CHAPTER 11

Ultraviolet Radiation Changes

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Chapter 11

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Contents

SCIENTIFIC SUMMARY

A major consequence of ozone depletion is an increase in solar ultraviolet (UV) radiation received at the Earth's surface. This chapter discusses advances that have been made since the previous assessment (*WMO, 1990*) to our understanding of UV radiation. The impacts of these changes in UV on the biosphere are not included, because they are discussed in the effects assessment (UNEP, 1991). The major conclusions and recommendations are:

- Significant improvements in the UV data base have occurred since the last assessment. Spectral measurements are becoming available, but, to determine trends, long-term accurate measurements of UV are required at unpolluted sites.

- Biologically damaging UV has been observed to more than double during episodes of ozone depletion in Antarctica. Smaller episodic enhancements have been measured in Australia. The observed enhancements are consistent with the results of radiative transfer calculations for clear sky conditions.

- An erythemal Radiative Amplification Factor (RAF) of 1.25 ± 0.20 has been deduced from measurements of ozone and UV at a clean air site. This is in agreement with the RAF derived from model calculations (RAF = 1.1 at 30° N).

- There is an apparent discrepancy between observed UV trends from the Robertson-Berger (RB) network and those calculated from TOMS ozone data. Cloud variability, increases in tropospheric ozone and aerosol extinctions may have masked the UV increase due to ozone depletion. In addition, the data record available for comparison is short, and the instrument calibration (which is critical) is still in question. However, at a high-altitude European observatory, the observed positive trends in UV appear to be larger than expected. Further studies of the effects of cloud and aerosol on UV are required.

- Clear-sky radiative transfer calculations using ozone fields measured by the TOMS instrument show that during the 1980s erythemally active UV has increased significantly at latitudes poleward of 30°, with larger increases in the Southern Hemisphere, particularly at high latitudes.

- Significant increases in UV effects are most likely to appear first in the Southern Hemisphere where in the summer, historical ozone levels are lower and the Earth-Sun separation is a minimum. Further, in the Southern Hemisphere, stratospheric ozone losses are more severe, tropospheric ozone has not increased, and aerosol concentrations are lower.

- Existing chemical models underestimate the changes in the observed ozone fields. Therefore, they cannot be used to accurately predict future changes in UV fields.

11.1 UV MEASUREMENTS AND ANALYSES

11.1.1 Interpretation of Ultraviolet-B (UVB) Time Series Data

The most comprehensive time series of UVB data are those from the Robertson-Berger (RB) network. However, a study by Scotto *et al.* (1988) showed no increase in UVB at U.S. observation sites, despite the decrease in stratospheric ozone. Investigations to understand the reasons for this surprising result have continued. Increases in tropospheric ozone that more than compensated for stratospheric ozone losses were proposed by Brühl and Crutzen (1989). However, recent analyses of TOMS data and tropospheric ozone trends suggest an increase in UVB should still have been observed (UNEP, 1991). Increasing local pollution at the measurement sites has also been suggested. Since the industrial revolution, reductions in Northern Hemisphere UVB have already occurred due to aerosol extinction. The decreases in UVB caused by increases in aerosols since the industrial revolution probably exceed the increases due to ozone depletion (Figure 11-1, from Liu *et al.* [1991]). On a local scale, changes in pollution at the network sites may therefore be significant in the analysis period (1974-1985).

The RB meters have a relatively low sensitivity to ozone depletion. Typically a 1 percent reduction in ozone produces an increase of less than 1 percent in the RB-weighted irradiance (UNEP, 1991), and it is possible that the trends in UVB irradiance measured by the RB network have been masked by natural variability in cloud cover. A study by Beliavsky *et al.* (1991) argues that because of natural cloud variability, decades of data would be required before UVB trends would be detectable without supporting measurements.

Frederick and Weatherhead (1991) have examined RB data from two sites in the U.S. (Bismarck and Tallahassee) at which Dobson ozone data were available (Figure 11-2). They concluded that monthly trends in the RB data are consistent with expectations based on Dobson column ozone measurements for the months of high UVB irradiance, April through September. However, large differences exist between modeled and clear-sky results in the period November
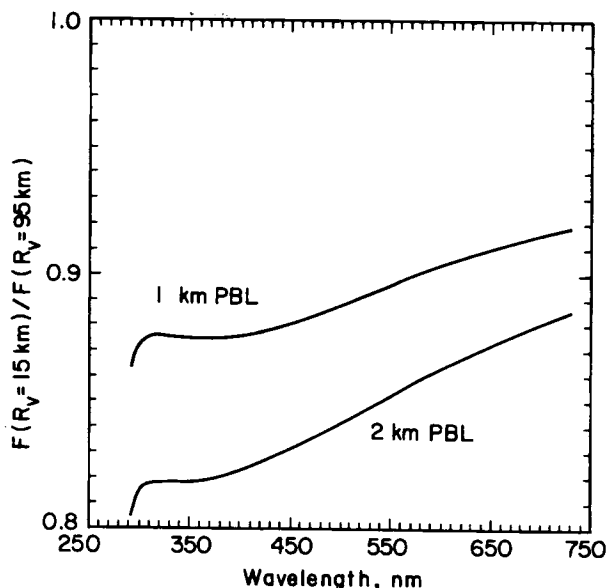

Figure 11-1 Ratio of daily surface solar radiation for 15-km visual range (typical Northern Hemisphere) to that for 95-km visual range (clean air) as a function of wavelength, for assumed aerosol boundary layer heights of 1 and 2 km (from Liu *et al.*, (1991)).

through February. The reason for this discrepancy is unknown at present. We understand that the calibration of this network is currently being evaluated, and a publication is likely to appear. With the information currently available, there are still questions about the calibration of this network.

RB data obtained from the high-altitude European observatory at Jungfraujoch has been used in conjunction with measurements of global radiation (G) between 300 and 2000 nm, to eliminate cloud and aerosol effects, and reveal trends in UVB (Blumthaler and Ambach, 1990). Updated measurements that include data from 1990 (M. Blumthaler, private communication, 1991) are shown in Figure 11-3. The plot shows the departures from the long term mean in the ratio UVB/G. The data show irregular variations, but unlike the U.S. data, there is a superimposed trend, which corresponds to UVB increases of 10 ± 5 percent per decade, which is larger than that expected (Madronich, 1991) from the changes in ozone measured over the same period (Chapter 2). However, the effects of the 1982 El Chichón volcanic eruption on these data may be significant either through its possible influence on
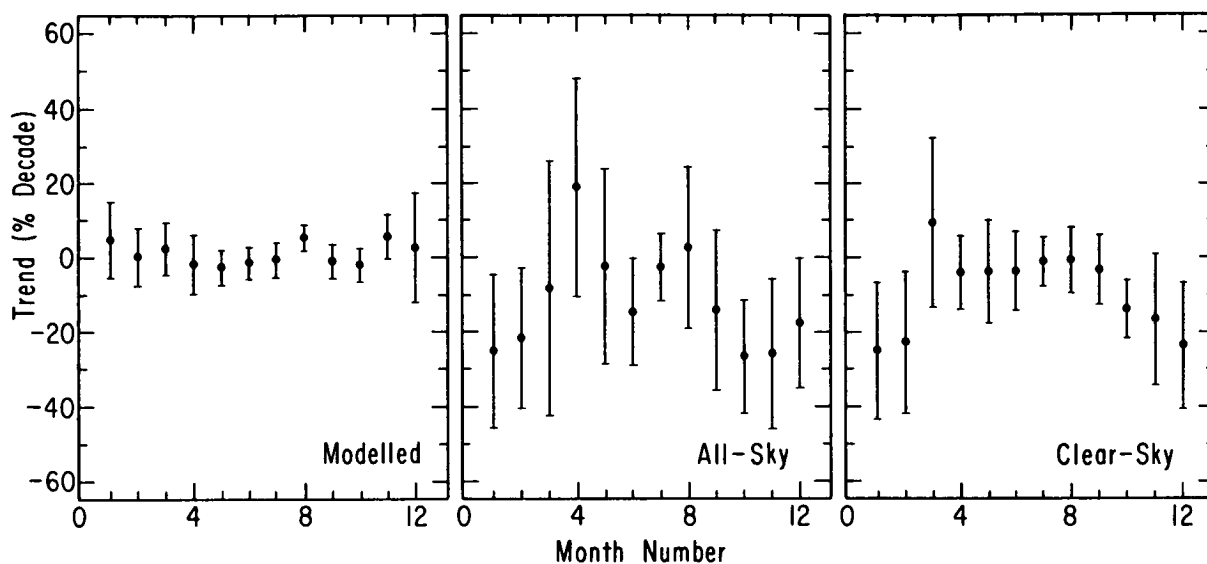
11.3

ULTRAVIOLET RADIATION CHANGES

Figure 11-2 Trends by month of the year in the Robertson-Berger (RB) meter data set for Bismarck U.S., derived for the period 1974-1985. Error bars denote 95 percent confidence limits. Left panel: Results derived from radiative transfer calculations using Dobson ozone data as inputs. Center panel: Trends in the entire RB data set, including the influence of clouds. Right panel: Trends in a clear-sky subset of the RB data base (from Frederick and Weatherhead, 1991).
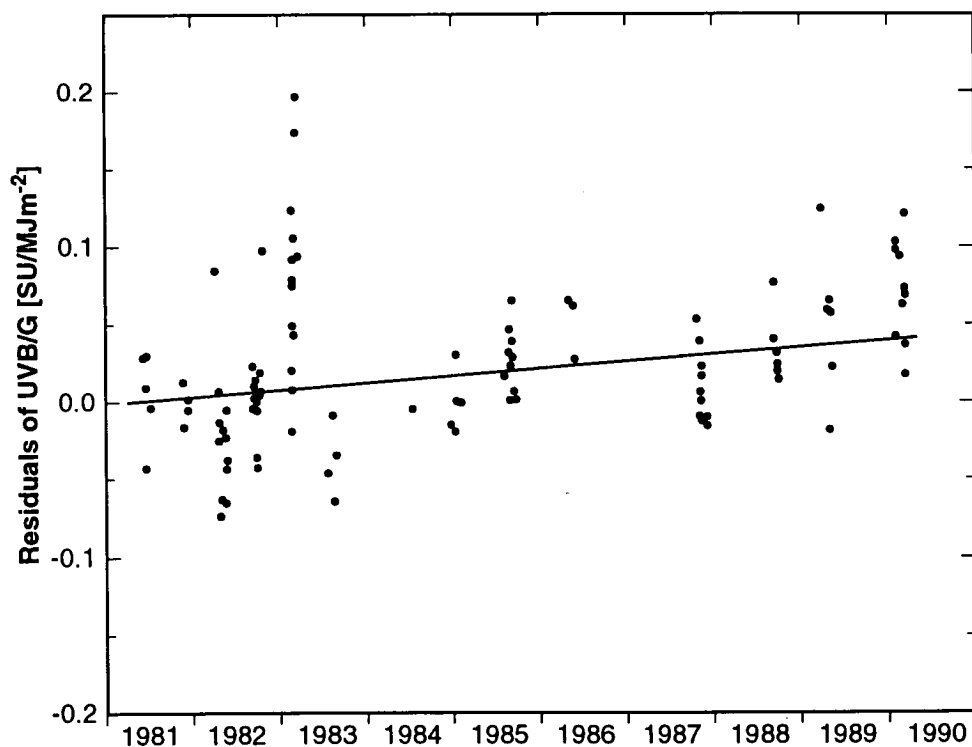

Figure 11-3 Long-term tendency of the residuals from the long-term means of the ratios UVB/G, measured at Jungfraujoch observatory between 1981 and 1990. The regression line is also shown (Blumthaler, private communication, 1991).

ozone that was anomalously low at these latitudes in 1983 (WMO, 1990), or through changes in the wavelength-dependent aerosol optical depth (Kent *et al.*, 1991).

There has been an increasing awareness that spectral measurements are required to study the effects of changes in ozone on UV radiation. The RB response does not accurately represent any of the diverse biological action spectra of interest (UNEP, 1991), whereas spectral data can be accurately convolved with various action spectra. In addition, the spectral information enables greater confidence in instrument calibration, and identification of the reasons for any changes in UV. For example, spectral measurements have enabled ozone column amounts to be deduced, and facilitated determination of cloud and aerosol effects (Stamnes *et al.*, 1990). The time series of UV spectral measurements is too short at present to determine trends, but useful insights have nevertheless been gained already from analyses of this type of data.

11.1.2 Effects of Antarctic Ozone Depletion

In 1988 the National Science Foundation established four sites for monitoring solar UV and visible radiation in the high-latitude Southern Hemisphere. Three of these sites are on the Antarctic continent, at the South Pole, McMurdo, and Palmer Stations, and one is located at Ushuaia, Argentina. Results from McMurdo (Stamnes *et al.*, 1990), and from Palmer Station on the Antarctic peninsula (Lubin *et al.*, 1989; Lubin and Frederick, 1991) have appeared in the literature. To date the focus has been on changes in surface ultraviolet irradiance associated with the springtime depletion in ozone.

The UV radiation field over Antarctica varies with the solar elevation, clouds and haze, and the atmospheric ozone amount. Over Palmer Station (latitude 64.8° S), clouds, in a monthly averaged sense, reduce the surface UV irradiance to approximately 50 to 60 percent of the values that would prevail under perpetually clear skies. The springtime depletion in ozone constitutes a relatively recent perturbation to the highly variable radiation background. The two issues to consider here are (a) the magnitude of the reduction in ozone and (b) the
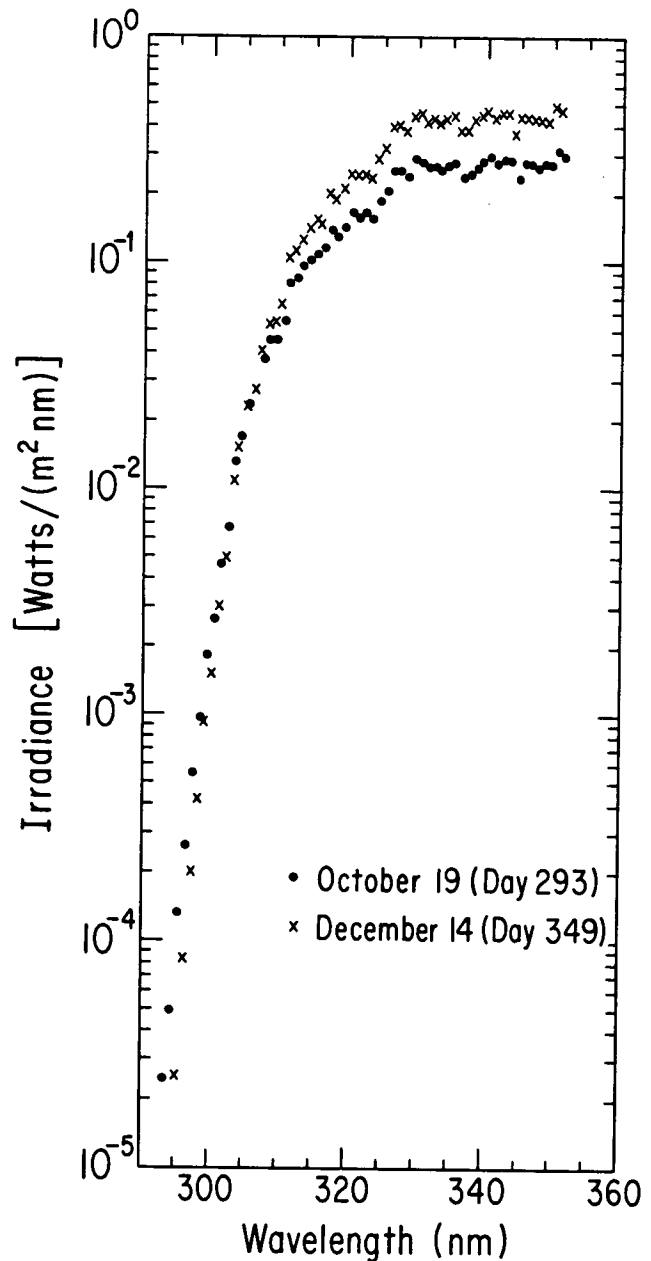

Figure 11-4 Spectra of ultraviolet solar irradiance measured at local noon from Palmer Station, Antarctica, in 1988. Day number 293 (Oct. 19) is the time of minimum ozone, while day number 349 (Dec. 14) is representative of conditions near summer solstice.

11.5

timing of the reduction relative to the normal seasonal cycle in solar radiation.

Figure 11-4 presents two spectra of surface UV irradiance measured at local noon from Palmer Station on days number 293 (Oct. 19) and 349 (Dec. 14) of 1988 (Lubin *et al.*, 1989). The former date was the day of minimum ozone, while the latter is near summer solstice. Based solely on solar elevation, one would expect the largest irradiances in December. Figure 11-4 shows this to be the case at wavelengths longer than 315 nm. However, at shorter wavelength, the measured irradiances for October equal and then exceed those in December. This is the manner in which a reduction in ozone appears in UV radiation at the earth's surface. Although the enhanced irradiances exist at wavelengths

where the absolute energy flux is small, living cells are quite sensitive to damage in the spectral region from 300 to 315 nm.

The springtime ozone depletion of 1988 had vanished from the Antarctic peninsula by mid-November. However, during 1990 reduced ozone amounts persisted over Palmer Station well into December. The combination of low ozone and high solar elevation led to unusually large irradiances as shown in Figure 11-5 (Frederick and Alberts, 1991). The points denote ratios of the noontime irradiance measured at 306.5 nm, near the peak of the biologically weighted spectrum, to that at 350.0 nm, where absorption by ozone is insignificant. Use of this irradiance ratio removes the influence of clouds, to a
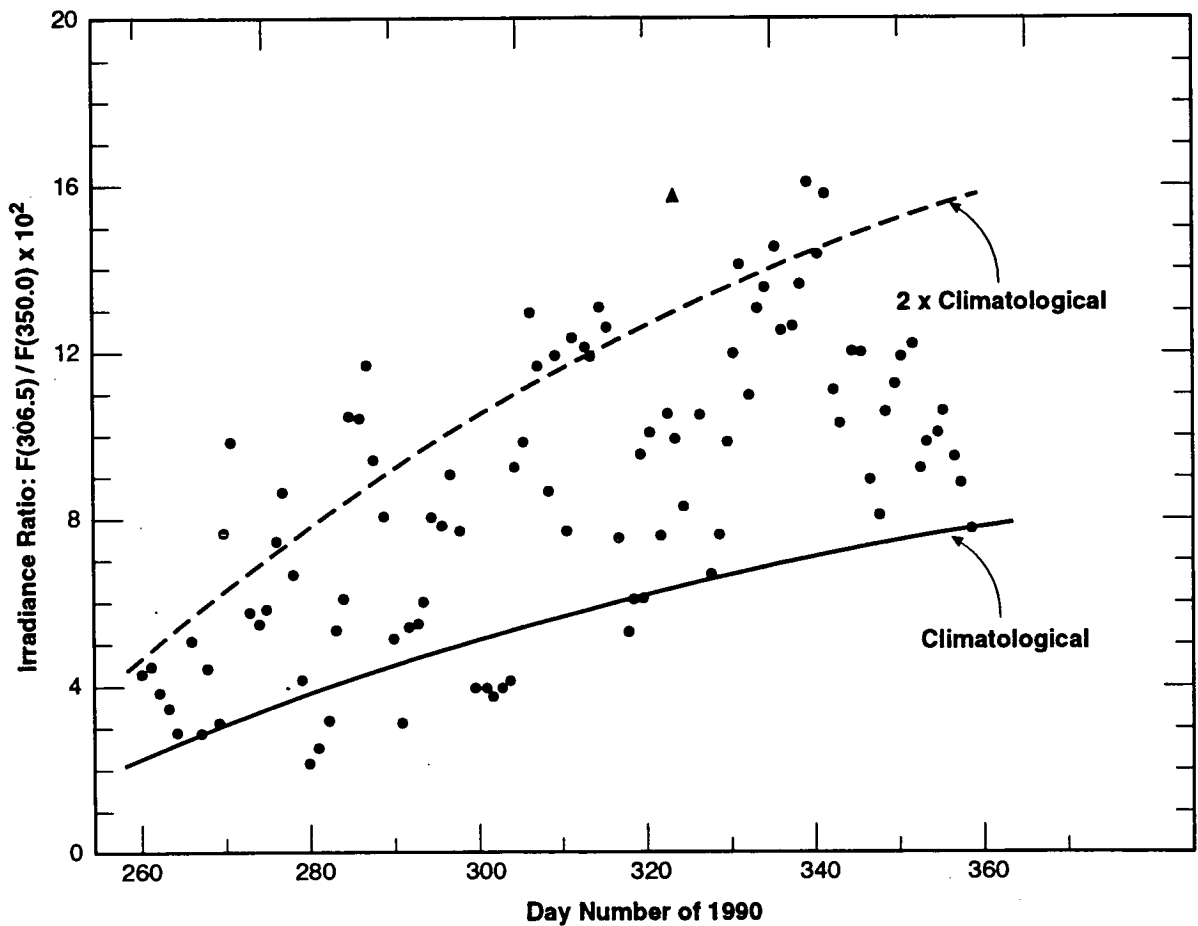

Figure 11-5 Ratios of noontime solar irradiance at 306.5 nm to that at 350.0 nm (points) for the Austral spring of 1990 at Palmer Station. The solid curve labeled "climatological" is a calculation based on ozone amounts that are typical of those in the absence of a depletion. The dashed curve is twice the climatological irradiance ratio.

good approximation, so the points indicate variations associated with ozone only. The solid line represents computed ratios based on the ozone climatology of Nagatani *et al.* (1988) in which any springtime ozone reduction is small. The dashed line indicates double the climatological prediction. Approximately 20 percent of the days during the spring of 1990 had irradiance ratios in excess of the climatological prediction by a factor of 2 or more, and the enhancement persisted into early December when the daylight period is long. Measurements from McMurdo Station during 1990 yielded similar results, with ozone depletions persisting in December to give enhancements in biologically weighted radiation by a factor of three (Stamnes *et al.*, 1991). The variations in observed UVB irradiances in Antarctica have been shown to be consistent with the results of radiative transfer calculations (Stamnes *et al.*, 1990).

The minimum ozone levels over Antarctica occur in October. At this time, solar elevations are relatively low, so that the maximum UV fluxes occur later in the year. However, the transmission of sea-ice has a strong seasonal maximum in spring so that organisms that live under the ice sheet may be at risk (Trodahl and Buckley, 1989). In terms of the potential ecological effects, the duration of the ozone depletion is likely to be an important quantity. When ozone amounts remain low into December, the instantaneous and 24-hour integrated UV irradiances discussed above can be far in excess of the maximum values experienced in Antarctica prior to the 1980s.

11.1.3 Global Effects

UVB perturbations have also been seen at mid-latitudes in the Southern Hemisphere, from episodic intrusions of ozone-poor air from the Antarctic ozone hole. For example, Roy *et al.* (1990) showed an association between high UVB levels in Melbourne, Australia, and ozone-depleted air arriving from Antarctica in late 1987. Figure 11-6 shows the strong anticorrelation between UVB (integrated over the wavelength range 285-315 nm) and ozone. The impacts of the ozone changes on the observed UV are consistent with model predictions, although calculated irradiances are 10 percent smaller.

The Southern Hemisphere is where increases in UV stresses are most likely to appear first. Historically, UV levels there have been high because

of the lower ozone amounts in summer compared with the Northern Hemisphere, and because the Earth-Sun separation is smallest in January. Further, in the Southern Hemisphere stratospheric ozone losses are more severe, tropospheric ozone has not increased, and aerosol concentrations are lower (McKenzie, 1991).

In absolute terms, even small percentage decreases in ozone are important in the tropics, since UVB levels there are already large. A 10 percent decrease in ozone in the tropics would lead to a UVB increase that is larger than the total UVB at mid-latitudes (Ilyas, 1989). In view of this sensitivity, more tropical measurements of UV are clearly required, even though the most recent analyses of TOMS satellite ozone indicate that there have been no changes of statistical significance at equatorial latitudes.

11.1.4 Radiative Amplification Factor Deduced from Measurements

A suitable long-term data base does not yet exist to enable global UV trends due to ozone depletion to be determined. It has, however, been demonstrated that under similar observing conditions (*i.e.*, same ozone, sun angle, clear skies), any changes between 1980 and 1988 in the measured spectral distribution of UV at Lauder, New Zealand (45°S, 170°E), were small (Bittar and McKenzie, 1990). Since December 1989, spectral measurements from Lauder have been made routinely at fixed Solar Zenith Angles (SZAs) and near local noon, whenever weather conditions permit. Typical spectra obtained at midday in winter and summer are shown in Figure. 11-7a. The figure also shows the erythemal weighting function (McKinlay and Diffey, 1987) used in the analyses that follow in the remainder of this chapter. The integrated midday erythemal irradiance in winter (Figure 11-7b) is only 10 percent of that in summer, due mainly to differences in the SZA.

Seasonal variations in ozone are large at mid-latitude sites, enabling these measurements to be used to investigate the relationship between UV and ozone (and other factors such as cloud cover and sun angle). Observations obtained at fixed SZAs over a year were used, and variations due to seasonal changes in the Sun-Earth separation were removed using a simple trigonometric correction. Data from 1990
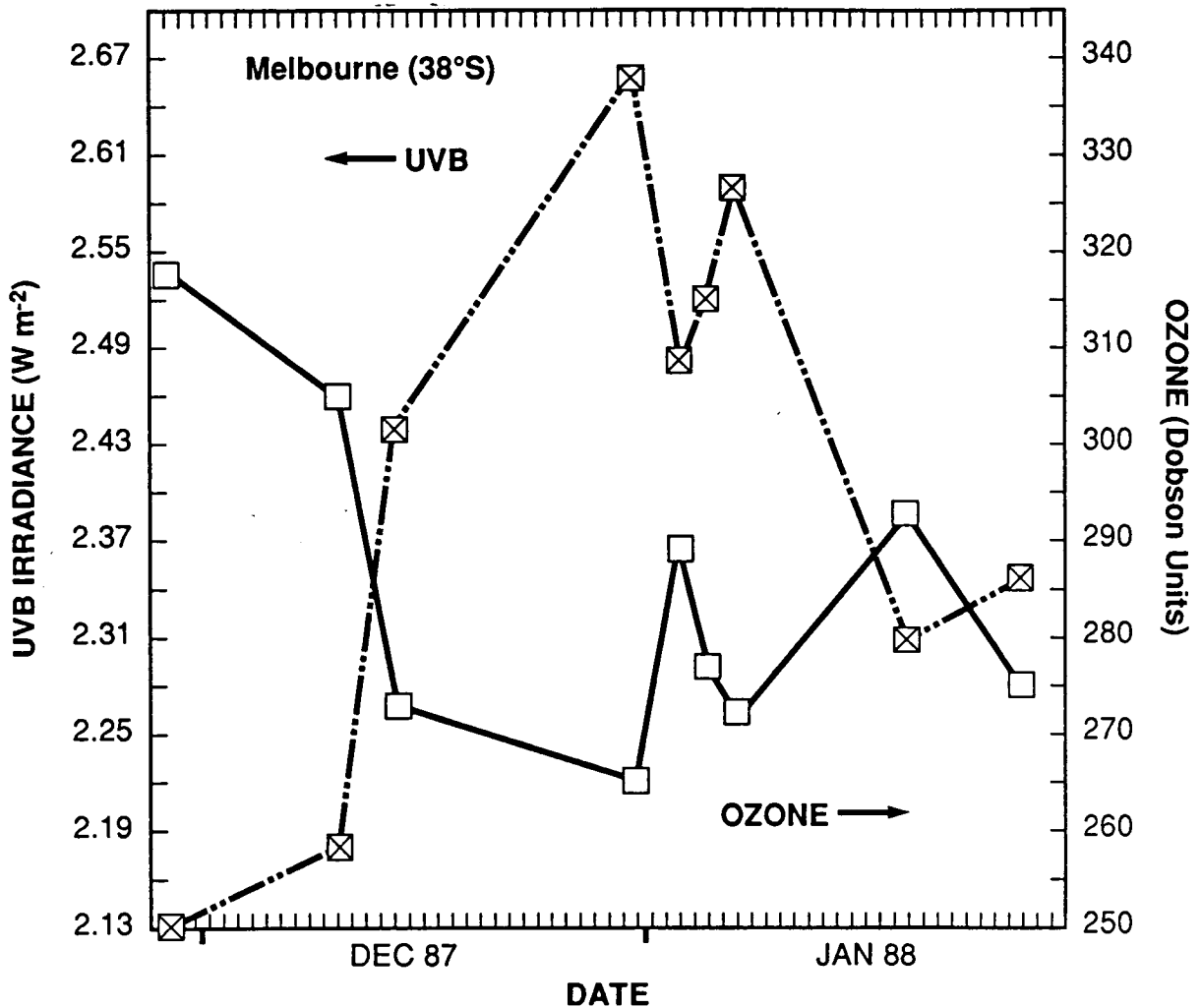
Figure 11-6 Comparison of solar UVB radiation (285 to 315 nm) and ozone at Melbourne, Australia (38° S), during the intrusion of ozone-poor air in December 1987 and January 1988 (from Roy et al., (1990)).

were used in the analysis. In this period, variations in aerosol extinction were relatively small.

Figure 11-8 shows the relationship between ozone column and erythemally weighted UVB for SZA = 60 . The influence of clouds and SZA on UVB dominate over ozone effects. Clouds frequently reduce the irradiances by 50 percent or more (no observations are attempted if rain is imminent). The clear-sky subset of this data was used to deduce the increase in erythemal UV (EUV) that would result from a 1 percent decrease in ozone. This RAF: [RAF = -(d(EUV)/EUV)/(d(O$_3$)/O$_3$)] was then used to reconstruct the curves in the figure. Similarly, RAFs were derived for other SZAs. Figure 11-9 shows these RAFs as a function of SZA. The spread

of results between morning and afternoon UV measurements, and between TOMS and Dobson ozone data, indicates the uncertainty in the measurements. Thus the RAF derived from these measurements is 1.25 ± 0.20 (McKenzie et al., 1991).

The computed daily integrated RAF for this action spectrum at 30°N is 1.1, and is insensitive to cloud and tropospheric aerosol variations (UNEP, 1991). However, the calculated effect of an ozone redistribution from the stratosphere to the troposphere will lead a decrease in UV for small solar zenith angles (Brühl and Crutzen, 1989), but may lead to an increase for large solar zenith angles (Tsay and Stamnes, 1991a). Stratospheric aerosols (from volcanos) have a similar effect (Tsay and Stamnes, 1991b), so that
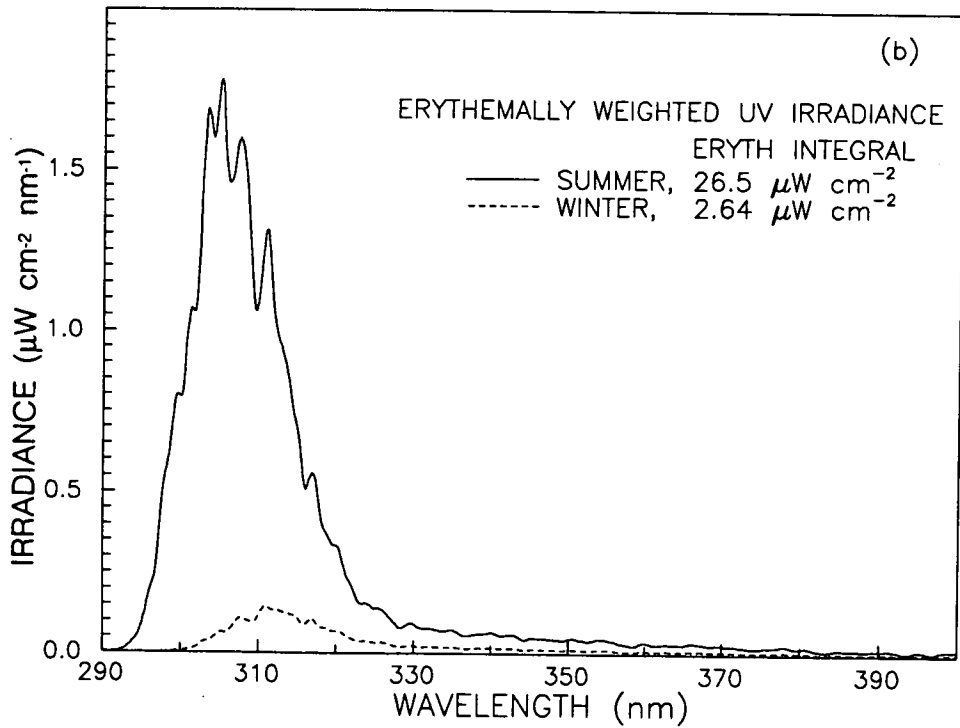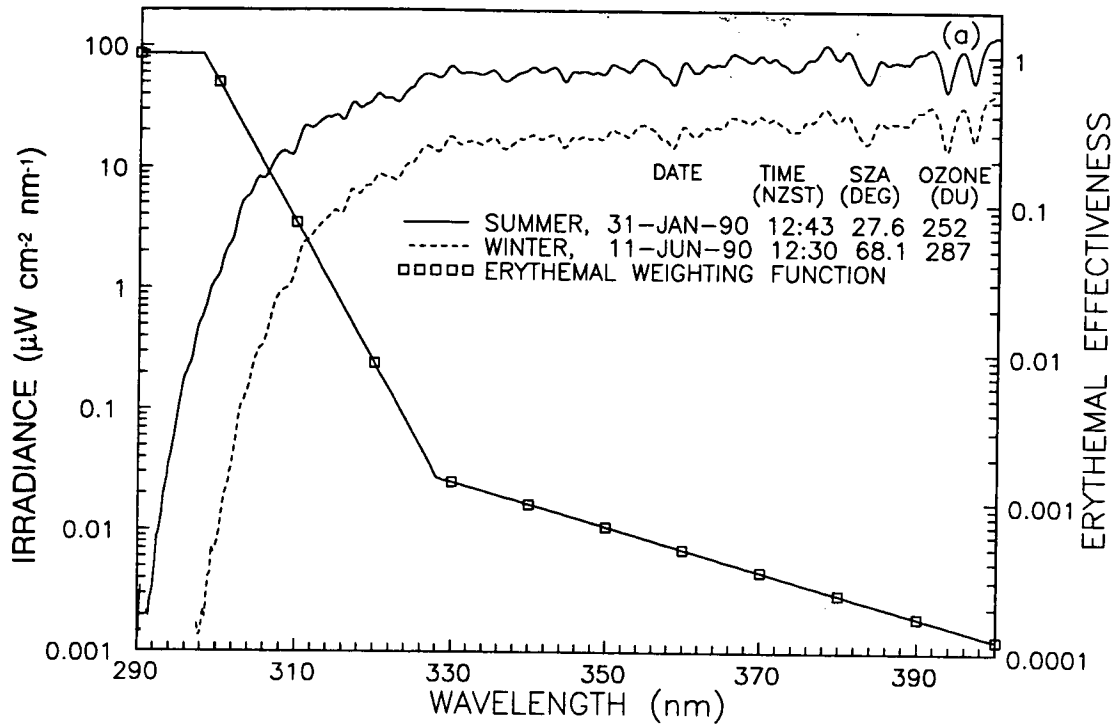
Figure 11-7 (a) Typical noon spectra of UV irradiance at mid-latitudes for summer and winter, showing the erythemal action spectrum used in the calculations that follow, (b) corresponding erythemally weighted irradiances.
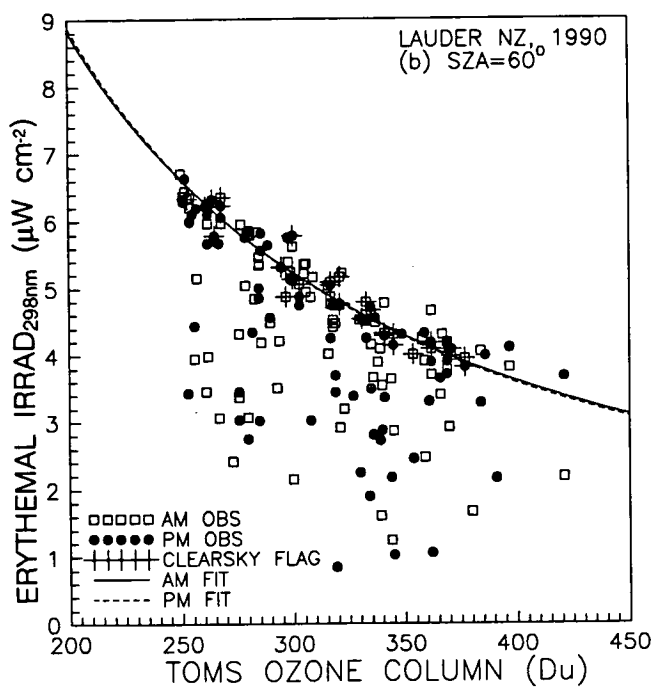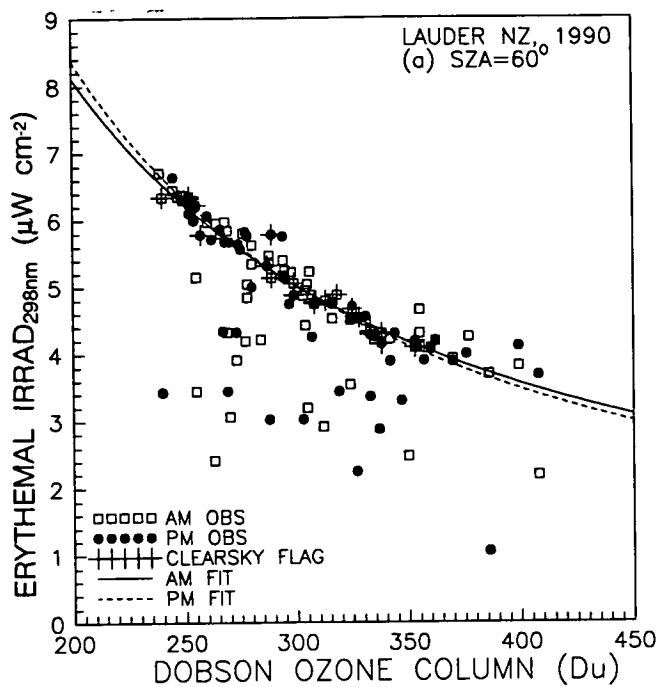
Figure 11-8 Relationship between erythemal UV (EUV) measured at SZA = 60° , and ozone (and cloud) measured at the same site (a) Ozone measured by Dobson, (b) ozone measured by TOMS. Observations that were positively identified as being cloud-free are flagged. The best-fit values of RAF = -[d(EUV)/EUV/d(O$_3$/O$_3$)] to these points were found for both morning and afternoon observations, and used to construct the fitted curves shown.
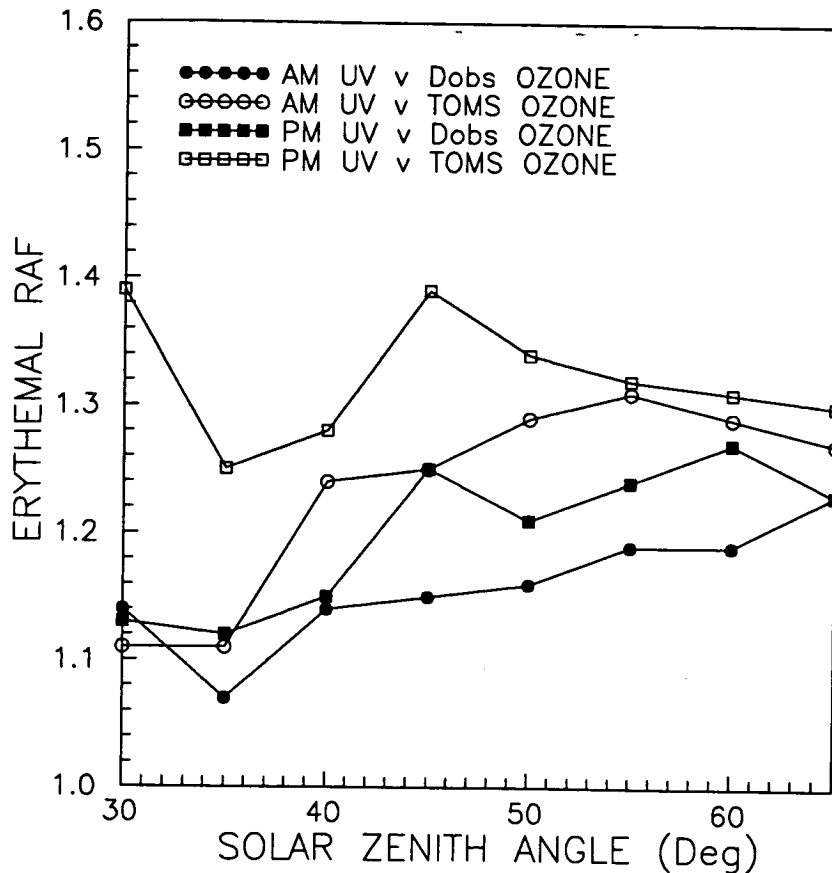
Figure 11-9 RAFs as functions of solar zenith angle, deduced from measurements of erythemally weighted UV irradiance and total ozone. Results have been separated into morning and afternoon observations, and the RAFs are deduced for both Dobson and TOMS ozone measurements.

impacts of ozone vertical redistributions and stratospheric aerosols on UV will depend on latitude and season.

11.2 CHANGES IN ULTRAVIOLET RADIATION BASED ON MEASURED AND COMPUTED OZONE AMOUNTS

11.2.1 Objectives and Limitations

This section presents computed changes in UV irradiances based on ozone values taken from measurements and two-dimensional models. Consistent with the focus of this assessment on the stratosphere, the present work addresses only those changes in UV irradiance related to changes in

column ozone. The results should not be interpreted as the changes that would have actually occurred, but rather as the changes that would have occurred if column ozone were the only variable. In particular, the calculations do not account for a change in the partitioning of ozone between the stratosphere and troposphere and assume clear, pollution-free skies. All results were obtained with the radiative transfer model described by Frederick and Lubin (1988).

This analysis reports the erythemal irradiance integrated over the entire daylight period. This is defined by the convolution over wavelength of the action spectrum for erythema (McKinlay and Diffey, 1987) with the computed spectral irradiance incident on the ground integrated from sunrise to sunset. The absolute erythemal irradiance, in joules per square meter of horizontal area, depends on the action

spectrum being normalized to unity at wavelengths less than 298 nm. The extension of the spectrum to 400 nm implies that the weighted irradiance has a weaker sensitivity to changes in ozone than was the case with older action spectra, which terminated at shorter wavelengths. It is important to recognize that the values reported here depend on the action spectrum adopted. While the action spectrum for erythema is a standard reference, it is not appropriate to all biological responses. For example, using the action spectrum appropriate for damage to DNA, the sensitivity to ozone is increased, while for photosynthesis inhibition, the RAF is near 1 (UNEP, 1991). A biologically weighted irradiance provides an index of the radiation dose received by an organism, but quantitative predictions must be based on an established relationship between dose and response. A large percentage change in irradiance may or may not correspond to a large percentage change in biological response. Similarly, small percentage changes in irradiance are not necessarily insignificant. Such considerations receive further attention in the companion "Effects Assessment" document.

Figure 11-10 presents contours of daytime integrated erythemal irradiance as functions of latitude and month. The column ozone values used here are from the TOMS Version 6 data set for the year 1980. The patterns are as expected from the elevation of the sun and the duration of daylight. Large absolute values exist in the tropics and in the summer hemisphere, while a sharp latitudinal gradient exists in winter. These results represent the baseline case against which to measure percentage changes in irradiance over periods of years.

11.2.2 Changes in Erythemal Radiation Based on TOMS Ozone Measurements

Figure 11-11 gives the percent change in daytime integrated erythemal irradiance from 1980 to 1990 as functions of latitude and month based on zonally and monthly averaged measurements from TOMS. The results show increases of 8 to 12 percent in the mid- to high-latitude winter and spring of the Northern Hemisphere. The changes from 1980 to 1990 are typically 4 to 8 percent in the northern mid-latitude summer and 4 to 12 percent in the southern summer. Note that the largest percentage changes appear in
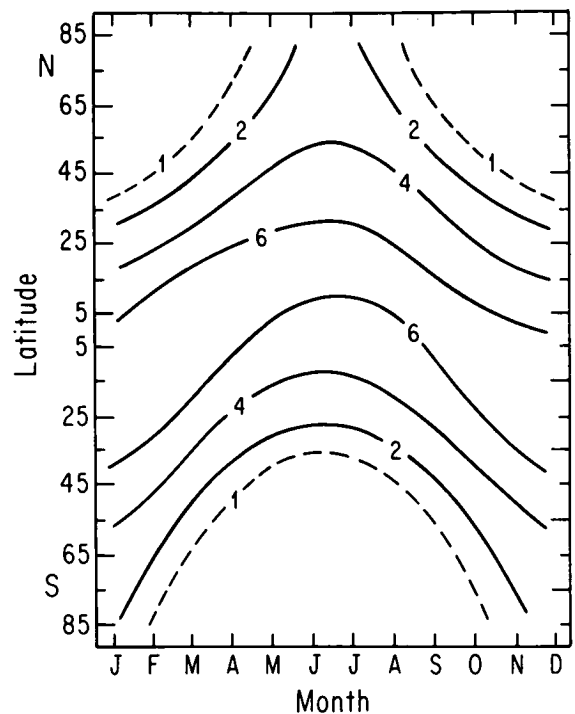

Figure 11-10 Latitudinal and monthly distribution of daytime integrated erythemal irradiance in kilojoules per square meter of horizontal area based on TOMS zonally averaged column ozone measurements from 1980.

winter when the absolute irradiances are small. The cross-hatched area in Figure 11-11 is a region of large gradients in irradiance associated with the prolonged Antarctic ozone depletion of 1990. The UV enhancements in this region are in excess of 25 percent.

The annually integrated irradiance is a useful index that incorporates both the large annual cycle in radiation and the seasonal changes in ozone. Figure 11-12 presents the percent change in annually integrated erythemal irradiance between 1980 and 1990 as a function of latitude. The changes are near zero within 30° latitude of the equator but become positive at latitudes poleward of 30° in each hemisphere. The increases reach 10 percent at high northern latitudes. The extended high-latitude, Southern Hemisphere ozone depletion of 1990 led to
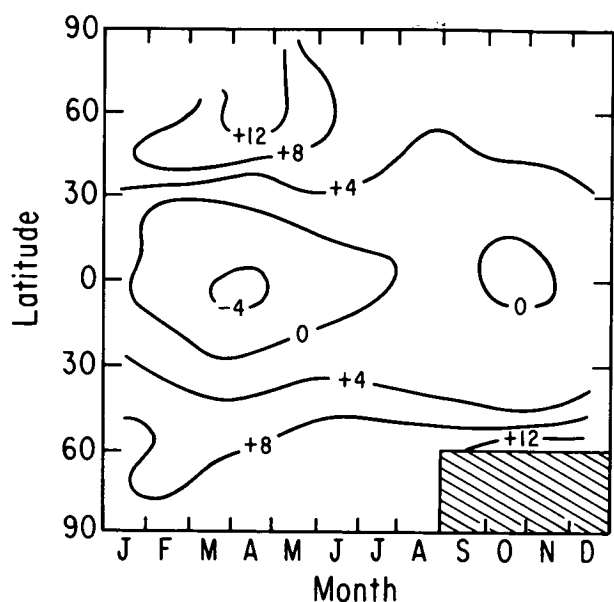
Figure 11-11 Percentage changes in daytime integrated erythemal irradiance as functions of latitude and month based on column ozone changes measured by the TOMS instrument from 1980 to 1990.
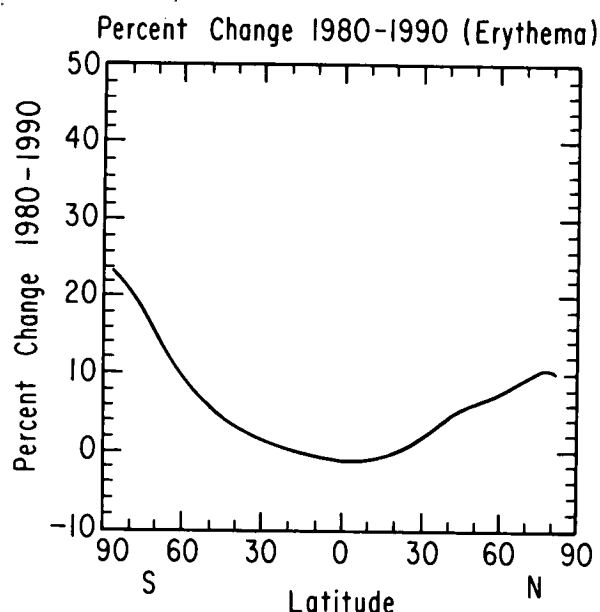
Figure 11-12 Percentage change in annually integrated erythemal irradiance between 1980 and 1990 as a function of latitude.

large ultraviolet irradiances in late spring and early summer. These influence the annually integrated irradiances, giving enhancements of 10 to 24 percent compared with 1980 at latitudes poleward of 60°S.

11.2.3 Predicted Changes in Erythemal Radiation Based on Computed Ozone Values

Current chemical models seriously underestimate the ozone losses observed by TOMS between 1980 and 1990 (see Chapter 2). Therefore they cannot be used to accurately predict future changes in UV fields. Nevertheless, the models are qualitatively in agreement that ozone losses due to atmospheric chlorine will reach a peak around the year 2000, when the peak chlorine loading is expected to maximize given full or near-full compliance with the Montreal Protocol (see Chapter 8, Scenario A). Erythemal UV levels are expected to be enhanced by a factor of two over 1990 levels by 2000, with a gradual reduction thereafter. By 2020, UV levels are

expected to have reverted to 1990 levels. It must be stressed, however, that these are crude estimates, because the model simulations are incomplete.

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