone and molecular column amounts over the approximately six scans at nearly the same tangent altitude (0.5 km). This variance yields error bars that are proportional to the ozone concentration over a broad range of altitudes between approximately 30 and 2 mbar [*Chu et al.*, 1989]. Therefore, a correlation between the SAGE II profile error bars and the ozone mixing ratios at the same level is found. Above approximately 1 mbar the random error in measuring atmospheric radiance should translate into an ozone error bar that increases with altitude. To reduce this effect, the profile is smoothed over 5 km during its retrieval.

For Umkehr profiles close to the standard profiles used to obtain the partial derivatives for use in the Umkehr retrieval [*Mateer and Dütsch*, 1964], errors due to instrument calibration, absorption coefficients and their temperature dependence, multiple scattering, and a no-refraction assumption suggest measurement errors of the order of 10% in layers 4 through 8, with larger errors elsewhere [e.g., *DeLuisi*, 1979; *DeLuisi et al.*, 1985; *WMO*, 1980]. "Errors for profiles that are not close to one of the standard profiles have not been determined; they may be significant" [*WMO*, 1988, p. 138]. It should, however, be noted that the standard Umkehr retrieval technique [*Mateer and Dütsch*, 1964] uses the same northern hemisphere, midlatitude-based, standard ozone profiles at all latitudes. It is well known that the Umkehr measurements are susceptible to errors due to stratospheric aerosols [*Dave et al.*, 1979; *DeLuisi*, 1979; *Reinsel et al.*, 1989], and we have addressed that effect in a separate paper [*Newchurch and Cunnold*, 1994]. While "the accuracy of the aerosol correction schemes used so far is still an open question" [*WMO*, 1988, p. 147], available research suggests that during the period of this study, the effect probably averages no more than 5% in the upper Umkehr layers. Because of the uncertainty in the aerosol correction, we have not applied an aerosol correction to the Umkehr data analyzed here.

The SAGE II instrument measures ozone by absorption of visible solar radiation at 600 nm. The ozone absorption coefficient in this region results from the work of *Penney* [1979], who found the coefficient to be independent of temperature. The Dobson instrument in the Umkehr mode measures scattered ultraviolet solar radiation. The ozone absorption coefficient in this ultraviolet region results from the measurements of *Vigroux* [1953, 1967], which are the basis of the International Ozone Commission/World Meteorological Organization (IOC/WMO) 1968 ozone measurement scale. This scale was updated in 1992; however, the Umkehr data analyzed in this paper are on the 1968 scale. While the relationship between the IOC/WMO 1968 and 1992 scales for total ozone is established as (IOC/WMO 1992) = 0.9743 * (IOC/WMO 1968), no relationship between the Penney visible-wavelength scale and either of the IOC/WMO ultraviolet scales is established. The Umkehr profile response to changes in total ozone is not necessarily a constant factor in all layers. The ozone absorption coefficient on the Penney scale used for SAGE II has an uncertainty of 6% (1σ) [*WMO*, 1988]. Therefore, because of the uncertainty of the relationship between the ultraviolet (Umkehr) and visible (SAGE) ozone absorption coefficient scales, the point of zero difference (i.e., the zero on the abscissa of Figures 1–6) is also uncertain.

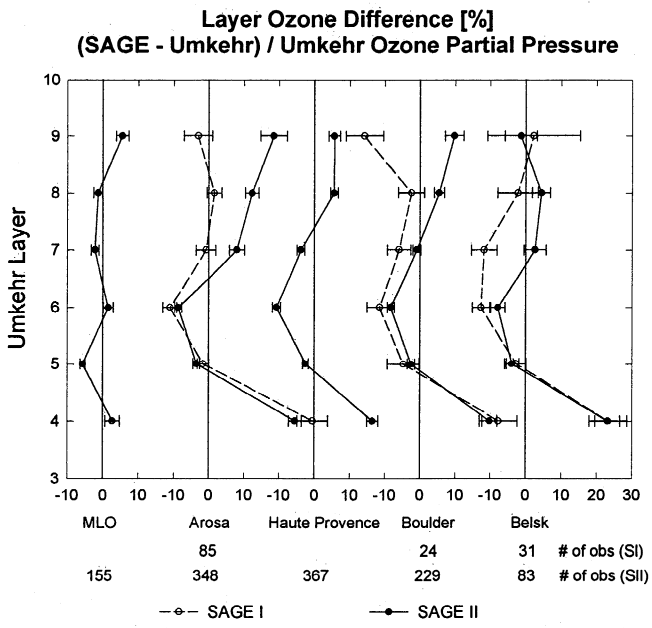

Figure 2. Layer ozone partial pressure differences between SAGE II and Umkehr (solid lines) and between SAGE I (version 6.1) and Umkehr (dashed lines) at Arosa, Boulder, and Belsk (SAGE II and I) and at Mauna Loa Observatory and Haute Provence (SAGE II only). Differences are ±2 SEM. Number of coincidences <1000 km and <14 hours) indicated below station name.

Case Study Parameters

The results of our research derive from using SAGE II data and World Ozone Data Center (WODC) Umkehr data to compare coincident ozone profile measurements between October 1984 and April 1989. The WODC database reports Umkehr ozone amounts as layer partial pressures in the standard Umkehr layers. The SAGE II ozone number densities (or corresponding ozone mixing ratios), which are reported at 1-km altitude intervals, were converted to ozone partial pressures at standard Umkehr intervals using trapezoidal integration with National Meteorological Center (NMC) temperatures supplied with the SAGE II data. More specifically, we compute the layer ozone partial pressure as $1/n * \Sigma (\chi p)$ where χ is the SAGE layer ozone mixing ratio, p is the SAGE layer pressure, and n is the number of SAGE layers in an Umkehr layer. Because we interpolate the SAGE data to the exact pressure boundaries of the Umkehr layers (defined with the surface at 1 standard atmosphere = 1013 mbar) and sum over SAGE layers within each Umkehr layer, this interpolation procedure assumes that the logarithm of pressure varies linearly within 1-km SAGE-layer intervals.

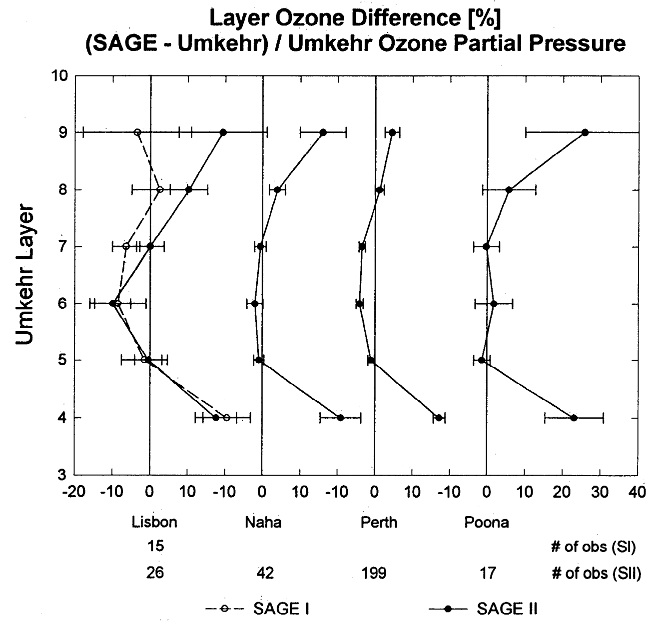

Figure 3. Layer ozone partial pressure differences between SAGE II and Umkehr (solid lines) and between SAGE I (version 6.1) and Umkehr (dashed lines) at Lisbon (SAGE II and I) and at Naha, Perth, and Poona (SAGE II only). Differences are ±2 SEM. Number of coincidences (<1000 km and <14 hours) indicated below station name.

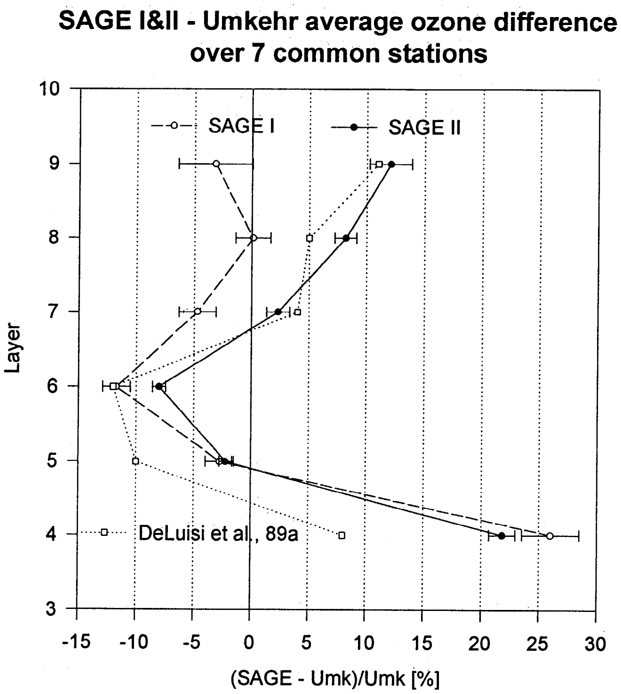

Figure 4. Layer ozone partial pressure differences between SAGE I version 6.1 (open circles), SAGE II (solid circles), and Umkehr averaged over stations Arosa, Belsk, Boulder, Edmonton, Lisbon, New Delhi, and Tateno. Error bars are ±2 SEM. Shown for comparison (dotted line) are the *DeLuisi et al.* [1989a] differences between original Umkehr retrievals and retrievals from radiances derived from SAGE II and ozonesonde data.

Some confusion exists in the literature over the actual values of the Umkehr-layer pressure boundaries. Some authors have used 1000 mbar as the lowest boundary [e.g., *Dütsch and Staehelin*, 1992; *Newchurch et al.*, 1987]; others use 1 standard atmosphere (1013 mbar) [e.g., *Mateer and DeLuisi*, 1992]. The pressure boundaries used in both the 1964 and 1992 Umkehr algorithms and used for the World Ozone Data Center Umkehr database are defined in terms of standard atmospheres (1013 mbar at the surface; C. L. Mateer, personal communication, 1994). This difference in layer definition leads to the former definition's (1000 mbar)

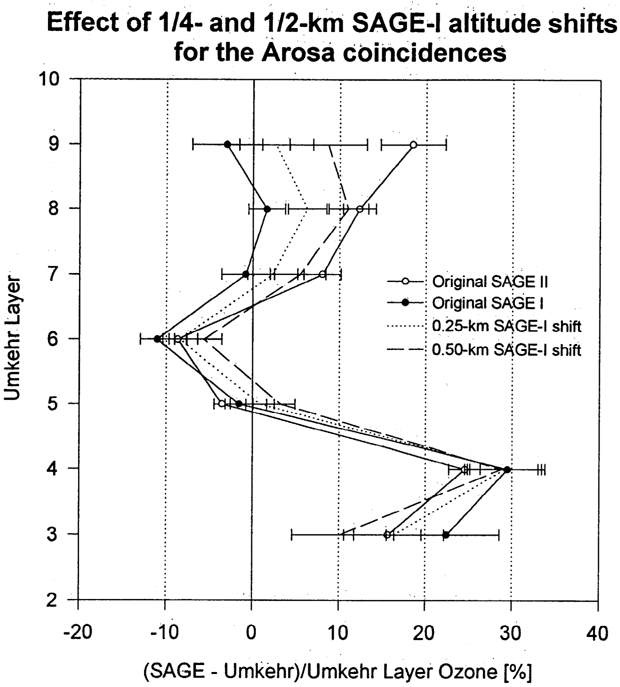

Figure 5. The effect of shifting the SAGE I reference altitude upward 0.25 km (dotted line) and 0.50 km (dashed line) for the Arosa coincidences. The solid line with solid circles represents the unshifted SAGE I–Umkehr differences; the solid line with open circles represents the SAGE II–Umkehr ozone differences. Error bars are 95% confidence intervals of the mean difference.

having pressure boundaries 1.3% lower than the actual Umkehr layer boundaries. The altitude shift of the layer boundaries varies with height because it is $0.13 \times RT/g$, and the temperature T varies with height. At 200 K the height difference is 76 m; at 270 K the height difference is 103 m. In layers above (or below) the ozone peak, this boundary difference leads to a layer ozone-amount difference in proportion to the vertical gradient of ozone amount. In layer 8, for example, 1.3% pressure difference corresponds to 0.1 km altitude difference at 250 K (the 1000-mbar definition layer being at a higher altitude than the actual Umkehr layer). Based on Figure 5, in which the sensitivity of SAGE profiles to an altitude shift of 0.25 km is shown for a different purpose, this layer boundary shift results in a 1.8% difference in layer 8 ozone partial pressure on average.

Because the fundamental SAGE measurement observes slant column number density, which is inverted to vertical profile of number density with an onion-peeling algorithm [*Chu et al.*, 1989], deriving mixing ratios requires knowledge of the temperature and pressure at the measured altitudes. SAGE uses the measured atmospheric density along with the NMC temperatures to derive the mixing ratio. One can also then write ozone partial pressure directly as a function of ozone number density and temperature at a given pressure (see, for example, *U.S. Standard Atmosphere* [1976, Table 19]). The SAGE ozone number densities, temperatures, pressures, and mixing ratios are all self consistent in this regard. Because we compute the SAGE partial pressure within the precise Umkehr pressure boundaries, this quantity is directly comparable to the Umkehr partial pressure.

While both the previous comparison using SAGE I (version 5.5) data [*Newchurch et al.*, 1987] and the preliminary results of the SAGE II study given by *Newchurch and Cunnold* [1990] allowed coincidences within 4000 km and 30 hours, the SAGE I and SAGE II results reported here allow only cases whose coincidences are within 1000 km and 14 hours. We report the results from Umkehr stations with at least 13 SAGE II coincidences. The time (14 hours) and distance (1000 km) criteria sometimes allowed multiple SAGE profiles to coincide with one Umkehr measurement and also allowed multiple Umkehr profiles (e.g., A.M. and P.M.) to coincide with a single SAGE profile. These selection criteria produced 215 profile pairs from 159 Umkehr profiles with 156 SAGE I profiles and 1789 profile pairs from 1384 Umkehr profiles with 1163 SAGE II profiles. The population included 14 Umkehr stations representing both hemispheres, but primarily midlatitudes of the northern hemisphere.

Mean SAGE II–Umkehr Differences

The average ozone partial pressures ± 1 standard deviation (s.d.) in Umkehr layers 3–10 appear in Table 1 for observation pairs with both SAGE II and Umkehr measurements available in layers 3–10. That table also reports the Umkehr ozone amounts for layers 1 and 2 for the same sets of observations. The average partial pressures for the seven common stations appear in Figure 6 with 1-s.d. error bars. The Dobson total ozone associated with the Umkehr observations averaged over the seven stations with both SAGE I and SAGE

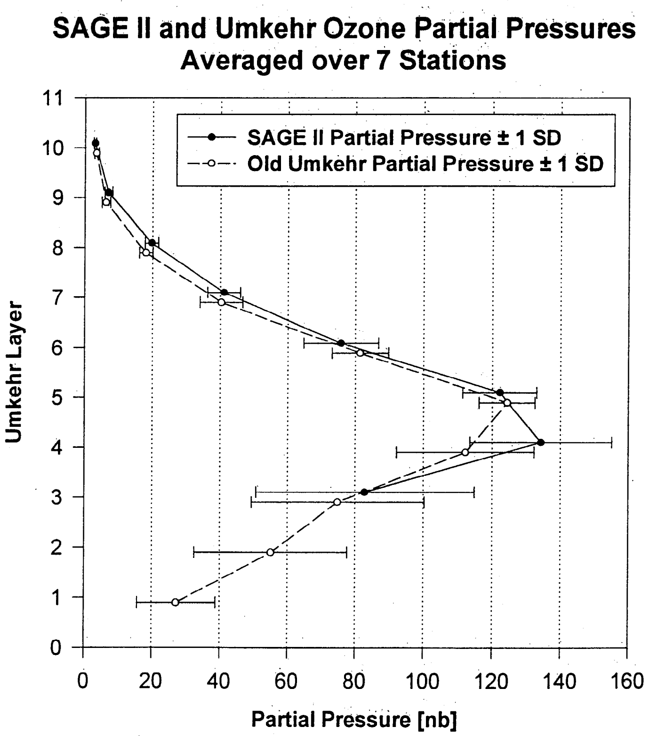

Figure 6. Average layer ozone partial pressures averaged over seven stations (Tateno, Edmonton, Arosa, Boulder, Belsk, Lisbon, and New Delhi) for Umkehr (open circles) and SAGE II (solid circles) ±1 standard deviation (s.d.). The Dobson total ozone average is 314 ± 23 (1 s.d.) DU. These averages derive from 918 coincidence pairs within 1000 km and 14 hours. The data points are displaced ±0.1 layer for clarity.

Table 1. Mean and 1 Standard Deviation Values for Umkehr and SAGE II Partial Pressures

	Umkehr		SAGE II	
Layer	7 Stations	14 Stations	7 Stations	14 Stations
10	3.3 ± 0.7	3.3 ± 0.6	2.9 ± 0.4	2.8 ± 0.3
9	6.2 ± 1.2	6.1 ± 1.2	6.9 ± 1.2	6.7 ± 1.2
8	18.1 ± 2.0	18.3 ± 1.8	19.7 ± 2.0	19.6 ± 2.0
7	40.3 ± 6.3	42.8 ± 6.5	41.1 ± 4.8	42.6 ± 5.5
6	81.4 ± 8.3	84.8 ± 9.4	75.7 ± 11.1	80.0 ± 14.0
5	124.4 ± 8.2	126.3 ± 9.3	122.2 ± 10.8	124.0 ± 10.8
4	112.3 ± 20.0	110.1 ± 19.9	134.4 ± 20.8	128.9 ± 23.7
3	74.8 ± 25.5	68.1 ± 29.7	82.8 ± 32.1	74.4 ± 35.2
2	55.1 ± 22.6	50.1 ± 27.2		
1	27.2 ± 11.5	27.0 ± 11.7		

Average over 918 coincidences at seven stations (Tateno, Edmonton, Arosa, Boulder, Belsk, Lisbon, and New Delhi) and over 1789 coincidences at 14 stations (previous seven stations plus Perth, Sapporo, Mauna Loa Observatory, Kagoshima, Naha, Poona, and Haute Provence).

II observations available is 314 ± 23 (1 s.d.) DU and averaged over the 14 stations is 310 ± 23 (1 s.d.) DU.

Comparing the 918 seven-station differences of the total ozone amount in layers 3–10 reveals SAGE II is (6.2 ± 0.6)% (2 * standard error of the mean (SEM)) higher than Umkehr. Averaged over the 764 seven-station coincidences where SAGE II reports layer 2 ozone, the difference is (4.4 ± 0.8)% (2 SEM). The comparable differences for the 1789, 14-station, layer 3–10 amounts and 1448, 14-station, layer 2–10 amounts are (4.8 ± 0.4)% and (3.0 ± 0.6)% respectively (SAGE II higher than Umkehr in all averaged comparisons).

The differences in layer ozone between SAGE II and Umkehr at 14 individual Umkehr stations appear in Figures 1–3. Because of the smaller number of SAGE II observations in layers below 4, the ozone differences are not reported for individual stations in those layers. The solid lines represent SAGE II/Umkehr ozone differences while the dashed lines at seven stations represent SAGE I (version 6.1)/Umkehr differences. There is a characteristic vertical structure to almost all the SAGE II/Umkehr ozone differences, namely, SAGE II observations yield values 10–20% larger than Umkehr values in layer 9, 5–10% smaller values in layer 6, and approximately 15–20% larger values in layer 4. Layers 5 and 7 tend to be transition layers between the layers where the maximum and minimum differences are found. A similar vertical structure was found by *DeLuisi et al.* [1985] in comparisons between Umkehr and solar backscattered ultraviolet (SBUV) observations, with difference peaks occurring in layers 1, 6, and 8. Comparisons between SAGE II and SBUV [*Wang*, 1994] show smaller differences (less than 5% in layers 5–9 and less than 10% in layer 4) and serve to confirm that the Umkehr observations are giving results different from the SAGE II and SBUV retrieval algorithms.

The average of the 1789 SAGE II/Umkehr pairs at the 14 stations shown in Figures 1–3 indicates the following significant percentage differences (SAGE II-Umkehr)/Umkehr with 2σ SEM: Umkehr layer 4, (18.3 ± 0.8)%; layer 5, (−1.6 ± 0.4)%; layer 6, (−6.2 ± 0.5)%; layer 7, (0.8 ± 0.6)%; layer 8, (7.7 ± 0.6)%; and layer 9, (12.0 ± 1.1)%. Because of the large number of pairs, these 2 × SEM are small relative to the potential uncertainties discussed in the error budget section. Because of residual El Chichon aerosols the Umkehr measurements in layer 8 may be biased low by up to 4% [*WMO*, 1988], which could reduce the layer 8 difference of 8% by half. However, as indicated by *Newchurch and Cunnold* [1994], the regression of SAGE II aerosol amounts on SAGE II–Umkehr ozone differences in layer 9 is nearly as often positive as negative among these 14 stations and the 14-station average is (−2 ± 1)% (2 SEM) in layer 8 for the period studied in this paper.

One source of differences between the vertical structure of Umkehr and SAGE II profiles results from differences between the Umkehr a priori profiles and the mean SAGE II profile. There are at most four pieces of information in the Umkehr measurements [*Mateer*, 1965]. Accordingly, the retrieval algorithm is designed to completely suppress eigenvectors of the measurements greater than 4 and to significantly damp the effect of measurement eigenvector 4. Therefore, the retrieved Umkehr profiles will contain contributions from eigenvectors greater than 4 only from the a priori profiles, and this will be partially true for eigenvector 4 also. Compared to ozonesonde measurements, the Umkehr profiles are found to be low in layer 4 and high in layers 2 and 6 [*Mateer and Dütsch*, 1964]. In fact, roughly 20% differences versus ozonesondes are reported for layer 4 by *DeLuisi and Mateer* [1971]. Compared to the mean SAGE II profile in the comparisons in this paper, the a priori Umkehr profile is high in layers 5–9 (and highest in layers 6 and 7) and low in layers 2–4. The fact that errors in the Umkehr a priori profiles are responsible for much of the vertical structure in the SAGE II/Umkehr differences is confirmed not only by the vertical scale of the differences, which corresponds to that of the third or fourth Umkehr measurement eigenvector [see *Mateer*, 1965], but also by the study by *DeLuisi et al.* [1989a]. In that study a set of monthly mean, midlatitude ozone profiles from SAGE II were used as input to a forward radiative transfer calculation to generate synthetic Umkehr and SBUV radiance measurements. These radiances were then inverted by the standard algorithms. (Based on the DeLuisi et al. Table 1, a referee has pointed out that the SAGE II data appears to have been incorrectly processed, perhaps because of a 1-km altitude error. However, we believe that their SAGE-Umkehr differences are not very sensitive to the initial ozone profiles; therefore, because both the SAGE II altitude and the inverted-profile altitudes are offset by the same amount, the profile differences are comparable here). The average differences between the test (i.e., SAGE II) profiles and the retrieved Umkehr profiles in that study are included as the dotted line in Figure 4. In layer 9, for example, the Umkehr values are expected to be roughly 11% low due to the retrieval procedure alone, and the vertical structure of the differences is similar to those found in our study. In contrast, the differences DeLuisi et al. calculated between SBUV and SAGE II (i.e., those due to the retrieval algorithm) were less than 5% in layers 5–9 and 8% in layer 4, which suggests that the SBUV a priori profiles are more realistic than the Umkehr a priori profiles.

Although we believe Umkehr a priori profile effects are the reason for many of the SAGE II/Umkehr profile differences shown in Figure 4, there are other known sources of Umkehr measurement error [*DeLuisi et al.*, 1985]: wavelength-dependent inconsistencies and temperature dependencies in the ozone absorption coefficients, forward model limitations, instrumental errors, and the effect of the Umkehr adjustment in total ozone values introduced in 1968. The wavelength-dependent inconsistencies and the temperature dependencies have been well documented; the first of these errors is expected to lead to overestimation of ozone by the Umkehr technique in layers 7, 8, and 9 by approximately 7–10% but by less than 6% at the other levels [*WMO*, 1988, p. 142]. This correction, which is incorporated into a new Umkehr retrieval algorithm [*Mateer and DeLuisi*, 1992] based on the Bass-Paur ozone cross sections [*Bass and Paur*, 1985; *Paur and Bass*, 1985] will lead to a decrease in the Umkehr estimates, including the total columnar amount. In the Umkehr retrieval algorithm, the neglect of the temperature dependence of the ozone absorption cross sections causes errors to increase in the upper three layers. This effect, which was evaluated by *DeLuisi* [1971], leads to an ozone overestimation from the combined errors of absorption coefficients and temperature dependencies of approximately 14% in layers 8 and 9, 10% in layer 7, and 0–5% in layers 3–6 [*WMO*, 1988, p. 142].

A new Umkehr retrieval procedure using improved a priori profiles and the new temperature-dependent cross sections is now producing routine WODC Umkehr profiles [*Mateer and DeLuisi*, 1992]. It will be interesting to repeat the SAGE II comparison based on the results from this algorithm. Based on the results from the old algorithm, the expected effects of removing the a priori profile errors, and the effects of cross-section adjustments cited above, we would expect that the new Umkehr technique will produce smaller ozone amounts than SAGE II in the upper stratosphere by roughly 10%. The integrated column amounts in layers 3 through 10 are approximately 5% less for Umkehr (old algorithm) than for SAGE II. Therefore, if SAGE II total column amounts are to agree with Dobson measurements (based on the *Vigroux* [1967] cross sections), then SAGE II would have to report significantly less ozone (~10%) than Umkehr reports in layers 1 and 2. This effect might be even more pronounced for Dobson AD-wavelength pair measurements based on the Bass-Paur cross sections, which result in a 2.57% reduction in the column measurements [*Hudson et al.*, 1992]. Based on the importance of a priori estimates of profile structure in layers 1–4 for Umkehr and SBUV measurements and some observed differences between SAGE II and ozonesonde measurements below 20 km altitude [e.g., *Veiga et al.*, 1995], it is important to assemble an accurate global climatology of ozone below 20 km altitude.

Comparison of SAGE II–Umkehr and SAGE I–Umkehr Differences

The open circles in Figure 4 represent the average SAGE I/Umkehr percentage ozone difference of 214 cases over the seven Umkehr stations with SAGE I coincidences shown in Figures 1–3. The solid circles in Figure 4 portray the average SAGE II/Umkehr percentage ozone differences of 918 cases at the seven SAGE I stations. While all 14 stations in Figures 1–3 contain SAGE II coincidences, only seven of those stations contain SAGE I coincidences. The SAGE II/Umkehr 14-station averages (not plotted) are within 3% of the SAGE II/Umkehr seven-station averages in layers 4, 7, and 9, and within 2% in layers 5, 6, and 8. Likewise, a subset of SAGE II/Umkehr coincidences within 500 km (as opposed to those within 1000 km) also did not produce significantly different results. Comparing SAGE II to SAGE I from the seven common stations shows that in layer 8, SAGE II is 10% higher than Umkehr, on average, while SAGE I is 2% higher than Umkehr. The disparity diminishes with decreasing altitude from 7% in layer 7, to 4% in layer 6, 1% in layer 5, and −5% in layer 4. Alternatively, we can state that using Umkehr profiles as a basis of comparison, SAGE II values exceed SAGE I (version 6.1) values by amounts which increase with altitude from 1% in layer 5–10% in layer 8 and 16% in layer 9. Some of the differences in layers 7–9 may be due to aerosol effects on the Umkehr profiles. This aerosol effect during this SAGE II period with average stratospheric aerosol optical depths of 0.01 is estimated by *Reinsel et al.* [1989], *DeLuisi et al.* [1989a], and *Newchurch and Cunnold* [1994] to be approximately 0–1% in layer 7, 2–3% in layer 8, and 2–4% in layer 9. The aerosol effect during SAGE I would be smaller, probably by less than half the SAGE II correction. Applying these aerosol corrections to the Umkehr ozone measurements would diminish the SAGE I/SAGE II discrepancy by roughly 1–2% in the upper Umkehr layers.

The ozone trend estimate in layer 8 (40 km) from Umkehr observations is −1.1% per year over the 8-year period from 1979 to 1987 [*WMO*, 1988]. The SAGE II/SAGE I trend estimate in layer 8 over the 7-year period from SAGE I to SAGE II (1980–1986) is −0.4% per year [*McCormick et al.*, 1989]. Adjusting for the SAGE I/Umkehr versus SAGE II/Umkehr bias in layer 8 would reconcile the trend differences between the two measurement systems. A small systematic error in reference altitude for SAGE I or SAGE II observations would change ozone mixing ratios in proportion to the gradient of the ozone concentration profile. This potential error would produce the largest percentage ozone changes in layers 8 and 9, and significant changes of opposite sign would occur below the ozone peak concentration (e.g., layer 3). The procedures for obtaining reference altitude are different for SAGE I and SAGE II, with somewhat more confidence being given to the SAGE II values. A 0.25-km to 0.5-km systematic upward reference altitude shift for SAGE I, similar to the quoted uncertainty in reference altitude, would increase ozone by approximately 5–10% in layers 8 and 9 and would result in similar differences for those observed between SAGE I and Umkehr, and SAGE II and Umkehr in layers 4–8. Figure 5 shows the result of shifting the SAGE I reference altitude 0.25 km and 0.5 km for the Arosa coincidences. As seen from Figures 2 and 4, Arosa is representative of the mean ozone differences. This possibility would need to be confirmed, however, by comparisons against other data sets and by further evidence of ozone errors of opposite sign below the ozone maximum.

Correlations Between SAGE II and Umkehr Parameters

While calculating the regression of SAGE II/Umkehr ozone differences on aerosol loading, *Newchurch and Cunnold* [1994] calculated an extensive set of correlation coefficients in an attempt to characterize the regression's significance. The set of variables in this case study included the following Umkehr identification parameters: date, time, wavelength pair, number of iterations to converge to an acceptable profile, minimum and maximum zenith angle during the observation, station, layer ozone amounts (given as partial pressures), and total ozone (both measured by the

Table 2. Significant Correlations of Umkehr Layer Ozone Partial Pressure With Several Variables

Variable	UMK3	UMK4	UMK5	UMK6	UMK7	UMK8	UMK9	O3TOT
UMK3	1							
UMK4	0.89	1						
UMK5			1					
UMK6	−0.41		0.81	1				
UMK7			0.57	0.90	1			
UMK8					0.41	1		
UMK9						0.81	1	
SO33	0.64	0.52						
SO34	0.69	0.65						
SO35			0.51	0.54	0.44			
SO36			0.56	0.72	0.65			
SO37			0.48	0.67	0.66			
SO38						0.44	0.47	
SO39				−0.40			0.51	
TROPALT	−0.61	−0.46	0.42	0.50				−0.50
LAT				−0.44				
O3TOTAL	0.89	0.89						1

UMK$_x$, Umkehr layer ozone partial pressure; SO3$_x$, SAGE II layer ozone partial pressure; TROPALT, tropopause altitude; LAT, latitude; O3TOTAL, Umkehr total ozone. These correlations derive from 1184 cases.

standard Dobson procedure and inferred directly in the Umkehr inversion). Case variables also included the following SAGE parameters: distance between SAGE II and Umkehr coincidences; time difference between SAGE II and Umkehr coincidences; stratospheric aerosol optical depth at 0.525 μm; SAGE II latitude, longitude, and time; SAGE II event type (sunrise or sunset), tropopause temperature, density, and altitude; SAGE II ozone partial pressures and aerosol optical depths in layers 4–9; and season (e.g., December, January, and February are winter). Tables 2–6 derive from this set of 58 variables. Because in some cases data on one or more of the 58 variables were missing, the cross-correlation values in these tables include only 1184 of the 1789 coincidences in Figures 1–3. In order to highlight the most important parameters, the tables list only correlations greater than or equal to 0.40. The tables were generated as follows: they (1) retained all of the 58 variables that yielded correlation coefficients greater than or equal to 0.40 with the SAGE II/Umkehr ozone difference in any layer and, (2) included the cross correlations greater than 0.40 of those selected variables.

This analysis combined a number of latitudes and seasons, but focused primarily on the northern hemisphere during winter. While interpreting these correlations, note that correlation coefficients do not indicate the temporal scale of the events responsible for the correlation (e.g., synoptic events during winter or the annual cycle). Therefore, our results might be somewhat different from previously reported results for a single site and/or for a single season.

Figure 7 shows the correlations between SAGE II and Umkehr ozone for each layer. In layers 5, 8, and 9, correlations smaller than in the other layers appear to be characteristic of comparisons between Umkehr and other ozone measurements (see, e.g., *DeLuisi et al.* [1985] and, for layer 5, *DeLuisi and Mateer* [1971]). While reasons for the smaller correlations in these layers have been hypothesized in the past, we shall attempt here to provide supporting evidence for these hypotheses.

The correlations between Umkehr and SAGE ozone observations and between the ozone variances and layer-to-layer correlations observed by these instruments should depend upon the signal-to-noise ratios of the measurements. For example, layers in which atmospheric ozone variability is larger should, in principle, result in larger correlations. Because the observational comparison period discussed in this paper covers several years, the applicable time scales of

Table 3. Significant Correlations of SAGE II Layer Ozone Partial Pressure With Several Variables

Variable	SO33	SO34	SO35	SO36	SO37	SO38	SO39
SO33	1						
SO34	0.79	1					
SO35			1				
SO36	−0.50	−0.48	0.66	1			
SO37	−0.41	−0.41	0.51	0.86	1		
SO38						1	
SO39				−0.44	−0.44	0.62	1
TROPALT	−0.82	−0.76		0.65	0.58		−0.40
O3TOTAL	0.60	0.64					
LAT			−0.43	−0.49	−0.43		

SO3$_x$, SAGE II layer ozone partial pressure; TROPALT, tropopause altitude; O3TOTAL, total ozone amount; LAT, latitude. These correlations derive from 1184 cases.

Table 4. Significant Correlations of the SAGE II–Umkehr Percentage Ozone Difference in Layer x With Several Variables

Variable	S-U3	S-U4	S-U5	S-U6	S-U7	S-U8	S-U9
S-U3	1						
S-U4	0.64	1					
S-U5			1				
S-U6	−0.45		0.48	1			
S-U7				0.56	1		
S-U8					0.49	1	
S-U9						0.75	1
UMK3							
UMK4		−0.41					
UMK5							
UMK6					−0.40		
UMK7					−0.53		
UMK8						−0.53	−0.58
UMK9							−0.54
SO33	0.58	0.41		−0.41			
SO34		0.40		−0.40			
SO35			0.61	0.46			
SO36		−0.48		0.76			
SO37		−0.43		0.61			
SO38						0.44	
SO39							
TROPALT	−0.42			0.46			

S-U$_x$, SAGE II–Umkehr layer ozone difference in layer x; UMK$_x$, Umkehr layer ozone partial pressures; SO3$_x$, SAGE II layer ozone partial pressures; TROPALT, tropopause altitude. These correlations derive from 1184 cases.

atmospheric variability consist of both seasonal and synoptic-scale variations. Figure 8 illustrates the time series of coincident measurements at six stations (Arosa, Boulder, Haute Provence, Mauna Loa Observatory, Perth, and Tateno) based upon the measured ozone contents in Umkehr layer 6. It is evident, in this case, that the contribution to the variability from the seasonal cycle is larger than the contribution from the (wintertime) synoptic variability. As expected, the overall variability is significantly smaller at Mauna Loa than at the midlatitude sites. Therefore, in this layer the ability of these instruments to resolve the seasonal cycle in ozone at midlatitudes dominates the correlation between SAGE II and Umkehr measurements. Table 7 compares the magnitude of the seasonal cycle in each Umkehr layer (as seen by SAGE II) at approximately 45°N against synoptic variability there. Seasonal cycle and synoptic variability are of similar magnitude except in layers 5 and 8, where the seasonal cycle is particularly small. In layer 5, both timescales of variation possess a relative minimum and the variability is of comparable magnitude to the noise level in an individual SAGE II ozone profile.

The small correlation between the SAGE II and Umkehr measurements in layer 5 is related to the reduced natural variability in this layer. Layer 5 (31.3–15.6 mbar) represents a transition from dynamical control of the zonal mean ozone distribution at midlatitudes at lower altitudes to chemical control at higher altitudes [e.g., *Cunnold et al.*, 1980]. As a result, the seasonal cycle undergoes a change in phase [*Dütsch*, 1971, 1979] from a summertime maximum in layer 6, which is chemically produced as discussed, for example, by *Frederick et al.* [1984], to an early spring maximum in layer 4 resulting from the accumulation of ozone produced by downward motion over the course of the winter. For these reasons the horizontal gradient of ozone also reverses sign in this layer [e.g., *WMO*, 1988].

The more recent version [*Hsu and Cunnold*, 1992] of the three-dimensional dynamical-chemical model of *Cunnold et al.* [1975] uses T18 truncation and two-dimensional distributions of NO$_x$, Cl$_x$, and HO$_x$ to calculate the relatively small ozone variability between 31.3 and 15.6 mbar. For example,

Table 5. Significant Correlations of SAGE II Layer Aerosol Optical Depths in Layer x and Total Stratospheric Aerosol Optical Depth With Several Variables

Variable	AERO4	AERO5	AERO6	AERO7	AERO8	AERO9	AEROTOT
AERO4	1						0.51
AERO5	0.60	1					
AERO6		0.73	1				
AERO7			0.67	1			
AERO8				0.62	1		
AERO9					0.88	1	
SO33		−0.43				0.47	
SO34		−0.40					
SO35							
SO36	0.49	0.65					
SO37		0.51	0.42				
SO38							
SO39							
UMK3						0.40	
UMK4							
UMK5							
UMK6							
UMK7							
UMK8							
UMK9							
TROPALT		0.42	0.46				−0.51
S-U6		0.45	0.62	0.41			

AERO$_x$, SAGE II layer aerosol optical depth in layer x; AEROTOT, total stratospheric aerosol optical depth; SO3$_x$, SAGE II layer ozone partial pressure; UMK$_x$, Umkehr layer ozone partial pressure; TROPALT, tropopause altitude; S-U6, difference between SAGE II and Umkehr ozone partial pressures in layer 6. These correlations derive from 1184 cases.

this model shows that in winter, the residual, downward circulation is producing poleward and downward sloping ozone contours in layer 4; but in layer 6 the chemical losses of zonal mean ozone at midlatitudes are producing poleward and upward ozone contours. This model provides some information on the magnitude of synoptic-scale ozone variability at midlatitudes. The equation for the longitudinal deviations (χ^*) from the zonal mean ozone ($\bar{\chi}$) is written (to the level of approximation in this model)

$$\frac{\partial \chi^*}{\partial r} = -v^* \frac{\partial \bar{\chi}}{\partial y} - w^* \frac{\partial \bar{\bar{\chi}}}{\partial z} + \left(\frac{\partial \chi^*}{\partial t}\right)_{\text{chem}} - \text{NONL} \qquad (1)$$

where NONL is the nonlinear horizontal advection terms, and $\bar{\bar{\chi}}$ is the globally averaged mixing ratio. The value $(\partial \chi^*/\partial t)_{\text{chem}}$ is the chemical source term for χ^*, which is explicitly evaluated in the model but is sometimes approximated by $-\alpha\chi^* - \beta T^*$ [e.g., *Stolarski and Douglass*, 1985]. The latter representation is helpful in understanding the role temperature plays in creating or destroying ozone variations; α and β have been estimated for this purpose by making incremental perturbations in model T and χ fields (The values are found to be similar to those given by Stolarski and Douglass.) The nonlinear contribution to horizontal advection consists of wave-wave interactions and plays a significant role in redistributing wave energy. However, it should not contribute much to the irregularity generation and loss when summed over all the waves and over time. The small diffusion contribution to this equation is neglected in these discussions.

Table 6. Significant Correlations of the One Standard Deviation of SAGE II Ozone Partial Pressure in Layer x and the Number of Iterations Required for Umkehr Algorithm Convergence With Several Variables

Variable	SD6	SD7	SD8	SD9	Iterations
UMK4	0.52				
UMK5			0.55	0.44	−0.76
UMK6			0.66	0.62	−0.76
UMK7			0.57	0.60	−0.68
UMK8					−0.48
O3TOTAL	0.42				
SO34	0.56				
SO35			0.58	0.60	−0.41
SO36			0.83	0.83	−0.69
SO37			0.62	0.61	−0.77
SO39					−0.49
S-U4	0.42				
S-U5		0.43			
S-U6			0.68	0.50	
AERO4	0.42				
AERO5		0.40	0.41		
AERO6			0.54		
AEROTOT	0.65				
TROPALT	−0.49		0.46		
SD7	0.45	1			

One standard deviation is equivalent to one error bar. SDx, standard deviation of SAGE II ozone partial pressure in layer x; ITERATIONS, number of iterations required for Umkehr algorithm convergence; UMKx, Umkehr layer ozone partial pressure; O3TOTAL, Umkehr total ozone; SO3x, SAGE II layer partial pressure; S-Ux, difference between SAGE II and Umkehr layer ozone partial pressures; AEROx, SAGE II layer aerosol optical depth; AEROTOT, total stratospheric aerosol optical depth; TROPALT, tropopause altitude. These correlations derive from 1184 cases.

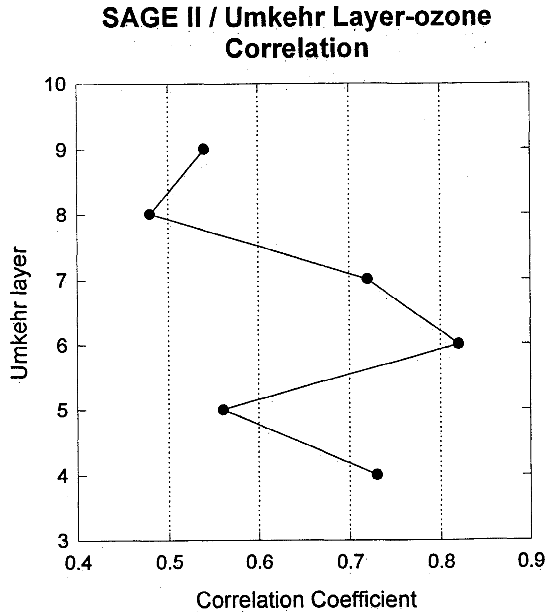

Figure 7. The correlation between SAGE II and Umkehr ozone partial pressures by layer for layers 4–9 using all 14 Umkehr station coincidences.

Taking the square roots of the monthly mean values of the (individual terms)^2 and dividing by the monthly zonal mean mixing ratio of odd oxygen produces the Figure 9 data for February at 41°N. The rms irregularity amplitude for ozone divided by its mean mixing ratio is shown in Figure 10; the correlations between ozone and temperature and between ozone values at different levels of the model are also shown. The latter correlations, shown for 2 and 4 model-level separations, correspond to slightly more than 1 and 2 Umkehr layer separations. These two figures can be compared against the Umkehr/SAGE II results and can aid in interpreting those levels at which synoptic variations dominate the variability.

As seen in Figure 10, ozone and odd oxygen synoptic variations are smallest in layers 5, 6, and 7 (shown by the standard deviations, read off the top axis, as a function of height). The large variations in layer 4 are produced by the horizontal and vertical effects of advection while the large variation in layer 9 is produced by chemical effects related to the temperature-dependent effects in the chemistry (compare the magnitudes of the chemical adjustment terms relative to the advection terms shown in Figure 9). In layers 5, 6, and 7 the effects of advection dominate, but the advection terms are fairly small at these levels. This is due, in part, to the fact that the horizontal and vertical gradients of odd oxygen change sign in this region and, more importantly, because upward propagating wave energy at higher planetary wavenumbers is being damped in the background zonal wind structure. Moreover, the amplitude of ozone irregularities is dependent not only on the rate of generation, but also on its duration. Note that the product and loss terms change the irregularities on a timescale of approximately 1 day except where the chemical terms are largest (near 1 mbar). For irregularities produced by advection the duration is $(k\bar{u})^{-1}$ where k is the wavenumber and $\bar{u}$ is the mean zonal wind; the duration, therefore, becomes shorter at higher levels in the stratosphere where $\bar{u}$ is larger. This advection

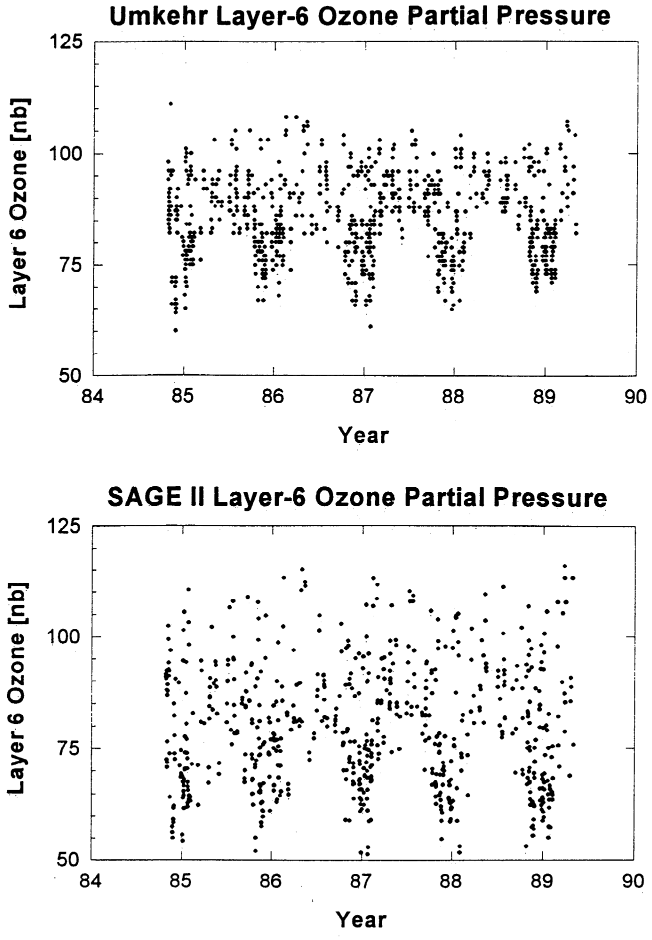

Figure 8. The annual variation of layer 6 ozone partial pressures measured by Umkehr (upper panel) and by SAGE II (lower panel). These data comprise coincidences at six Umkehr stations: Arosa, Boulder, Haute Provence, Mauna Loa Observatory, Perth, and Tateno.

contributes to the reduction of irregularity amplitudes with height in this region. In layers 8 and 9, irregularity amplitudes increase again due to the strong sensitivity of the chemistry to temperature fluctuations. Note also that the transition from a positive to a negative correlation with temperature occurs at approximately 5.5 mbar. This altitude is below the level where the chemical terms become approximately equal to the advection term (~3.5 mbar). *Douglass et al.* [1985] pointed out that advection can produce negative ozone-temperature correlations if the gradients of ozone and temperature are of opposite sign. This condition occurs in winter at stratospheric levels because of an ozone maximum at mid- to high latitudes produced by the greater sensitivity of the photodissociation of ozone compared to the photodissociation of molecular oxygen to variations in solar zenith angle [*Cunnold et al.*, 1976; *Frederick et al.*, 1984]. Because this level is close to the maximum zonal wind speed level and planetary waves that penetrate to this level tend to increase in amplitude with height, the advection term in this model again begins to increase above approximately 2 mbar.

The small correlation between SAGE II and Umkehr ozone measurements in layer 5 is, therefore, associated with the small ozone variability in that layer on both synoptic and seasonal timescales. The minimum correlation in layer 8 is also related to ozone variability in layer 8. This correlation arises from the much-reduced seasonal cycle in that layer and from the fact that synoptic-scale temperature-induced variations have not attained the amplitudes that they attain in layer 9.

Figure 11 depicts the atmospheric variance explained by the SAGE II/Umkehr correlations (the correlation times the product of the standard deviations) and the unexplained variances (equal to the variances of the measurements less the explained variance). As indicated in the previous paragraph, the explained variances in layers 5 and 8 are observed to be relatively small. The unexplained variances for SAGE II are larger than the expected precision of the measurements [*Cunnold et al.*, 1989], especially in layer 6. This discrepancy is due to a residual, real atmospheric variability in the SAGE II/Umkehr difference resulting from the greater vertical resolution of the SAGE II measurements and the fact that more than one SAGE II profile is sometimes being compared against a single Umkehr profile. Residual standard deviations for Umkehr at most levels are similar to standard deviations in Umkehr/SBUV differences reported by *DeLuisi et al.* [1985]. However, the excessively small Umkehr residual variance in layer 6 indicates that because of smoothing and deficiencies in the standard profiles, the Umkehr technique is underestimating the atmospheric variance of ozone in this layer, and our procedure for calculating the residual variance is subtracting more ozone variability than is being captured by the Umkehr technique. Figure 7 shows the ozone partial pressures in layer 6 at six different stations combined. It is apparent that in this layer, SAGE II occasionally shows some very low values in winter that are not being observed by the Umkehr technique. This is the primary reason that the total variance of ozone in this layer observed by the SAGE II technique is much larger than that observed by the Umkehr technique.

The layer-to-layer correlations between the ozone variations observed by Umkehr and SAGE II should also be interpreted on the basis of amplitude and phase variations in the seasonal cycle and synoptic-scale variations with height. First, however, note that correlations between adjacent layers are typically approximately 0.7 for SAGE II and 0.8 for Umkehr observations (see Tables 2 and 3), indicating that the broader weighting functions for the Umkehr observa-

Table 7. Contributions of the Seasonal Cycle and (Wintertime) Synoptic-Scale Effects to the Umkehr Layer Variations of Ozone Expressed as a Percentage of the Zonal, Annual-Mean Value

		Seasonal Cycle		
Umkehr Layer	Pressure Range, m atm	Amplitude, %	Time of Maximum	Synoptic Variations, %
4	62.5–31.25	15	March	14
5	31.25–15.6	4	July	7
6	15.6–7.8	10	July	12
7	7.8–3.9	9	July	10
8	3.9–1.95	5	Dec.	10
9	1.95–0.98	14	Dec.	16

These results are based on SAGE II measurements between 40° and 50°N. The synoptic variations are based on residual standard deviations of the measurements and, therefore, include measurement errors.

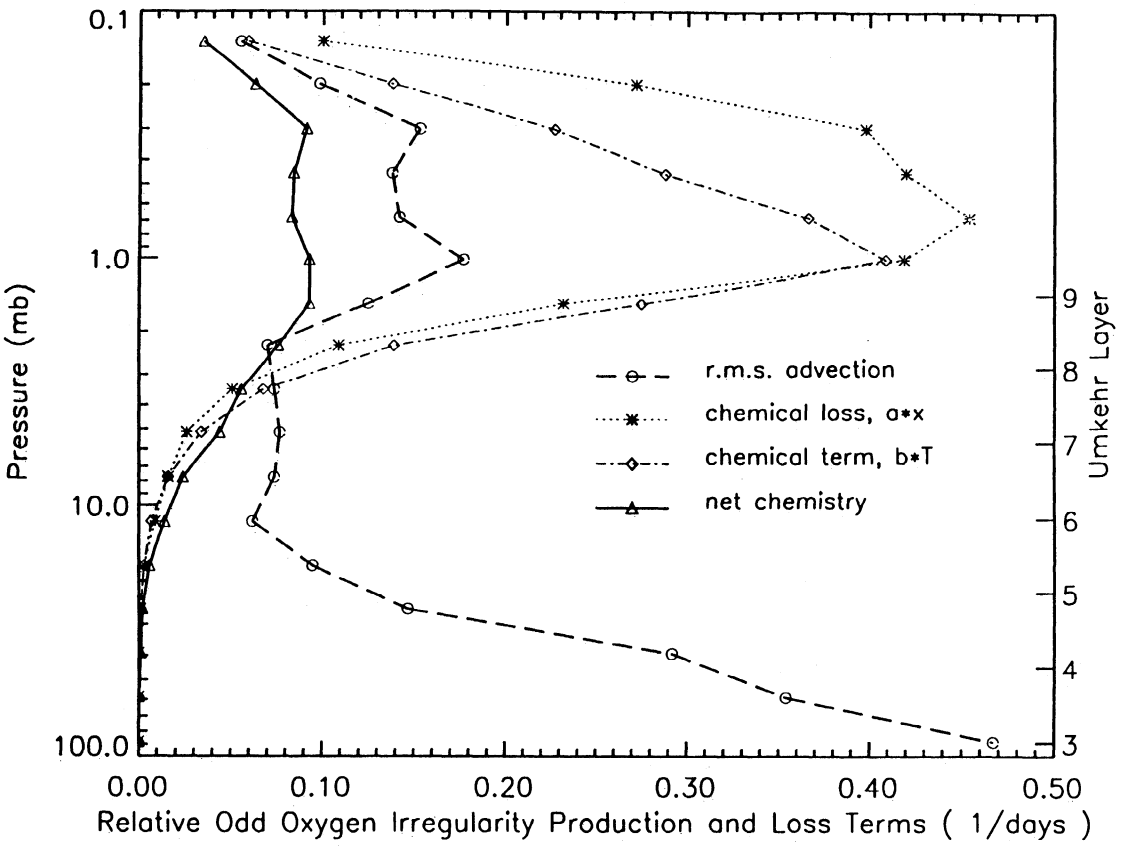

Figure 9. A summary of the terms responsible for the variations of odd oxygen in each layer during the month of February. Each term is calculated as a standard deviation of the terms in (1) divided by the zonal mean, monthly mean value of odd oxygen. The "linear" zonal mean horizontal and vertical advection terms have been combined into an rms advection term. The chemical terms are given as separate responses to the effects of temperature and ozone variations as well as a combined net chemistry term signal.

tions [*Mateer*, 1965; *WMO*, 1988] are introducing extra correlation. The largest layer-to-layer correlations are between layers 5 and 6, layers 6 and 7, and layers 8 and 9. The strong layer 6 and layer 7 correlations are produced by the large seasonal variations of similar phase in these two layers. The correlation between layers 8 and 9, while physically related to synoptic-scale variations, is more likely simply the result of the broad averaging kernel in the Umkehr measurements, which, as shown in Figure 9, is substantially correlated (the weaker seasonal variations in these two layers also have similar phase). The correlation between layers 5 and 6 is perhaps surprising but arises from the weak, but in-phase, seasonal cycle in layer 5.

There are also significant correlations between ozone variations two layers apart. Correlations between layers 5 and 7 and layers 4 and 6 also arise from the seasonal cycle. Negative correlations between layers 7 and 9 may arise from both synoptic and seasonal variations, although the seasonal effects should be the stronger of the two.

Other Significant Correlations

Discussing correlations between SAGE II ozone and aerosols, *Cunnold and Veiga* [1991] argued that such correlations can be produced by synoptic-scale variability in the advection terms. They further argued that horizontal advection is particularly important because the observed ozone/aerosol correlation reverses at approximately 27 km altitude, which is where the meridional ozone gradient reverses sign, and is several kilometers below the altitude of the maximum ozone mixing ratio. The SAGE II ozone/aerosol correlations reported in Table 5 are weaker than those given by *Cunnold and Veiga* [1991] because those listed in the table include seasonal effects and some latitudinal variation. Nevertheless, the correlations show that ozone and aerosol variations are positively correlated in layers 6 and 7 where the meridional gradient of both constituents gives decreasing concentrations with increasing latitude and altitude.

Conclusions

A case study of 1789 comparisons between SAGE II and Umkehr ozone (using 1384 Umkehr profiles and 1163 SAGE II profiles within 1000 km and 14 hours representing 14 Umkehr stations) reveals that the average layer-ozone differences are 18% in layer 4, 12% in layer 9, and less than ±10% in layers 5–8. The differences are significantly different from zero at the 2σ level in all layers. SAGE II is greater than Umkehr in the upper and lower layers and is less than Umkehr in the middle layers. The vertical profile of mean differences is similar in shape to other previously observed Umkehr differences [*DeLuisi et al.*, 1985, 1989a]. This characteristic shape in the mean differences appears to be related to deficiencies in the Umkehr retrieval algorithm

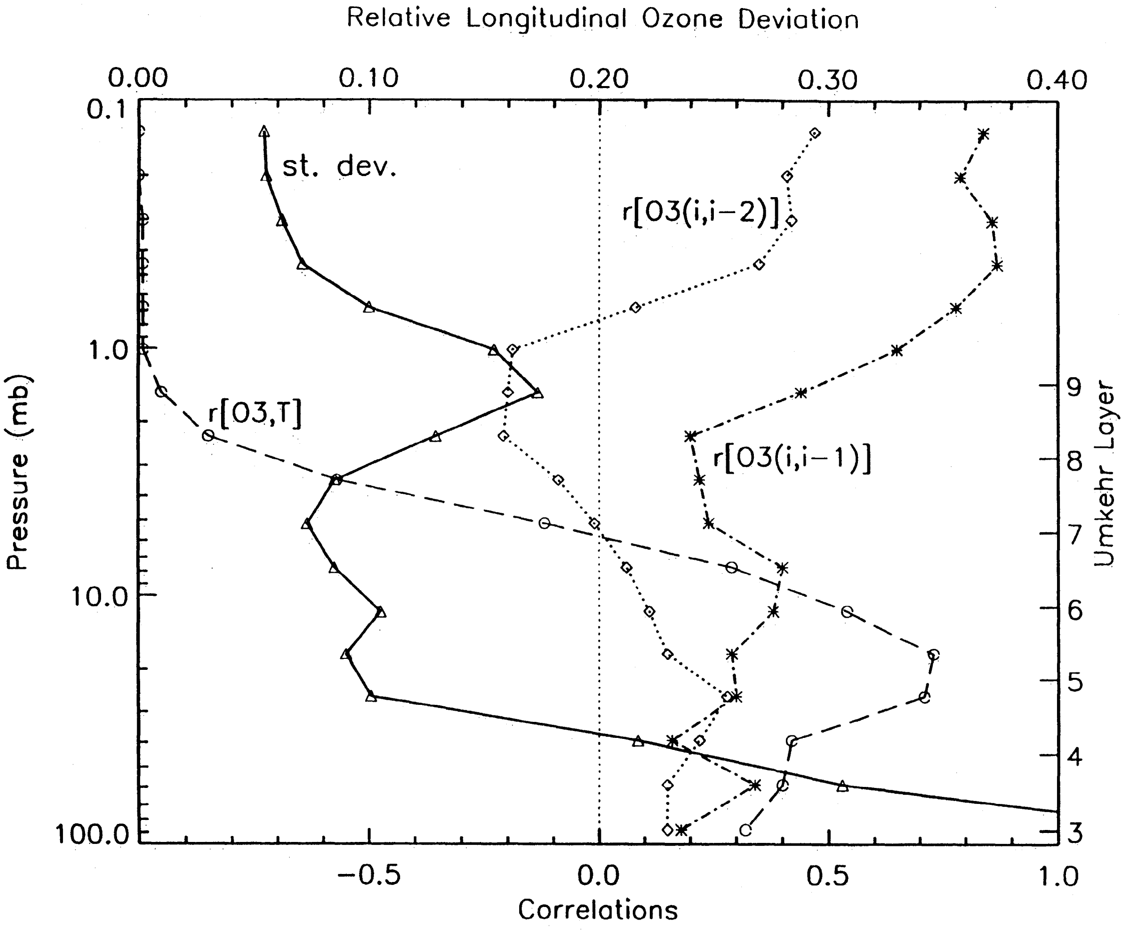

Figure 10. The calculated ozone variations at 41°N during February in the three-dimensional model [*Hsu and Cunnold*, 1992]. The variations are standard deviations expressed as percentages of the monthly mean, zonal mean value. Also shown are calculated correlations between ozone and temperature variations and correlations between ozone variations at model levels separated by $\Delta\ln(p) = 0.81$ and 1.62. The latter correspond approximately to separations of 1 and 2 Umkehr layers.

primarily arising from a priori profile errors. After also approximately accounting for the known effects of absorption coefficient errors in the Umkehr retrievals, residual differences between SAGE II and Umkehr are estimated to be less than 10%, with SAGE II larger.

The larger negative ozone trend from 1979 to 1986 (−1.1% per year), indicated by Umkehr measurements in layer 8 [*WMO*, 1988], is reflected in the fact that the average SAGE II/Umkehr layer-ozone difference is 10% greater than the average SAGE I/Umkehr layer-ozone difference in layer 8. Adjustment for this SAGE II/SAGE I bias relative to Umkehr would reconcile the previously smaller SAGE II/SAGE I trend of −0.4% per year with the Umkehr trend estimate in layer 8. The difference between SAGE II/Umkehr and SAGE I/Umkehr decreases with decreasing altitude from 16% in layer 9 and 10% in layer 8 to −5% in layer 4. This SAGE II/SAGE I bias relative to Umkehr might be explained by a systematic error of 0.25–0.5 km in the SAGE I reference altitudes.

The correlations between SAGE II and Umkehr layer ozone are smallest in layers 5, 8, and 9. This behavior is similar to correlations between Umkehr and SBUV reported by *DeLuisi et al.* [1985]. It is also associated with reduced ozone variability in Umkehr layers 5 and 8 and the strong

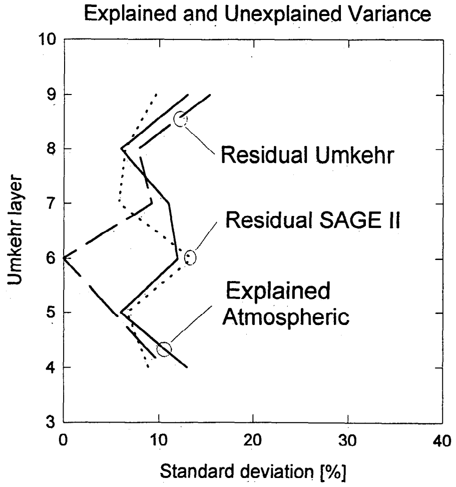

Figure 11. The atmospheric variance explained by the SAGE II/Umkehr correlations (correlation times the product of the standard deviations) and the residual variances (equal to the variances of the measurements less the explained atmospheric variance: Umkehr is dashed line, SAGE II is dotted line) all expressed as standard deviations (square root of variance).

dependence of Umkehr layer 9 ozone on layer 8 ozone. Three-dimensional chemical-dynamical model calculations indicate that these lower correlations and reduced ozone variability can be understood in terms of the increasing importance of chemistry in producing the seasonal cycle of ozone above Umkehr layer 5 and the large ozone response to synoptic-scale temperature variations in layer 9. These calculations also show that the zero correlation between ozone and temperature occurs at slightly lower altitudes than where the chemical terms become of equal magnitude to the advection terms, indicating that negative correlations between these two quantities can be caused by advective effects. This point has previously been emphasized by other authors [e.g., *Douglass et al.*, 1985]. The Umkehr technique is having greater difficulty than the SAGE technique in representing the effect of these transitions because of the poorer vertical resolution of the Umkehr technique.

Umkehr layer 6 ozone partial pressures possess less variability than SAGE II. This appears to be related to a failure to retrieve some low, wintertime ozone amounts. Layer 6 SAGE II ozone amounts are negatively correlated with layer 4 SAGE II ozone amounts but positively correlated with layer 6 aerosol amounts. These correlations appear to be physically based [*Cunnold and Veiga*, 1991] and result, primarily, from horizontal advection effects.

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