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Trends in Ozone Profile Measurements

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Chapter 5

Trends in Ozone Profile Measurements

Contents

5.1 SUMMARY AND INDEX

After a general introduction to the nature of this chapter, a brief summary of each section is given as an extended index.

5.1.1 Introduction

Atmospheric modelers predicted (in 1984, for example) that, within about a century, release of chlorofluorocarbons at the 1980 rate (along with a doubling of carbon dioxide and methane and a 20 percent increase of nitrous oxide) would change the global average ozone column between +0.2 and −5.2 percent, and that the change in local ozone at 40 km would be −35 to −55 percent (*WMO*, 1986, Chapter 13). Because local ozone in the upper stratosphere has great sensitivity to chlorine, there is an emphasis on studying this region as a possible early indicator of global ozone change. The Solar Backscatter Ultraviolet (SBUV) satellite instrument has four channels that are used to measure total ozone, and other channels that are used to measure the vertical profile of ozone in the upper stratosphere. The ground-based Dobson stations measure the total ozone vertical column; some Dobson instruments are used in the Umkehr mode to measure the vertical profile of ozone. Chapter 4 is concerned with trends that have occurred in the ozone vertical column, and Chapter 5 addresses trends in the vertical profiles of ozone in the upper stratosphere, where ozone is especially sensitive to chlorine. This region is variously given as 30 km to 50 km, 16 mb to 1 mb, or Umkehr layers 6 through 9.

The SBUV instrument was launched on the Nimbus–7 satellite in October 1978. For the period 1979–1985, the newly (1986) interpreted data showed, among many other things, 1) that the maximum local ozone reduction occurred at an altitude of 50 km, instead of at the theoretically predicted 40 km (*WMO*, 1986, Chapter 13) and 2) that, between ±30 degrees latitude, the maximum local ozone reduction was 20 to 25 percent instead of the theoretically predicted 10 to 15 percent (*WMO*, 1986, page 761). The relatively narrow purpose of this chapter is to confirm, disprove, or modify the SBUV-reported ozone changes in the middle and upper stratosphere. Eight other satellite and ground-based systems were identified that give information about the ozone vertical profile between 1979 and 1987 and that are judged applicable to this study (Table 5.1). To the extent that the SBUV trends are not supported, the question becomes: What trends in ozone are indicated by the other observations?

Table 5.1 Ozone Measuring Systems and Periods of Available Data

Type	Description	Time Period
Satellite	SBUV	October 1978 to February 1987
Satellite	SAGE	February 1979 to November 1981
Satellite	SAGE–II	November 1984 to present
Satellite	SBUV–II	December 1984 to present
Ground-based	Umkehr stations using Dobson spectrophotometer	1950's to present
Satellite	SME	January 1982 to December 1986
Satellite	SMM	(SMM or UVSP) 1985 to present
Satellite	LIMS	October 1978 to May 1979
Rocket	ROCOZ–A	1985

5.1.2 Solar Backscatter Ultraviolet (SBUV) Instrument

According to the archived SBUV data for 1979–1986, the ozone changes are not subtle effects buried in noisy data, requiring a detailed analysis to see whether they are statistically significant. They are large effects, clearly visible to the naked eye (Figures 5.1–4). The approach of this chapter is first to compare the SBUV results against other satellite and ground-based systems in terms of conspicuous aspects of the primary data, and only later to examine derived statistical quantities.

5.1.3 Ozone Trends From Comparison of Stratospheric Aerosol and Gas Experiment (SAGE) –I and –II

5.1.3.1 Conspicuously Visible Results

A comparison of SAGE–I and SBUV ozone measurements is presented for February 1979 through November 1981, and of SAGE–II and SBUV ozone measurements for October 1984 through December 1986. The SBUV data were searched for those events nearly coincident in time and space to the SAGE–I and –II events (Figure 5.5). The working data for such coincidences were analyzed as time series in several latitude bands; e.g., see Figures 5.6–11 for Umkehr layers 6 to 9 at 40°N and 40°S. With some exceptions at layer 6, SAGE–I ozone layer amounts are consistently lower, by 4 or 5 percent, than SBUV amounts in 1979–1981, but SAGE–II ozone layer amounts are consistently higher, by 10 ± 3 percent, than SBUV amounts in 1984–1986—a change of up to 15 percent. For Umkehr layers 6 through 9, the 1980–1985 offset between SAGE and SBUV data increases monotonically with altitude by between 4 percent and 15 percent (Figure 5.16). The magnitude and sign of this conspicuous offset are a large fraction of the entire change in ozone given by SBUV data between 1979 and 1986 (Figure 5.4). The large decrease in ozone that SBUV reports in layers 7 to 9 over this same period, 8 to 17 percent, is not supported by SAGE–I and SAGE–II data comparisons. On the basis of conclusions reached in Chapters 2 and 3, this difference is ascribed to an insufficiently corrected degradation of the SBUV diffuser plate.

5.1.3.2 Small Ozone Changes Requiring Careful Statistical Analysis

SAGE–I and SAGE–II satellite data were used to estimate the change in the upper stratospheric ozone profile between 1980–1981 and 1985–1986. The fundamental SAGE measurements are concentration profiles as a function of geometric altitude from 25 km to 50 km. On the basis of spatial intersections between SAGE–I and SAGE–II over corresponding 2-year periods that are 5 years apart, comparisons are performed between SAGE–I and SAGE–II ozone concentration measurements. (Because of the differences in the sampling pattern, the number of intersections between SAGE–I and SAGE–II is much smaller than the number of coincidences between SAGE and SBUV, causing the SAGE–I and –II comparisons to be noisy. Compare Figure 5.5) The percentage differences are averaged in time within 10-degree latitude bands and plotted versus altitude in Figure 5.17. The magnitude of the differences is only on the order of 5 percent. The altitudes of maximum percentage ozone reduction are between 40 km and 45 km, and the magnitudes of these reductions vary between 2 and 8 percent. With some exceptions, the pattern is an ozone decrease in the upper stratosphere and another decrease, near 25 km, between 1980 and 1986.

These ozone profiles were averaged over the region of maximum density of SAGE–I and –II coincidences, 20–50°N and 20–50°S (Figure 5.18). The average ozone profiles show an ozone

decrease between 35 km and 45 km, with the maximum ozone reduction of 3 percent occurring at 40 km; another region of similar percentage ozone decrease occurring at about 25 km; and essentially zero ozone change at 30 km and at 50 km. The 95 percent confidence level for the average ozone reduction in the upper stratosphere indicated by SAGE over the 5-year period is ± 3 percent. The estimated relative systematic error is ± 2 percent between the SAGE–I and SAGE–II instruments. The unexpected 3 percent ozone reduction indicated at 25 km, near the ozone concentration maximum, should be given careful consideration in the future to see if it is a weak manifestation of the low-temperature ozone destruction process shown in the Antarctic spring.

5.1.4 Solar Backscatter Ultraviolet II (SBUV–2)

The national plan for ozone monitoring is to launch other SBUV instruments, about every 2 years, to obtain overlapping periods of ozone satellite data, and to use this matching procedure, along with the Dobson instruments, to correct for instrumental degradation. The first example of this plan was the SBUV–2 system, launched in December 1984, which has been returning data suitable for deriving total ozone and ozone profiles since early 1985. The most powerful method of verifying, modifying, or disproving the SBUV-reported trends would be to compare at least two aspects of SBUV and validated SBUV–2 data: 1) the ozone magnitudes reported by the twin instruments immediately after launch, and 2) any change using the first 2 years of SBUV and the corresponding 2 years of SBUV–2 5 years later (as was done with SAGE–I and –II). Members of the team responsible for SBUV–2 data told the Ozone Trends Panel in January 1988 that the reinterpreted data were so preliminary and so incompletely examined (even 3 years after launch) that they should not be used in this report.

5.1.5 Umkehr Measurements of Upper Stratospheric Ozone

Direct examination of the Umkehr data for layers 6, 7, and 8 shows that ozone decreased noticeably between 1979 and 1986, but this simple method of inspection is complicated by the large effect of aerosols from the El Chichón eruption in the middle of this period (Figures 5.24–26). In terms of the injected quantity of stratospheric sulfate aerosols, El Chichón was one of the most powerful volcanoes of the century. An objective method for correcting the effect of aerosols on Umkehr observations uses stratospheric aerosol profiles observed by light detection and ranging (lidar), a particle-size distribution based on stratospheric (but not site-coincident) measurements, ozonesonde profiles, and radiative transfer theory similar to that for the Umkehr inversion algorithm. This method was applied to five northern midlatitude Umkehr stations (between 36°N and 52°N) to estimate changes in the ozone profile from 1978 through 1987. Combining statistical errors and estimated errors caused by aerosols, Umkehr data for five stations show ozone changes: −3 ± 3 percent in layer 6; −8 percent ± 4 percent in layer 7; and −9 percent ± 5 percent in layer 8, between 1979 and 1986. At layer 8, for example, the ozone change given by SBUV is about −15 percent (Figure 5.4) and that given by SAGE–I and –II is −3 ± 3 percent (Figure 5.18). The SAGE and Umkehr error estimates are for a 95 percent confidence level but do not include possible systematic errors.

5.1.6 SBUV, SAGE–I, Limb Infrared Monitor of the Stratosphere (LIMS) Ozone Intercomparison (Spring 1979)

These data show that three totally different, newly launched satellite systems agree with each within a range of about 4 percent in measuring zonal mean ozone amounts in Umkehr layers 6 to 9.

5.1.7 Trends at Upper Boundary of the Stratosphere (SBUV, Solar and Mesosphere Explorer [SME], and Solar Maximum Mission [SMM])

At 1 mb, the upper altitude limit of SBUV measurements and the lower altitude limit of SME measurements, 5 years of SME data (1982–1986) and 3 years of SMM data (1985–1987) at 55 km show no conspicuous ozone decrease. This absence of trend at 55 km is evidence against a 20 percent decrease at 50 km, which is given by SBUV.

5.1.8 Rocket Ozonesonde (ROCOZ–A)

In March to April 1979 and 1985, two series of rocket ozone soundings were conducted at Natal, Brazil. Above 22 km, stratospheric ozone variability was 2 percent or less during the 3 weeks of each measurement campaign, with stratospheric temperature and pressure variabilities half that amount. ROCOZ–A was used as a transfer instrument to compare various satellites during one of these periods of quiet atmosphere. For Umkehr layers 6, 7, 8, and 9, five instruments (in 1979, SBUV, LIMS, and SAGE–I; in 1985, SBUV, SAGE–II, and ROCOZ–A) gave instrument-to-instrument variability of 4 or 5 percent.

In Section 5.1.2 it is stated that this chapter looks first for conspicuous trends in the data, readily seen by the eye. In this section, this approach is extended to obtain an overall judgment about the ability of satellites to measure trends in upper stratospheric ozone.

5.2 SOLAR BACKSCATTER ULTRAVIOLET INSTRUMENT (SBUV)

The SBUV instrument, launched on the Nimbus–7 satellite in October 1978, was in operation until February 1987. It measured backscattered ultraviolet solar radiation at a time close to local noon; algorithms translated these measurements into vertical profiles of ozone from the middle to the top of the stratosphere. Additional channels of the instrument simultaneously measured the total vertical ozone column. In its circumpolar orbit, SBUV obtained enough data in a day to yield the total ozone column and the vertical ozone profile between about 30 km to 50 km over the entire globe, except the region of polar night (Bhartia et al., 1985). This accumulation of ozone measurements has gone on continually from late 1978 to mid-1987 to yield a magnificent body of data.

These ozone data are the product of remote measurements, and the final product is the result of an inversion of the physical measurements using a mathematical algorithm and requiring input of other atmospheric quantities. The NASA Ozone Processing Team translated the raw physical measurements from SBUV and deposited the results in a publicly available archive. For the period 1979–1985, the newly interpreted data showed, among other things, that the maximum local ozone reduction occurred at an altitude of 50 km and that there was more than a 20 percent local ozone reduction from pole to pole at 50 km. For 1985 relative to 1979, atmospheric modelers calculate that chlorofluorocarbons and variations in the solar cycle would have reduced local ozone by a maximum of about 5 to 12 percent and the altitude of maximum reduction would be about 40 km (see Chapter 7 of this report).

In the summer of 1986, a member of the NASA Ozone Processing Team presented the SBUV results to the Subcommittee on Health and the Environment of the House Committee on Energy and Commerce. Members of Congress expressed their concern that if ozone is really decreasing two or three times faster than the atmospheric modelers predict, and in a different region of the

stratosphere, it is very important to understand why it is happening. In direct response to the Congressional request, the Ozone Trends Panel was established. The following samples of SBUV data illustrate the features that stimulated the formation of the Ozone Trends Panel.

The global series (70°S to 70°N) of monthly average ozone data for November 1978 through September 1984 is shown for Umkehr layers 6 to 9 in Figure 5.1. The plots in the left column show the original data in Dobson units, and those in the right column show data that have been deseasonalized by removing the annual and semiannual seasonal components (Reinsel et al., 1988). The plots show a definite downward trend in the SBUV ozone data, and annual variations that are larger than the decreasing trend. The graphs of ozone in Umkehr layer 6 show a sharp dip beginning in mid-1982, ascribed to the volcanic eruption of El Chichón in April 1982.

The ozone data at the 1-mb level from the SBUV files are plotted for 40°N and 10°N latitudes and as a function of time from fall 1978 to spring 1987 in Figure 5.2 (Aikin, private communication, 1987). Like Figure 5.1, this figure shows conspicuous ozone decreases between 1979 and 1987, and seasonal oscillations of ozone even larger than the decreasing trend. Figure 5.2 illustrates an important sampling requirement for any attempt to check the SBUV data against limited data sets. If one used n + ½ years of data, for example, one would produce strongly different linear trends depending on whether the first point was at the minimum or maximum of the seasonal cycle. One should use an exactly integral number of years of data or a proper statistical method to remove seasonal oscillations.

Another presentation of SBUV data is given in Figure 5.3, which for 50°S shows vertical profiles of ozone mixing ratios from 25 km to 57 km and for the intervals 1979–1982, 1979–1984, and 1979–1986 (Chandra, 1987). For 1979–1986, the maximum ozone reduction, 25 percent, occurs at 50 km. Figure 5.4 shows a more extensive set of similar data given as contour plots of local ozone reduction as a function of altitude and latitude. This figure shows local ozone reductions at 50 km to be 20 percent or more at all latitudes (Chandra, 1987).
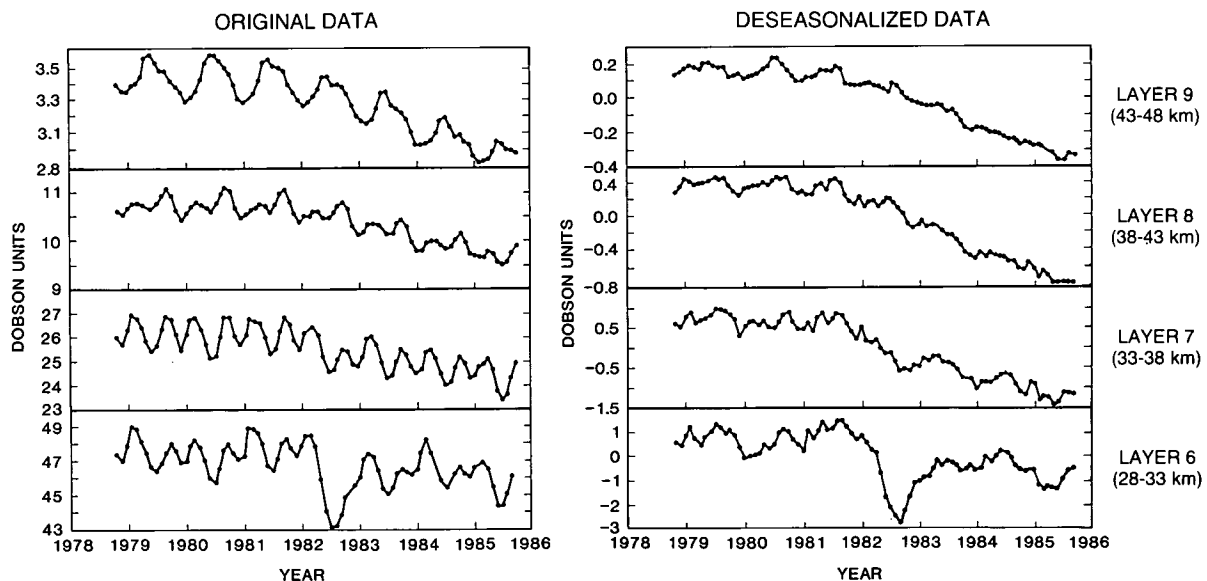
Figure 5.1 Global averages of SBUV ozone data for November 1978 to September 1984 using data between 70°S and 70°N with equal surface weighting, including Umkehr layers 6 to 9.

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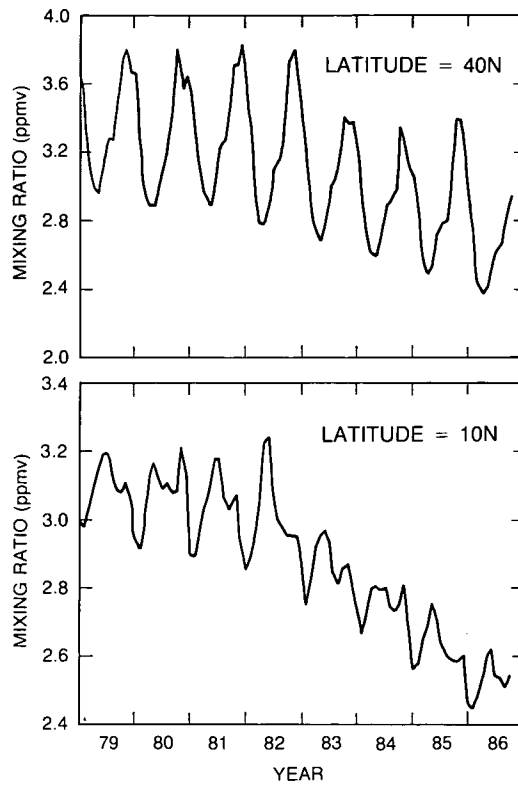
Figure 5.2 The SBUV weekly mean mixing ratios at 1.0 mb (about 50 km) for latitudes 10°N and 40°N.
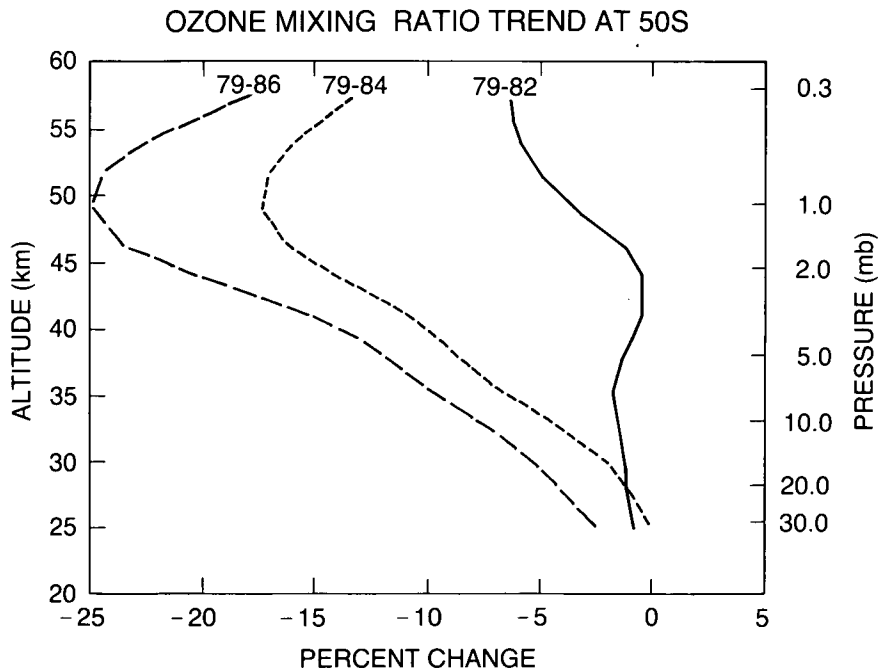
Figure 5.3 The trend in SBUV ozone mixing ratio as a function of height for three periods, January 1979 to March 1982 (pre-El Chichón period), January 1979 to December 1984, and January 1979 to October 1986. For each period, the percentage change is computed using a least square fit of a time series containing the annual, semiannual, and linear trend terms (Chandra, 1987).

TREND IN OZONE MIXING RATIO (% CHANGE FROM 79 - 86)
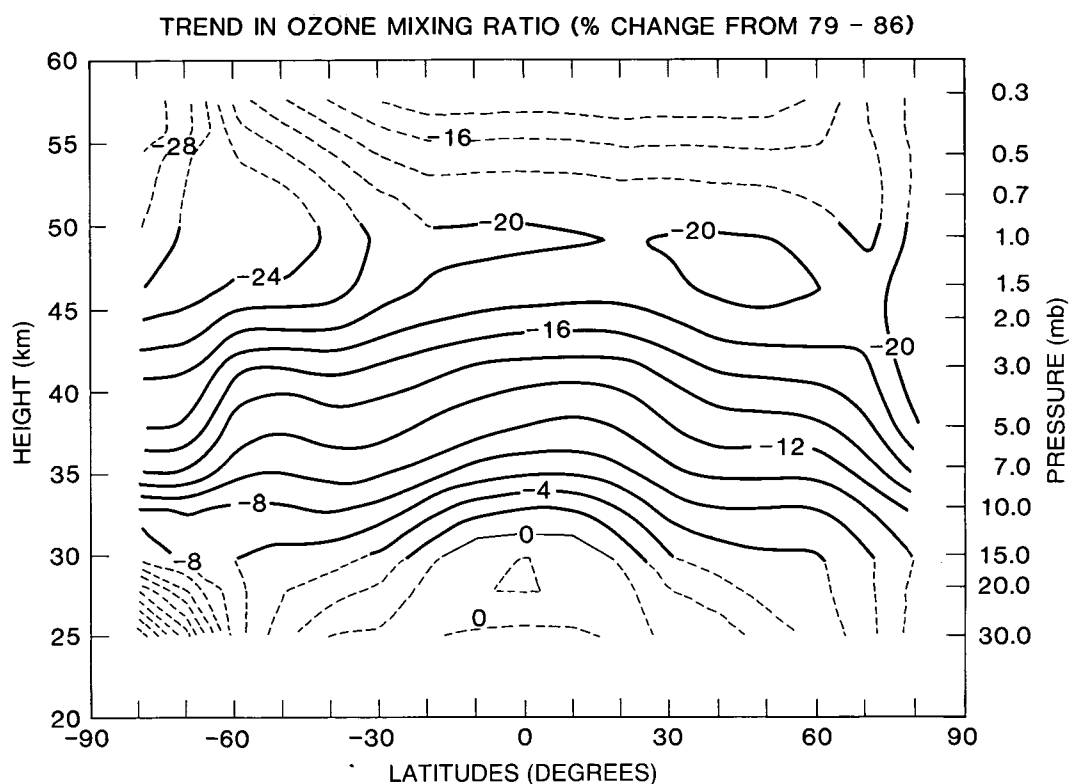
Figure 5.4 The percentage change in ozone mixing ratio as a function of altitude and latitude from 1979–1986. The percentage change is computed for each pressure and latitude, as in Figure 5.3.

Eight other systems (listed in Table 5.1) give information about the ozone vertical profile between 1979 and 1987 and are judged to be applicable to this study. In checking the SBUV trends, it must be appreciated that the SBUV data represent the only complete global set collected on a daily basis over an 8-year period. Other ozone data sets have one or more restrictions: limited time coverage, limited spatial coverage, or limited altitude range. In most comparisons reported here, the data of these restricted systems are matched in space and time with a portion of the data of the complete SBUV set. For any single comparison, differences between SBUV and the other system could be due to systematic errors in SBUV, to systematic errors in the other system, to the mutual errors of the two systems, or to sampling errors.

As discussed in Chapter 2, the different instruments measure different properties of ozone; it is sometimes not a straightforward matter to compare one system with another. For example, the primary data product from SBUV is the column of ozone over the Umkehr ozone layers, defined in terms of atmospheric pressure, and the primary data product from SAGE is the ozone concentration as a function of altitude. For these two systems to be compared, it is necessary to translate the SAGE concentrations into SBUV pressure layers using local atmospheric temperatures and pressures from roughly coincident auxiliary meteorological observations. Between the beginning of this study in December 1986 and its conclusion in April 1988, most of the satellite data sets were reevaluated from the beginning to maximize their value in testing for ozone trends.

Since the archived SBUV data challenge the results of current theoretical models, theoretical models are not used as a screen for what to believe or not as far as the data are concerned. The

first examination of the data is strictly empirical; evaluations are based on considerations such as calibration, algorithms, statistics, and searching examinations for systematic errors. The stratosphere is extremely complex, and not all data studied here point in the same direction. The approach used is one of considering all the data, considering the results from this report's chapters on calibrations and algorithms, and formulating general conclusions, including estimates of errors. These general conclusions, derived from the observational data, are then compared with theoretical predictions of the atmospheric models.

5.3 OZONE TRENDS FROM COMPARISON OF SAGE–I and SAGE–II

5.3.1 Introduction

The two satellite experiments, SAGE–I and SAGE–II, infer atmospheric constituents by measuring the solar-spectral transmission profiles attenuated by the Earth's limb during a local satellite sunrise or sunset (solar occultation technique). This method is suited to measuring long-term changes in atmospheric species because it is self-calibrating—that is, the measured solar irradiances are normalized with respect to the observed unattenuated solar irradiance for each profile. The presence of ozone is inferred from the transmission measurements in the 600 nm region at the center of the Chappius band, using an iterative onion peel inversion scheme (discussed in detail in Chapter 3). The constructed ozone profiles extend from cloud tops upward to a height where the signal-to-noise ratio limits the usefulness of the information; for SAGE–I, the upper limit is about 55 km, and for SAGE–II it is approximately 65 km. The vertical resolution of the retrieved ozone profile is 1 km, but because of increased random noise at higher altitudes, each profile of ozone concentration is smoothed over a 5 km layer at heights greater than about 45 km.

SAGE–I and SAGE–II use essentially the same instrument design; both instruments have almost identical optical pathway assemblies. Minor differences between the two sensors lie in the addition of three more channels to the SAGE–II instrument to the four on SAGE–I, the use of a rectangular field of view on SAGE–II versus a circular one on SAGE–I, and the use of narrower band passes on SAGE–II.

The principal sources of error in the measurement of an individual ozone profile are radiometric imprecision, digitizer truncation, and scan-mirror pointing errors. These random errors are approximately uncorrelated vertically; their combined effect on an individual retrieved ozone profile is estimated at each point on the profile from the variance of the measurements from approximately four to five scans of the SAGE mirror across the viewing altitude. This uncertainty is provided to the data user in the form of error bars for each ozone profile. Each SAGE profile, however, also possesses an uncertainty in reference altitude of approximately 0.25 km, which contributes to uncertainties in profile repeatability.

Table 5.2 lists the expected systematic errors of SAGE–I and SAGE–II ozone measurements. The principal uncertainties arise from instrument scan-mirror calibration and our knowledge of the absorption cross-section of ozone at 0.6 fm convolved with instrument bandpass and solar spectrum. Aerosols can also produce biases in the ozone retrievals, but only at altitudes where aerosol concentrations are large (i.e., mostly below 25 km). Table 5.3 lists the random-error estimates of the SAGE–I and –II instruments. As can be seen, the random error components for both SAGE instruments are about 10 percent, for a vertical resolution of 1 km. As indicated in Table 5.2, the imprecision is much less for SAGE estimates of the ozone content of Umkehr

Table 5.2 SAGE Systematic Errors

	SAGE-I	SAGE-II
Ozone absorption cross-section	6 %	6 %
Scan mirror calibration	2.0%	1.0%
Rayleigh cross-section	0.5%	0.5%
Aerosol optical properties		
Altitudes <25 km	4.0%	4.0%
Altitudes >25 km	<1.0%	<1.0%

Table 5.3 SAGE Errors Affecting the Precision and Repeatability of Ozone Measurements for a Vertical Resolution of 1 km

Random errors		Ozone errors due to 0.25 km uncertainty in reference height (%)
Altitude (km)	SAGE-I and -II (%)	
45	12	6
35	9	6
25	8	3

layers. Thus, the absolute uncertainty in the SAGE measurements is approximately 6 percent between 25 km and 50 km altitude, provided a sufficient number of measurements is made. The relative systematic error between the SAGE instruments is expected to be 2 percent or less (Cunnold et al., 1984 and 1989; McCormick et al., 1984a). For the sake of this report, all SAGE-I and SAGE-II ozone data were recalculated on a common basis using the most recent physical and spectroscopic data. This major reworking of raw data and indepth interpretation of the results were completed by the SAGE team in 6 months.

5.3.2 Calculation of SAGE-I and -II Umkehr Layer Amounts

The primary ozone data product of SAGE-II is concentration as a function of geometric altitude with a vertical resolution of 1 km. In order to generate a data product from SAGE-I and -II, comparable to that of SBUV, SAGE-I and -II profiles must be vertically integrated over pressure levels corresponding to the Umkehr layers used with the SBUV data. Thus, there must be a conversion from SAGE-I and -II altitudes to pressure levels. Meteorological information used to make this conversion was obtained from the National Meteorological Center (NMC) global data set.

Given an Umkehr layer bounded by pressure levels p_b and p_t, the objective is to obtain an estimate of the layer amount as given by the integral

$$N = \int_{h_b}^{h_t} n(h)\ dh$$

where $n(h)$ is the SAGE-I and -II ozone number density and h is altitude, with h_b and h_t the altitudes corresponding to the pressure levels p_b and p_t, respectively. The trapezoidal rule was

used to obtain the approximation to N. The only assumption was that the logarithm of pressure varies linearly with altitude over the range of 1 km or less. Linear interpolation was used to obtain estimates of the SAGE–I and –II ozone concentration corresponding to the pressure levels pb and pt. Only layer amounts corresponding to Umkehr layers 6 to 9 were computed and compared in this study.

5.3.3 Generation of Matching Pairs Between SAGE and SBUV Data

Interannual atmospheric variability of ozone, combined with the differences between SAGE–I and –II and SBUV geographical coverage, preclude any simple comparison between the ozone layer amounts reported by both instruments. To minimize these inherent differences, the SBUV Nimbus–7 Compressed Profile Ozone (CPOZ) Version 5 data were searched for those events nearest in space and time to individual SAGE–I and –II events. The "pairing" of the satellite observations is expected to eliminate biases in the comparison due to seasonality and spatial sampling differences. SAGE–I and –II pairs were generated in the following manner: for each SAGE–I or SAGE–II event, all SBUV events within 12 hours of the SAGE event were isolated; from these SBUV events, the one that was spatially closest in longitude and latitude to the SAGE event was chosen.

The SBUV data search produced approximately 6,500 SAGE–I/SBUV pairs that, on average, were separated by 0.3 ± 0.1 day in time, 7 ± 6 degrees in longitude, and 1 ± 1 degrees in latitude. Approximately 19,000 SAGE–II/SBUV pairs were generated that, on average, had a separation of 0.3 ± 0.1 day in time, 6 ± 4 degrees in longitude, and 1 ± 1 degrees in latitude. The working set of SAGE–I and –II/SBUV pairs encompassed the periods February 22, 1979, to September 28, 1981, and October 25, 1984, to December 31, 1986; the first period corresponds to almost all of the measurement period for SAGE–I, and the second to the first 2 years of SAGE–II measurements.

SAGE–I and –II scan the atmosphere at Earth's limb near the terminator twice on each of its 15 daily orbits. The orbital inclination causes the observation latitude to range periodically from approximately 75°S to 75°N. The latitudes of the SAGE–I measurement locations are displayed in Figure 5.5. Due to the SAGE–I orbital elements, the exact date of repeat coverage changes from year to year. The latitudes of SAGE–II measurement locations also are displayed in Figure 5.5. Unlike SAGE–I, almost perfect overlap occurs in latitude from one year to the next. Any gaps in the curves are periods during which no satellite occultations occurred. Because of power problems on the satellite, only sunset data were taken by SAGE–I after July 1979.

For analysis purposes, the SAGE–I and –II and SBUV pairs were spatially grouped into 13 latitude bands of a 10-degree width each. These are marked in Figure 5.5, with bands centered at 0, ±10, ±20, ±30, ±40, ±50, and ±60 degrees. The pairs were also temporally grouped into clusters. A cluster is a collection of events sampled between the time SAGE–I and –II enter, and subsequently exit, a given latitude band. The duration defining a cluster is limited to a maximum of 1 week. A given latitude band might contain more than one cluster if SAGE sampled the latitude for a period greater than 1 week.

5.3.4 Characteristics of the SAGE–I and –II and SBUV Layer Amounts

When arranged in a time series, the sequence of cluster means displays the expected features of seasonal ozone variability. The cluster means of SAGE–I and SBUV are shown in Figures 5.6,
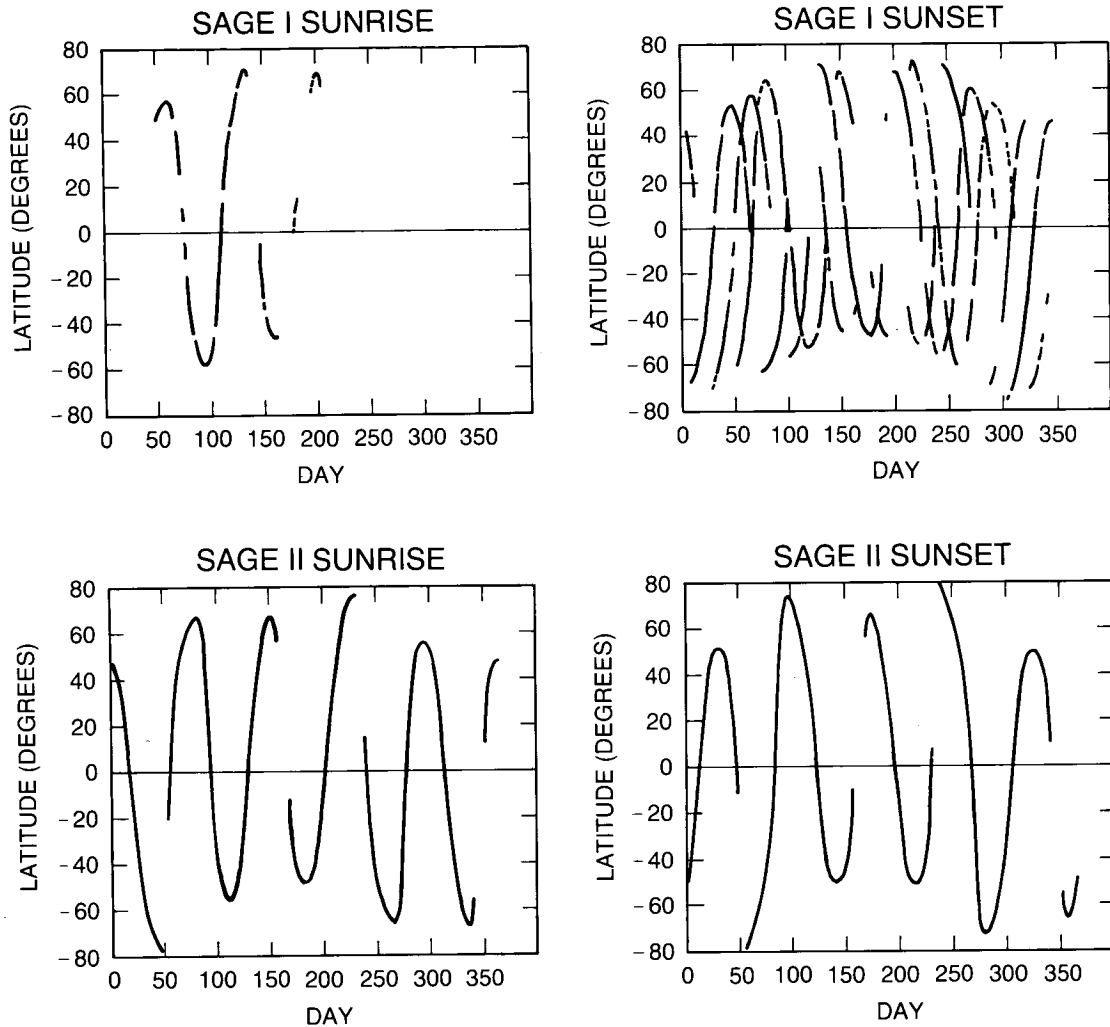
Figure 5.5 SAGE–I and SAGE–II yearly latitudinal coverage. In order to differentiate between the years in SAGE–I sunset, the peak at julian day 80 occurred in 1979; the peak at julian day 67 occurred in 1980; the peak at julian day 49 occurred in 1981. Note that because of almost perfect overlap, the SAGE–II latitudinal coverage appears as a single curve even though several years are plotted.

5.7, and 5.8 for 40°S, Equator, and 40°N, respectively. Those for SAGE–II and SBUV are shown in Figures 5.9, 5.10, and 5.11 for 40°S, Equator, and 40°N, respectively.

Both the SAGE–I/SBUV and the SAGE–II/SBUV comparisons clearly display the annual variation of ozone at midlatitudes and the semiannual oscillation at the Equator. Furthermore, both instruments appear to respond in a manner similar to shorter term variations. It is clear from Figures 5.7, 5.8, and 5.9 that SAGE–I and SBUV track each other reasonably well, with a slight tendency for the SAGE–I layer amounts to be lower than the corresponding SBUV layer amounts. The results indicate the positive finding that both SAGE–I and –II and SBUV showed similar seasonal and shorter term fluctuations in the ozone in Umkehr layers 6 to 9. This detailed agreement as a function of time is significant when one considers that the techniques are totally different, incorporating extinction in the green wavelength region at spacecraft sunrise or sunset, as compared to backscattered ultraviolet measurements taken from a different spacecraft at the nadir.

Figure 5.6 Cluster means of SAGE–I and SBUV at 40°S. The vertical bar is the 95 percent confidence interval on the cluster mean. Lines connecting means are intended only as a visual aid. SAGE-I, solid squares; SBUV, open squares.

Figure 5.7 Cluster means of SAGE–I and SBUV at the Equator. The vertical bar is the 95 percent confidence interval on the cluster mean. Lines connecting means are intended only as a visual aid.

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Figure 5.8 Cluster means of SAGE–I and SBUV at 40°N. The vertical bar is the 95 percent confidence interval on the cluster mean. Lines connecting means are intended only as a visual aid.
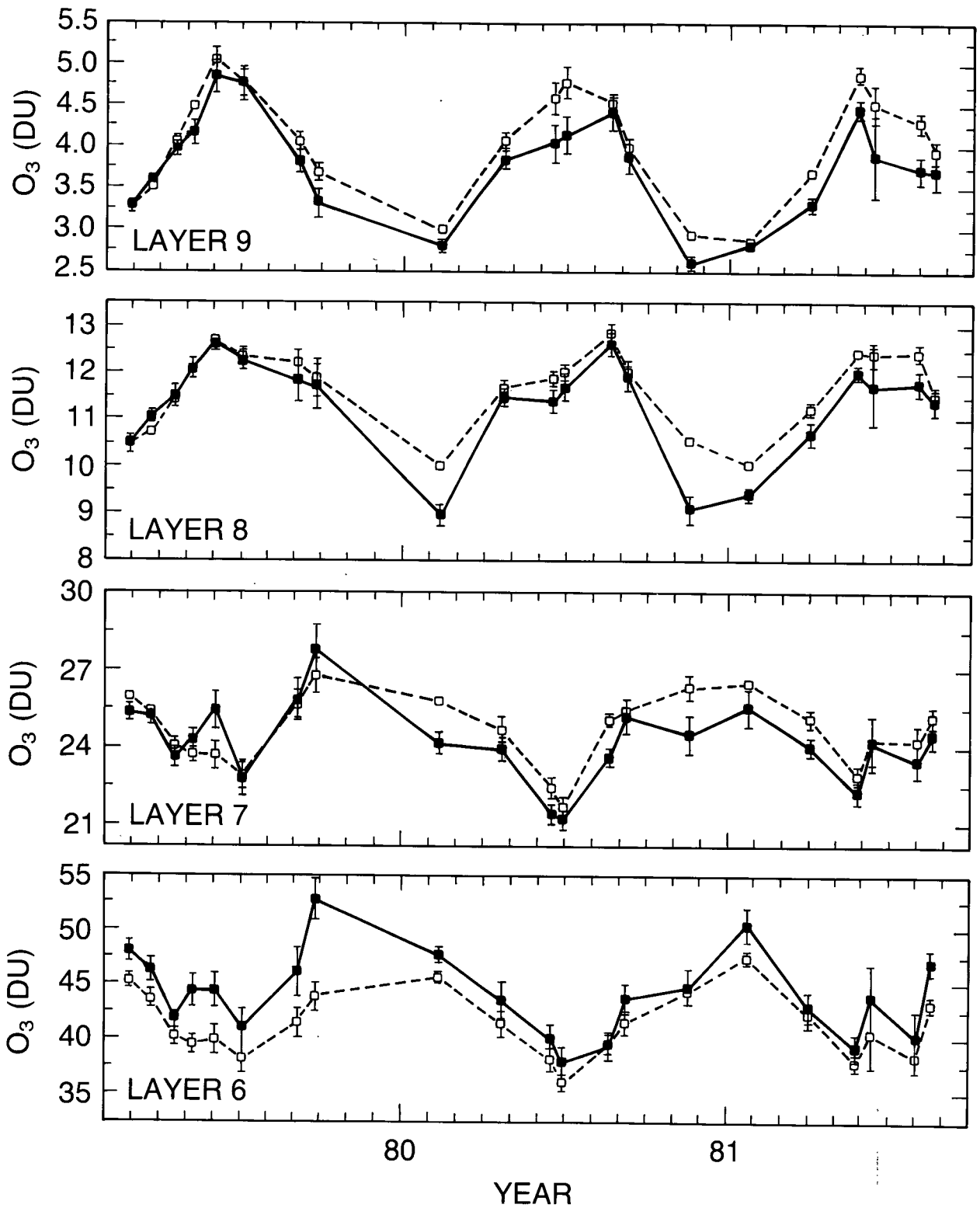
Figure 5.9 Cluster means of SAGE–II and SBUV at 40°S. The vertical bar is the 95 percent confidence interval on the cluster mean. Lines connecting means are intended only as a visual aid. SAGE-II, solid squares; SBUV, open squares.
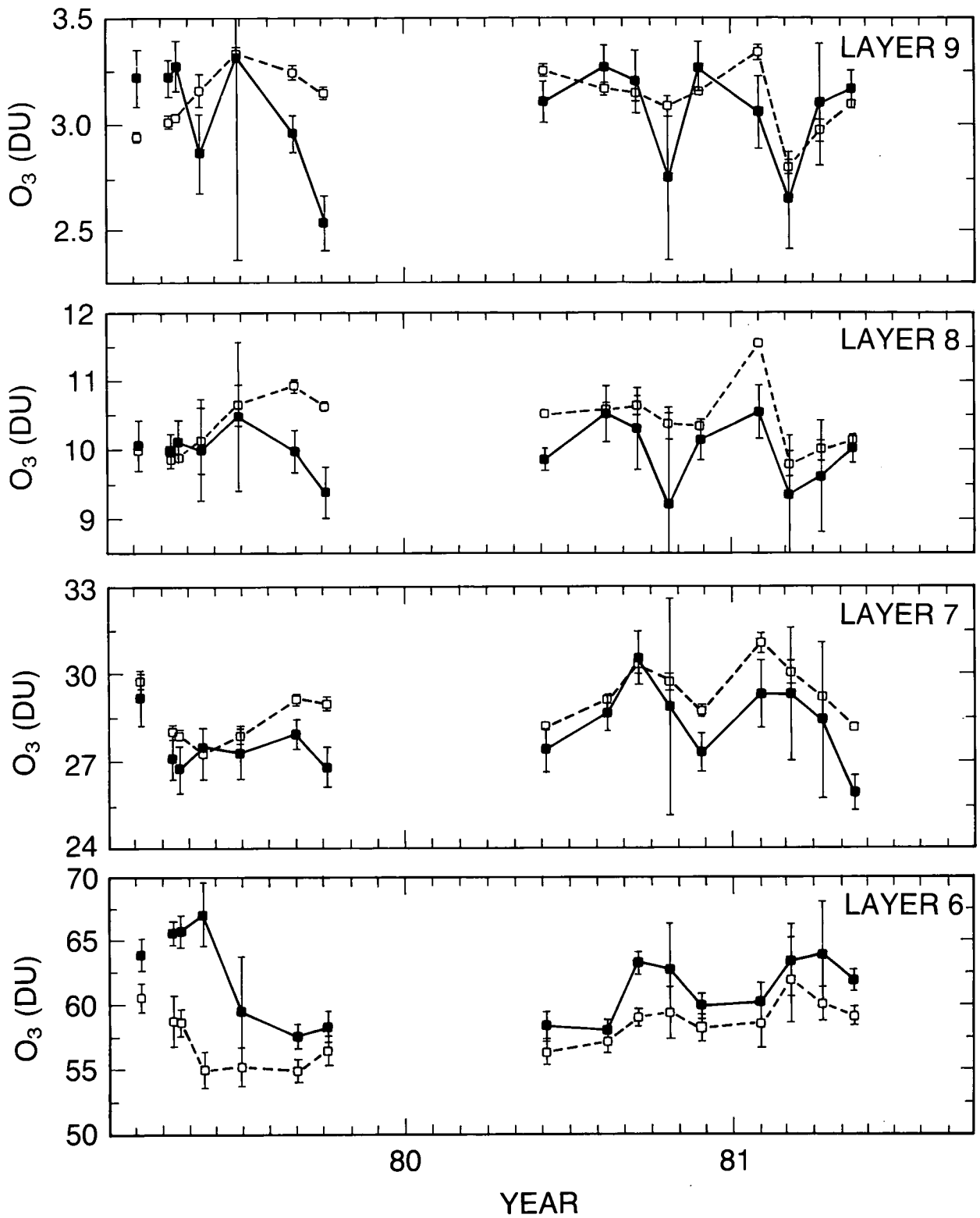
Figure 5.10 Cluster means of SAGE–II and SBUV at the Equator. The vertical bar is the 95 percent confidence interval on the cluster mean. Lines connecting means are intended only as a visual aid.
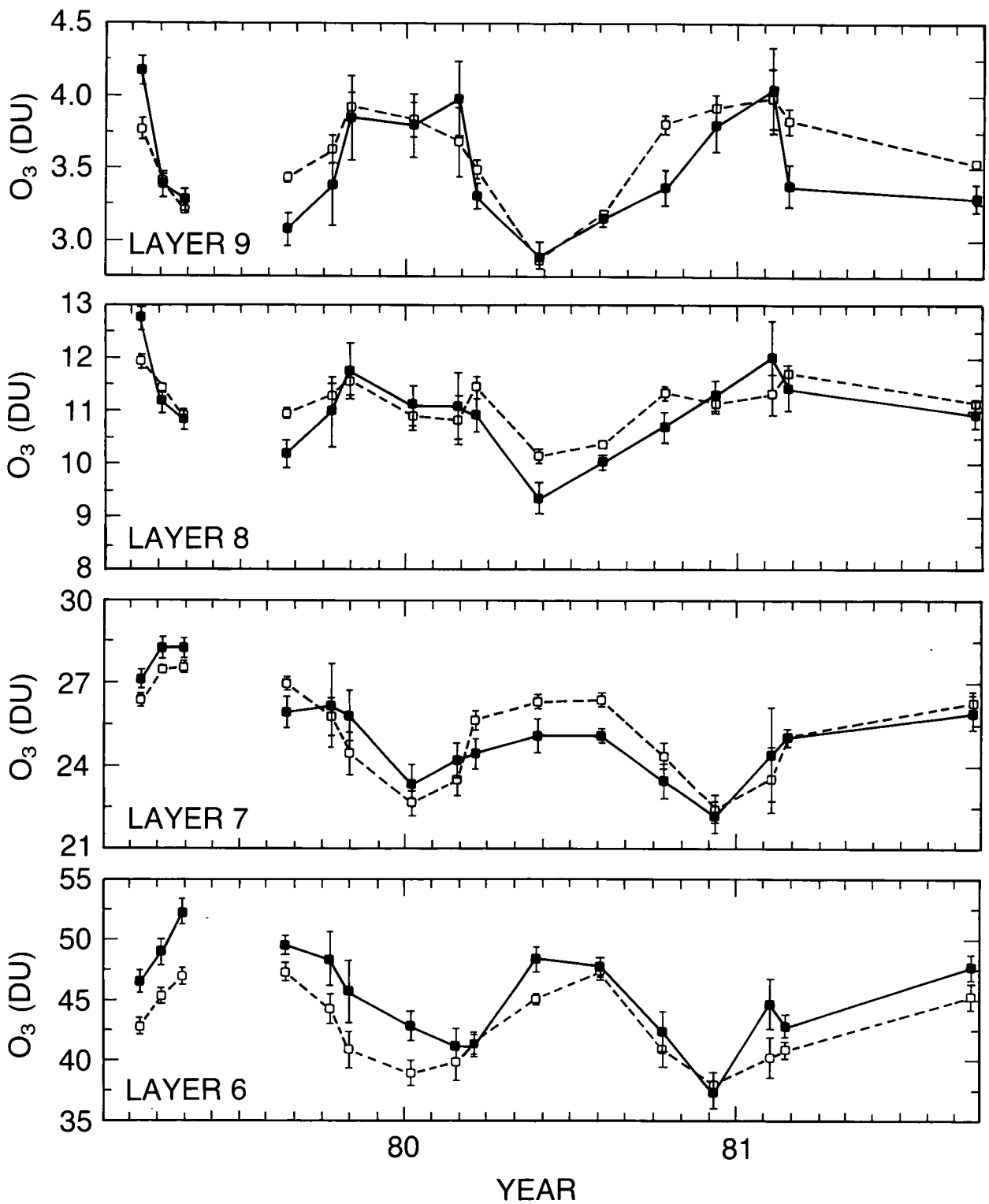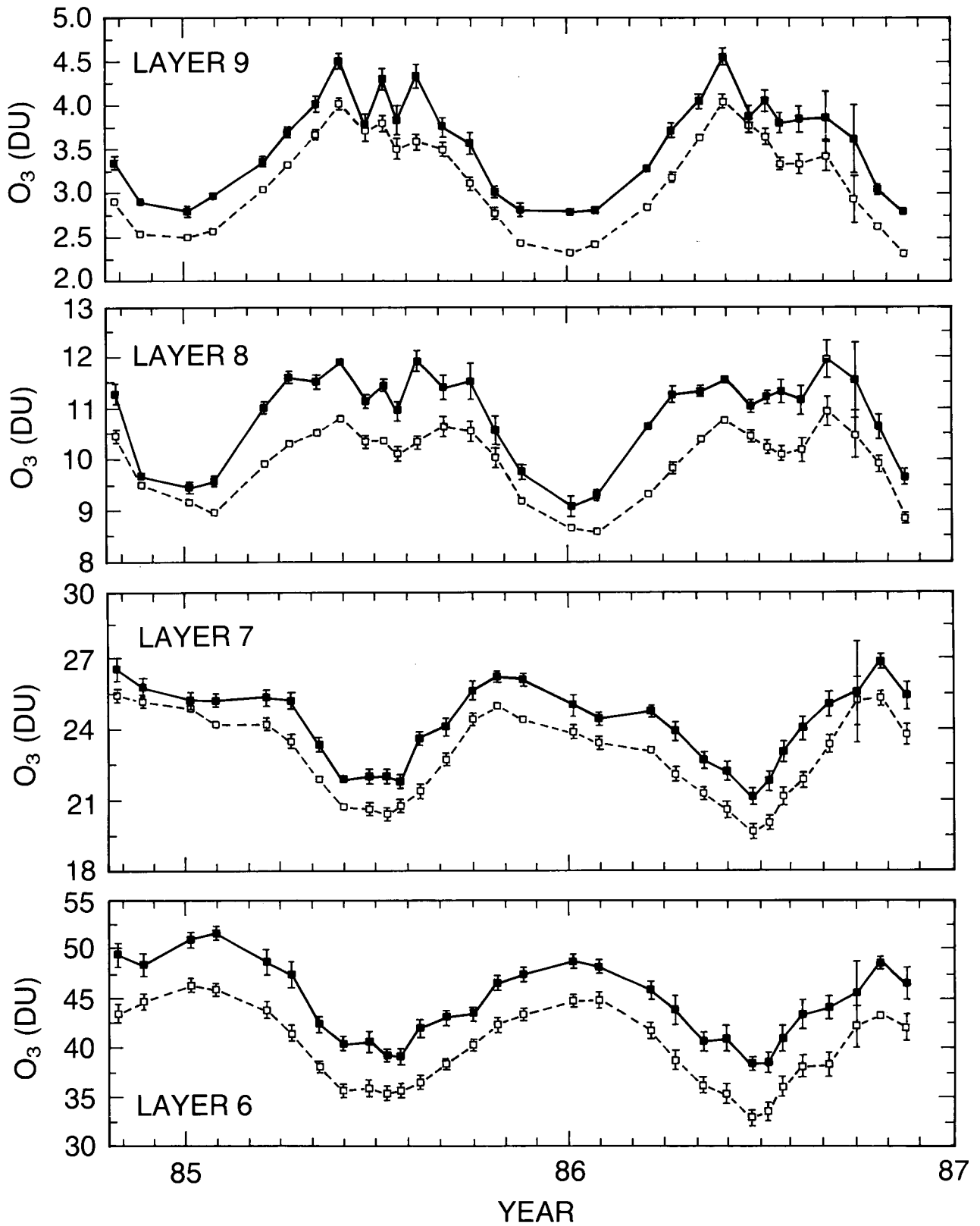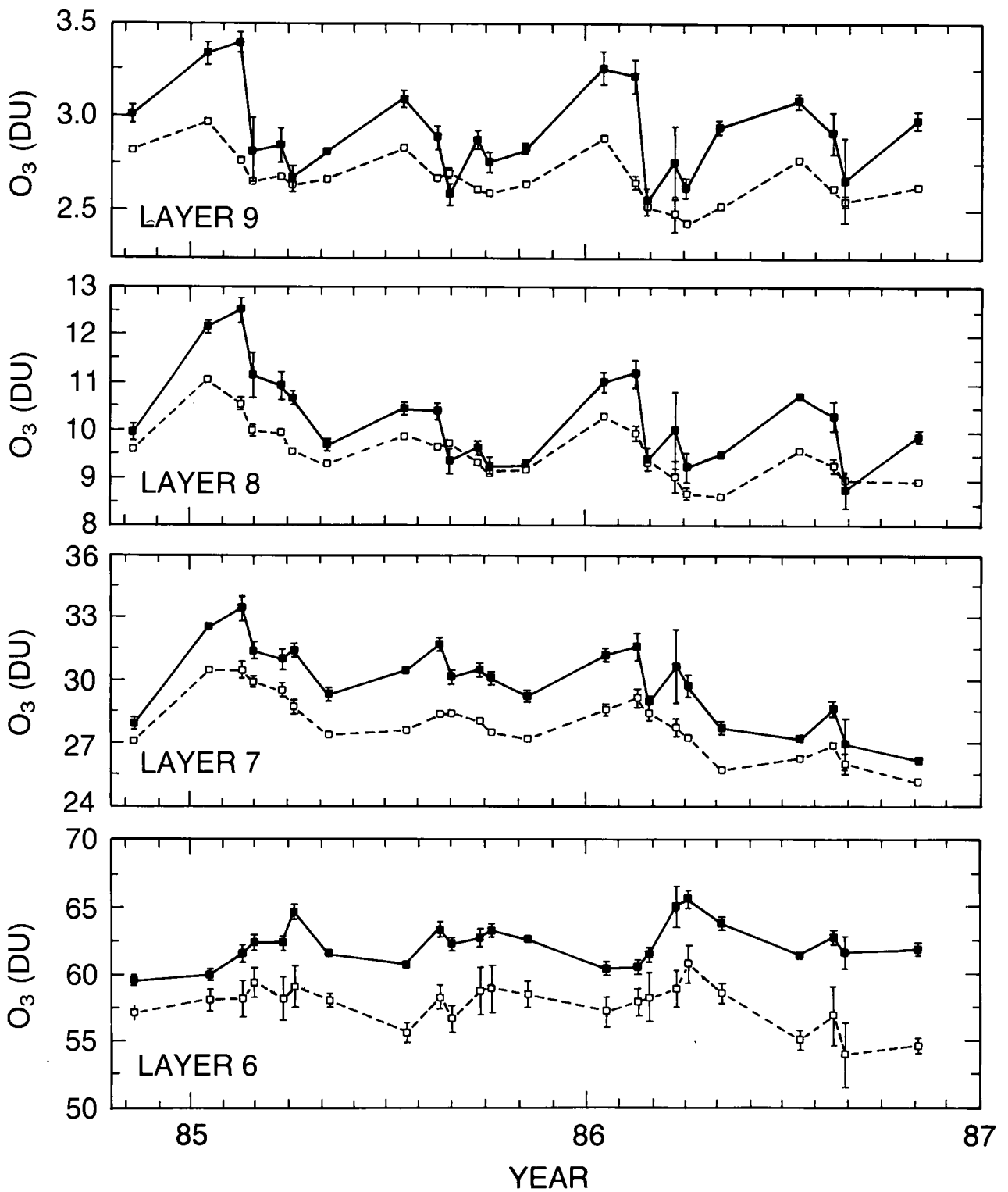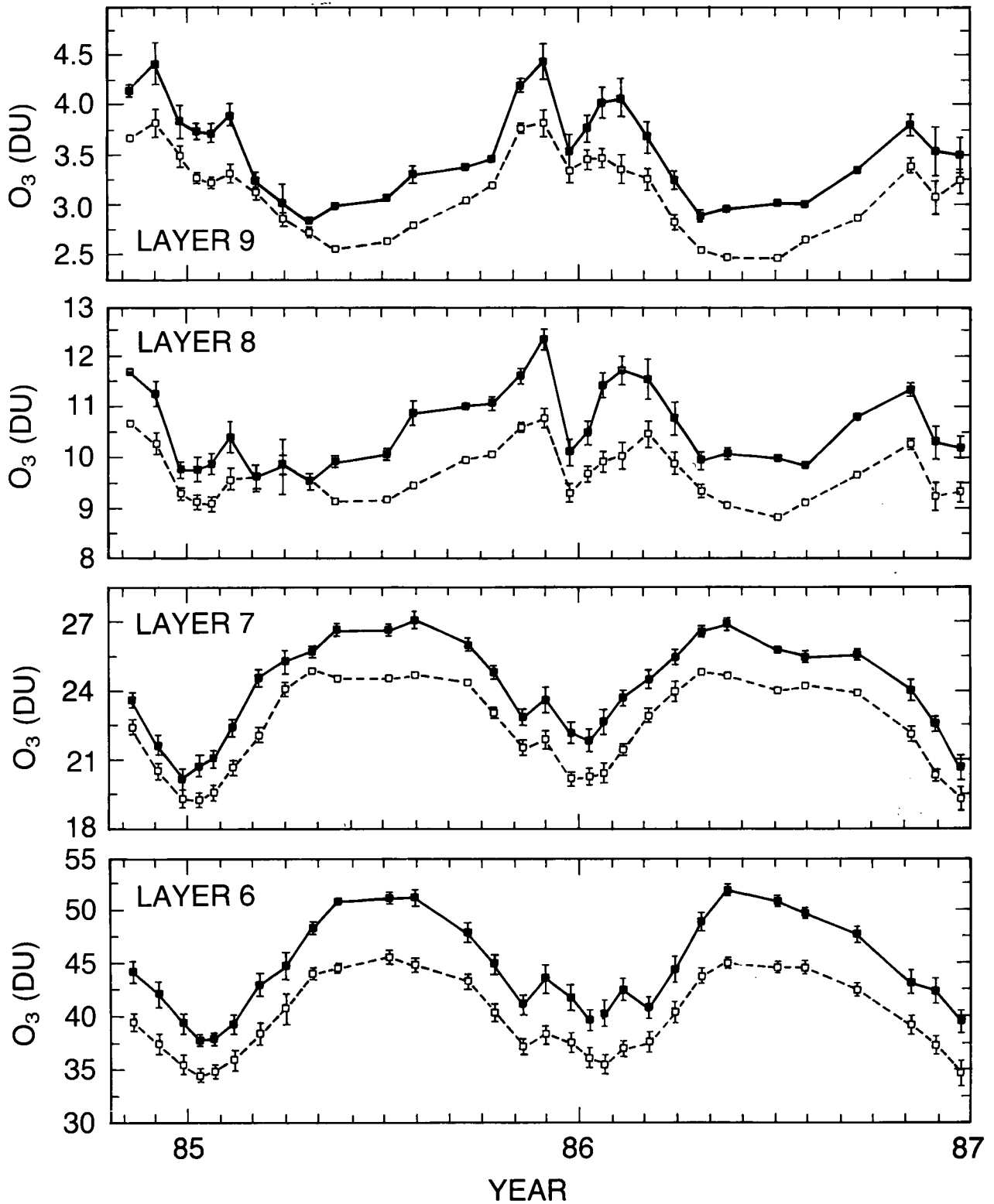
Figure 5.11 Cluster means of SAGE–II and SBUV at 40°N. The vertical bar is the 95 percent confidence interval on the cluster mean. Lines connecting means are intended only as a visual aid.

When contrasting SAGE–II with SBUV (Figures 5.9 through 5.11), it is apparent that the two instruments track each other well—i.e., the shapes are similar; however, SBUV layer amounts are systematically lower than the corresponding SAGE–II layer amounts.

To reduce the large seasonal variability seen in Figures 5.6 through 5.11, the cluster means are averaged over an integral number of years. The 24-month averages are presented in Figure 5.12 as a function of latitude for the four Umkehr layers for the SAGE–I period, October 24, 1979, to October 23, 1981, and for the SAGE–II period, October 24, 1984, to October 23, 1986. Figure 5.12 shows that the latitudinal variation is similar for both the SAGE–I and SBUV instruments, with SBUV zonal ozone greater than SAGE–I at all levels other than 6. These same latitudinal variations are also evident in the SAGE–II/SBUV comparisons; however, a larger consistent bias exists at all latitudes with SBUV averages lower than SAGE–II zonal averages.

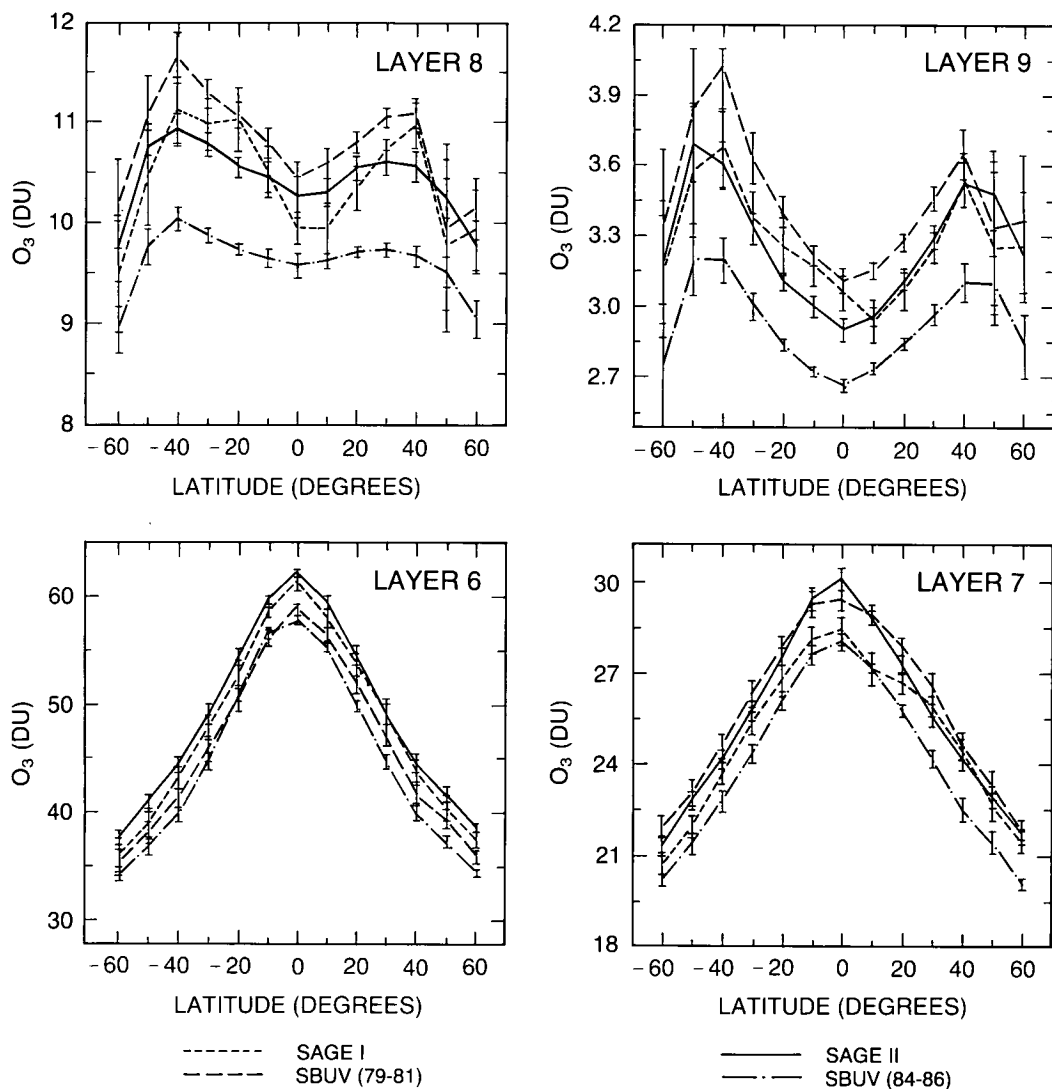**Figure 5.12** Time average of the cluster means. The averaging period for SAGE–I was October 24, 1979, to October 23, 1981. The averaging period for SAGE–II was October 24, 1984, to October 23, 1986. The corresponding SBUV data were similarly averaged. The vertical bars are the standard error of the mean of the cluster means. The sizes of the error bars reflect the seasonal ozone variability.

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The latitudinal cluster-mean averages of the SBUV data show a decrease at all levels except 6 between the two periods at all latitudes. Any apparent differences between SAGE–I and SAGE–II are accentuated by the fact that their corresponding cluster means were not "paired"; hence, seasonality may affect the differences. The same holds for the SBUV (1979–1981) and SBUV (1984–1986) cluster-mean averages.

5.3.5 Difference Between SAGE–I and –II and SBUV Pairs

To quantify the information contained in the time series of the previous section, averages of the cluster-mean percentage differences are computed. Figure 5.13 displays the differences between SAGE–I/SBUV and SAGE–II/SBUV, with SBUV as the reference. The percentage differences are essentially constant across the latitudes, and the means are almost always significantly different.
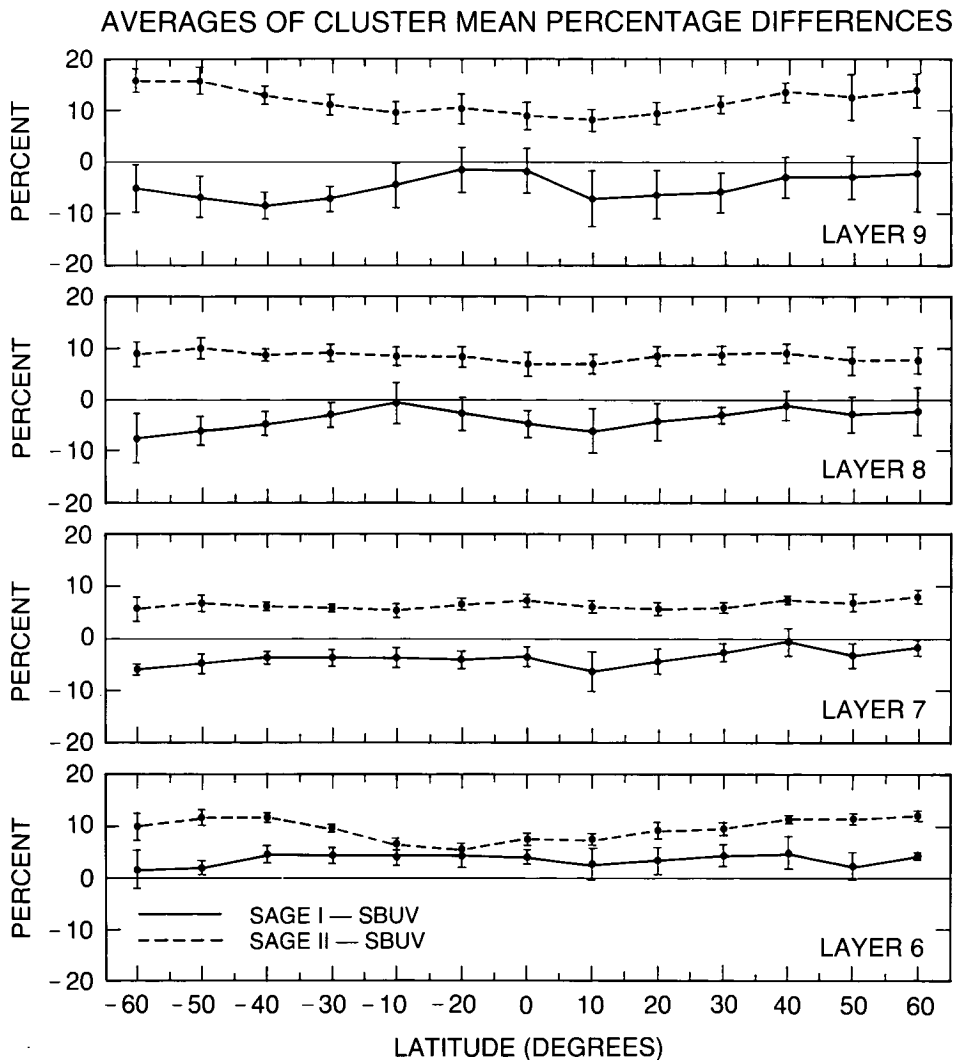

Figure 5.13 The average of the percentage difference between SAGE–I and –II and SBUV cluster means with SBUV the reference. The vertical bars are the 95 percent confidence interval of the time average. Only variation between the cluster mean percentage differences contributed to the size of each confidence interval. The averaging period was identical to that used for Figure 5.12.

The cluster-mean differences presented in Figure 5.14 were averaged in latitude and are shown in Figure 5.15. In this figure, the SBUV ozone layer amounts are greater on average than the SAGE–I amounts in layers 7 to 9 by about 4 to 5 percent and are smaller than the SAGE–I amounts in layer 6 by 4 percent. Much larger differences are found between SAGE–II and the SBUV layer amounts in these four layers, with SBUV lower by between 6 to 11 percent.

Because of seasonal sampling differences, the averaging process used to produce Figures 5.13 and 5.14 should not be used to compare SAGE–I with SAGE–II, nor SBUV (1979–1981) with SBUV (1984–1986). A method that reduces seasonal and spatial biases selects sets of profiles in which SAGE–I and SAGE–II sample the same month of the year within the same latitude band. Such a period of time is called an "intersection" and is defined to be a period of time in the year, of approximately 1 month's duration, during which both SAGE–I and SAGE–II sampled the same latitude band. It should be noted that an intersection is independent of the actual year during which measurements were made; it is defined strictly in terms of the month within the year. Within the 13 latitude bands being considered, 102 intersections were isolated such that both halves of the year were equally represented. The SAGE–I and SAGE–II profiles were averaged
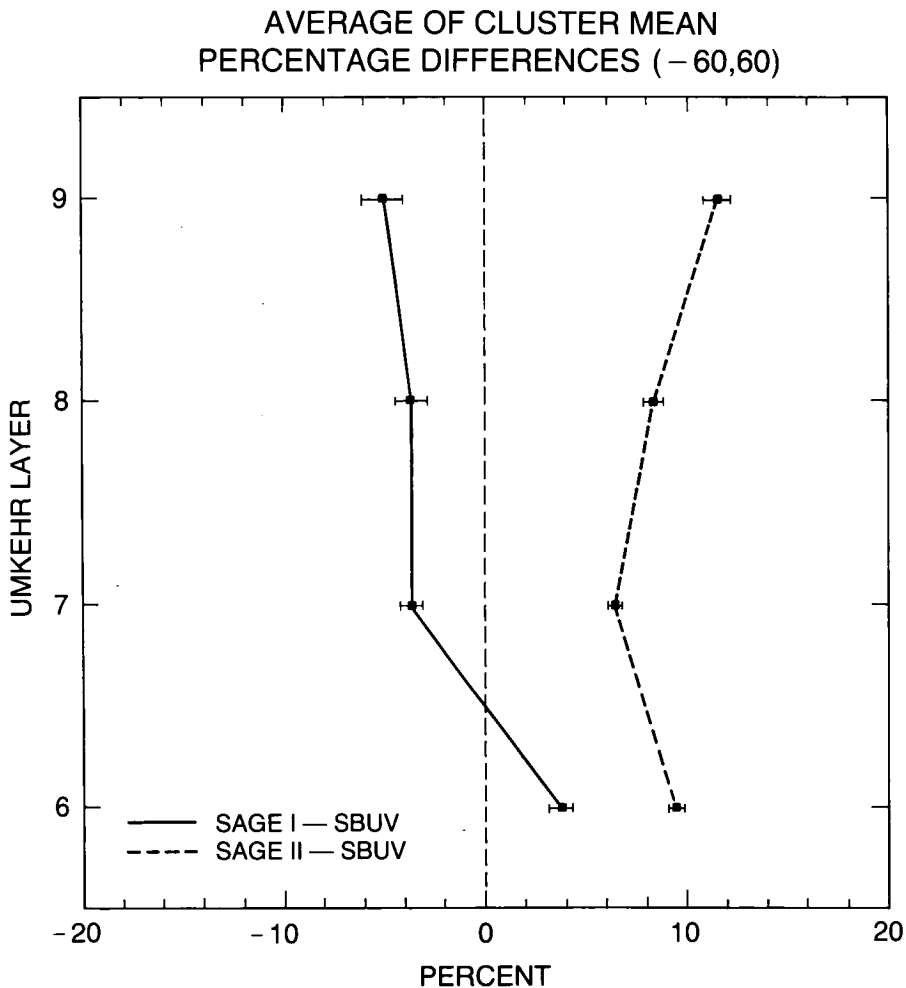

Figure 5.14 Time averages of the percentage difference between SAGE–I and –II and SBUV cluster means with SBUV the reference. Averaging was done over all latitude bands for the time period used in Figure 5.12. The horizontal bars are the 95 percent confidence interval of the time average.

AVERAGES OF INTERSECTION MEAN PERCENTAGE DIFFERENCES
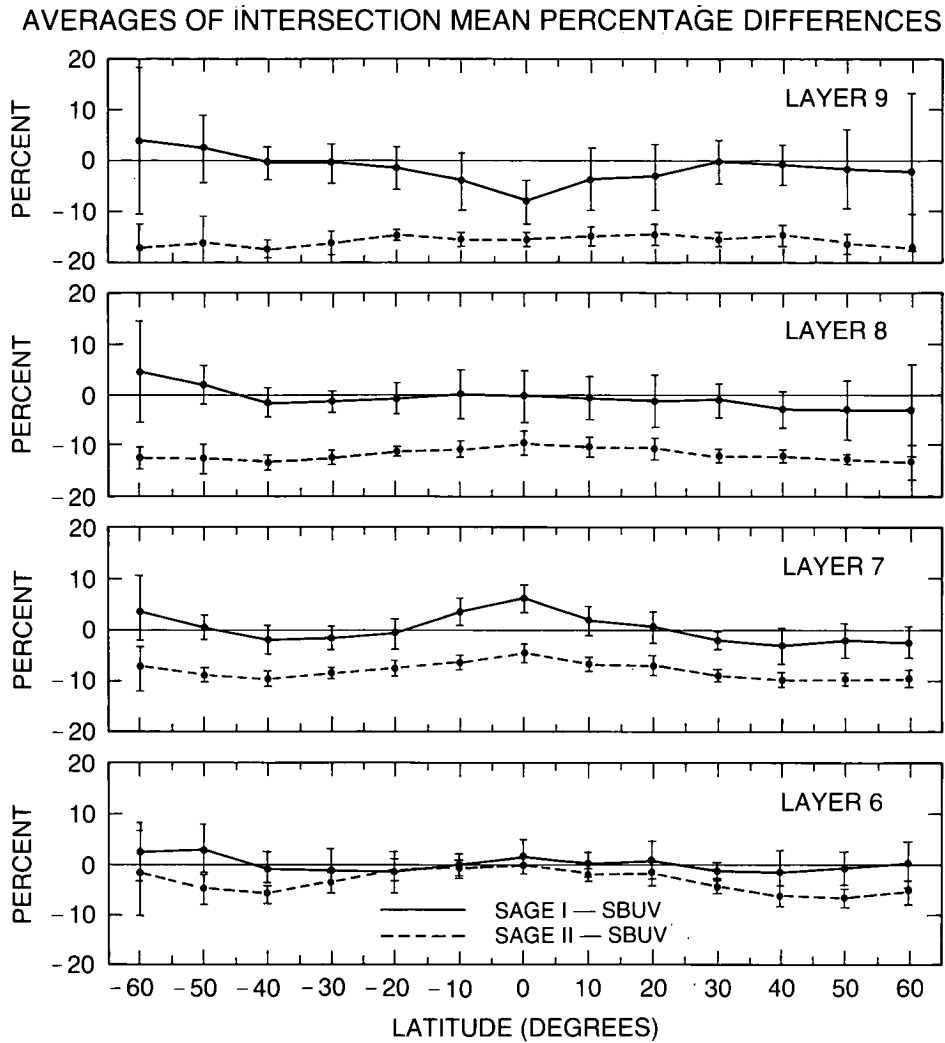
Figure 5.15 Averages of the percentage difference between the cluster means of SAGE–II and SAGE–I (SAGE–I the reference) or SBUV (1984–1986) and SBUV (1979–1981) (SBUV 1979–1981 the reference). Percentage differences were computed at SAGE–I and SAGE–II intersections. For each latitude band there were approximately eight intersections and thus eight percentage differences that were averaged to produce one point on the graph. The vertical bar represents twice the standard error of the mean percentage difference and reflects only the variation between the eight percentage differences in the latitude band.

for each intersection. The percentage difference between the SAGE–II mean and the SAGE–I mean was computed within each intersection. The SAGE–I mean was taken as reference. The SBUV (1979–1981) and SBUV (1984–1986) profiles were processed in a fashion analogous to the SAGE–I and SAGE–II profiles. SBUV (1979–1981) was used as reference for the percentage calculations. As in Figure 5.13, percentage differences are displayed as a function of latitude in Figure 5.15. Again, there is only slight variation in the differences with latitude. The percentage differences are averaged in latitude and are presented as a function of Umkehr layer in Figure 5.16. It should be noted, in Figure 5.16, that the magnitude of the difference between SBUV (1984–1986) and SBUV (1979–1981) steadily increases from approximately 3 percent at layer 6 to 16 percent at layer 9. However, the differences between SAGE–II and SAGE–I remain relatively constant and are less than 2 percent.

AVERAGE OF INTERSECTION MEAN
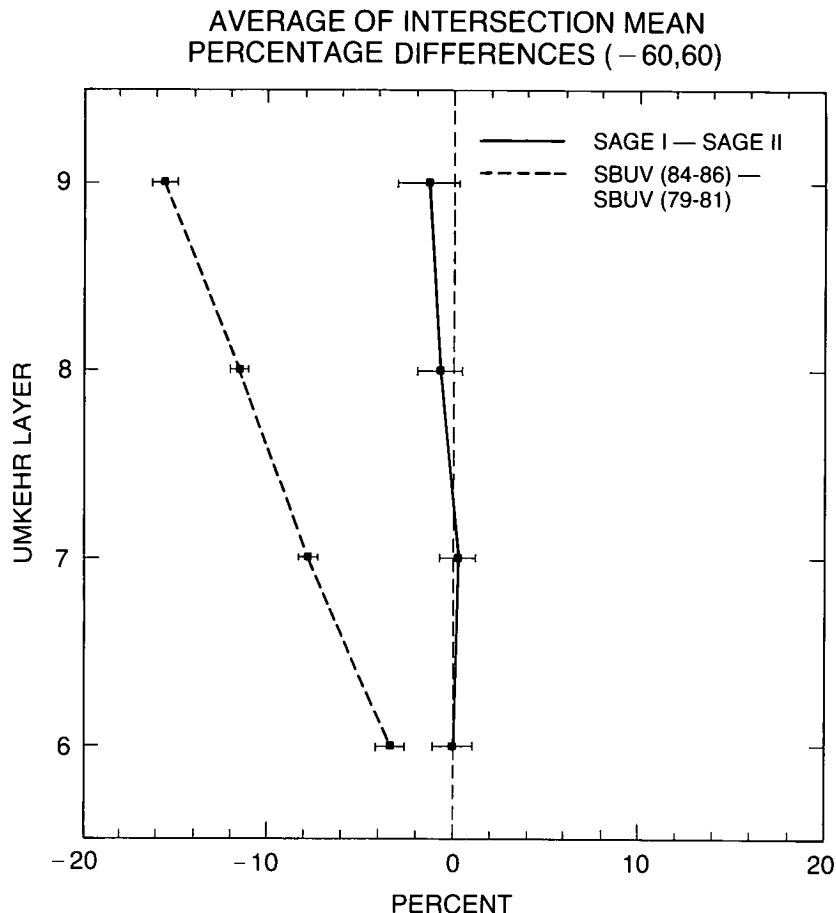PERCENTAGE DIFFERENCES (−60,60)

Figure 5.16   Latitudinally averaged mean percentage difference between SAGE–II and SAGE–I (SAGE–I the reference) or between SBUV (1984–1986) and SBUV (1979–1981) (SBUV 1979–1981 the reference). The horizontal bars represent twice the standard error of the mean percentage difference.

The differences between Figures 5.13 and 5.15 and between Figures 5.14 and 5.16 are a result of different sampling criteria. Figures 5.13 and 5.14 include all two-way coincidences between SAGE–I or SAGE–II and SBUV. Figures 5.15 and 5.16 include three-way coincidences: SAGE–II with seasons and latitude corresponding to SAGE–I but 5 years apart, and with SBUV.

5.3.6 Changes in SAGE–I to SAGE–II at Geometric Altitudes

The previous comparisons between SAGE–I and SAGE–II involved the Umkehr-layer amounts and were designed to compare SAGE–I and –II with SBUV observations. The conversion to Umkehr-layer amounts is not necessary when comparing SAGE–I and SAGE–II alone. In the following development, the fundamental SAGE measurements are used; that is, the SAGE–I and –II concentration profiles are defined in terms of geometric altitude, ranging from 25 km to 50 km. Again, only profiles corresponding to the SAGE–II and SAGE–I intersections are used. The cluster percentage differences are averaged in time within 10-degree-latitude bands and plotted against altitude in Figure 5.17. The magnitude of the differences is only on the order of 5 percent. Because of small sample sizes, these comparisons are noisy. With some notable exceptions at high altitudes and also near the Equator, the prevailing pattern is an ozone decrease in the upper stratosphere and another decrease near 25 km between 1980 and 1986.

Figure 5.17 Mean percentage difference between SAGE–II and SAGE–I at the geometric altitudes of SAGE (SAGE–I is the reference). For each latitude band approximately eight intersections were available from which to compute percentage differences. The average percentage difference along with its standard error are plotted. The standard error reflects only the variation between the eight percentage differences in a given latitude band.

The identical analysis is performed using two wider latitude bands: 20°N to 50°N and 20°S to 50°S, an area over which there is relatively dense sampling. The mean percentage differences appear in Figure 5.18. The agreement between the two hemispheres is apparent, with the magnitude of the ozone change from SAGE–I to SAGE–II being less than 5 percent at any altitude. Between 35 km and 45 km there is an ozone-reduction profile with a maximum ozone reduction of about 3 percent centered at 40 km, at about 30 km there is zero change, at about 50 km there is zero ozone change (unlike SBUV), and, near 25 km, there is another region of ozone reduction. As in the previous analyses using Umkehr layer amounts and considering potential systematic errors, the SAGE–I and –II measurements do not support a large decrease in global stratospheric ozone above 25 km.

5.4 SOLAR BACKSCATTER ULTRAVIOLET II (SBUV–2)

The National Oceanic and Atmospheric Administration (NOAA)–9 satellite with the SBUV–2 instrument package onboard was launched on December 12, 1984 (Oslik, 1984). While some instruments on NOAA–9 are no longer operating, the SBUV–2 is still sending data back on a daily basis. The SBUV–2, while similar to the SBUV, is different, as shown in Table 5.4.

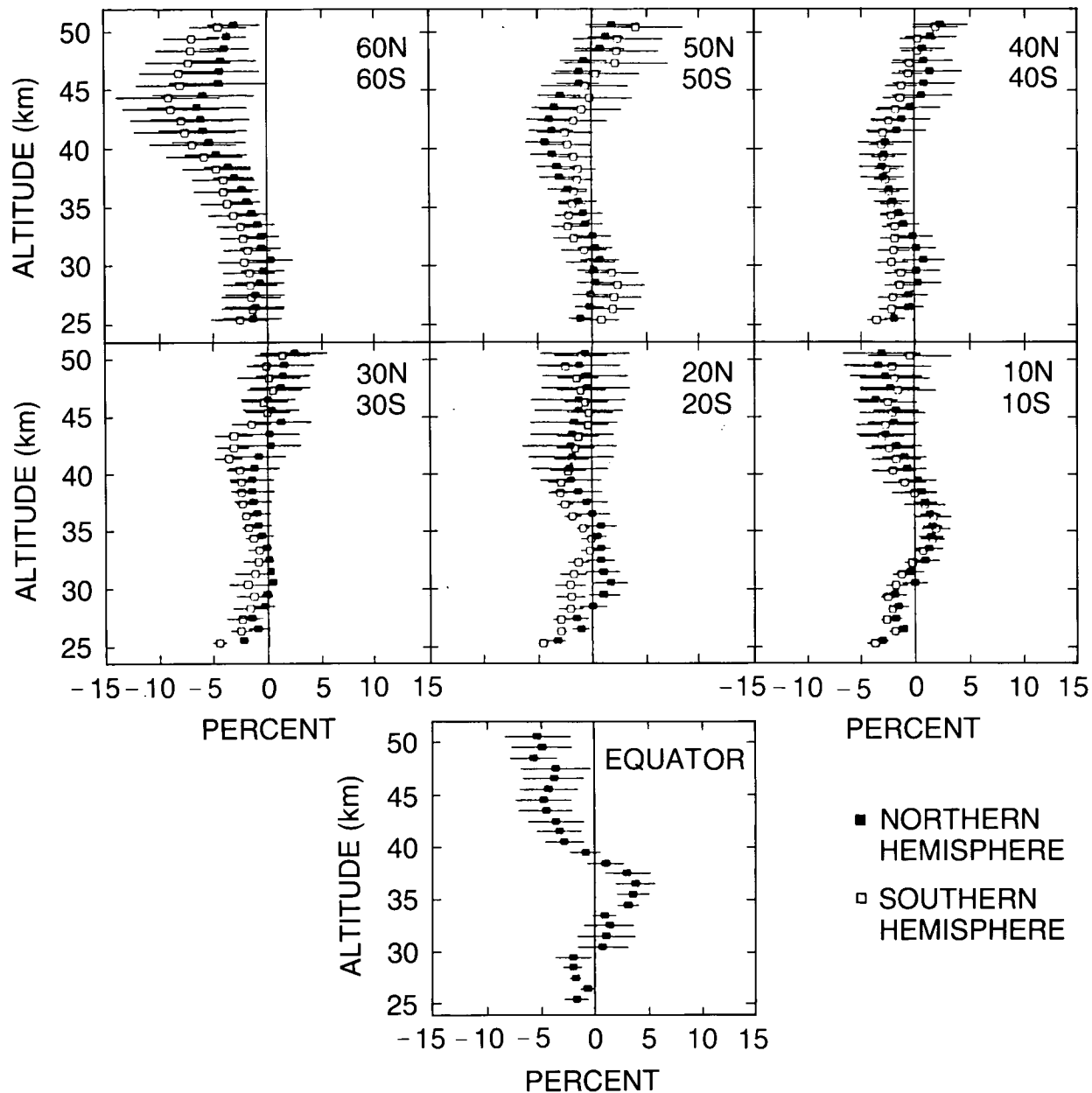**[SAGE II (10/84-9/87) — SAGE I (2/79-11/81)]/SAGE I MIDLATITUDES COMBINED**
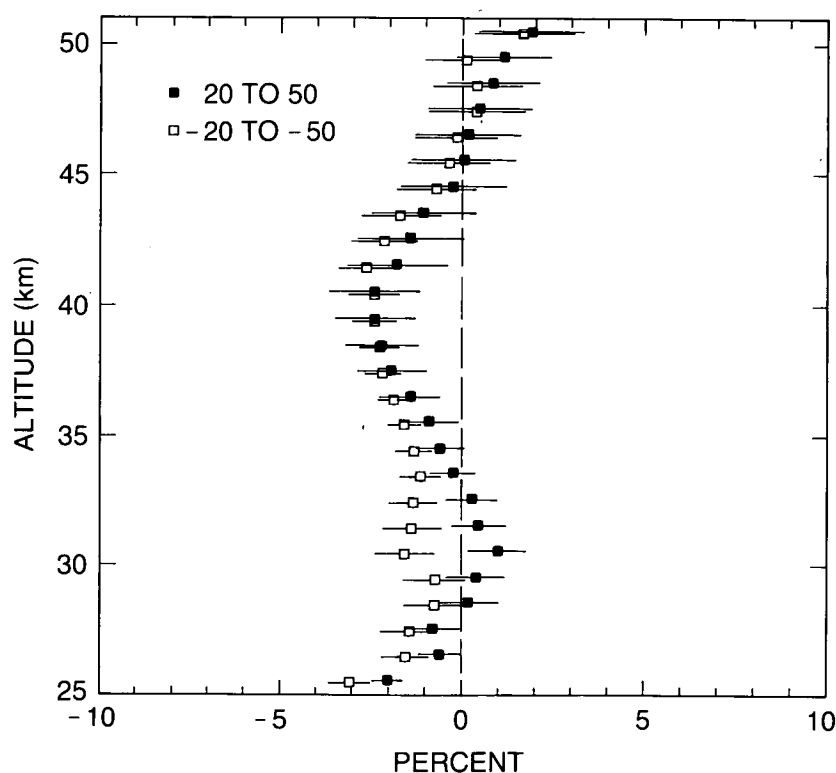
Figure 5.18 Mean percentage difference between SAGE–II and SAGE–I at the geometric altitudes of SAGE (SAGE–I is the reference). All intersections occurring between 20°N to 50°N (or 20°S to 50°S) were combined into one sample. The percentage difference at each intersection was computed. These percentage differences were averaged and plotted for each altitude. The sample standard error was also computed and plotted as the horizontal bar at each point. Within each hemisphere, approximately 2,500 SAGE–I profiles and 6,000 SAGE–II profiles were used in computing the statistics.

Table 5.4 Comparison of Important Features Between SBUV-2 and SBUV

Features	SBUV-2	SBUV
Monochromator mode	4 (discrete, sweep, wavelength, and position)	4 (step, continuous, wavelength and cage [cam])
Control of monochromator	FIX System; FLEX system mode (wavelengths can be changed by command)	One fixed system
Scene mode	4 (Earth, Sun, wavelength calibrate, diffuser check)	2 (Earth and Sun)
Diffuser position	4 (stow, Sun, wavelength calibration, or diffuser check & decontamination)	2 (stow and Sun)
Mercury Lamp position	2 (stowed and deployed)	1
CCR wavelength	379 nm	343 nm
Shortest wavelength of discrete mode (other 11 wavelengths match)	252 nm (in FIX system)	255.5 nm
Wavelength calibration steps	12	5
Electronic calibration	Every scan in retrace	By command
Scanning		
discrete mode	32 sec	32 sec
sweep mode	192 sec	112 sec
Sampling time		
discrete	1.25 sec	1 sec
sweep	0.1 sec	0.08 sec
Diffuser check	Yes	No
Diffuser Decontamination	Yes	No
Gain Range	Two from PMT anode 1 from PMT cathode	Three from PMT One from ref. diode
IFOV	11.3 × 11.3 degrees	11.3 × 11.3 degrees
Discrete (step scan) scanning direction	From short to long wavelengths	From long to short wavelengths

SBUV data show a surprisingly large decrease of stratospheric ozone, especially in the upper stratosphere, from 1978 to the present (Heath, 1986), but the Algorithm and Calibration subgroups of the Trends Panel suggest that the apparent decrease could be due in whole or in part to degradation of the reflector plate in the SBUV system. SBUV-2 takes the same great volume and the same kind of data as SBUV, and has the same flight pattern. The most powerful method of verifying, modifying, or disproving the SBUV-reported trends would be to compare at least two aspects of SBUV and validated SBUV-2 data: 1) the ozone magnitudes reported by the twin instruments immediately after launch (if SBUV-2 is consistently higher than SBUV, then the ozone decrease shown by SBUV is probably correspondingly in error) and 2) a systematic difference between the first 2 years of SBUV and the corresponding 2 years of SBUV-2 to get a good estimate of how much ozone has changed over the intervening period. The other

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sections of the report of this subcommittee of the Trends Panel have intercompared upper stratospheric SBUV data with those of other satellites or ground-based instruments, which measure different ozone properties, make far fewer ozone measurements, and cover different spatial trajectories than the SBUV instrument. This procedure is more indirect and less revealing than the direct comparison between the two twin, overlapping, SBUV instruments would be.

Using a convenient but inappropriate algorithm, SBUV–2 data have been analyzed and saved since April 1985. These data show seasonal variations similar to those of SBUV, but, in view of known deficiencies of the algorithm used to process the data, no quantitative use is made of these data (Nagatani and Miller, 1987). This subcommittee of the Trends Panel issued requests between April 1987 and July 1987 for the SBUV–2 reinterpreted data. NOAA scientists began to reinterpret the SBUV–2 data in September 1987, using an appropriate algorithm. The newly processed data for August 1985 were issued in preliminary form in late 1987. The differences between SBUV–2 and SBUV data are positive throughout. The aging SBUV instrument reports less ozone than the newly launched twin instrument, indicating that the older instrument had degraded more than it was believed to have in 1986 (Heath 1986). However, the SBUV–2 data were so preliminary at the time of this report that they were not used. These have since been discussed in a recent report (Ohring et al., 1989).

The national plan for monitoring stratospheric ozone is to use Dobson stations and SBUV satellites as mutually interactive systems, to send up another SBUV instrument about every 2 years, and to establish calibration continuity between successive instruments by studying overlapping measurements.

SBUV–2 was launched 2 months after SAGE–II in 1984. The differences between SAGE–I and SAGE–II are at least as great as those between SBUV and SBUV–2. Although it is not SAGE's job to monitor stratospheric ozone, the SAGE team made a great effort to reinterpret all the SAGE–I and SAGE–II ozone data in about 6 months; they produced the meaningful account given in Section 5.3. It is the job of the National Environmental Satellite, Data, and Information Service (NESDIS) of NOAA to monitor stratospheric ozone using SBUV satellites and Dobson ground-based stations. Although January 1988 is more than 3 years since SBUV–2 was launched, the NOAA team said in January 1988 that the SBUV–2 data were not interpreted well enough to go into this report.

5.5 UMKEHR MEASUREMENTS OF UPPER STRATOSPHERIC OZONE

5.5.1 Comparison of Upper Stratospheric Umkehr Ozone Patterns With SBUV Observations at the Same Time and Place

Eight years' worth of archived data from the SBUV were collocated in time and space with all of the Umkehr station reports available as of July 1987 from the World Ozone Center. The criteria for matching were that SBUV and groundstation data be from the same day, and that the center of the SBUV field of view be within 1 degree of latitude and 10 degrees longitude of the station. For this study, 11 stations were selected to provide the greatest temporal coverage over the 7-year period: Kagoshima (31.6°N), New Delhi (28.6°N), Sapporo (43.1°N), Tateno (36.1°N), Arosa (46.8°N), Boulder (40.0°N), Belsk (51.8°N), Lisbon (38.8°N), Perth (31.9°S), Poona (18.5°N), and Naha/Kagamizu (26.2°N).

As discussed in the algorithm chapter of this report, the Umkehr gives its best ozone results in layers 4 to 8 to a vertical resolution of about 2.5 layers (12 km); the SBUV provides information for layers 6 to 9 with a vertical resolution of 10 km. Layers 6 to 8 are presented in this comparison.

Sample data for the Tateno station are shown for Umkehr layers 6, 7, and 8 in Figures 5.19 to 5.21. In each case, the upper panel gives the collocated SBUV ozone measurements in Dobson units, and the lower panel gives the corresponding Umkehr data. Both methods show the large seasonal variations of ozone. The SBUV data are less noisy than those obtained by the Umkehr method. From 1982 to 1983, Umkehr layer 8 shows a strong downward perturbation by the El Chichón volcano, and levels 6 and 7 show a smaller volcanic effect. These SBUV data show no conspicuous effect of El Chichón, but, in Figure 5.1, SBUV showed a 9 percent decrease in layer 6
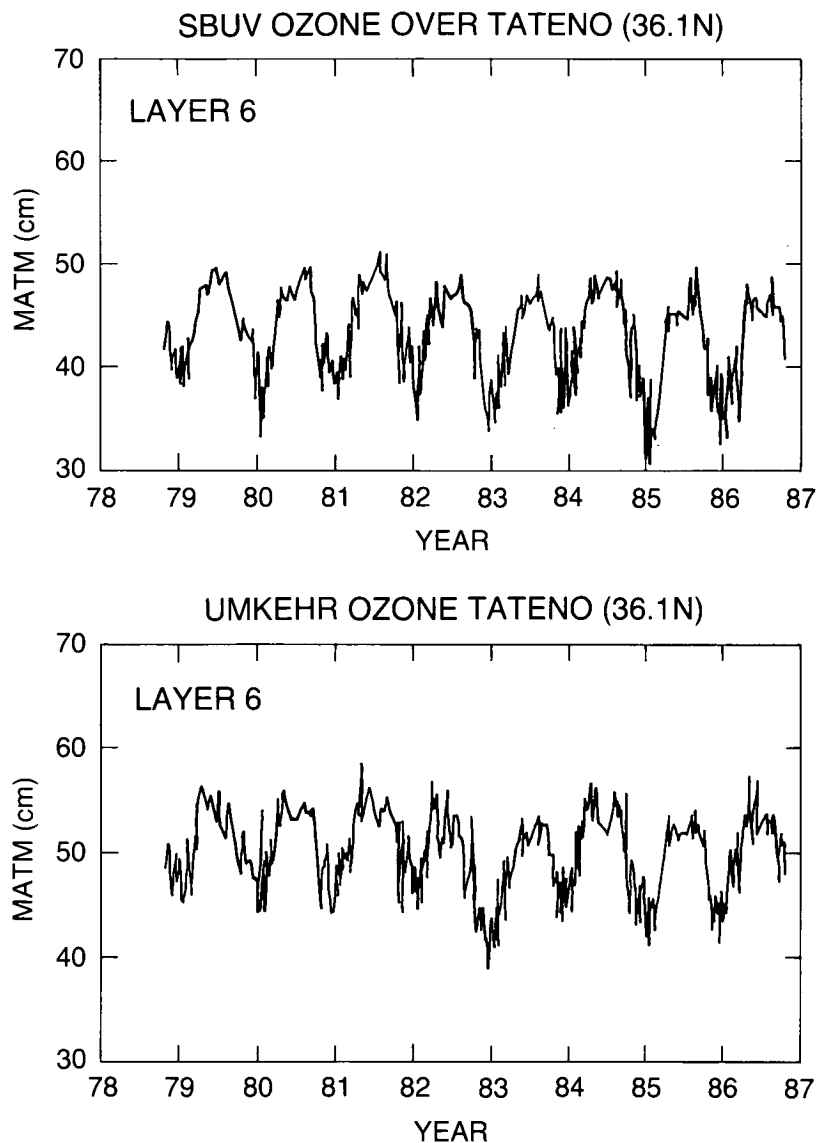

Figure 5.19 Direct presentation of ozone observations (Dobson units) from the Umkehr station at Tateno (36°N) in the lower panel and collocated SBUV ozone observations in the upper panel from 1979 through 1986 for Umkehr layer 6.

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SBUV OZONE OVER TATENO (36.1N)
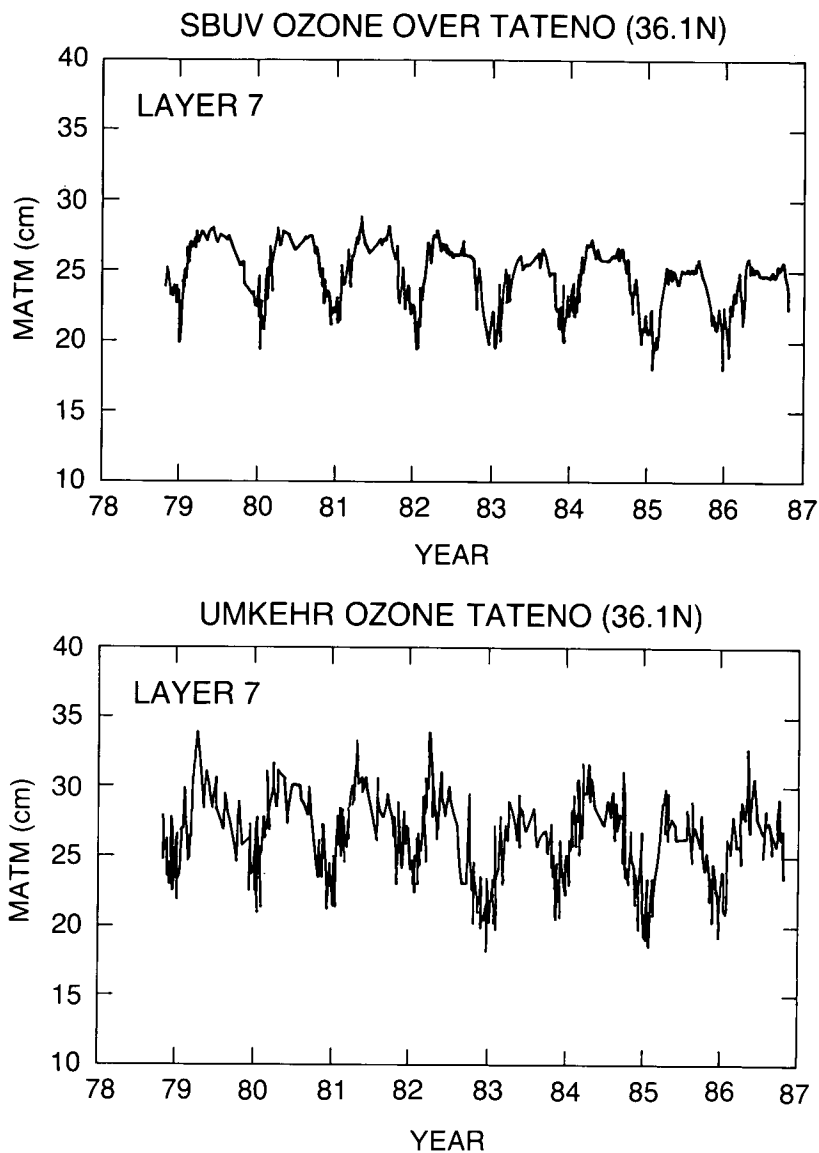

UMKEHR OZONE TATENO (36.1N)

Figure 5.20 Same as 5.19, except for Umkehr layer 7.

late in 1982, presumably caused by El Chichón. The Umkehr method must look up through the volcanic cloud to observe layers 6 to 8, but the SBUV system looks down; these layers lie largely (but not entirely) above the volcanic cloud. In the upper panels of Figures 5.19 to 5.21, the SBUV data show a clear-cut decrease over the 8 years in levels 7 and 8, and perhaps a slight decrease in level 6. A comparison of the early years with the last years of the Umkehr data shows a distinct ozone decrease, but the trend is confused by the effects of El Chichón during the middle years.

Another way to compare the collocated SBUV and Umkehr data visually is to plot the ratio, Umkehr–SBUV, against time at layer 8 for all 11 Umkehr stations (Figure 5.22). El Chichón erupted in month 40 on this plot. By taking ratios, the seasonal variations are largely removed. If this ratio is parallel to the time axis throughout the period, the Umkehr station is in agreement with the SBUV overflights in trend. Flaws in the data include noise in the ratio, sparsity of data and gaps of data at some stations, and the effect of El Chichón. For those stations with a large

SBUV OZONE OVER TATENO (36.1N)

UMKEHR OZONE TATENO (36.1N)
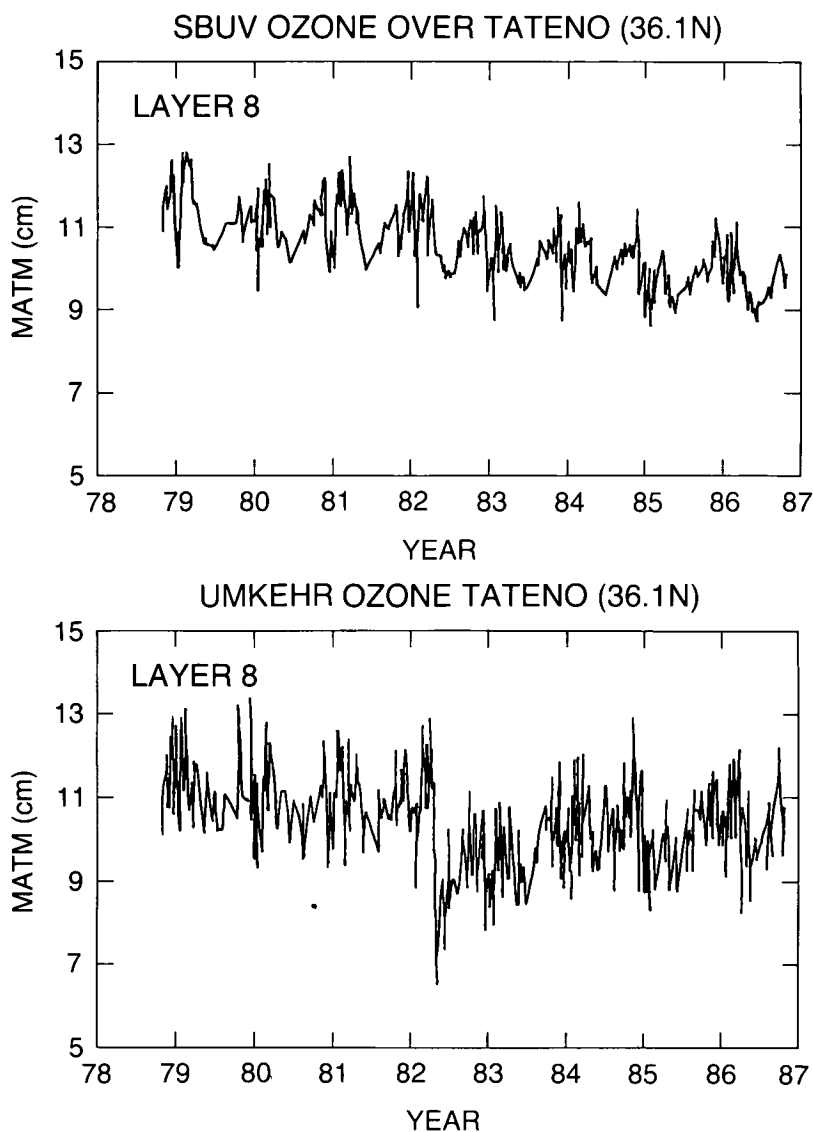
Figure 5.21 Same as 5.19, except for Umkehr layer 8.

density of points, visual comparison of the Umkehr–SBUV ratio during the first and the last year appears to show Umkehr ozone to be larger than that for SBUV by 5 to 10 percent. The decrease of ozone at this Umkehr layer, indicated by the collocated SBUV, is 15 percent; thus, this visual comparison indicates that the ozone decrease seen by Umkehr is less than that seen by SBUV over this period.

A time series statistical analysis was carried out for the SBUV trend shown for observations coincident with each Umkehr station (omitting Boulder) and for the bias, SBUV–Umkehr. To minimize the effect of El Chichón in the comparison, all Umkehr measurements for 36 months after the eruption of El Chichón were eliminated from the regression. This means that Umkehr comparisons are based on only 5 years of data: 3.5 years of data before the eruption, and only 1.5 years of data after the 3-year gap.

Figure 5.22 Ratio of Umkehr ozone measurements in layer 8 to collocated SBUV measurements for 7 years after launching of SBUV in November 1978. Eleven Umkehr stations are included.
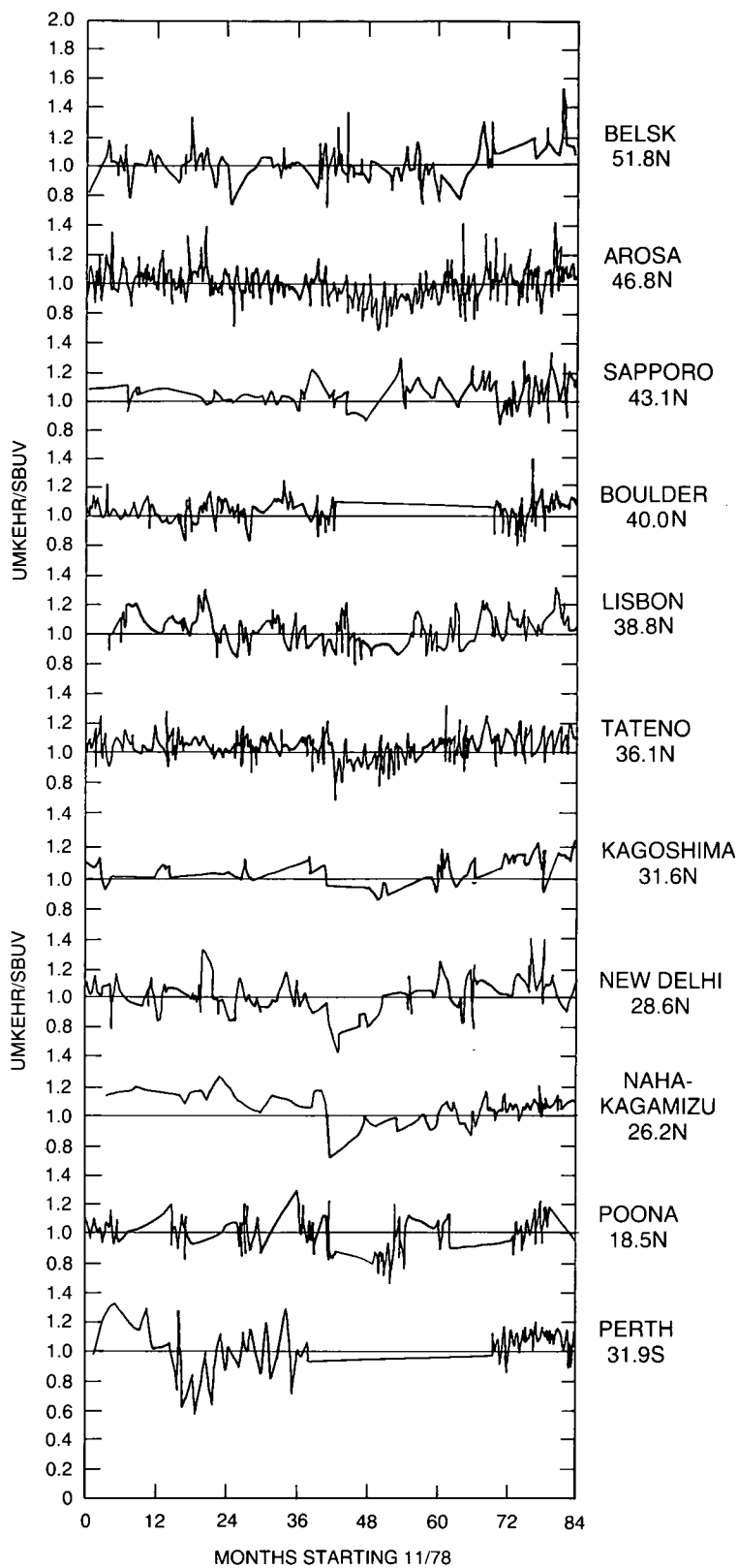
In order to remove residual seasonal variation remaining in the bias and to derive the drift between the long-term trend of the two time series, a linear regression model was fit to the percent difference, Δ = SBUV–Umkehr, such that:

$\Delta = b + dt + a_1\cos2\pi t + a_2\sin2\pi t + a_3\cos4\pi t + a_4\sin4\pi t$.

$\Delta = 100 \times$ (SBUV–Umkehr)/SBUV.

t = time in year measured from November 1, 1978, the starting day of SBUV measurements.

b = intercept of the regression line at $t = 0$, representing the bias (systematic difference) between SBUV and Umkehr.

d = drift between SBUV and Umkehr (percent per year).

The annual and semiannual terms were included to model second-order seasonal effects in the SBUV–Umkehr difference. The regression model was fit individually to the data in each layer from each station, and an estimate of the drift (d) for the network was computed along with its 95 percent confidence interval. The results of the individual stations were combined using a weighting function proportional to the number of observations and inversely proportional to the square of the standard deviation. The change in SBUV ozone was estimated using the same regression model (described above) applied to the coincident SBUV data. Table 5.5 shows the 8-year drift of SBUV relative to the Umkehr network, the total change in SBUV over the Umkehr network, and the change in Umkehr computed using the SBUV as a transfer standard. The 95 percent confidence intervals (not including possible systematic errors) are included in the table.

Table 5.5 SBUV Trend Collocated With 11 Umkehr Stations, the Trend of the Difference (SBUV–Umkehr), and the Derived Umkehr Trend for 1979 to 1986

Trends are expressed as percent change in 8 years (95 percent confidence level). No corrections are made for aerosols except to omit 3 years of data after eruption of El Chichón. Compare with line (B) in Table 5.7

Quantity	% ozone change in 8 years		
	Layer 6	Layer 7	Layer 8
SBUV	-7 ± 1	-12 ± 1	-15 ± 2
(SBUV–Umkehr)	-5 ± 3	-3 ± 3	-5 ± 4
Umkehr	-2.4 ± 2.6	-9.6 ± 3.3	-10.4 ± 4.3

This method of reducing the effect of El Chichón aerosols on the Umkehr network is regarded as insufficient, and the problem of correcting for aerosols is considered in the next section.

5.5.2 An Analysis of Northern Midlatitude Umkehr Measurements Corrected for Stratospheric Aerosols for 1979 to 1986

5.5.2.1 Introduction

This section is based on a report by DeLuisi et al. (1983), some of which is directly quoted here. This report is also discussed in Chapter 10, and that discussion is not repeated here.

Umkehr observations of ozone profiles have been used in a variety of ways to assess characteristics, variations, and trends in ozone concentration in the upper stratosphere (e.g., Bojkov, 1969a; Angell and Korshover, 1983b; Reinsel et al., 1984; and others). They have also been used for comparison with ozone profile data from other observational methods such as ozone-

sondes, satellite, and lidar (Craig et al., 1967; DeLuisi and Mateer, 1971; DeLuisi and Nimira, 1977; DeLuisi et al., 1979; DeLuisi et al., 1985; Megie et al., 1985, and many others). Moreover, they are the observations that revealed a serious drift in the sensing of upper stratospheric ozone by the SBUV (Fleig et al., 1981).

It is well known that the Umkehr is affected by the presence of stratospheric aerosols (DeLuisi, 1969 and 1979; Dave et al., 1979) that act as additional scatterers and attenuators not included in the present inversion algorithm for ozone profiles (Mateer and Dütsch, 1964). The empirically derived errors are well matched by the theoretical calculations of Dave et al. (1979), who accounted for multiple scattering and atmospheric sphericity. In principle, an observed aerosol profile using lidar can be used to calculate the error to a concurrent Umkehr observation (see Chapter 10).

5.5.2.2 Procedure

Monthly averages of lidar aerosol profile data from Langley, VA; Boulder, CO; Aberystwyth, Wales; Haute Provence, France; and Garmisch–Partenkirchen, F.R.G., were used in a radiative transfer computer code developed for the previous work of Dave et al. (1979). The aerosol size distribution was selected from a collection of samples made by NASA/Ames U2 flights to the interior of the El Chichón cloud (Oberbeck et al., 1983). The radiative transfer code requires realistic midlatitude ozone profiles that vary with season. The ozone profile data used in these calculations were supplied from the work of Tiao et al. (1986).

The radiative transfer code by Dave et al. (1979) was used to compute an Umkehr with stratospheric aerosols and an Umkehr without stratospheric aerosols. The difference between the Umkehr with stratospheric aerosols and the corresponding one without is called the "Umkehr error."

5.5.2.3 Results and Discussion

Figure 10.22 is a plot of monthly average stratospheric aerosol optical thickness vs. time derived from the lidar observations. The results of the aerosol observations and calculated ozone profile errors (Figure 10.21) are used to correct Umkehr measurements from five stations in the northern midlatitudes. These stations are Belsk, Poland; Arosa, Switzerland; Lisbon, Portugal; Boulder, CO; and Tateno, Japan (compare Figure 5.22). These stations were chosen solely on the basis of their higher frequency of measurements compared to other stations. Data are analyzed in terms of monthly averages, from 1979 to 1986, of the five Umkehr stations.

The monthly average Umkehr errors (the corrections to be applied to the data) and the lidar optical depths are given over the 8-year period in Table 5.6. The maximum optical thickness of 0.113 occurred in January 1983, and the maximum corrections for aerosols were -4.6 percent for layer 6, -14.7 percent for layer 7, and -26.0 percent for layer 8. For layer 7, for example, the corrections were about -0.5 percent in 1979 and -2 percent in 1986, showing less than total recovery from El Chichón even in 1986.

One check on the corrected Umkehr data is to take Figure 5.11, which gives the time series of the SAGE–II and SBUV cluster mean at 40°N, and to insert the corrected Umkehr data on the plot, as in Figure 5.23. The SAGE–II and SBUV data are the zonal average of the matched clusters; the Umkehr data are from the Tatena, Arosa, Belsk, and Lisbon stations. The Umkehr data show the same seasonal trends at all layers as those shown by SAGE–II and SBUV, including the opposite

Table 5.6 Corrections for Aerosols Applied to Umkehr Data on the Basis of Lidar Measurements and DeLuisi's Model

The values are the calculated percentage error due to aerosols in the monthly average ozone reported for the stations Tateno, Arosa, Boulder, Belsk, and Lisbon at Umkehr layers 6, 7, and 8. "Tau" is the aerosol optical thickness as determined by lidar.

| Month	Year	Layer 6	Layer 7	Layer 8	Tau
JAN	1979	-0.4	-0.8	-0.4	0.001
APR		-0.2	-0.3	-0.5	0.001
JUL		-0.2	-0.6	-0.9	0.002
OCT		-0.3	-0.8	-0.3	0.001
JAN	1980	-0.1	-0.5	-0.8	0.002
APR		-0.3	-0.6	-0.8	0.002
JUL		-0.1	-0.7	-1.9	0.008
OCT		-0.1	-1.0	-1.3	0.006
JAN	1981	0.0	-0.2	-0.8	0.003
APR		-0.2	-0.6	-0.9	0.002
JUL		0.0	-1.0	-2.4	0.006
OCT		-0.5	-1.8	-1.5	0.004
JAN	1982	-0.1	-0.2	-0.9	0.005
APR		-0.8	-1.9	-2.2	0.010
JUL		-0.4	-2.7	-7.2	0.022
OCT		-0.8	-5.1	-15.1	0.044
JAN	1983	-4.6	-14.7	-26.0	0.111
APR		-1.9	-7.0	-14.8	0.081
JUL		-0.9	-6.0	-12.5	0.050
OCT		-0.3	-5.3	-8.7	0.036
JAN	1984	-0.7	-2.6	-6.7	0.029
APR		-0.6	-2.2	-6.3	0.022
JUL		-0.3	-2.2	-4.5	0.013
OCT		-0.4	-2.3	-3.6	0.013
JAN	1985	-0.5	-1.2	-3.8	0.013
APR		-0.3	-0.7	-3.5	0.011
JUL		-0.1	-1.1	-2.9	0.008
OCT		-0.2	-1.7	-2.7	0.009
JAN	1986	-0.4	-0.7	-2.4	0.007
APR		-0.1	-0.3	-2.4	0.007
JUL		-0.7	-1.9	-3.1	0.011
OCT		-0.5	-2.3	-3.4	0.009
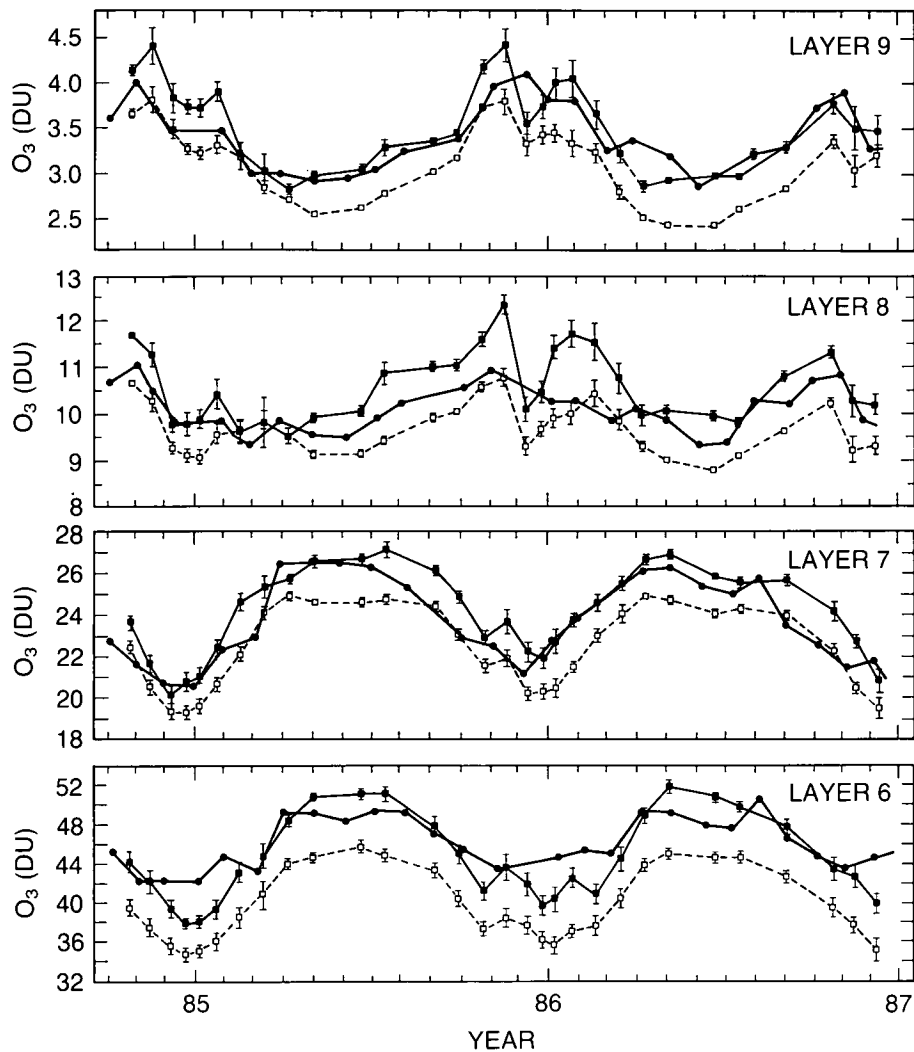
Figure 5.23 Aerosol-corrected Umkehr observations (Arosa, Belsk, Lisbon, and Tateno) plotted as a function of time in comparison with zonal average SAGE–II and SBUV data at 40°N latitude. This figure is a copy of Figure 5.11 with the Umkehr data added.

phases at layers 6 and 7 relative to layer 9. In absolute value, Umkehr agrees very well with SAGE–II in layers 6 and 9, the agreement is good in layer 7, and, in layer 8, Umkehr parallels SBUV better than SAGE–II parallels SBUV (layer 8 is in the transition region between the out-of-phase layers 7 and 9, and comparisons here are strongly dependent on details of sampling). This good agreement between the time series data of Umkehr and the satellites is not necessarily evidence for the validity of the aerosol correction factors for Umkehr, since these corrections are already small for the data in this figure (compare Table 5.6).

For 1979–1986, the uncorrected Umkehr data and the corresponding corrected Umkehr data are plotted for layers 6, 7, and 8 in Figures 5.24 to 5.26. The uncorrected data show a notable decrease between mid-1982 and mid-1983. The correction removes most of the anomaly, but the final values remain lower at the end of the record compared to the beginning. If one examines the long-term features in these figures, it is obvious that the ozone in layers 7 and 8 tends toward lower values.
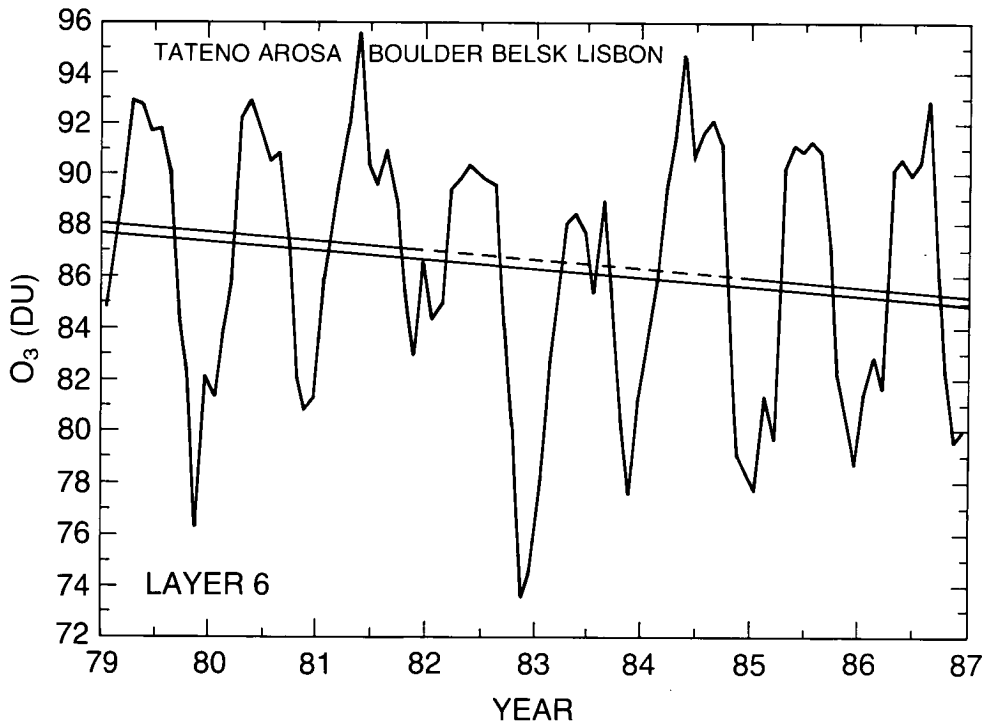
420
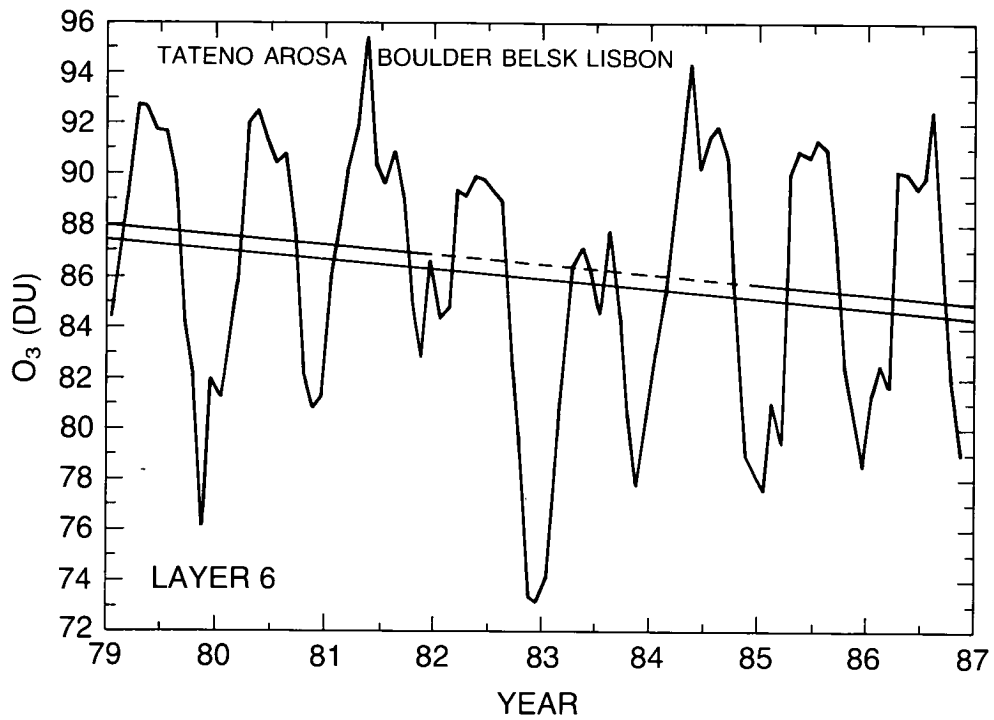
Figure 5.24 Plots of monthly average ozone concentration vs. time in Umkehr layer 6 for five Umkehr stations for precisely 7 years, including 1979 through 1986. Data were supplied courtesy of the World Ozone Data Center in Toronto. The data in the upper panel data have not been corrected for stratospheric aerosol error. Note the error effects of El Chichón during the winter of 1982–1983. The data in the lower panel have been corrected for aerosols by DeLuisi et al. (private communication, 1988). The least-squares lines are: Solid line includes all 7 years of data; Solid-dashed-solid line omits precisely the 3 years 1982, 1983, and 1984.

Figure 5.25 Same as 5.24, except it is for layer 7.

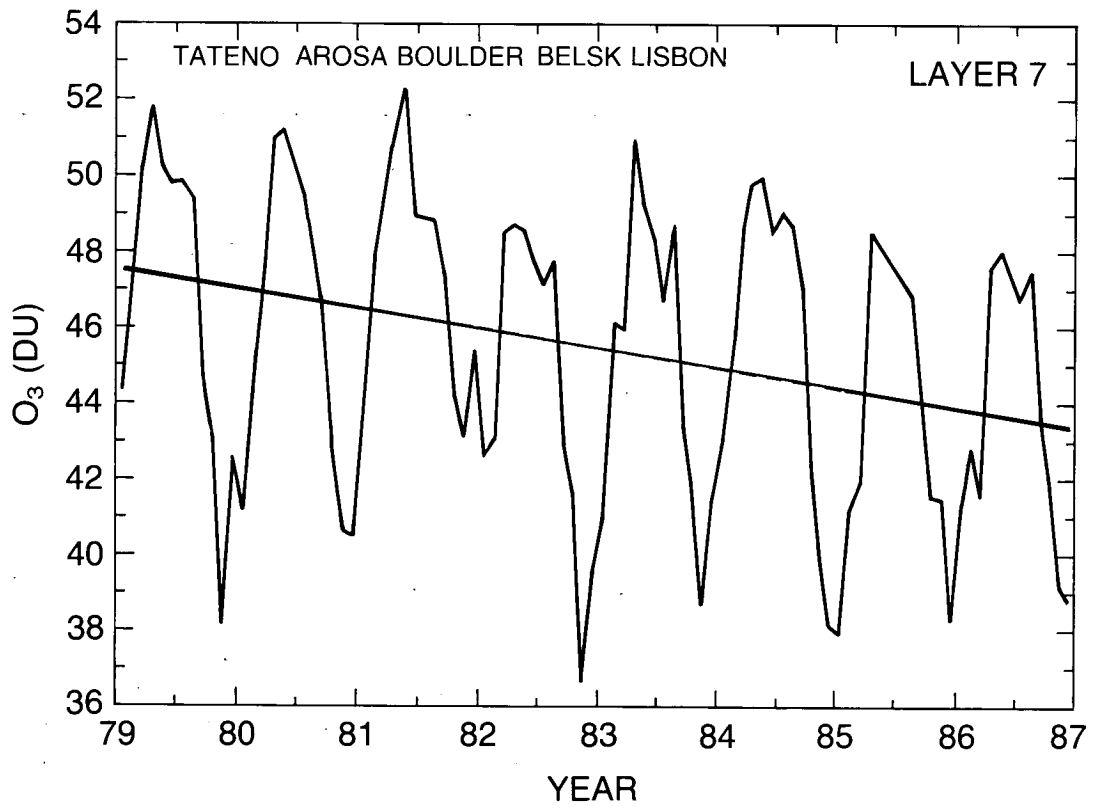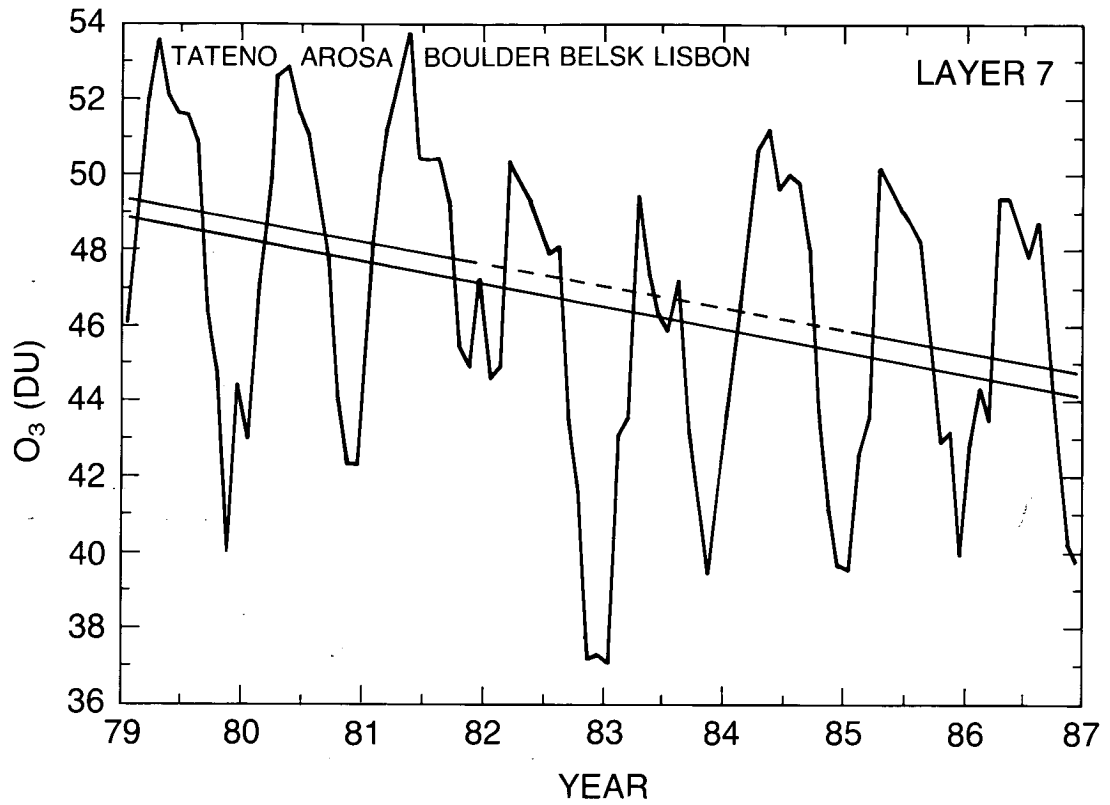For each of the six panels of these figures, there are two lines. The solid line is simply a linear least-squares fit of all the data (including seasonal cycles) from January 1, 1979, through December 31, 1986. The other line is similar, including the data from January 1, 1979, through December 31, 1981, omitting data from January 1, 1982, through December 31, 1984 (the El Chichón eruption occurred in the spring of 1982), and including data from January 1, 1985, through December 31, 1986. All 12 lines show an ozone decrease between 1979 and 1986. In any one figure, the slope of the line including 8 years of data and the slope of the line omitting 3 years of data (mostly after El Chichón) appear to be about the same. These slopes are given in Table 5.7. In all cases, the decreasing slope is less steep when aerosol corrections are made; the greatest difference, occurring in layer 8, is -12.6 percent without correction and -8.7 percent with correction. In each case, the slope for the full 8 years is close to that with 3 years of data removed (1982, 1983, and 1984). For Umkehr layers 6, 7, and 8, the ozone change over the 8-year period (including aerosol correction) is -3.1, -8.5, and -8.7 percent, respectively. SBUV reports ozone changes of about -5, -10, and -15 percent at these altitudes. The maximum ozone change shown by SAGE–I and SAGE–II is about -3 ± 3 percent at Umkehr layer 8 with an estimated systematic error of ± 2 percent.

Table 5.7 Linear Least-Squares Ozone Trends in Umkehr Layers 6, 7, and 8 From January 1, 1979, to December 31, 1986

Trends were derived from four different ways of treating the data: (A) All data, uncorrected for aerosols, (B) Excluding data from January 1, 1982, to December 31, 1984, uncorrected for aerosols, (C) All data, corrected for aerosols, (D) Excluding data from January 1, 1982, to December 31, 1984, corrected for aerosols. Percent change over the 8-year period. Compare Figures 5.23 to 5.25.

Aerosol correction	Years excluded	% ozone change in 8 years		
		Layer 6	Layer 7	Layer 8
(A) Uncorrected		-3.5	-10.0	-12.6
(B) Uncorrected	1982, 1983, 1984	-3.5	-9.7	-11.4
(C) Corrected		-3.1	-8.5	-8.7
(D) Corrected	1982, 1983, 1984	-3.2	-8.8	-8.9

Simple visual inspection of the Umkehr figures or examination of the least-squares slopes presented in the figures shows that the five north midlatitude Umkehr stations give an ozone reduction in the upper stratosphere smaller than that indicated by SBUV and greater than that given by SAGE–I and –II. The next section examines the problem of error estimates of the Umkehr data.

5.5.3 Error Estimates for the Umkehr Trends

5.5.3.1 Sensitivity to Assumed Particle Size Distribution

One uncertainty in calculating the aerosol corrections is the size distribution of the particles. A sensitivity study was made using three different size distributions (including two extreme cases) for each of three different periods (Table 5.8). Where the corrections are large, the two-sigma spread of the correction due to extreme variations in assumed size distributions is about 20 percent of the correction itself—4.6 percentage units out of 21.5—and the average of the three extreme distributions is not largely different from the preferred distribution based on

observed aerosols. The correction for aerosols is not highly dependent on the aerosol size distribution used.

Table 5.8 Sensitivity Study of the Effect of Three Different Assumed Size Distributions for Aerosols: The Distribution Function Based on Observed Aerosols and Two Widely Different Arbitrary Distributions

The mean Umkehr error or the calculated aerosol correction factor is given in percentage units, and twice the standard deviation of the three correction factors is given in the same percentage units. The second set of three values gives the Umkehr error based on the preferred distribution function that was used. The optical thickness is γ.

Date	γ	Mean Umkehr error $\pm$ 2σ (%) Layer 6	Layer 7	Layer 8
December 1982	0.087	-1.5 $\pm$ 1.0	-9.4 $\pm$ 3.8	-21.5 $\pm$ 4.6
August 1983	0.041	-1.1 $\pm$ 0.4	-6.4 $\pm$ 2.0	-10.4 $\pm$ 2.4
December 1985	0.008	-0.3 $\pm$ 0.2	-0.9 $\pm$ 0.2	-2.3 $\pm$ 0.8
		Corresponding values for the preferred distribution function Layer 6	Layer 7	Layer 8
December 1982	0.087	-2.1	-10.3	-23.3
August 1983	0.041	-1.4	-7.4	-11.6
December 1985	0.008	-0.3	-1.1	-2.6

5.5.3.2 Sensitivity to Choice of Umkehr Stations

There is one common condition under which a comparison can be made between a 5-station Umkehr network and an 11-station Umkehr network. The last line of Table 5.5 is to be compared with line (B) of Table 5.7. These results are for uncorrected Umkehr data with 3 years omitted to minimize the effect of El Chichón for the 11-station study (Wellemeyer, private communication, 1987) and the 5-station study (DeLuisi et al., private communication, 1988), respectively. For the three Umkehr layers, 6, 7, and 8, these two analyses give, respectively, the 8-year ozone changes (-2.4, -3.5), (-9.6, -9.7), and (-10.4, -11.4). The maximum difference is 1.1 percentage point. The weighting factors used to combine the stations give low weight to the sparse, noisy cases shown in Figure 5.22, and the entire network gives very nearly the same trends as the five stations with the largest density of observations.

Another sensitivity test was to compare results using the five stations with the results found by eliminating either Lisbon or Boulder. Essentially the same results were reached, with or without Lisbon or Boulder.

5.5.3.3 Estimated Trend Error Due to Uncertainty in the Aerosol Correction Algorithm

There is a line of argument that gives insight into the magnitude of the aerosol error. A comparison of the corrected and uncorrected Umkehr time series in Figures 5.24 to 5.26 at the time of maximum aerosol correction (January 1983) suggests that the correction at layer 8 may be too large. One may take as the uncertainty due to aerosols one-half the spread between applying and not applying the correction used here. In percentage points, the full spread between the 8-year ozone decrease, with and without any aerosol correction, is
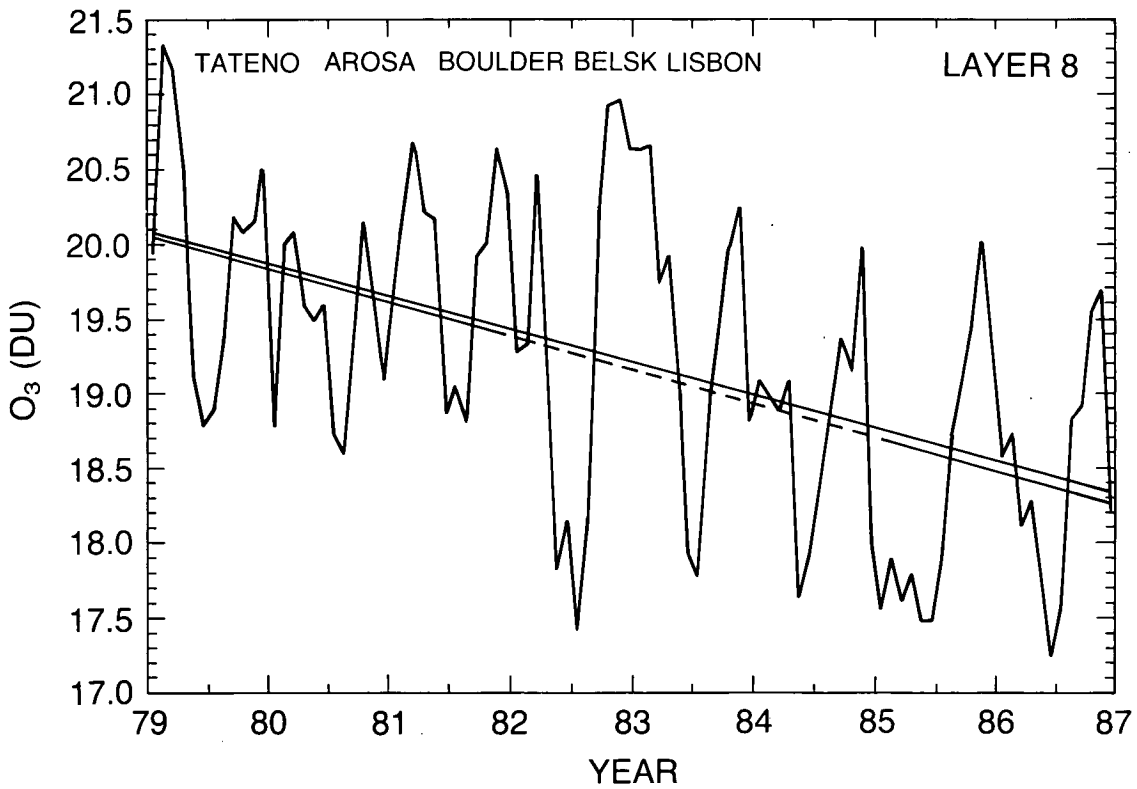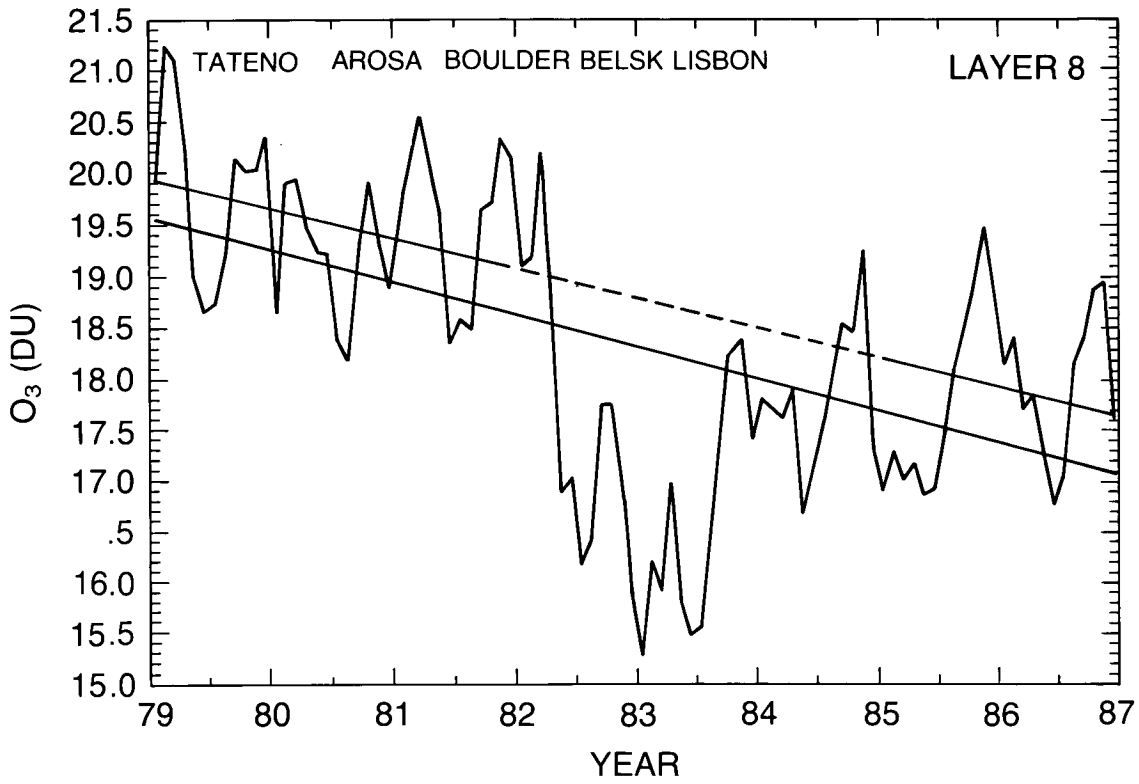
Figure 5.26 Same as 5.24, except it is for layer 8.

-3.1 to -3.5 at layer 6
-8.5 to -10.0 at layer 7
-8.7 to -12.6 at layer 8 (Table 5.7).

With these assignments, the ozone decreases over the 8-year period, including errors just for uncertainty in the aerosol corrections, are

-3.1 ± 0.2 at layer 6
-8.5 ± 0.8 at layer 7
-8.7 ± 2.0 at layer 8.

5.5.3.4 Statistical Errors

Pending an analysis of the statistical errors of the aerosol-corrected Umkehr trends (Table 5.7), the statistical error estimates from the uncorrected 11-station study (Table 5.5) are adopted for the aerosol-corrected trends. This approach may overestimate the error for the five stations selected for their high density of observations, since it includes the stations with sparse and noisy data (Figure 5.22). However, the sparse, noisy data are given low weight by the N/σ^2 weighting function. The estimated random errors are then:

± 2.6 percent at layer 6
± 3.3 percent at layer 7
± 4.3 percent at layer 8.

5.5.3.5 Sampling or Systematic Error

For the five midlatitude stations used in this section, the average reduction of total ozone (as found by local Dobson measurements) across the 8-year period is 6.6 percent, whereas the average value for the renormalized Total Ozone Mapping Spectrometer (TOMS) data at comparable latitudes is 3 or 4 percent (Chapter 4). In the Umkehr method, ozone values reported at layers 6 to 8 are based on features of the observations that are not strongly dependent on total ozone, and a sampling difference in total ozone may make no difference in the upper stratospheric profile. If the large change in total ozone is caused by drift in calibration, then the reduction of ozone reported in the upper stratosphere is probably overestimated. At present, this possible error is not quantified.

5.5.3.6 Central Values and Combined Aerosol and Statistical Error Estimates

The central values of the Umkehr trends are taken to be those corrected for aerosols, including the full 8 years of data (line (C) of Table 5.7). The (95 percent confidence level) statistical error estimates (Section 5.5.3.4) are combined (root sum of squares) with the estimate of the maximum aerosol errors (Section 5.5.3.3). The 8-year ozone changes derived from Umkehr, rounded to the nearest percentage point, are regarded as:

-3 ± 3 percent at layer 6
-8 ± 4 percent at layer 7
-9 ± 5 percent at layer 8.

These error estimates do not include the effect of possible systematic errors besides aerosols.

5.6 SBUV, SAGE–I, AND LIMS OZONE INTERCOMPARISON (SPRING 1979)

The purpose of this study is to examine quantitatively the degree of consistency in stratospheric ozone measurements from three satellite instruments, SBUV, SAGE–I, and LIMS, which were operating at the same time during spring 1979 (Gille and Russell, 1984; Remsberg et al., 1984). The analysis is an intercomparison of the ozone data from these instruments in terms of ozone column abundance in four Umkehr layers (6 to 9). In the case of SAGE–I and LIMS, it is necessary to convert their primary measured ozone quantities to ozone Umkehr layer amount for comparison purposes. Since the sampling locations of the SAGE–I instrument are distributed in a narrow latitudinal belt for a 24-hour period, as opposed to the nearly global observations of the SBUV and LIMS for the same period, the comparison analysis is carried out by following the SAGE–I latitudinal sampling progression. Because the three satellite instruments never sampled at the same locations and times, the comparison is made in terms of the zonally averaged ozone layer amount in these Umkehr layers. The ozone data from SBUV are from the version 5 retrieval, the SAGE–I ozone data are a recently revised product (Chapters 2 and 3), and the LIMS data are the combined mode zonal mean coefficients from the LIMS Map Archival Tapes (LAMAT).

The SAGE–I instrument takes 15 sunrise and 15 sunset measurements per day, which are distributed almost evenly in the longitudinal direction along a nearly constant latitude circle. The mean value derived from these 15 sunrise/sunset SAGE–I daily measurements represents the zonal mean for that day. The corresponding daily zonal means of SBUV and LIMS were obtained by interpolation with latitude. Table 5.9 gives the latitudinal progression of the daily SAGE–I data for both sunrise and sunset measurements during spring 1979.

Table 5.9 The Beginning and Ending Dates (in 1979) and Latitudes of Four Cases of Longitudinal Progression of the SAGE–I Observations

| SAGE–I | Begin | | End | |
	Date	Latitude	Date	Latitude
1 Sunrise	March 2	57.1°N	March 31	55.4°S
2 Sunset	March 2	37.3°S	March 21	64.0°N
3 Sunrise	April 6	57.7°S	April 29	41.8°N
4 Sunset	April 1	50.7°N	April 28	51.8°S

For the cases of March 1979 sunrise and of April 1979 and SAGE–I sunset, the zonal mean ozone layer amounts are given in Figures 5.27 and 5.28. The standard deviation of the SAGE–I instrument about its zonal means, shown by the vertical bar, is less than 10 percent except at high latitudes. The standard deviation for LIMS about its zonal mean is about 4 percent, and that for SBUV is about 2 percent. The three satellite systems show the same pattern with latitude. The same data are presented in Figures 5.29 and 5.30 as the deviation of each instrument against the mean of the three. The results displayed in these two figures show that SBUV data are about 3 percent systematically lower than the other instruments in layer 6, but not systematically different from the other satellite instruments in layers 7, 8, and 9.

For each of the three satellite instruments, the four Umkehr layers, and the four times, the root-mean-square deviation from the average of the three instruments is given in Table 5.10. For 15 of 48 entries in the table, the deviations are less than 3 percent; for 23 of 48 entries the deviations are between 3 percent and 5 percent; and for 10 of 48 entries the deviations are greater than 5 percent but less than 10 percent. These data give an example of how closely three totally
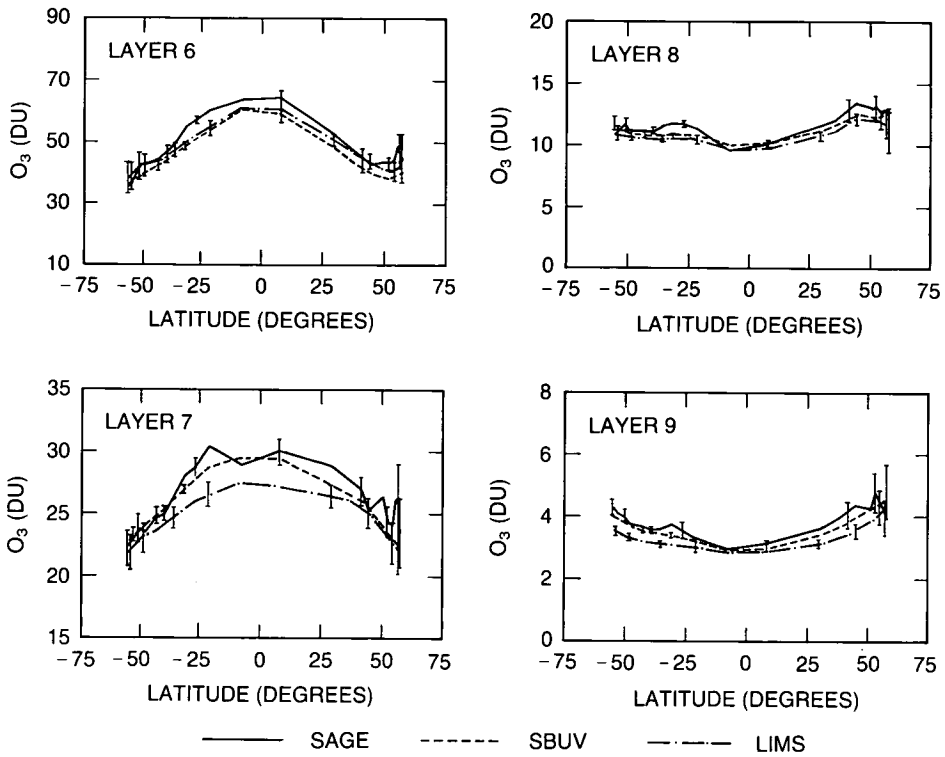
Figure 5.27 Comparison of zonal mean ozone layer amount calculated from the SBUV, SAGE–I, and LIMS observations for the case of March 1979 SAGE–I sunrise (Table 5.9).
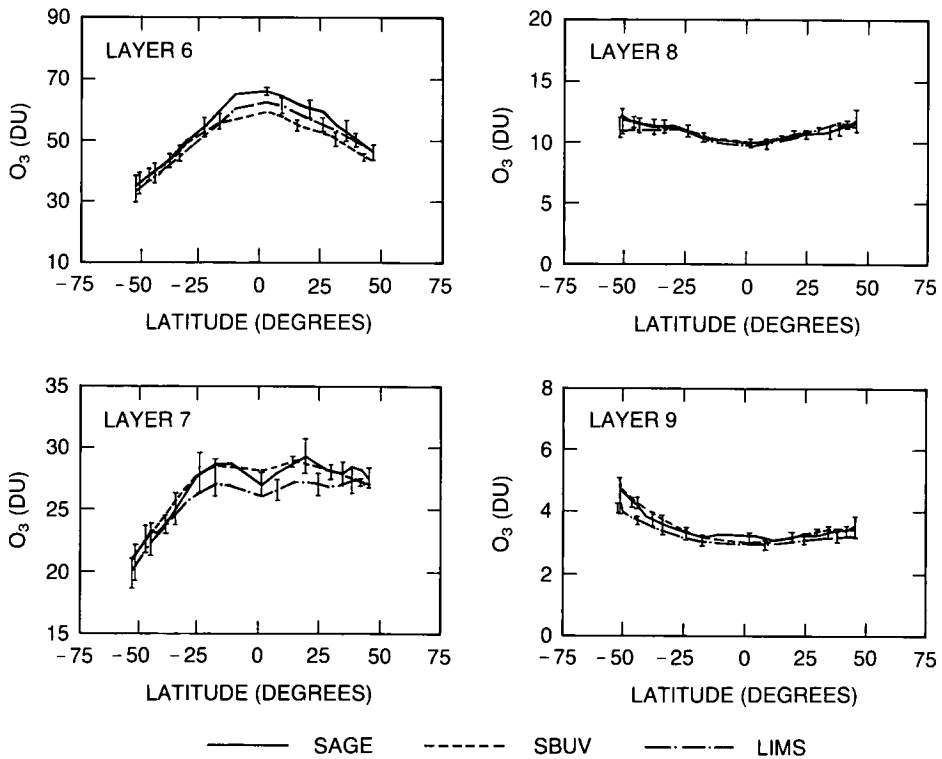

Figure 5.28 Same as Figure 5.27 except for April 1979 SAGE–I sunset.
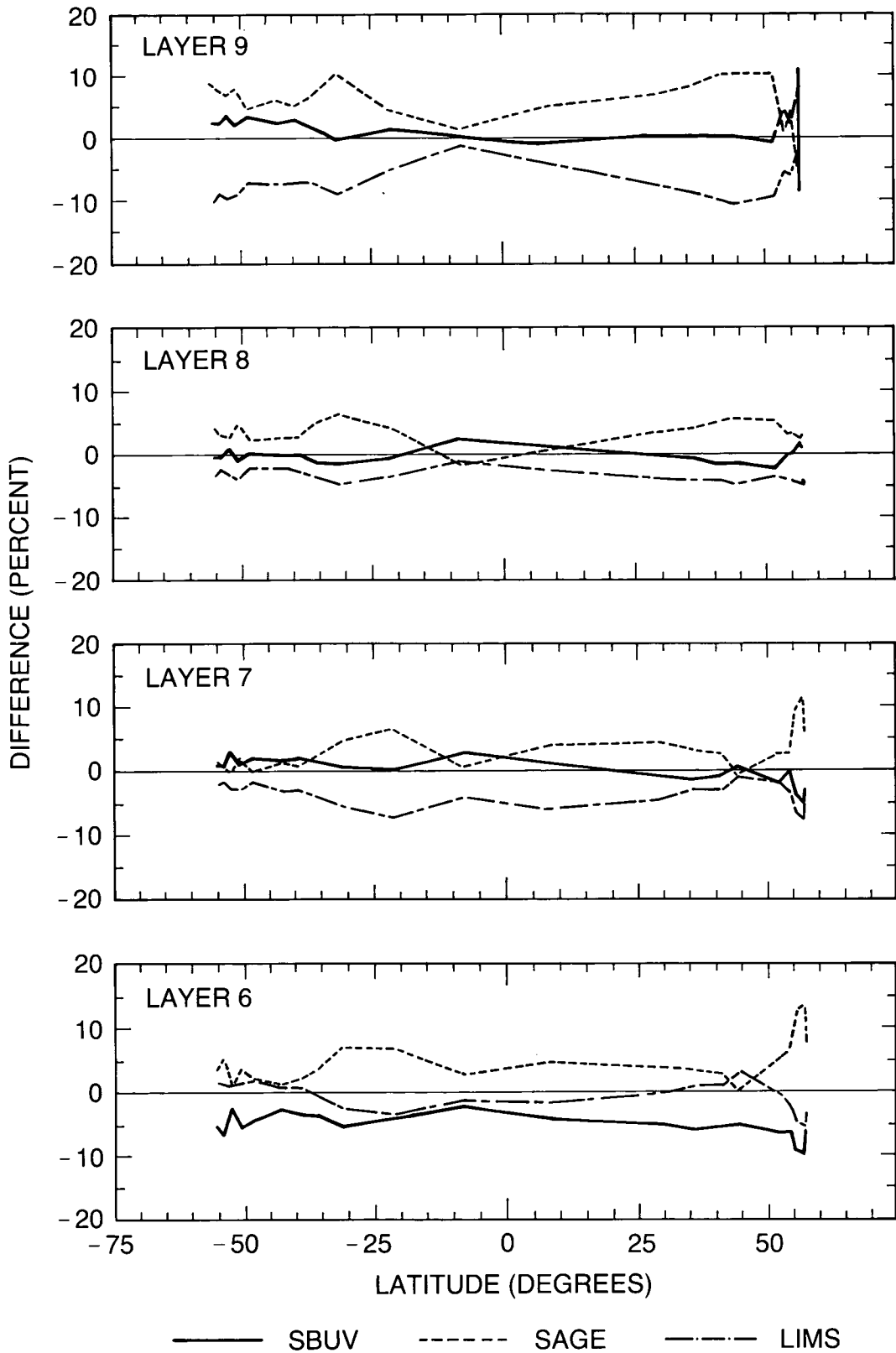
428

Figure 5.29 Percentage difference of zonal mean ozone layer amount of SBUV, SAGE–I, and LIMS from the average for the case of March 1979 SAGE–I sunrise (Table 5.9).
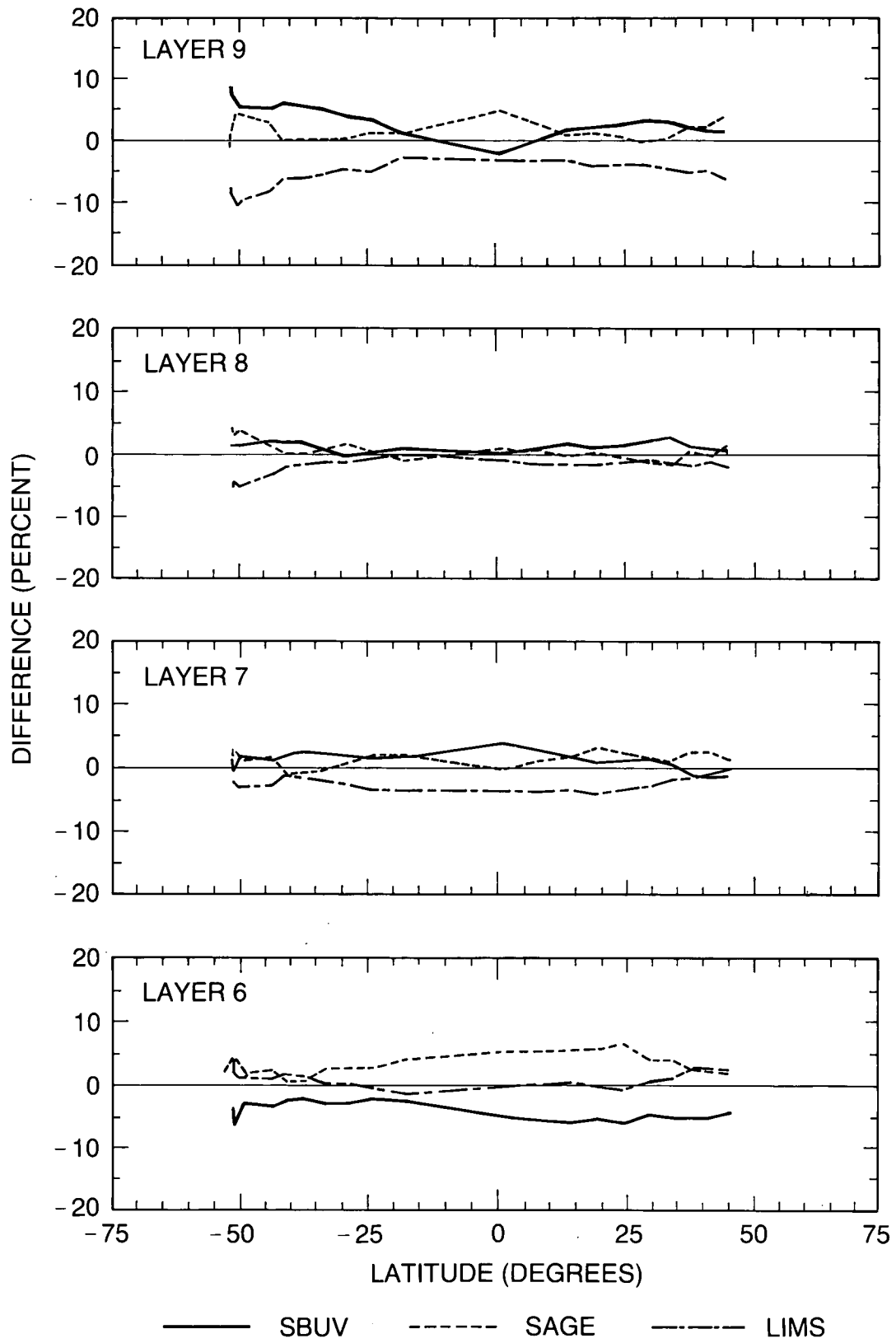
Figure 5.30 Same as Figure 5.29 except for April 1979 SAGE–I sunset.

different, newly launched satellite systems agree with each other in measuring zonal mean ozone amounts in the four Umkehr layers in the middle to upper stratosphere (about 4 percent).

Table 5.10 Estimated Overall Percentage Differences of the Calculated Zonal Mean Ozone Layer Amount of SBUV, SAGE–I, and LIMS With Respect to the Average of These Instruments

| | Umkehr Layer | | | | | |
| | Layer 6 | | | Layer 7 | | |
SAGE–I	SBUV	SAGE	LIMS	SBUV	SAGE	LIMS
1 Sunrise (March 1979)	4.5	6.3	2.6	2.4	4.2	4.6
2 Sunset (March 1979)	2.8	3.1	1.6	3.8	2.8	4.0
3 Sunrise (April 1979)	5.1	3.7	1.3	2.9	1.5	3.7
4 Sunset (April 1979)	3.8	3.6	1.2	2.8	1.4	3.4
	Layer 8			Layer 9		
	SBUV	SAGE	LIMS	SBUV	SAGE	LIMS
1 Sunrise (March 1979)	1.6	3.6	4.4	4.2	6.1	8.9
2 Sunset (March 1979)	3.0	4.1	4.2	3.3	7.7	8.6
3 Sunrise (April 1979)	1.6	3.2	3.9	3.0	7.3	9.5
4 Sunset (April 1979)	2.6	1.7	3.3	6.2	1.8	6.9

5.7 TRENDS AT UPPER BOUNDARY OF THE STRATOSPHERE (SBUV, SME, SMM)

5.7.1 SBUV Results

The SBUV instrument reports the largest percentage local ozone reduction at 50 km, the upper boundary of the stratosphere (Figure 5.4), and the upper limit of direct information content from SBUV (Chapter 3). Two satellite instruments have measured ozone in the mesosphere down to an altitude just above the upper limit of SBUV (Rusch et al., 1984; Aikin et al., 1984; Aikin, private communication, 1987). Although these instruments do not cleanly overlap SBUV, they provide evidence about ozone trends at the upper boundary of the SBUV region. The time series data of these two instruments are examined here.

5.7.2 Solar Mesospheric Explorer

The Solar Mesospheric Explorer (SME) is described by Rusch et al. (1984) and in the calibration and algorithm chapters of this report. The SME spacecraft measures ozone by means of two instruments. The ultraviolet spectrometer (UVS) operates as an ultraviolet backscatter instrument, as is the case with SBUV, but the SME UVS is used in a limb-viewing mode rather than the nadir, as with the SBUV. The near-infrared spectrometer (NIRS) operates by limb viewing the 1.27 μ airglow emission that arises from excited molecular oxygen produced during ozone photodissociation. Ozone concentrations can be derived from the 1.27 μm emission.

Certain instruments on the SME are known to drift with time, and SME has onboard methods for the indirect calibration of the drifting instruments (Chapter 3). In 1987, the SME team reinterpreted and updated the SME data, including an analysis of the drift of the ultraviolet spectrometer (Rusch and Clancy, 1988). The sensitivity of the upper channel of the ultraviolet

spectrometer was judged to have decreased 4.8 ± 1.37 percent per year. This correction and its uncertainty affect the ozone trends, as indicated by both the UVS and the NIRS methods.

The ozone-mixing ratios as measured by the SME UVS (+) and the SBUV (*) at 1.0 mb in 1982 are shown as a function of latitude in Figure 5.31. The data are monthly averaged values for the two instruments. The absolute values of the ozone-mixing ratio and the latitude dependence are in agreement for most times and locations. The results agree generally within 10 percent.

Trends in ozone at 0.75 mb are evaluated from the SME data by both the airglow and infrared methods. The trends are derived using average (0° to 60°N) ozone-mixing ratios from each instrument for the first 2 weeks in June for the 5 years 1982–1986. The SME data are limited to the June period, as processing for other times is not yet complete and the satellite attitude was optimum in June. The trends, derived from the June data by use of a linear least-squares fit, are 1.57 percent per year for the UVS and 2.4 percent per year for the NIRS. The airglow results can be evaluated by a method that is independent of the UVS and that relies only on the spacecraft attitudes determined by the horizon sensors; this method gives an ozone increase of 1.8 percent per year. By using the extremes (2σ) of the uncertainties in the UVS sensitivities in inverting the data (4.8 ± 1.37 percent per year), the range in the trends is shown in Figure 5.32. The values of the ozone trends at the extremes of the sensitivity changes are -0.7 and +4.1 percent per year. These values from SME are inconsistent with the large ozone decreases displayed by SBUV in Figures 5.3 and 5.4.
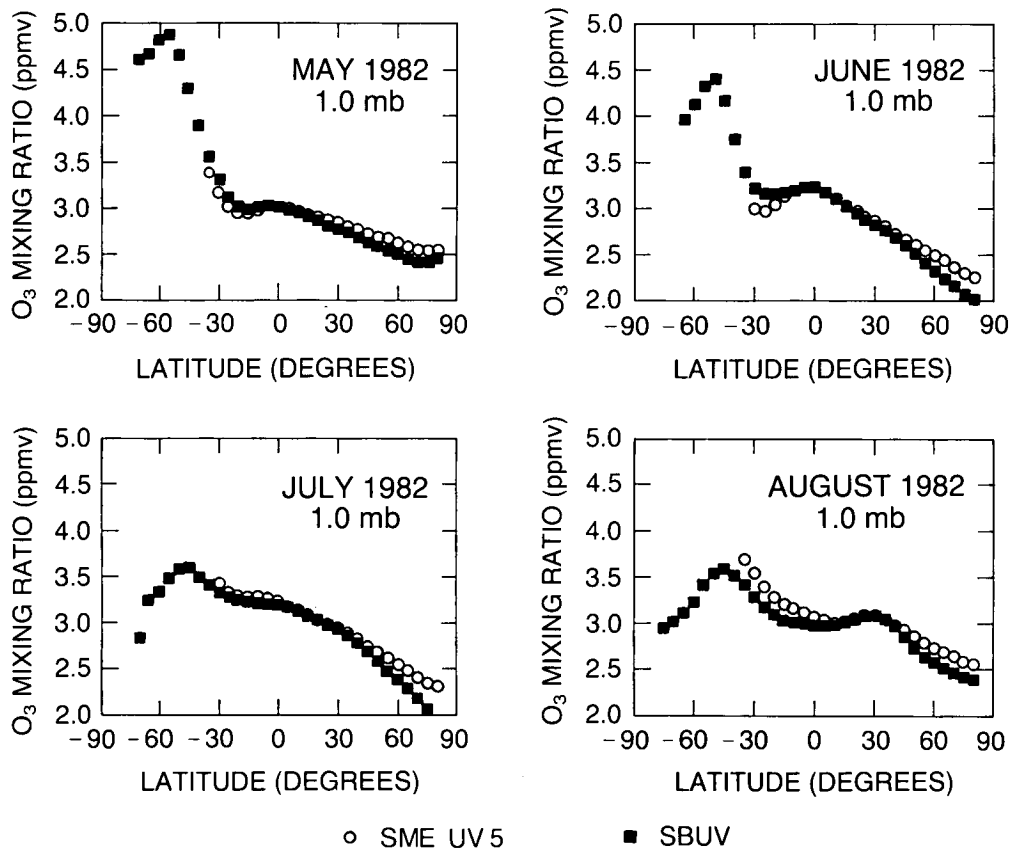

Figure 5.31   SME UVS (+) and SBUV (*) average (0° to 60°N) mixing ratios at 1.0 mb for May, June, July, and August.
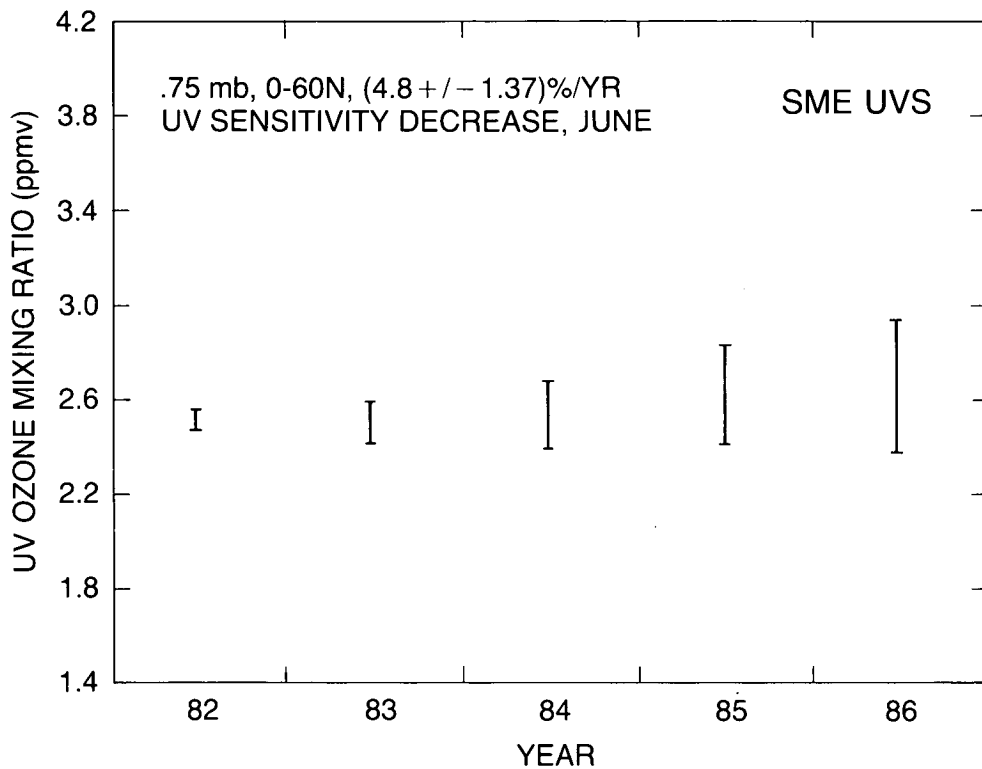
Figure 5.32 Envelope of maximum (2σ) trend of ozone mixing ratios from the UVS instrument of SME for June 1982 to 1986 at 0.75 mb. The error bars denote the range of the data (2σ) resulting from uncertainty in the determination of UVS sensitivity change with time.

5.7.3 Solar Maximum Mission

Ozone altitude profile data from 1984–1988 have been obtained by observing solar occultation with the Ultraviolet Spectrometer Polarimeter (UVSP) on the Solar Maximum Mission (SMM) spacecraft. Launch occurred in early 1980, and solar pointing was lost in late 1980. In-orbit spacecraft repairs were effected in 1984; operations have continued since that time. Details of the instrument and its performance are described by Woodgate et al. (1980). The method of obtaining ozone concentrations as a function of altitude is given by Aikin et al. (1984) and by Aikin (private communication, 1987).

The SAGE instrumentation operates on the same solar occultation principle as the SMM experiment, except that longer wavelengths are employed by SAGE. The altitude range of SAGE is about 25 km to 60 km. Several SMM and SAGE profiles were compared; for example, see Figure 5.33. The concentration of ozone reported by SAGE–II is systematically neither higher or lower than that of SMM (UVSP on the figure).

Figures 5.34 and 5.35 present the weekly mean ozone concentration at an altitude of 55 km plotted as a function of time for the latitude of 20° north and south. Also shown as a histogram is the total number of occultations included in each weekly mean. Since occultation observations were interrupted for a variety of reasons, the data record is not continuous, and there is not a uniform number of points in each sample. The SMM data show seasonal variations, but no obvious trend.
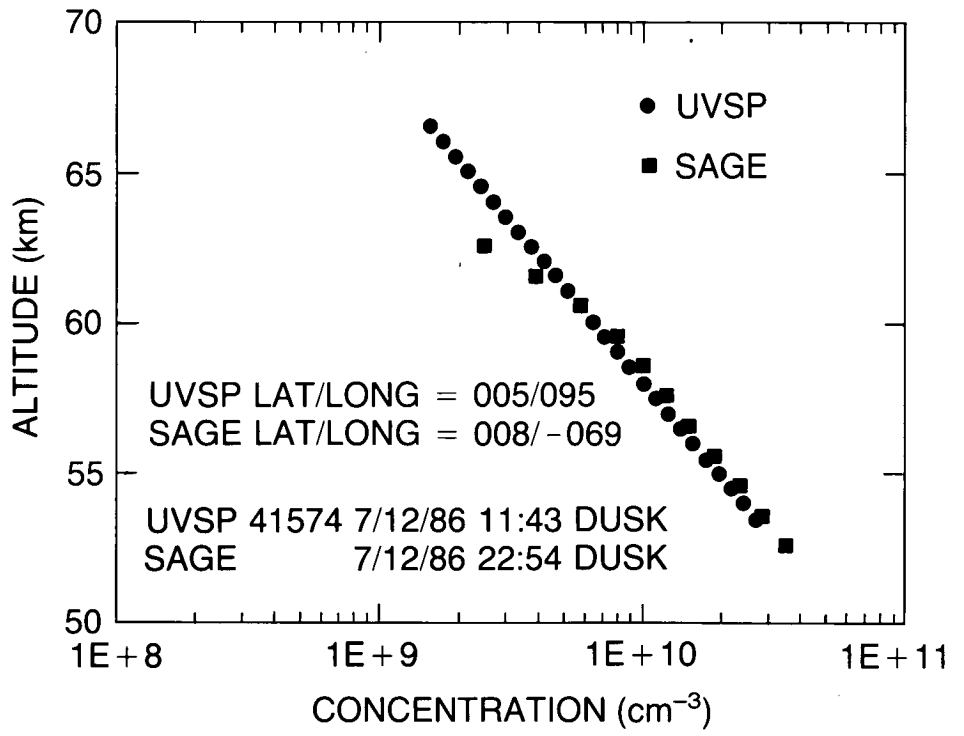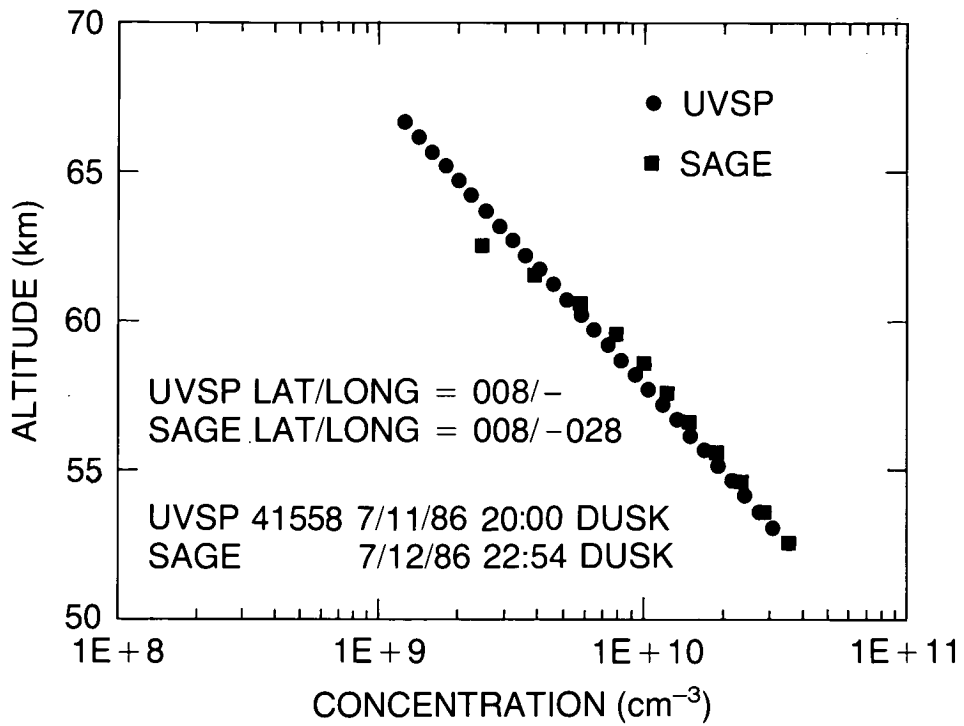
Figure 5.33 Ozone concentration versus altitude for SMM (UVSP) and for SAGE–II.

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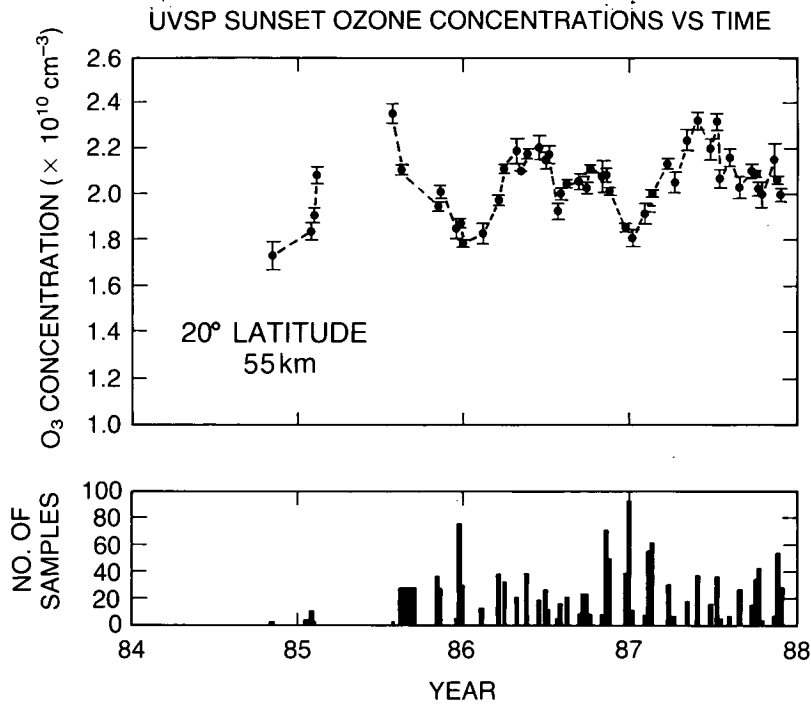
Figure 5.34 Sunset ozone concentrations from the SMM instrument in the 53–57 km region plotted as a function of time for 20°N. Each point represents a weekly mean. The histogram gives the number of profiles, contributing to each weekly mean point. The solid curve is the SBUV 0.4 mb weekly mean ozone concentration. The SBUV and SMM data were taken at different local times; at these altitudes, ozone changes during the diurnal cycle.
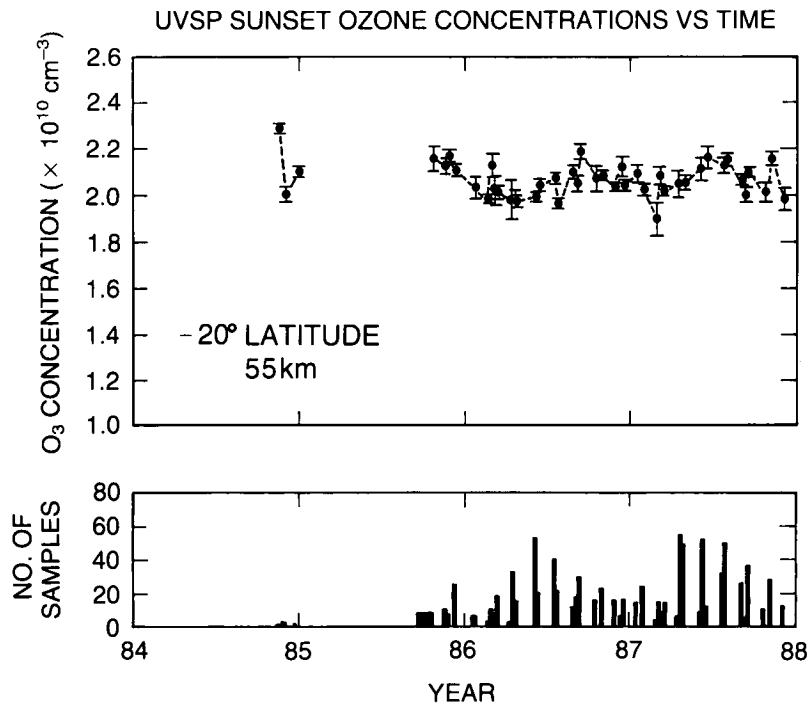
Figure 5.35 Same as Figure 5.34, except at 20°S.

5.7.4 Conclusions

The body of ozone data taken by SME and SMM between 53 and 57 km supports the conclusion by SAGE–I and –II that no large ozone decreases occurred at 50 km between 1979 and 1987.

5.8 ROCKET OZONESONDE (ROCOZ–A)

5.8.1 Introduction

The ROCOZ–A ozonesonde measures the solar ultraviolet irradiance over its four filter wavelengths as the instrument descends on a parachute. The amount of ozone between the ROCOZ–A radiometer and the Sun is calculated from the attenuation of solar flux as the instrument falls, using the Beer–Lambert law. The fundamental measurement from ROCOZ–A is ozone overburden (column amount) versus radar altitude from 20 km to 52 km. Aspects of ROCOZ–A included in this section are discussed by Barnes and Simeth (1986) and Barnes et al. (1986 and 1987), and in Chapter 2.

5.8.2 Estimates of the Accuracy of ROCOZ–A Ozone Profiles

The accuracy estimates for ROCOZ–A come from an internal, unpublished error analysis. A laboratory flight simulator based on long-path-length photometry (DeMore and Patapoff, 1976) has been constructed to calibrate ROCOZ–A ozone readings. The accuracy of the ozone column amounts and ozone number densities from ROCOZ–A, including auxiliary pressure and temperature measurements, has been estimated at 6 to 8 percent.

5.8.3 Comparison With In Situ Instruments

ROCOZ–A ozone measurements have been compared with those from an in situ UV absorption photometer during the Balloon Ozone Intercomparison Campaign (BOIC) (Hilsenrath et al., 1986). In one comparison, ROCOZ–A measured 5 to 10 percent higher than the in situ photometer for atmospheric pressures between 50 mb and 4 mb. In a subsequent balloon flight spanning 6 mb to 2 mb, a ROCOZ–A ozonesonde was compared with the same photometer and with a mass spectrometer from the University of Michigan (Anderson and Mauersberger, 1981); ROCOZ–A read higher than the in situ photometer by 8 percent and lower than the mass spectrometer by 4 percent. There is cause for concern in this intercomparison, since the in situ photometer and the mass spectrometer are both considered to be absolute instruments.

Hilsenrath et al. (1986) report laboratory comparisons of in situ photometers during BOIC. There is good agreement between the photometers flown on BOIC and similar agreement between the photometers and the ozone standard instrument from NBS. There is strong evidence to support the quality of the ozone measurements from the in situ photometers in BOIC.

On the other hand, there is a series of high-quality laboratory results with the Minnesota mass spectrometer. Hanson and Mauersberger (1985 and 1986) have used the mass spectrometer to study the vapor pressure of ozone at liquid argon temperatures. Mauersberger et al. (1987)

used long-path photometry to show 0.5 percent agreement between the thermodynamic vapor pressure standard and the ozone cross-section at 253.65 nm.

5.8.4 Ozone Measurements at Natal, Brazil

In the late 1970's and early 1980's, satellite measurements of the equa-torial stratosphere and mesosphere showed low variability in ozone during the Southern Hemisphere autumn (Frederick et al., 1984; McPeters et al., 1984; Rusch et al., 1984). In March and April 1985, NASA and the Brazilian space agency (INPE) conducted a series of ozone soundings at Natal, Brazil. The measurements were made in conjunction with over-passes of the SME, the SAGE–II instrument on the Earth Radiation Budget Satellite, and the SBUV spectrometers on Nimbus–7 and NOAA–9. Seven series of flights were conducted from March 25 to April 15, 1985, producing atmospheric profiles of ozone, pressure, and temperature from the ground to 52 km (Barnes, 1988). Above 22 km, stratospheric ozone variability was 2 percent or less during the 3 weeks of the measurement campaign, with stratospheric tempera-ture and pressure variabilities half that amount.

5.8.5 Estimates of Instrument Repeatabilities, an Upper Limit on Their Imprecision

The 2 percent variability in upper stratospheric ozone at Natal, Brazil, for 3 weeks in March and April 1985 implies a comparable uniformity for ozone profiles over a large area around the measurement site. This condition removes the requirement of exact concurrence between satellite and in situ ozone measurements, allowing comparisons of larger data sets. For ROCOZ–A, the sample at Natal includes seven profiles from March 25 to April 15, 1985. For SBUV, the samples were taken from March 20 to April 19, with 32 profiles in 1979 and 38 profiles in 1985. All of the SBUV measurements were within 2 degrees in latitude and 24 degrees in longitude from Natal. For SAGE–II, the sample set includes 14 measurements from March 22 to April 17, 1985. Each SAGE–II profile is within 12 degrees in latitude and 15 degrees in longitude from Natal. The sampling area for SAGE–II reflects its more sparse spatial coverage, when compared with SBUV. The SAGE–I samples from 1979 are similar to those from SAGE–II in number and coverage, both in time and space. The LIMS measurements were taken from March 17 to April 20, 1979, and cover the latitude range from the Equator to 8°S latitude. The selection of LIMS, SBUV, SAGE–I, and SAGE–II data from the archives for this comparison with ROCOZ–A is described by Barnes et al. (1987).

The instrument comparisons are presented in terms of ozone amounts within Umkehr layers, the nominal primary product from the standard SBUV algorithm. For ROCOZ–A, both SAGE instruments, and LIMS, conversion to this form requires a significant change in units as well as independent knowledge of the temperature and pressure fields. Table 5.11 presents the ozone columns in Umkehr layers 6 to 9 as found by SBUV, SAGE–I, and LIMS in 1979 and as found by SBUV, SAGE–II, and ROCOZ–A in 1985. The reproducibility of each instrument is given by the standard deviations reported in Table 5.11, except that this figure includes any atmospheric variability, which for SAGE observations includes latitudinal variations over about a 12-degree range. The single layer reproducibilities vary from 1.4 to 7.3 percent, and the average of the 24 cases is 3.3 percent. These measures of reproducibility may be interpreted as an upper limit of the imprecision of the various instruments. The standard deviations of the means, involving from 6 to 38 profiles among the various instruments, are mostly less than 1 percent, and all are less than 2 percent. This high reproducibility of the individual systems suggests that most discrepancies reported between different instruments are due to systematic errors of the systems.

Table 5.11 Reproducibility of Satellite and Rocket Systems in Measuring Upper Stratospheric Ozone Near Natal, Brazil, During Periods of Atmospheric Stability in 1979 and 1985

Umkehr Layer	Ozone Layer Amount (a)	σ% (b)	Sample Size	σ of Mean %
	SBUV (1979)			
9	7.96(16) (c)	1.8	32	0.32
8	2.62(17)	1.4		0.24
7	7.60(17)	1.4		0.25
6	1.56(18)	2.5		0.44
	SAGE–I (1979)			
9	8.62(16)	6.1	13	1.54
8	2.76(17)	6.2		0.88
7	7.66(17)	7.1		1.26
6	1.74(18)	4.1		1.25
	LIMS (1979)			
9	7.89(16)	1.9	30	0.34
8	2.64(17)	2.2		0.41
7	7.22(17)	3.0		0.54
6	1.70(18)	1.7		0.29
	SBUV (1985)			
9	7.12(18)	1.7	38	0.27
8	2.58(17)	2.6		0.42
7	7.74(17)	2.2		0.36
6	1.58(18)	3.6		0.58
	SAGE–II (1985)			
9	7.84(16)	7.3	14	1.96
8	2.89(17)	4.3		1.16
7	8.10(17)	3.4		0.92
6	1.68(18)	2.0		0.53
	ROCOZ–A (1985)			
9	8.59(16)	1.9	6	0.78
8	2.92(17)	4.4		1.79
7	8.19(17)	3.9		1.49
6	1.67(18)	2.5		0.93

(a) Molecules cm^{-2} over Umkehr layer. (b) Relative standard deviation. (c) Read 7.96(16) as 7.96×10^{16}, etc.

Using the same data as in Table 5.11, an estimate of how much the individual instruments differ from each other is obtained; the average deviations of three instruments from their own average value are given in Table 5.12 for 1979 and 1985. These instruments, with the uniform atmosphere near Natal and the good reproducibility shown in Table 5.11, give an instrument-to-instrument variability of 4 or 5 percent.

Table 5.12 Replication of Upper Stratospheric Ozone by Sets of Three Instruments*

The average of the three instruments and the standard deviation of the three instruments from the average.

Umkehr Layer	1979 Average Layer Amount (a)	σ %	1985 Average Layer Amount (a)	σ %
9	8.16(16)	5.0	7.85(16)	9.4
8	2.67(17)	2.8	2.80(17)	6.6
7	7.49(17)	3.2	8.01(17)	3.0
6	1.67(18)	5.8	1.64(18)	3.1
	Average	4.2	Average	5.5

*Compare Table 5.11.
(a) Molecules cm^{-2} over Umkehr layer.

5.8.6 Comparison of SAGE–II and SBUV With ROCOZ–A Ozone Vertical Profiles

The composite ozone vertical profile obtained by ROCOZ–A and by chemical ozonesondes at Natal in spring 1985 (Barnes et al., 1987) is presented in terms of ozone concentration as a function of geometric altitude in Figure 5.36. The profiles of the percentage difference between ROCOZ–A and the ozone vertical profiles given by SBUV and by SAGE–II overflights are included in the figure. The comparisons are made in terms of the primary data from the respective satellite instruments. SAGE–II provides ozone concentrations versus altitude. Between 25 and 50 km, the differences, SAGE minus ROCOZ–A, are sometimes positive and sometimes negative, with an average of about -1 percent, and never exceeding 5 percent. The ROCOZ–A ozone data are translated into columns over Umkehr layers, and the difference, SBUV minus ROCOZ–A, is included on the figure. For Umkehr layers 6, 7, 8, and 9, the differences are all negative; that is, SBUV values are less than those of ROCOZ–A. The differences are 18 percent at layer 9 and 5 percent at layer 6.

5.8.7 Discussion of Instrument Comparisons Given in Sections 5.6, 5.7, and 5.8

The 12 percent difference between stratospheric ozone measurements from the Minnesota mass spectrometer and the ultraviolet spectrometers flown in the BOIC (Section 5.8.3) gives rise to the following speculation: there may be some unrecognized atmospheric optical effects that perturb ozone measurements by some of the remote sensing instruments. For example, nitric oxide fluorescence near 255 nm is known to overlap one of the SBUV lines, but such fluorescence lines, which are observed in the laboratory with decreasing intensity at intervals up to about 390 nm, might also cause variations in apparent ozone in some instruments. Other unrecognized atmospheric fluorescence or absorptions may be occurring.

The data in Section 5.6 give an example of how closely three totally different, newly launched satellite systems agree with each other over a 6-month period in measuring zonal mean ozone
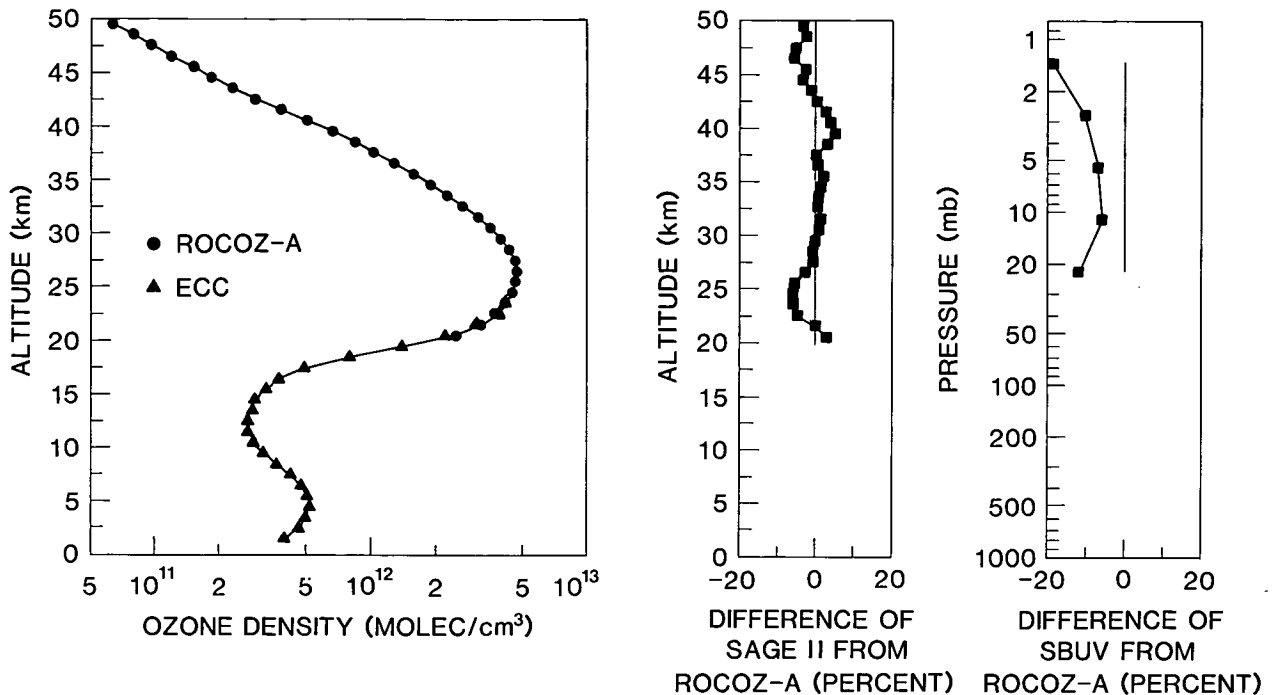
OZONE DENSITIES AT NATAL, BRAZIL, MARCH/APRIL 1985

Figure 5.36 Average ozone vertical profile based on ROCOZ–A and chemical ozonesondes at Natal, Brazil, in March and April 1985. Middle panel: SAGE–II minus ROCOZ–A, vertical profile of ozone percentage difference at Natal in 1985 as a function of geometrical altitude. Right panel: SBUV minus ROCOZ–A, vertical profile of ozone percentage difference at Natal in 1985 at Umkehr layers and as a function of pressure.

amounts in the four Umkehr layers in the middle to upper stratosphere (about 4 percent). For a 2-year period, the zonal average ozone values over four Umkehr layers for the newly launched SBUV and SAGE–I instruments agreed within about 4 percent from 60°N to 60°S (Figure 5.13). In the relatively uniform and slowly changing tropical stratosphere, two sets of three-way instrument comparisons (Section 5.8.5) showed the average deviations of each instrument from the average of the three to be about 5 percent. By extension, one is led to believe that the ability of current satellite systems to measure the absolute value of ozone in the upper stratosphere is not much better than about 4 percent. By further extension, it is difficult to believe that presently available remote sensing satellites can reliably detect changes in upper stratospheric ozone of much less than 4 percent.

5.9 CONCLUSIONS

From an examination of the agreements and differences between different satellite instruments (Sections 5.3. 5.6, 5.7, and 5.8), it is difficult to believe that existing satellite instruments determine upper stratospheric ozone much better than 4 percent; by extension, it probably would require at least a 4 percent change to be reliably detected as a change.

The best estimates of the vertical profiles of ozone change in the upper stratosphere between 1979 and 1986 are judged to be those given by the two SAGE satellite instruments.

- SAGE–II minus SAGE–I gives a much lower ozone reduction than that given by the archived SBUV data; for example, at temperate latitudes and at 40 km, SBUV gives 15 percent and SAGE gives 3 percent. With added considerations from Chapters 2 and 3, the difference is largely ascribed to systematic error in the treatment of the SBUV diffuser plate.

- The average SAGE profiles of ozone changes between 20 and 50 degrees north and between 20 and 50 degrees south are given by Figure 5.18. The altitude of maximum ozone reduction is 40 km, in agreement with atmospheric models. The magnitude of maximum ozone reduction is 3 ± 3 percent (95 percent confidence level) at 40 km. The central value of this ozone reduction is less than the consensus of current theoretical models; a set of different models gives ozone reductions that range from 5 to 12 percent at an altitude near 40 km (Chapter 7). The relative systematic error between SAGE–I and –II is estimated to be 2 percent (see Chapter 2); an error estimate for the models is not available.

- The SAGE–I and –II comparison gives an ozone reduction of about 4 percent at 25 km over temperate latitudes. This altitude is near the ozone concentration maximum, and this ozone change represents a much larger reduction of the ozone column than that given at 40 km. This observed ozone change at 25 km is larger than that given by theoretical models, and future studies should concentrate on the reality and explanation of this ozone reduction (for example, is it a weak manifestation of the features that give the large Antarctic ozone reduction?).

Five ground-based Umkehr stations between 36 and 52 degrees north, corrected for the effects of volcanic aerosols, report an ozone reduction between 1979 and 1987 at Umkehr layer 8 of 9 ± 5 percent (95 percent confidence level, including a term for uncertainty in the aerosol correction, but not including possible systematic errors). The central estimate of upper stratospheric ozone reduction given by SAGE at 40 km is less than the central value estimated by the Umkehr method at layer 8.

In the future, the best way to improve knowledge of ozone profile changes between 1979 and 1987 will be to compare the first 2 years of validated SBUV–2 data against seasonally matched 2 years of the early SBUV data, similar to the procedure used by SAGE–I and –II.

To measure upper stratospheric ozone changes as small as 5 percent in 10 years, the instrument operators and data interpreters must have an extremely high level of ability, sophistication, dedication, and financial support. Such a measurement is a formidable scientific and engineering challenge. It requires continual attention to instrument performance, calibration, and verification; there needs to be a large number of duplicate, overlapping measurements. This task will not be achieved if it is regarded as a routine monitoring operation.