# CHAPTER 9

# Surface Ultraviolet Radiation

**Lead Author:**
R.L. McKenzie

**Co-authors:**
M. Blumthaler
C.R. Booth
S.B. Diaz
J.E. Frederick
T. Ito
S. Madronich
G. Seckmeyer

**Contributors:**
S. Cabrera
M. Ilyas
J.B. Kerr
C.E. Roy
P.C. Simon
D.I. Wardle

# CHAPTER 9

## SURFACE ULTRAVIOLET RADIATION

### Contents

## SCIENTIFIC SUMMARY

- There is overwhelming experimental evidence that, all other things being equal, decreases in atmospheric ozone result in UV-B increases at the Earth's surface, in quantitative agreement with predictions by radiative transfer models.

- Large UV-B increases have been observed in association with the ozone "hole" at high southern latitudes. Biologically damaging radiation at the South Pole exceeded that in the Arctic by more than a factor of two, for the same solar zenith angle. At Palmer Station, Antarctica (64.5°S), erythemal and DNA-damaging radiation sometimes exceeded summer maxima at San Diego (32°N). These measured differences agree well with model calculations.

- Large increases in UV-B were measured, despite the natural variability in cloudiness, at northern middle and high latitudes in 1992/93 compared with previous years. These are the first reported examples of persistent increases associated with anomalous ozone reductions over densely populated regions.

- Clear-sky UV measurements at midlatitude locations in the Southern Hemisphere are significantly larger than at a midlatitude site in the Northern Hemisphere, in agreement with the expected differences due to ozone column and Sun-Earth separation.

- The increases in UV resulting from ozone reductions measured by satellite from 1979 to early 1994 have been calculated, assuming other factors such as pollution and cloudiness did not change systematically over this period. The calculated increases are largest at short wavelengths and at high latitudes. Poleward of 45°, the increases are significantly greater in the Southern Hemisphere. At 45° (N and S), the calculated increase at 310 nm was approximately 8 to 10 percent over this 15-year period, but there was considerable year-to-year variability.

- Tropospheric ozone and aerosols can reduce global UV-B irradiances appreciably. At some locations, tropospheric pollution may have increased since pre-industrial times, leading to some decreases in surface UV radiation. However, recent trends in tropospheric pollution probably had only minor effects on UV trends relative to the effect of stratospheric ozone reductions.

- Only a few studies have monitored UV-B over time scales of decades, and these have yielded conflicting results on the magnitude and even sign of the trends. Some studies may have been affected by problems with instrument stability and calibration, and local pollution trends. Recently published data from unpolluted locations appear to show the expected increases due to ozone depletion. The baseline UV irradiances present at mid and high latitudes before ozone depletion began are not known.

- Significant improvements have been made in UV instrumentation and its calibration. Intercomparisons between spectro-radiometers show, however, that it is still difficult to achieve absolute calibration accuracies better than ±5 percent in the UV-B region. Therefore, the detection of future trends will require careful measurements at short wavelengths that are more sensitive to changes in ozone.

- Cloud variability causes large temporal changes in UV. Although recent advances have been made, our ability to realistically model cloud effects is still limited.

- Scattering by stratospheric aerosols from the Mt. Pinatubo volcanic eruption did not alter total UV irradiances appreciably, but did increase the ratio of diffuse to direct radiation.

## 9.1 INTRODUCTION

Although the ultraviolet (UV) region represents only a small component of the total solar spectrum, these wavelengths are important because the photon energies are comparable with molecular bond energies in the biosphere. The UV radiation that reaches the Earth surface can be arbitrarily divided into 2 sub-regions: UV-B (280-315 nm), which is strongly absorbed by ozone; and UV-A (315-400 nm), which is only weakly absorbed by ozone. Less than 2 percent of the extra-terrestrial solar energy falls within the UV-B range, and only a small fraction of this reaches the surface.

Here we review progress in our understanding of UV at the surface since the last assessment (WMO, 1992) and attempt to identify remaining gaps in our knowledge. Impacts of UV increases (*e.g.,* effects on the biosphere, including human health and materials) are outside the scope of this report and are discussed in the UNEP "Effects Panel" reports (1991, 1994). Impacts on tropospheric chemistry that may result from changes in UV radiation fields are also discussed in Chapter 5 of this report. These may lead to either positive or negative feedbacks to stratospheric ozone depletion (UNEP, 1991 and 1994; Madronich and Granier, 1994).

Detailed reviews of our understanding of UV at the surface can also be found in Tevini (1993) and Young *et al.* (1993).

## 9.2 UPDATE ON TREND OBSERVATIONS

### 9.2.1 Results Derived from Broad-Band Meters

Analyses of broad-band data have focused on variability in the radiation received in specific geographic regions over time scales of months to years. The much-discussed work of Scotto *et al.* (1988) showed a decline in annually integrated irradiance measured by eight Robertson-Berger (RB) meters in the continental United States between 1974 and 1985. The average trend based on all stations was -0.7 percent per year, while the statistically significant values for individual stations varied from -0.5 to -1.0 percent per year. A careful analysis of the RB meter's operating characteristics was carried out shortly after the publication of Scotto *et al.* (1988). These studies showed that the spectral response functions of selected meters were remarkably stable over time, although small differences between instruments existed (DeLuisi *et al.,* 1992). As part of this evaluation, Kennedy and Sharp (1992) found no obvious problems in the RB meter system apart from a well-documented temperature sensitivity. This does not appear to be a likely explanation for the downward trends found by Scotto *et al.* (1988). However, some of the detailed information required to assess the stability of the RB meter network is no longer in existence. More recent work (DeLuisi, 1993; DeLuisi *et al.*, 1994) has uncovered a potential shift in calibration of the RB meter network in 1980 that could remove the downward trend found by Scotto *et al.* (1988). This issue merits further attention before definitive conclusions are reached.

Frederick and Weatherhead (1992) studied the time series of RB data from two specific sites, Bismarck (46.8°N) and Tallahassee (30.4°N), where Dobson column ozone data were available over the period from 1974 to 1985. They found that the derived trend in clear-sky RB data during the summer months was consistent with that expected from the Dobson data. However, during winter, when the measured broad-band irradiances were very small, a pronounced downward trend near -2 percent per year exists in the RB data. This differs in sign from spectrally weighted irradiance calculations for clear skies based on the Dobson ozone. The winter behavior in the RB data sets at Bismarck and Tallahassee is not readily explained by any known change in the atmosphere above these sites. Although the influences of cloudiness and ozone in the boundary layer can be detected in the output of the RB meter (Frederick *et al.,* 1993a), these influences are not likely to be causes of the winter trends in broad-band irradiance.

Blumthaler and Ambach (1990) reported an upward trend in RB readings made from an unpolluted site in the Swiss Alps at latitude 47°N during the period 1981 through 1989. Readings were expressed as ratios to the total solar irradiance measured by a pyranometer so as to remove the effects of aerosols. These measurements have continued, and the upward trend in the ratios was 0.7 ± 0.3 percent per year to the end of 1991, but results from 1992 were similar to those at start of the period. The analysis did not examine the trend by month of the year.

Recently, Zheng and Basher (1993) reported an upward trend in clear-sky RB data from Invercargill, New Zealand, at 46°S. The observation site is in an unpolluted region where changes in aerosols were small over the observation period. The deduced trend is anticorrelated in the expected way with column ozone data from the same location.

Temperature coefficients of order 1%/K have been reported for RB meters and their derivatives (Johnsen and Moan, 1991; Blumthaler, 1993; Dichter *et al.,* 1994). Of the trend analyses above, only that by Blumthaler and Ambach (1990) applied corrections for instrument temperature changes. New generation temperature-stabilized instruments are now available and are being tested against spectro-radiometers (Grainger *et al.,* 1993; McKenzie, 1994a).

### 9.2.2 Multi-Wavelength Measurements

The longest time series of UV irradiance at the ground has been published by Correll *et al.* (1992). A multi-filter instrument was used in Maryland (39°N, 77°W), over the period September 1975 to December 1990. The data show a large increase in UV-B, especially at shorter wavelengths over the period 1980 to 1987. The authors deduce from their measurements that the "RB-weighted" UV (over the interval 295-320 nm, however) would have increased by 35 percent over the period 1977-78 to 1985. This increase is much larger than expected from stratospheric ozone losses. The integral used would, however, show greater sensitivity to ozone loss than a real RB meter, which is more responsive at wavelengths longer than 320 nm in the UV-A region that are unaffected by ozone changes. A decrease in the irradiances after 1987 may be a consequence of changes to the instrument at that time, though the authors speculate that changes in aerosols and cloud conditions may have influenced the results.

### 9.2.3 Status of Trend Observations

The measurement of trends in UV is challenging from an instrumental point of view, and the availability and deployment of instruments to monitor trends in UV have been far from ideal. Instrument development over the past few years has continued to address the issues of stability, spectral response, spectral resolution, cost, and ease of maintenance in an attempt to meet the varied needs of the community. Short-term process studies have revealed strong anticorrelations between ozone and UV, in agreement with those expected from model calculations (WMO, 1992). Thus there is no doubt that, in the absence of other changes, reductions in stratospheric ozone will result in UV increases. However, the results of long-term studies have been conflicting. The network of RB meters was never designed to measure long-term trends, and questions still remain over the ability of broad-band meters to achieve this aim. Evidence now suggests that changing aerosol (and cloud) conditions can lead to increases or decreases in UV (Justus and Murphey, 1994). Further comparisons between RB measurements and pyranometer data at other sites are warranted. It is significant that at unpolluted sites, the observed increases in UV are comparable with those expected from ozone changes. Even at more polluted sites where UV has apparently not increased, it is reasonable to assert that current UV levels are greater than they would otherwise have been without ozone depletion. Better instruments are now available to monitor changes. These include improved broad-band monitors and sophisticated spectro-radiometers that can distinguish between changes caused by ozone and other effects such as aerosols and clouds. However, if current predictions are correct (see Chapter 13), much of the expected ozone depletion has already occurred. It will therefore be important to maintain careful calibration of these instruments over decadal time scales if trends in UV are to be discerned from natural variability. Although measurements from polluted sites will be of interest to epidemiologists and for process studies, instruments designed to monitor trends due to ozone depletion should generally be located at remote sites where tropospheric changes are minimized.

## 9.3 SPECTRO-RADIOMETER RESULTS

The observation period from spectro-radiometers is too short to detect trends. However, multi-year data are now available from a network of instruments operated by the National Science Foundation (NSF) (Booth *et al.,* 1994) and from several other groups (Gardiner *et al.,* 1993; McKenzie *et al.,* 1993; Kerr and McElroy, 1993; Ito *et al.*, 1994). Process studies using these data have already provided experimental corroboration of the modeled relationship between ozone and UV (WMO, 1992).

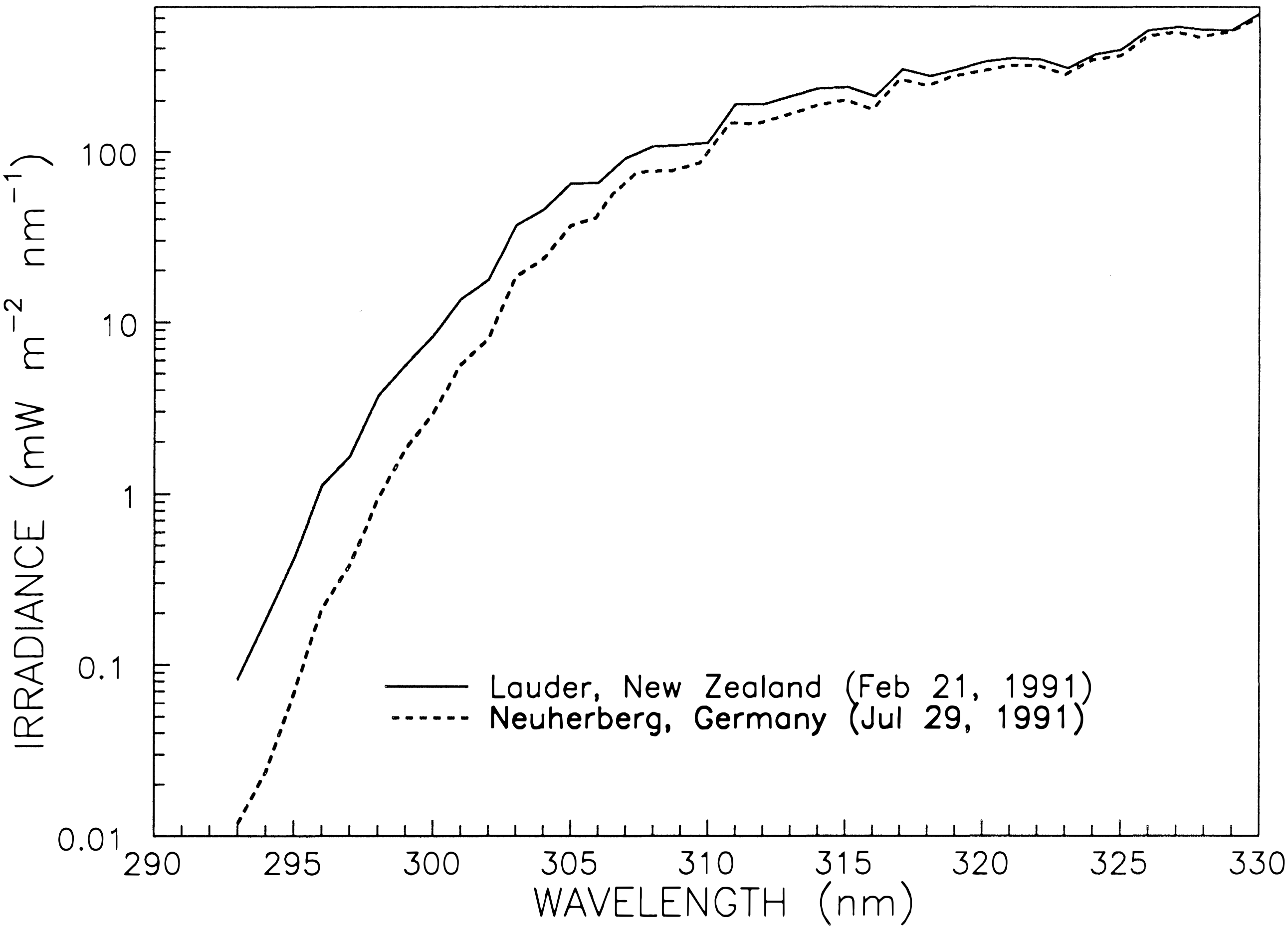

**Figure 9-1.** Measured clear-sky spectral irradiances in New Zealand and Germany for solar zenith angle 34.3°. The ozone column was 266 Dobson units (DU) in New Zealand and 352 DU in Germany. Note the logarithmic scale on the y-axis (adapted from Seckmeyer and McKenzie, 1992).

### 9.3.1 Intercomparisons

The measurement of solar UV spectral irradiances is demanding. The steep slope of the solar spectrum in the UV-B region (Figure 9-1) poses specific instrumental problems that must be overcome to cope with the wide dynamic range, the need to reject stray light adequately, and the need to align the wavelength accurately (McKenzie *et al.*, 1992). An additional problem concerns tracing the absolute calibration to a common standard. National standards laboratories themselves disagree by more than ±2 percent in the UV-B region (Walker *et al.*, 1991).

Excellent radiometric stability is required to measure UV trends or geographic differences. However, recent intercomparisons have revealed large calibration differences between some spectro-radiometers. Major sources of uncertainty are instability of sensitivity and cosine errors. Agreement at the ±5 percent level (Figure 9-2) is as good as can be expected at present (Gardiner *et al.*, 1993; McKenzie *et al.*, 1993; Seckmeyer *et al.*, 1994b). Further field and laboratory intercalibrations between instruments are required.

Given these measurement uncertainties, it will probably be necessary to use very short wavelengths in the UV-B that have a high sensitivity to ozone change to detect trends in UV due to the ozone depletions expected over the next decade. As one moves to shorter wavelengths, the sensitivity to ozone reductions increases dramatically. For example, a 1 percent reduction in

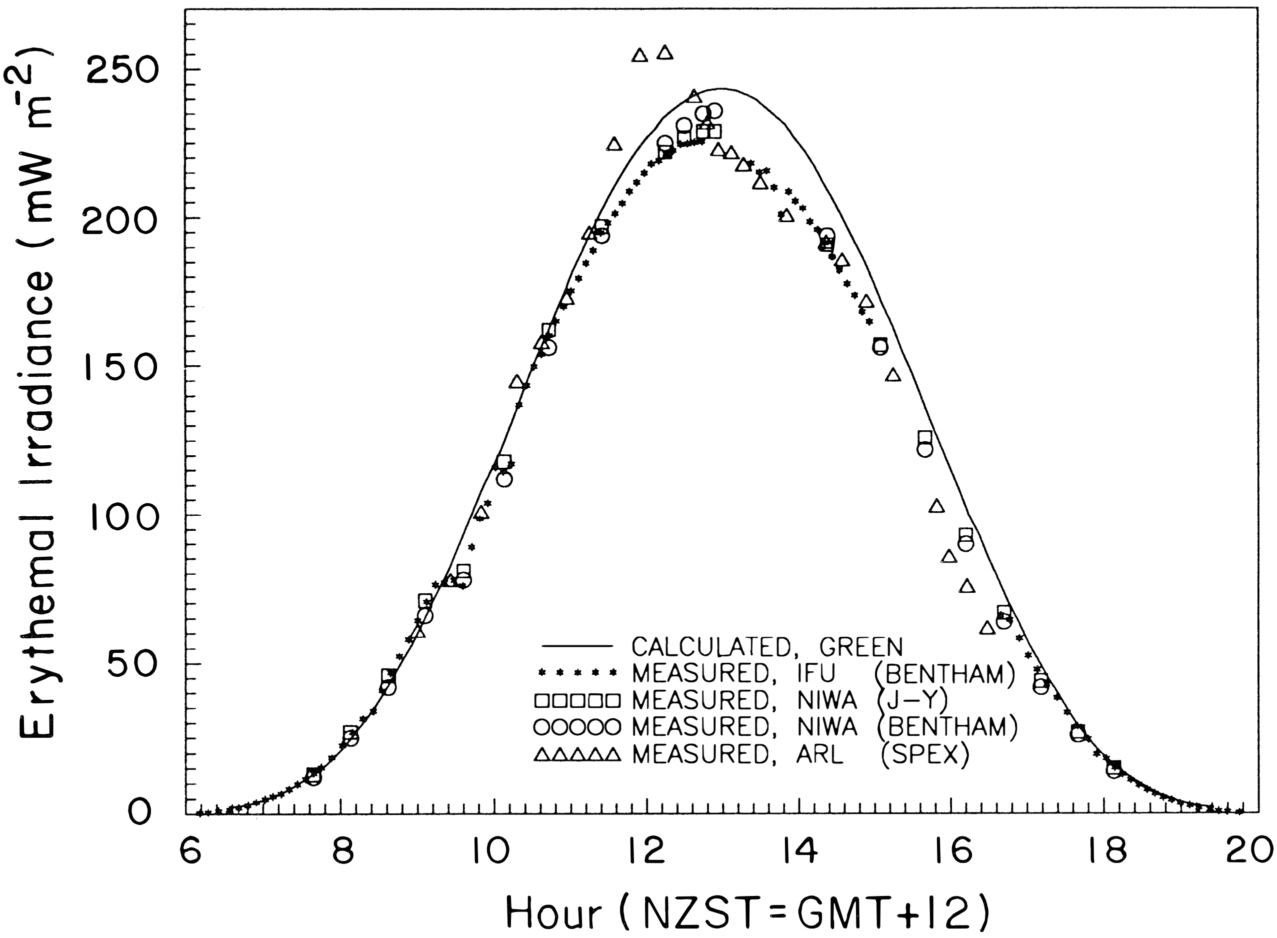

**Figure 9-2.** Comparison between measurements made with 4 spectro-radiometers at Lauder, New Zealand, on Feb 23, 1993. Instruments included were from National Institute of Water and Atmospheric Research, New Zealand (2), Australian Radiation Laboratory, Australia, and Fraunhofer Institute for Atmospheric Environment, Germany. Clear-sky model results are shown for comparison, although the observation day was not perfectly clear (adapted from McKenzie *et al.,* 1993).

ozone causes an increase of approximately 1 percent in UV at 310 nm, whereas the increase at 300 nm is 3 to 4 times as large (see Figure 9-12).

### 9.3.2 Geographic Differences

Although large geographical differences in UV-B are expected from theoretical considerations, there have been few published studies demonstrating measured geographic differences in UV-B radiation. A climatology obtained from a network of RB meters in the 1970s (Berger and Urbach, 1982) may be biased by the strong temperature coefficient of these instruments. Although the UV data base is improving, it still remains largely uncoordinated. Large latitudinal gradients have, however, been observed from the NSF network of spectro-radiometers, as discussed in Section 9.3.3 (Booth *et al.,* 1994).

Geographic intercomparisons based on measurements from the same instrument (Seckmeyer and McKenzie, 1992) have shown that for clear-sky observing conditions and similar solar zenith angles, UV irradiances measured in Europe are much less than in New Zealand (Figure 9-1). The differences are larger than expected from calculations using an earlier ozone climatology, though their spectral characteristics indi-

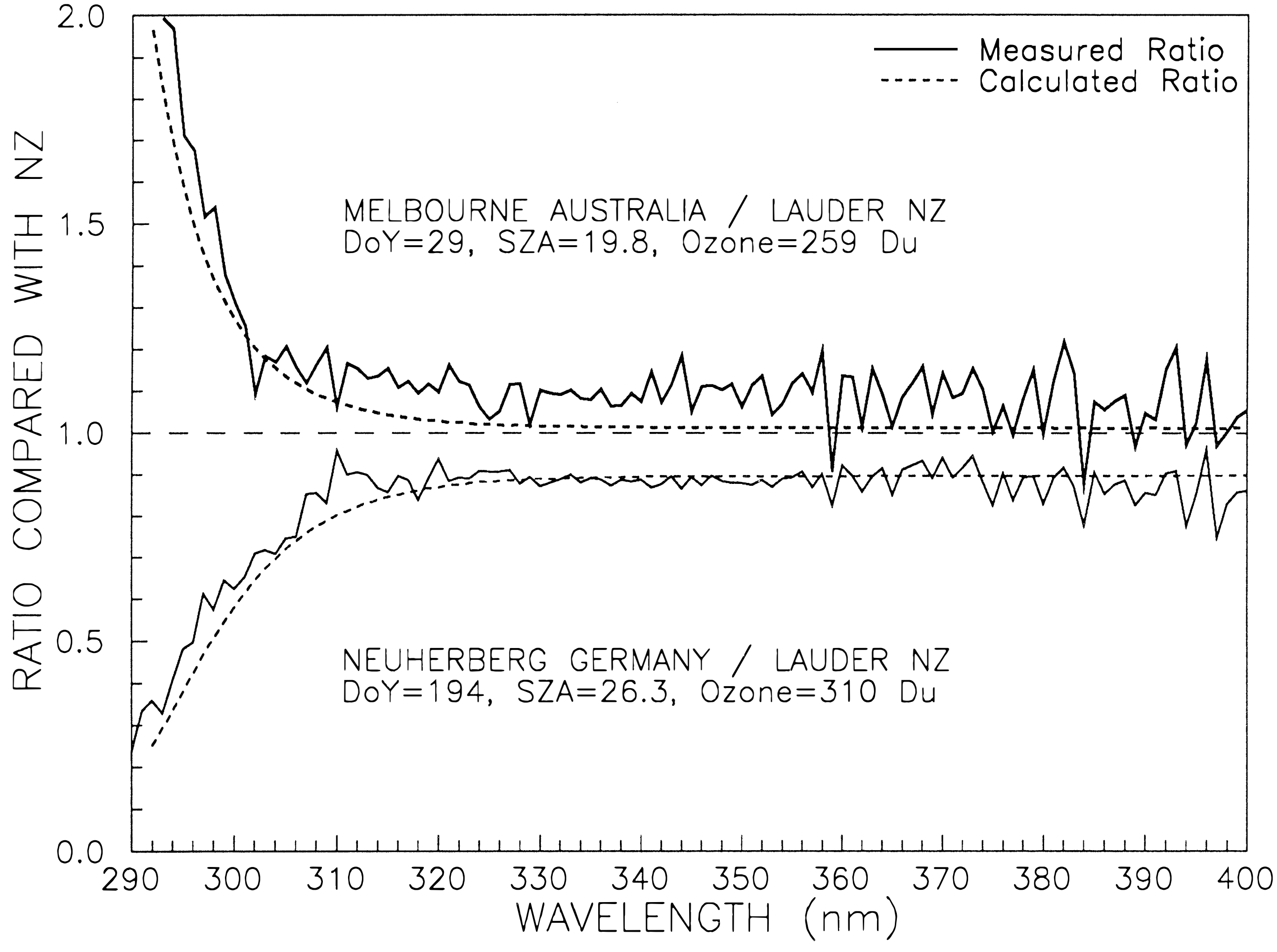

**Figure 9-3.** Geographic comparison between maximum clear-sky spectra measured in three countries. The ratios are with respect to a spectrum measured at Lauder on Dec. 27, 1992 (Day-of-Year [DoY] =362, sza=21.8°, ozone=278 DU). The smooth curves show calculated ratios assuming similar albedos and aerosol properties (adapted from McKenzie *et al.,* 1993).

cate that they are primarily due to ozone. This illustrates the importance of tropospheric ozone, which has increased in Europe (Staehelin and Schmid, 1991).

Data from cross-calibrated instruments have been used to compare the maximum clear-sky irradiances measured over several summers at three sites (McKenzie *et al.*, 1993). Ratios of these maximum clear-sky spectra obtained are shown in Figure 9-3. The maximum DNA-weighted UV (Setlow, 1974) measured in New Zealand (45°S) was 50 percent greater than at a similar latitude in Germany (48°N). UV irradiances in Australia (38°S) were significantly higher than in New Zealand. Figure 9-3 also shows ratios calculated with a simple model, assuming no differences in aerosol loading. The calculated differences in UV are due to differences in ozone, sun angle, and Earth-Sun separation. Measured and calculated ratios are in agreement within experimental uncertainties.

### 9.3.3 High Latitude (North and South)

Year-to-year variability in cloudiness is among the largest sources of variance in monthly integrated UV irradiance measured at the ground (Frederick *et al.,* 1993b; Diaz *et al.,* 1994), although this can vary from one location to the next, depending on the timing and severity of ozone depletions. At the NSF site in Ushuaia,

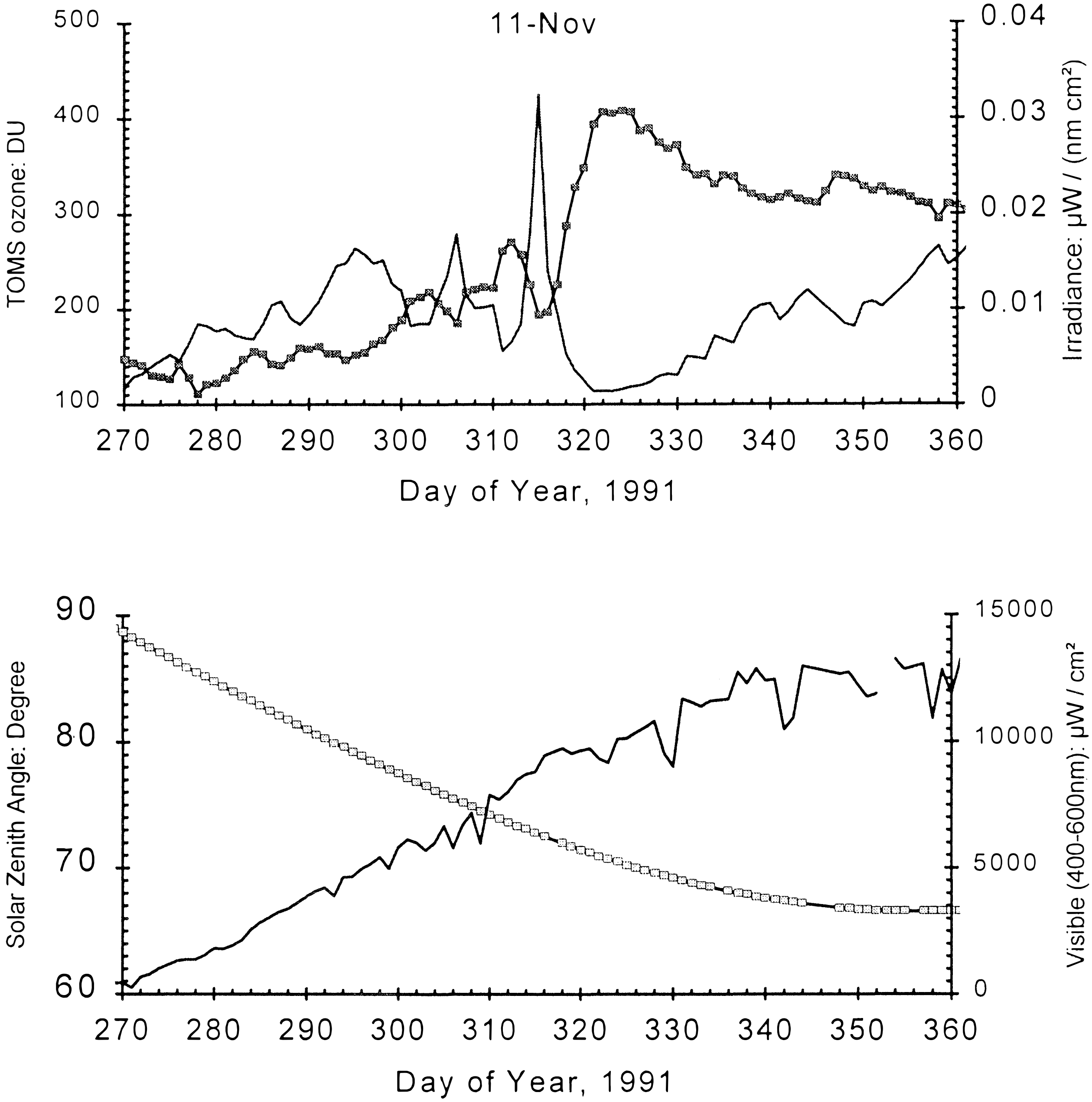

**Figure 9-4.** Time series showing details of daily mean values during the 1991 spring season at the South Pole. The upper panel shows the irradiance at 300 nm (line, right axis) and SBUV ozone (squares, left axis). The lower panel shows the integrated visible (400-600 nm) irradiance (line, right axis) and the solar zenith angle (squares, left axis). Adapted and updated from Booth *et al.*, 1994.

Argentina (54.6°S), the lowest ozone column amounts to date (1988-1992) were in 1992. However, the highest UV irradiances occurred in 1990, when the ozone hole persisted and was displaced towards South America. In December 1991, the erythemal UV (McKinlay and Diffey, 1987) was 45 percent larger than the zonal mean climatology, which is equivalent to moving 20° closer to the equator. Because radiation at 305 nm is sensitive to both ozone and cloud changes, whereas 340 nm radiation is insensitive to ozone, Frederick *et al.* (1993c) have investigated the irradiance ratio $I_{305}/I_{340}$ to remove cloud effects from UV measurements in Ushuaia. Over the summers of 1989-90 to 1992-93, these ratios were significantly larger than those deduced from a climatology of ozone measurements obtained over the period 1980 to 1986 (Frederick *et al.*, 1993c).

The unique geometry at South Pole Station (90°S) means that there are no diurnal cycles in solar zenith angle. This simplifies investigation of the relationship between UV, ozone, and other parameters. The strong anticorrelation between UV and ozone is demonstrated by Figure 9-4, which shows a UV maximum occurring on 11 November 1991 (day 315); a day when ozone was a local minimum. As is normal for Antarctica, the highest instantaneous UV irradiances (erythema, or UV-B) do not occur at the time of the greatest ozone depletion, but at a time closer to the summer solstice, combining the effects of higher solar zenith angles with relatively low ozone. In contrast, visible radiation increases steadily as the solar zenith angle decreases over the observation period (Figure 9-4). Perturbations by clouds are relatively small at this site, probably due to the high surface albedo and to extremely cold temperatures, which keep clouds from becoming optically thick. Although the relative increases are large, the absolute UV irradiances at this site are still small compared with those at mid or low latitudes.

Huge year-to-year variations in UV have been measured at the South Pole. These correlate with the location of the polar vortex and the persistence of springtime ozone depletion to times when higher solar elevations occur. Figure 9-5 shows that there are distinct differences between the timing of the seasonal maxima of UV-B and visible radiation. The UV has a maximum in the spring, whereas longer-wavelength radiation peaks near the summer solstice. UV in the range 298-303 nm was elevated by a factor of 4 in 1992 compared with 1991 (Booth *et al.*, 1994), and the 1992 maximum (November 29) occurred 18 days later than in 1991. Year-to-year variations were much smaller at longer wavelengths (338-342 nm) where ozone absorptions are small. In the 1993 austral spring, the lowest ever total column ozone amounts were recorded over Antarctica, bringing the highest UV irradiances for October at the South Pole.

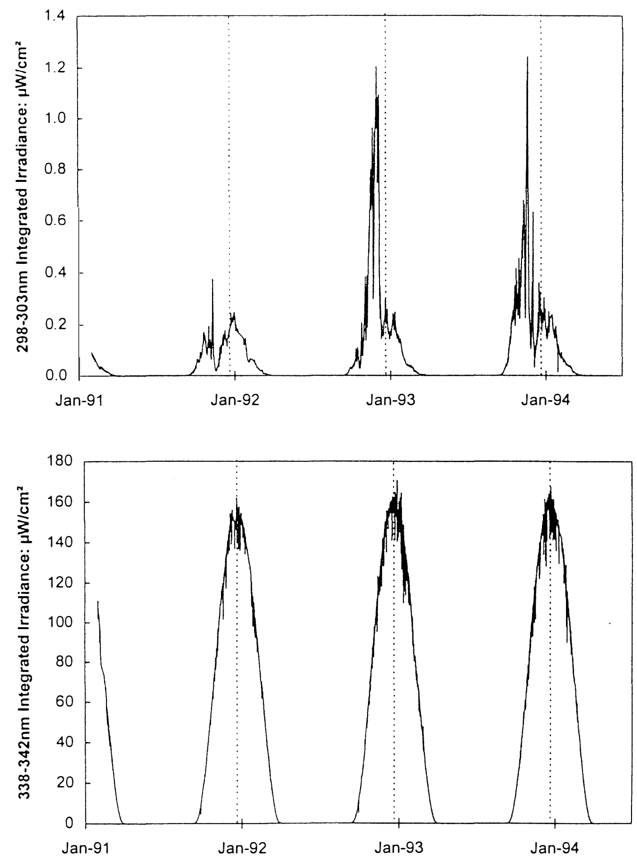

**Figure 9-5.** Hourly spectral irradiance integrated over 298-303 nm (upper panel) and over 338-342 nm (lower panel) at the South Pole between 1991 and mid-1994. Dotted vertical lines mark the summer solstices. Adapted and updated from Booth *et al.*, 1994.

The effects of Antarctic ozone depletions on UV irradiances have been clearly observed by comparisons with Arctic data. Figure 9-6 compares noontime irradiances (DNA-weighted and visible) from South Pole with those from an Arctic site at Barrow, Alaska (71.2°N, 156.5°W) as a function of solar zenith angle. DNA-

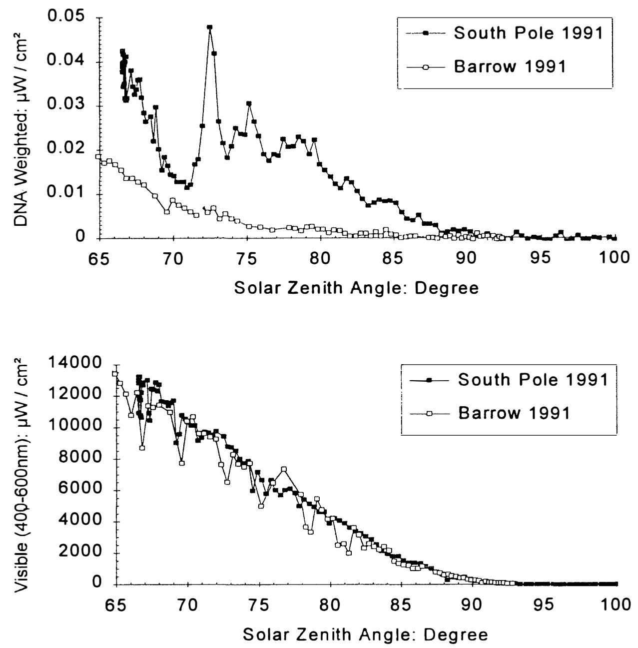

**Figure 9-6.** Comparison of time series of noontime radiation measurements at the South Pole in 1991 (solid squares) and Barrow, Alaska, (open squares) in the spring of 1991, plotted as a function of solar zenith angle. The upper panel shows DNA-weighted UV-B radiation, and the lower panel shows total visible radiation, 400-600 nm (Booth *et al.,* 1993).

weighted UV is several fold larger at South Pole during the period of the ozone "hole," while the visible irradiances are generally similar at both sites for similar solar zenith angles. In summer, the solar elevations are larger at Barrow than at South Pole, and the UV irradiances are larger. The lower panel of Figure 9-6 shows that cloud effects are relatively small at these sites. The NSF network installation at Barrow, Alaska, showed significantly elevated springtime UV-B in 1993 compared with previous years (Booth *et al.,* 1993).

At Palmer Station (64.5°S, 64°W), the highest biologically weighted UV doses of the six-year NSF network monitoring period were observed in late October of 1993, surpassing the previous records of early December, 1990. During this period, the noon readings of biologically damaging UV even exceeded the summer maximum measured at San Diego (32°N), as shown in Figure 9-7. Additionally, daily integrals of biologically weighted UV measured during the spring at Palmer Station sometimes exceeded those measured in summer in San Diego. Unlike the changes at the South Pole, the large UV doses at Palmer Station may have important biological consequences given the diversity of the marine ecosystem at these latitudes.

Large increases in spectral UV irradiance were observed in the Southern Ocean during the spring of 1990 as ozone-depleted air in the Antarctic vortex moved across the sampling site. These enhancements, which were apparent at the surface and beneath the ocean surface to depths of 35 m, were shown to have adverse effects on marine primary production (Smith *et al.,* 1992; Prezelin *et al.,* 1994; UNEP, 1994). Calculations with a coupled atmosphere-ocean radiative transfer model show that the effect of ozone depletion on UV-B penetration into the water depends on solar zenith angle and is more pronounced in spring than in summer (Zeng *et al.,* 1993).

### 9.3.4 Northern Hemisphere Midlatitude

Large ozone depletions have been measured at mid-Northern latitudes in 1992 and 1993. In the late winter and spring of 1993, the ozone was 7 percent below the climatological envelope. Decreases were larger at high northern latitudes, but smaller at equatorial and southern latitudes (Herman and Larko, 1994; also see Chapter 1). Depletions continued into the summer, when the UV irradiances are greatest.

The study by Kerr and McElroy (1993) was the first to show the effects of ozone depletions on integrated daily UV-B at midlatitudes, including cloudy conditions. Over the 4-year period to August 1993 there were large changes in ozone measured over Toronto, Canada (44°N, 29°W). Although there are gaps in the data and the observation period is rather short, a statistical analysis was performed. The ozone change over this period was reported as -4 percent per year in the winter months, and -2 percent per year for the summer, as measured by the Brewer spectrometer. The corresponding temporal changes in UV were small at wavelengths above 320 nm and increased toward shorter wavelengths. The increase at 300 nm was 35 ± 20 percent per year in winter (when UV flux is in any case rather weak) and 6 ± 10 percent per year in summer. The statistical significance of these results has been disputed (Michaels *et al.,* 1994) because some of the results were influenced by a few days in

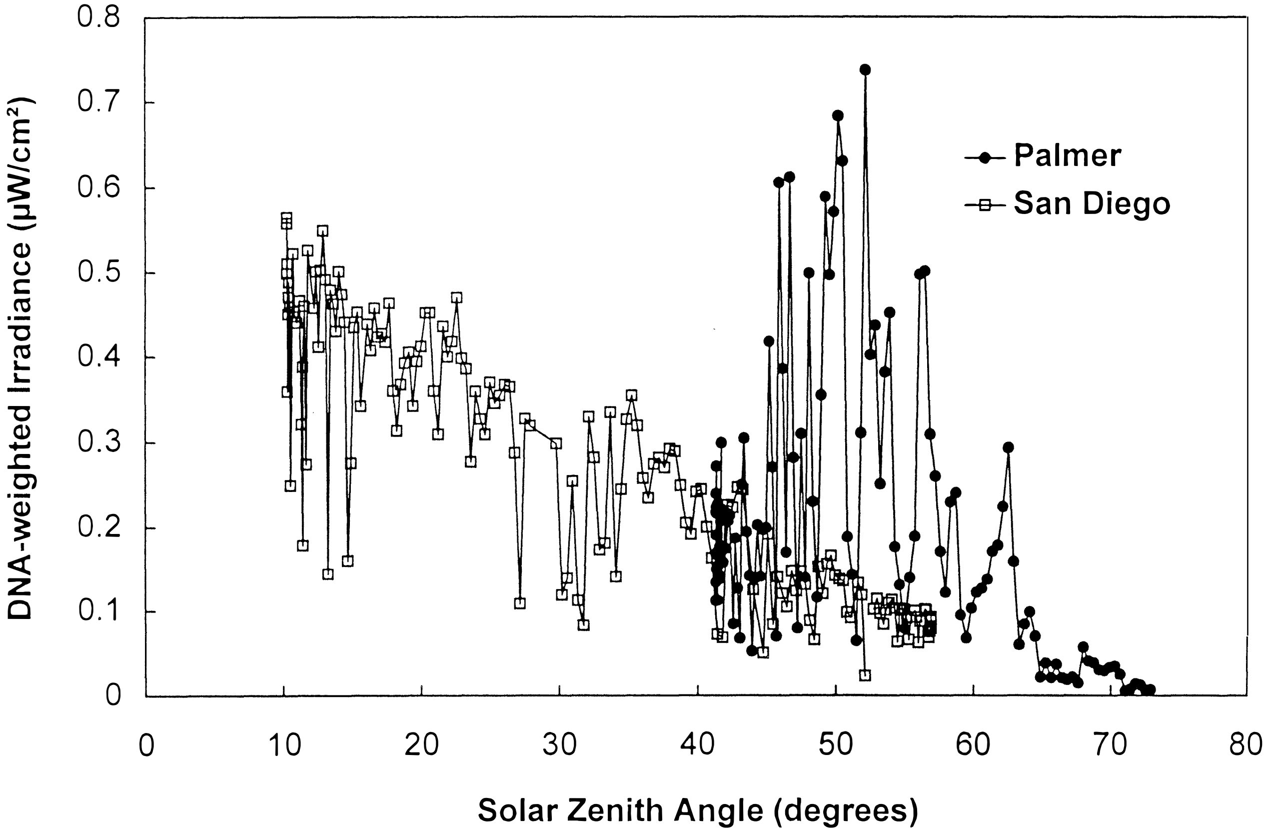

**Figure 9-7.** DNA-weighted noon irradiances measured in 1993 versus solar zenith angle: Palmer Station, Antarctica, compared with San Diego, USA.

March 1993 when particularly low ozone values were observed and because statistically significant increases at the shorter wavelengths occurred only in the last year. A later month-by-month analysis (Kerr and McElroy, 1994) showed that the increases at 300 nm persisted for several months.

By 1994, UV-B measurements had reverted to levels similar to those seen prior to 1992 (unpublished data), showing that the enhancements in 1992/1993 are better described as a perturbation, rather than a trend. In Toronto in the summer of 1993, ozone was 7.4 percent less than in 1989, and in the winter of 1992-93, ozone was 10.9 percent less than in 1989-90. As can be seen from Figure 9-8, changes in UV were small (statistically insignificant) at wavelengths greater than 320 nm, but were very large at 300 nm. The UV at 300 nm increased by factors of 1.3 and 1.9 in the summer and winter respectively. The increases were significant at the 95 percent confidence level. The resulting spectral differences in mean daily UV fluxes for the high-to-low year comparison show clearly that they are caused by ozone. Biologically weighted UV increases were clearly significant.

UV-B increases due to the lower ozone amounts in 1993 have also been reported in Europe. Large increases in UV-B in 1993 compared with 1992 were measured in Germany by Seckmeyer *et al.* (1994a), despite lower UV-A due to increased cloudiness in 1993. The UV recovery was incomplete at this site in mid-1994. The high variability of cloud cover masked the detection of possible increases in UV-B measured with broad-band detectors, and no significant UV increases due to ozone depletion were measured with the RB meter in Innsbruck (Austria) during the winter/spring of 1993 compared with the 1981-1988 period (Blumthaler *et al.*, 1994a).

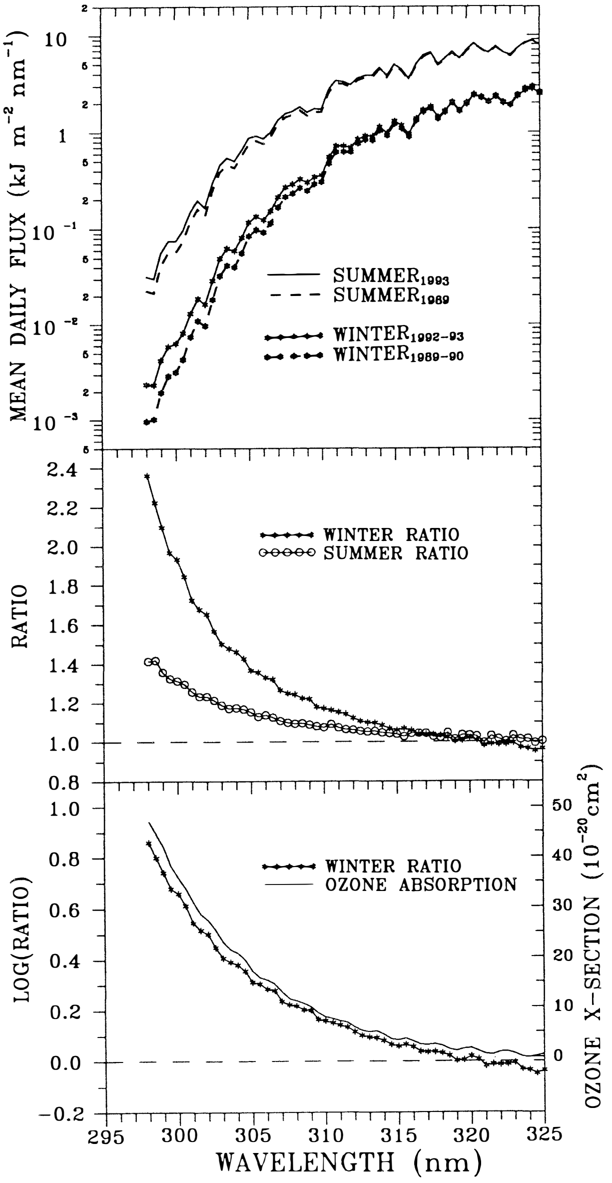

**Figure 9-8.** Impact of low ozone over Toronto, Canada, in 1992/1993 compared with earlier years. The top panel shows the mean daily UV flux as a function of wavelength for the summers of 1989 and 1993, and the winters of 1989-90 and 1992-93. The middle panel shows flux ratios for summer (1993 divided by 1989) and for winter (1992-93 divided by 1989-90). The bottom panel compares the observed changes as a function of wavelength with the ozone absorption spectrum. The log of the winter ratio is used because the intensity of UV-B radiation depends on the exponent of the absorption coefficient of ozone (adapted from Kerr and McElroy, 1993).

Spectral UV-B measurements made during the low ozone event of 1992/93 indicate that ozone decreases of 5-10 percent result in detectable increases of UV-B under all types of weather conditions. These decreases in ozone are similar in magnitude to long-term accumulated ozone losses at midlatitudes, as noted in Chapter 1. The confidence with which past and future trends can be determined will improve as the records of spectral UV-B measurements become longer.

## 9.4 IMPLICATIONS OF RECENT CHANGES

### 9.4.1 Stratospheric Aerosols from the Mt. Pinatubo Eruption

Although the Mt. Pinatubo eruption reduced global (*i.e.,* diffuse + direct) solar irradiance at the surface, any reductions were small in the UV region (Blumthaler and Ambach, 1994). However, there was a marked increase in the clear-sky diffuse/direct ratio throughout the UV region (Figure 9-9), so that shaded areas received substantially more UV in the summer following the eruption (McKenzie, 1994b; Blumthaler and Ambach, 1994). Some decreases in global UV have been reported (Smith *et al.,* 1993), but these decreases may be due to imperfect cosine responses of those instruments that underestimate the diffuse component from large zenith angles.

Model calculations suggest that aerosols from volcanic eruptions reduce the direct beam component, but increase scattered skylight, so that any decreases in global irradiance are small. Calculations show that under some conditions, volcanic aerosols can lead to increases at short wavelengths within the UV-B region (Michelangeli *et al.,* 1992), particularly at large solar zenith angles and for high surface albedos (Davies, 1993; Tsay and Stamnes, 1992).

The volcanic aerosol provides sites for heterogeneous chemistry to occur, leading to potential losses of ozone as discussed in Chapter 1 and Chapter 4. This would lead to additional enhancements of UV-B.

### 9.4.2 Tropospheric Pollution

Although tropospheric aerosols attenuate the direct beam (Blumthaler *et al.,* 1993), there is a lack of consensus regarding their effect on global irradiances. Some measurements suggest that there is only a small

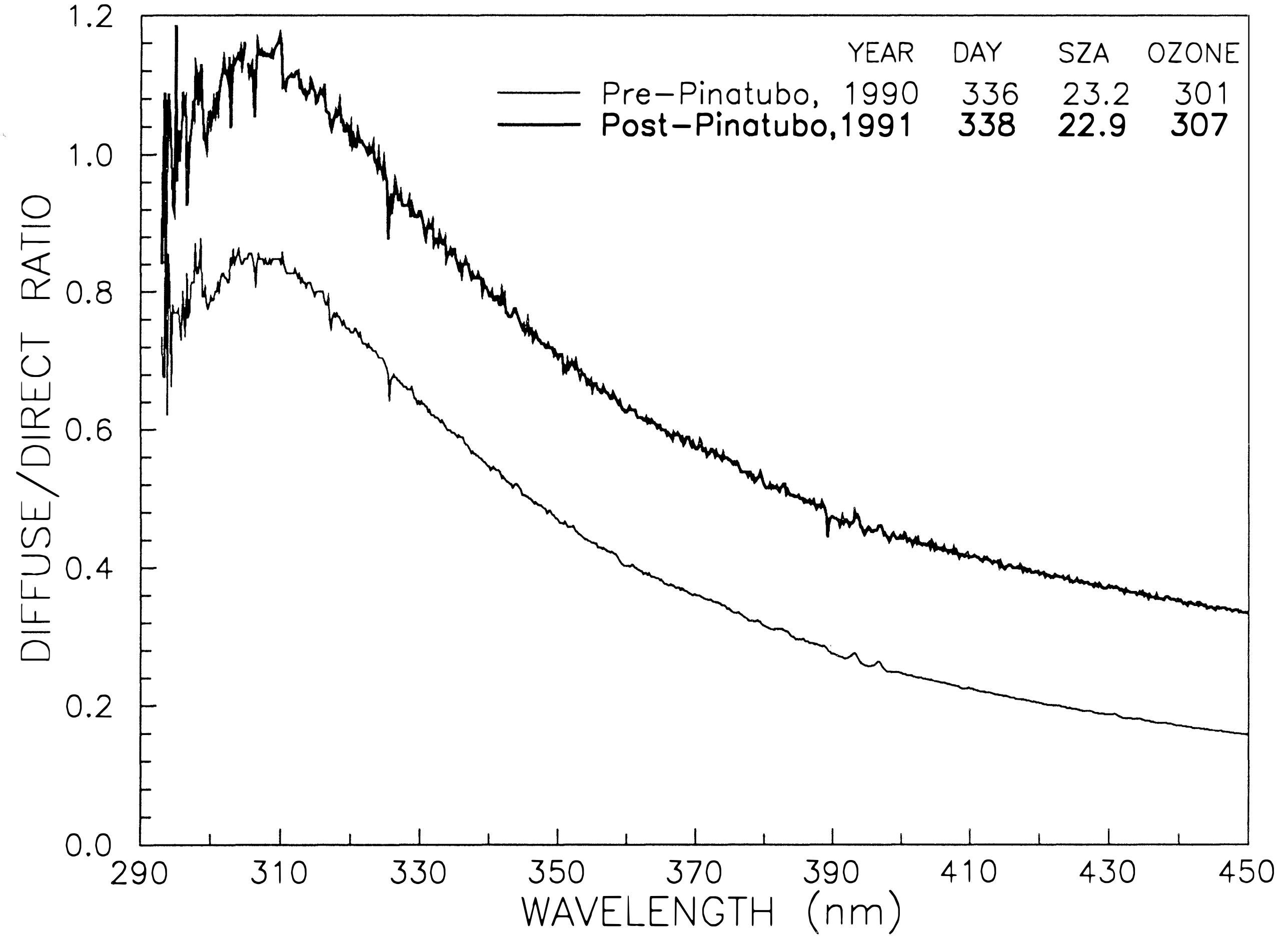

**Figure 9-9.** Comparison of clear-sky diffuse/direct ratios measured over Lauder, New Zealand as a function of wavelength for similar solar zenith angles before and after the eruption of Mt. Pinatubo (from McKenzie, 1994a).

effect on global irradiances (Seckmeyer and McKenzie, 1992; McKenzie *et al.*, 1993). Other measurements show that there are situations where they reduce UV irradiances considerably (Seckmeyer *et al.*, 1994a). Some model results suggest that aerosol effects can be large (Liu *et al.*, 1991).

Some regions, particularly in the Northern Hemisphere, have experienced increased tropospheric pollution (mostly sulfate aerosols and ozone) during the last century. It has been estimated that the corresponding UV (DNA-weighted) could have been reduced by 6-18 percent from the sulfate aerosol increases (Liu *et al.*, 1991) and by 3-10 percent from the tropospheric ozone increases (UNEP, 1991) in some industrialized regions. However, no direct information exists on pre-industrial stratospheric ozone, precluding accurate estimates of the net UV changes.

More recent tropospheric ozone trends in industrialized regions are estimated to contribute at most -2 percent per decade to the DNA-weighted UV, compared to +5 to +11 percent per decade from midlatitude ozone reductions (UNEP, 1991). Sulfur emissions have recently decreased in some regions while increasing in others (NRC, 1986), and the corresponding UV changes are expected to reflect such local variations.

Large increases in UV have been measured at high altitudes in Europe and South America. These altitude effects become more pronounced at shorter wavelengths

(Cabrera *et al.,* 1994; Blumthaler *et al.,* 1994b). At 300 nm, increases of 24 ± 4%/km have been measured in Europe for snow-free conditions (Blumthaler *et al.,* 1994b). UV-B increases of 18%/km have also been measured, although this included the effect of snow cover at the high elevation site (Ambach *et al.,* 1993). Larger gradients in UV-B have been observed during the winter near Santiago, Chile (33°S), though the same study reported gradients of only 4-5%/km in less polluted regions (Cabrera *et al.,* 1994). The calculated gradients for clear conditions are typically 5-8%/km (Madronich, 1993). Larger gradients result from increased tropospheric ozone or aerosols.

High concentrations of tropospheric pollutant gases (*e.g.,* $SO_2$, $NO_2$, $O_3$) can also have a significant influence on surface UV irradiances (Bais *et al.,* 1993).

### 9.4.3 Magnitude of Changes

Recent ozone losses in the Northern Hemisphere have been much larger than expected (Herman and Larko, 1994; Chapter 4), so that UV increases are much larger. For the first time, greatly enhanced UV was seen for extended periods of time in heavily populated latitude bands, and there may be future implications for human health (UNEP, 1994). However, the UV irradiances in 1993 were still less than for comparable southern latitudes where ozone and aerosol concentrations are lower, and where the minimum Sun-Earth separation occurs in summer.

Previously, the Radiation Amplification Factor *(RAF)* for changes in ozone was defined in terms of a linear relationship between incremental changes in ozone ($\Delta O_3$) and UV ($\Delta E$):

$$\mathrm{RAF} = -(\Delta E/E)/(\Delta O_3/O_3) \qquad (9\text{-}1)$$

If this definition is (incorrectly) applied to the large depletions in ozone that have occurred recently, the magnitude of the deduced increase in UV is underestimated. To avoid this problem, the radiative change due to ozone depletion has been reformulated in terms of a power law (Madronich, 1993) so that:

$$\mathrm{RAF} = \ln(E^*/E)/\ln(O_3/O_3^*), \qquad (9\text{-}2)$$

where $E^*$ and $E$ are two UV irradiances, and $O_3{}^*$ and $O_3$ are corresponding ozone amounts. With this definition, previously calculated *RAF* values, which agree well with measurements (*e.g.,* UNEP, 1991), can still be used to deduce the increases in UV caused by the large reductions in ozone that have occurred in Antarctica and more recently at midlatitudes. For example, Booth and Madronich (1994) have used measurements from Antarctica to show that the power relationship works well, even for ozone variations of a factor of two (Figure 9-10).

## 9.5 UPDATE ON PREDICTIONS

### 9.5.1 Semi-Empirical Method

No suitable data base exists to directly measure changes in UV that may have already occurred as a result of ozone depletion. Unfortunately, the potential to calculate temporal changes in UV at the surface is also limited by inadequacies in our capability to model the effects of clouds. A semi-empirical technique has been implemented to overcome these difficulties, so that UV-B can be inferred using solar pyranometer data to estimate cloud effects, and ozone data (Ito *et al.,* 1994). Satellite ozone data suitable for these studies are available from the year 1978, when ozone depletions were small.

The relationship between pyranometer data and ozone data to derive UV-B was verified using ground-based measurements of UV spectra at four sites in Japan, and the technique has been applied to infer historical records of UV over an eleven-year period at these sites. Over this period, the long-term changes were found to be small compared with the year-to-year variability. The geographical distribution of UV over Japan has also been deduced (Ito *et al.,* 1994).

Although the technique is imperfect, the historical record and geographical differences derived may provide useful information for users such as epidemiologists. The method will be more useful if it can be successfully applied to biologically weighted UV irradiances (*e.g.,* erythemal irradiance) rather than an unweighted integral (290-315 nm) which is relatively insensitive to ozone changes.

### 9.5.2 Calculated Changes in Clear-Sky UV Using Global Ozone Measurements

A multi-layer radiative transfer model (Madronich, 1993) was used to calculate UV irradiances (*i.e.,* the flux passing through a horizontal surface) and their

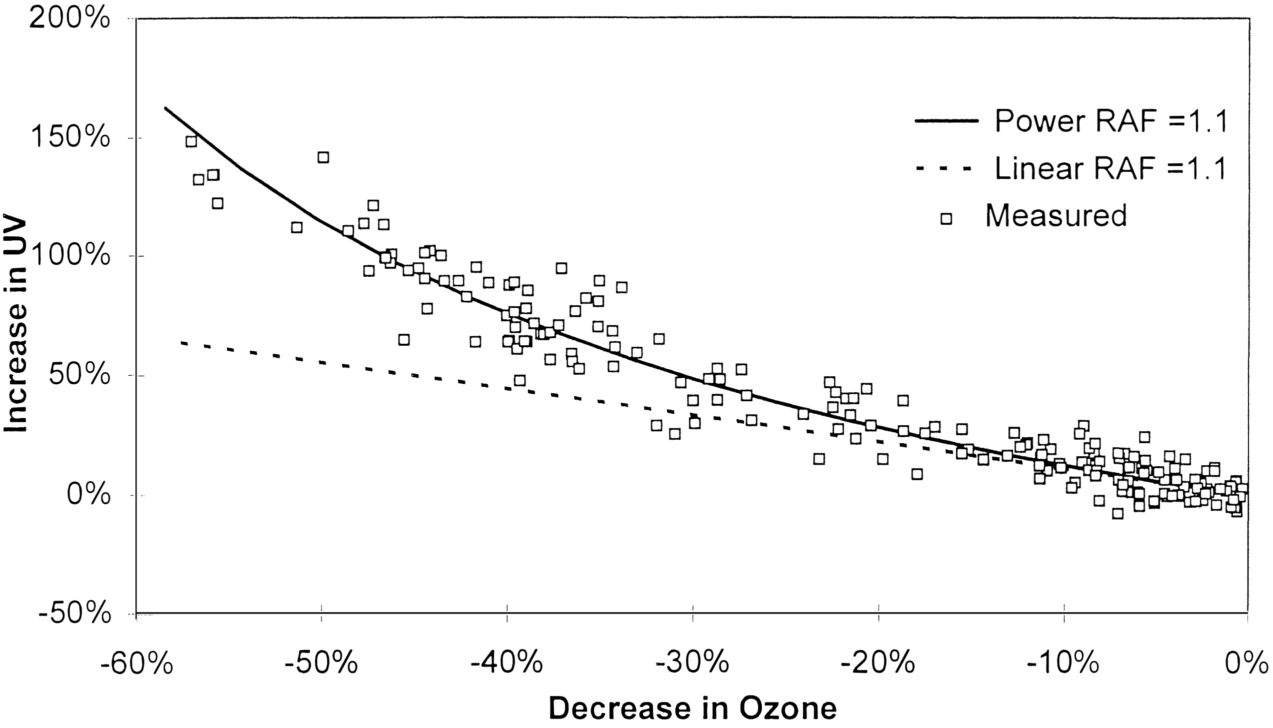

**Figure 9-10.** Dependence of erythemally weighted UV radiation on ozone column changes. Measurements from South Pole, 1 Feb. 1991 to 12 Dec. 1992 (from Booth and Madronich, 1994).

changes over time as a function of latitude using ozone fields from the Solar Backscatter Ultraviolet spectrometer (SBUV) and SBUV2 satellite instruments (see Chapter 1) over the period late 1978 through early 1994. The calculations presented are for clear-sky aerosol-free conditions, with a constant surface albedo of 0.05. The sensitivity of this model to changes in ozone has been assessed previously and agrees well with measurements (McKenzie *et al.*, 1991; UNEP, 1991). Here, we report calculated irradiances at selected wavelengths in the UV region. Corresponding biologically-weighted irradiances are discussed in the UNEP "Effects Panel" report (1994).

The calculated latitudinal variation in clear-sky UV for selected wavelengths using satellite ozone data over the period 1979 to 1992 is shown in Figure 9-11. The irradiances increase strongly with wavelength (note the logarithmic scale) and have maxima near the equator. Latitudinal gradients and hemispheric asymmetries increase at shorter wavelengths, where ozone absorptions are greatest. The hemispheric differences are most pronounced at latitudes poleward of 45°. At the shortest wavelength shown (300 nm), the daily spectral irradiance at the South Pole is an order of magnitude greater than at the North Pole.

The changes in these quantities over the period 1978 to 1994 (relative to the mean of the period) are shown in Figure 9-12. Changes are largest at latitudes where ozone depletions have been most severe, so that percentage trends increase towards the poles, with largest increases in the Southern Hemisphere. The effects of ozone reduction are much more important at shorter wavelengths.

The calculated time dependence of changes in 310 nm UV at latitudes 45° and 55° (N and S) for the period 1979 to 1994 is illustrated in Figure 9-13. The rate of increase in UV is not constant, but is anticorrelated with ozone changes which include perturbations due to the 11-year solar cycle. Hemispheric differences in the timing of the increases are also apparent. Percentage changes generally lead the absolute changes by a few months, as expected from the timings of greatest ozone

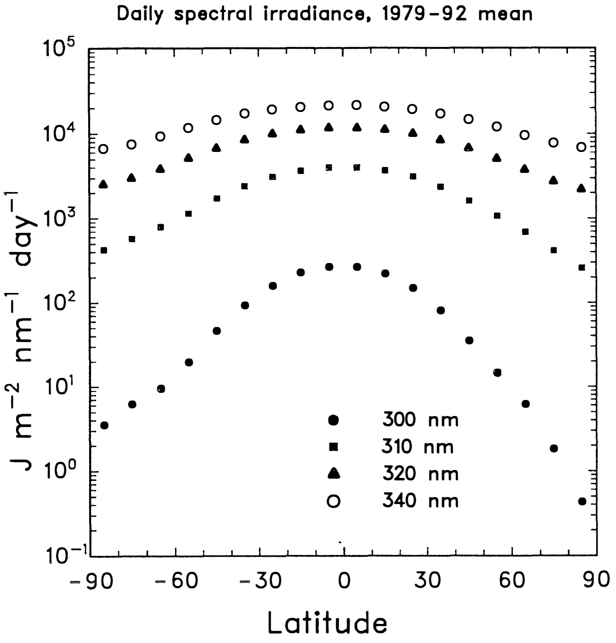

**Figure 9-11.** Calculated daily spectral irradiance, averaged over all months of 1979-1992, at different wavelengths. Sea level, cloudless and aerosol-free skies.

depletion (winter, spring) compared with the greatest natural UV levels (summer). The absolute changes approach zero in winter, when the UV has a minimum.

At latitude 45° the trend is approximately +0.5 percent per year in both hemispheres. At latitude 55° the trends are significantly larger, particularly in the Southern Hemisphere. Gradients are larger at shorter wavelengths and continue to increase at higher latitudes, where hemispheric differences become more pronounced.

### 9.5.3 Cloud and Albedo Effects

The analysis in Section 9.5.2 assumes cloud-free conditions. In practice, cloud variability causes large year-to-year changes in UV. The theory of radiative transfer through clouds is well developed, and algorithms for its numerical implementation are available (*e.g.*, Stamnes *et al.*, 1988). However, the practical application of the theory to the atmosphere is still limited because of incomplete cloud characterization.

Cloud cover at most surface observation sites is specified only as the fraction of sky covered by cloud, with little or no information about the optical depth or layering. Further, although cloud optical depth is not a strong function of wavelength, there is a nonlinear relationship between observed cloud cover and its effect in the UV-B region where a much larger fraction of the energy is diffuse (Seckmeyer *et al.*, 1994a). Measured reductions in UV-B are relatively small even for large fractional cloud covers (Ito *et al.*, 1994; Bais *et al.*, 1993).

Satellite measurements of clouds are more quantitative, but stratification of clouds is difficult to measure, and the cloud cover viewed from space is not generally the same as that viewed from the ground (Henderson-Sellers and McGuffie, 1990). Other complications arise from the nonlinear relationship between UV transmission and cloud optical depth, and the fact that cloud effects are modulated by surface albedo (Lubin *et al.*, 1994). Generally, with high surface albedo, the effective optical depth of clouds is reduced by multiple scattering effects between the surface and the cloud base, which

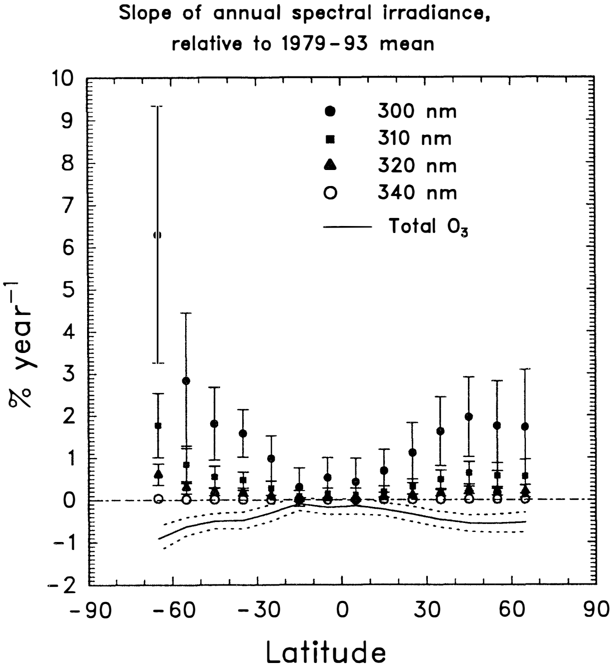

**Figure 9-12.** Calculated rate of increase of the annual spectral irradiances from 1978 to 1993. For comparison, the negative quadrants give the changes in annually averaged ozone column. Values are least-squares slopes expressed as percent of the 1979-1993 mean. Error bars are $2\sigma$.

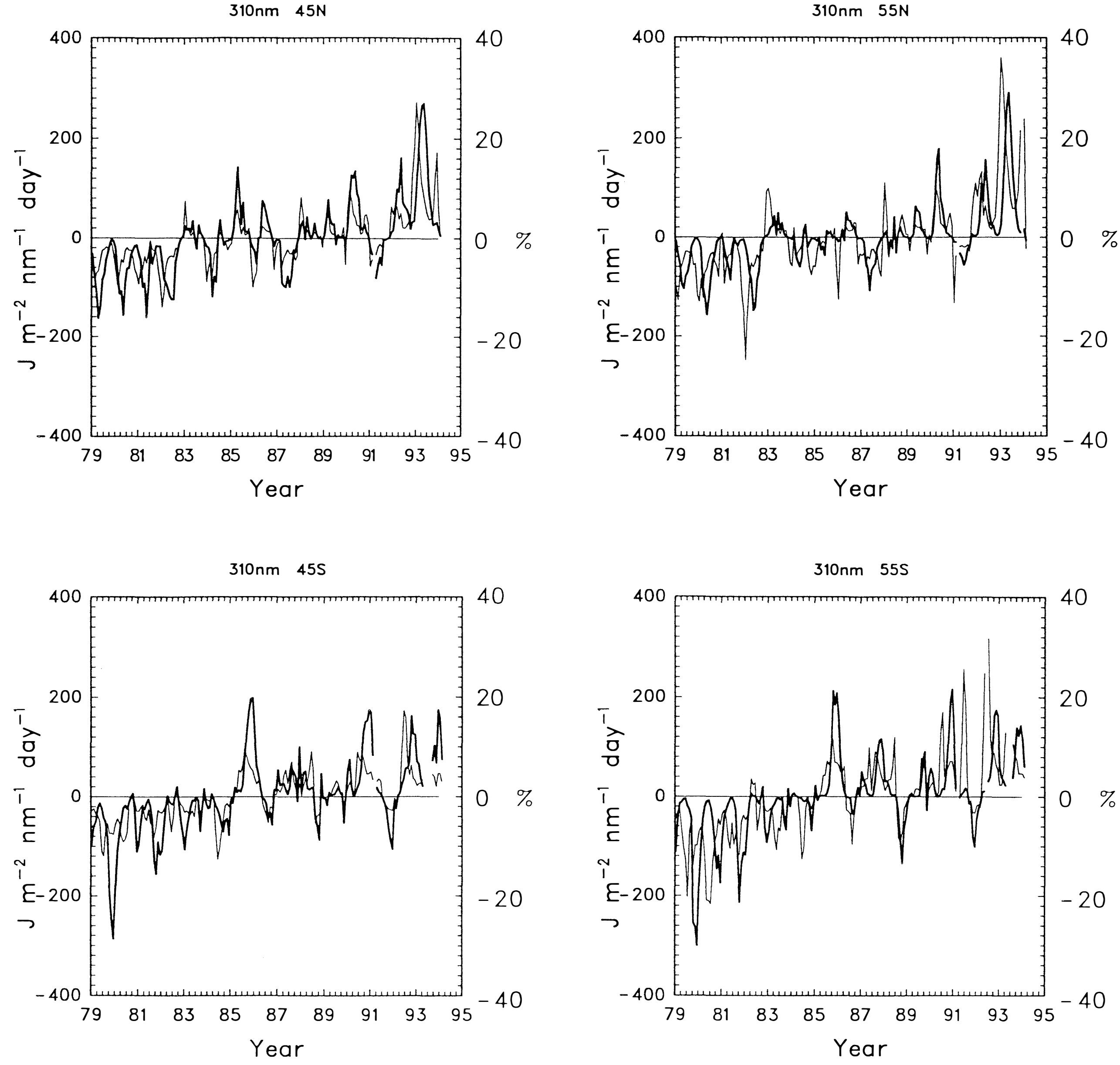

**Figure 9-13.** Calculated deviations from the 1978-1993 average monthly values of the daily spectral irradiance at 310 nm at latitudes 45° and 55° (N and S). Thick lines and left scales give absolute irradiance changes, thin lines and right scales give percent changes.

enhance the flux. Methods have, however, recently been developed and successfully implemented to map surface UV-B using multi-spectral satellite imagery (Lubin *et al.,* 1994).

### 9.5.4 UV Forecasts

In recent years, efforts have been made in several countries to educate the public concerning ambient UV-B levels. This information is often reported in the form of a daily UV index delivered with local weather forecasts (*e.g.,* Burrows *et al.,* 1994). Most of the indices in current use are based on erythemally weighted UV and are reported in a variety of forms, including arbitrary scales, weighted energy dose units, "burn times," and others. The information would be more useful if a single index could be agreed upon. The values forecast for these indices can be based on measurements, or models, or a combination of both. To be useful, such forecasts must be capable of assimilating ozone measurements in near real time and predicting changes in ozone fields within a few hours. No operational forecasts currently make realistic allowances for changes due to clouds. Ground-truthing and verifying predictive algorithms will be important in the development of UV indices.

## 9.6 GAPS IN OUR KNOWLEDGE

High quality extraterrestrial irradiances are required to test models against measurements and to deduce accurately the spectral consequences of changes in aerosol optical depth. New irradiance measurements from instruments on board the Upper Atmosphere Research Satellite (UARS) may fill this need (Lean *et al.,* 1992; Brueckner *et al.,* 1993; Rottman *et al.,* 1993).

Despite the importance of clouds in modulating UV transfer through the atmosphere, our ability to model their effects is poor. The role of aerosols has not been fully determined.

Detailed intercomparisons between measured and modeled UV are now being attempted (Wang and Lenoble, 1994; Zeng *et al.*, 1994). These require a wide range of measured input parameters (*e.g.,* aerosol and ozone profiles, cloud cover) to constrain the models. These measurements are often not available or inadequate. The validity of parameterizations of these quantities is also untested.

The achievable accuracy of UV measurements is limited by the lack of suitable irradiance standards. Robust protocols to maintain secondary standards and to transfer them accurately to field instruments are also lacking.

Detailed instrument intercomparisons and instrument-model comparisons are limited by our understanding of the effects of instrument errors due to imperfections in the cosine response. One approach would be to develop improved detectors for which these errors are small. In addition to cosine-weighted measurements that are already available, measurements of the angular dependence of sky radiances, altitude-dependences, and direct-sun observations may be useful for model validation (Seckmeyer and Bernhard, 1993).

Historical and geographic changes in UV radiation are not adequately understood. The data set produced by a network of broad-band meters would be a valuable source of information for the photobiology and epidemiology communities. All instruments must be characterized and calibrated in the same way. In the past there has been a lack of international coordination. The data from numerous, uncoordinated meters, while not necessarily incorrect, could provide questionable, and sometimes conflicting, information on long-term changes in broad-band solar UV radiation at the ground.

There is a lack of high quality spectral measurements of UV and ancillary measurements from the same site from which photobiological effects can be evaluated, and our understanding of the reasons for changes in UV can be improved. Useful ancillary measurements include ozone, total solar irradiance, aerosols (turbidity), and cloud cover.

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