Chapter 5

Surface Ultraviolet Radiation: Past and Future

Lead Authors:
J.B. Kerr
G. Seckmeyer

Coauthors:
A.F. Bais
G. Bernhard
M. Blumthaler
S.B. Diaz
N. Krotkov
D. Lubin
R.L. McKenzie
A.A. Sabziparvar
J. Verdebout

Contributors:
A. Arola
V.E. Fioletov
J.R. Herman
P.W. Kiedron
J.B. Liley
C.S. Long
S. Madronich
T.J. Martin
R. Meerkötter
P.J. Neale
H. Slaper
J.R. Slusser
P. Taalas
M. van Weele
E.C. Weatherhead
C.S. Zerefos

CHAPTER 5

SURFACE ULTRAVIOLET RADIATION: PAST AND FUTURE

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SCIENTIFIC SUMMARY

Important Confirmations of Previous Results

- Additional measurements have confirmed that decreases in column ozone lead to increases in surface ultraviolet (UV) radiation. The relationship has been further documented from existing and new sites. Spectral data records from 65 stations are now available in international data centers. Episodes with elevated UV irradiance associated with low total ozone continue to occur.

- There is clear evidence that the long-term UV changes are not driven by ozone alone, but also by changes in cloudiness, aerosols, and surface albedo. The relative importance of these factors depends on local conditions.

- Enhanced values of UV radiation continue to be observed at high latitudes in the Southern Hemisphere under the Antarctic ozone hole. Highest biologically weighted UV doses under the ozone hole are typically not observed in October when maximum ozone depletion occurs, but in November and early December when solar elevations are higher and low ozone values still prevail. Changes in the duration and spatial extent of the Antarctic ozone hole are therefore more important for Antarctic UV levels than the annual ozone minimum.

New Findings

- Satellite estimates of surface UV radiation from the Total Ozone Mapping Spectrometer (TOMS) dataset have been compared with ground-based measurements at several more sites since the previous Assessment. In general the estimates capture short-term and long-term variability. However, the estimates are systematically higher than ground-based measurements at many sites. The differences in monthly average erythemal ("sunburning") UV irradiance range from about 0% at some clean sites and up to 40% in the Northern Hemisphere. The fact that the agreement is better at the cleaner sites suggests that the differences are due to aerosols and/or pollutants near the ground.

- New algorithms have been developed that produce UV maps with improved spatial (down to 1 km) and/or temporal resolution (down to 30 minutes). These algorithms take into account the effects of clouds, surface albedo, topographical features, and aerosols by using information from other satellite and ground datasets, in addition to satellite column ozone data. The detailed maps have contributed to a better understanding of the geographical and temporal variability in surface UV radiation and have enabled specific UV impact studies. The achievable agreement between the results of such algorithms and ground-based measurements for monthly averages is within ±5%.

- The length of ground-based spectral UV measurement has reached more than 10 years for some sites. It has been shown that a record of 10 years is still too short to derive statistically significant trends.

- UV increases associated with the ozone decline have been observed by spectral measurements at a number of sites located in Europe, North America, South America, Antarctica, and New Zealand.

- Calculations based on pyranometer (total irradiance), total ozone, and other meteorological measurements have been used to reconstruct surface UV irradiance at several mid- to high-latitude sites. Pyranometer and other meteorological data serve as proxies for parameters affecting UV other than ozone. The reconstructed datasets, which extend backward in time to as early as the 1960s at some sites, show long-term increases in erythemal irradiance of about 6-14% over the last 20 years. At some sites approximately half of the changes can be attributed to total ozone changes. It is believed that the increases of UV irradiance derived from the ground-based reconstructed data are clear indicators of the long-term changes that have occurred since the 1980s. However, these reconstructions contain several assumptions on the nature of radiative transfer, are not measurements of UV irradiance, and are not representative on a global scale.

- The reconstructed datasets show that the number of hours of UV levels above certain threshold values has increased at some northern midlatitude sites since the 1970s. For example, in Toronto the number of hours per year with the UV Index above 7 has doubled.

- Snow cover can increase surface UV irradiance by more than 50%. The presence of snow several kilometers away from the observing site may still lead to significant enhancement. Three-dimensional radiative transfer models have shown that the region of significance (defined by increases of UV irradiance by more than 5%) can extend beyond a radius of 40 km.

- In the Antarctic, ozone depletion has been the dominant factor for increases in UV irradiance. The future evolution of UV radiation is therefore expected to follow the ozone recovery. However, because of changes in other influencing factors, such as changes in cloud cover, aerosols, or snow/ice cover, UV radiation may not return exactly to pre-ozone-hole values.

- Elsewhere, including the Arctic, the impact of other influencing factors can be comparable to the impact of ozone depletion. The large uncertainties in future changes of these prevent reliable predictions on the future evolution of UV irradiance. Furthermore, climate-change-induced trends in cloudiness, aerosols, and snow/ice cover are expected to be seasonally and geographically dependent, leading to differences in future UV irradiance in different parts of the world.

- The 2001 Intergovernmental Panel on Climate Change report (IPCC, 2001) states that decreases in sea ice cover over the Northern Hemisphere have occurred and are likely to continue. Furthermore, increases in global cloud cover are likely. Such changes lead to decreases in UV irradiance over large areas of the globe. Quantitative estimations of these effects and their regional dependence cannot yet be made. Although UV irradiance above the surface is enhanced by snow-covered areas, a decrease in sea ice and snow cover will result in an increase of UV dose for organisms living under water and on land areas previously covered by snow.

Advances in Our Understanding

- The effects of climate change on surface UV irradiance are twofold. The first effect is indirect and results from climate changes that influence total ozone. The second effect is direct and results from changes in other climatic variables such as clouds, aerosols, and snow cover.

- Spectral irradiance and actinic flux calculated by several radiative transfer models agree to within 2% when input assumptions are properly chosen. For cases when the Sun is close to the horizon and for shorter wavelengths, the relative standard deviations are somewhat higher (5%), but then irradiance is very small.

- The influence of tropospheric aerosols on UV irradiance may be larger than previously thought, and may affect large areas of the globe. This result is based on studies on the reduction of UV irradiance by aerosols using ground-based instruments and aircraft missions.

- Three-dimensional radiative transfer models have improved the understanding of atmospheric scattering and absorption processes. These models are used to study the effects of inhomogeneous features such as broken and scattered clouds, and nonuniform surface albedo.

- Advances have been made in the understanding of the penetration of UV radiation under water that have allowed the estimation of the underwater UV environment on a global scale using combined satellite datasets.

- A reanalysis of TOMS satellite data with respect to the influence of changes in cloudiness over Europe has confirmed the result found previously by ground-based measurements showing that pyranometric irradiance at the ground has decreased in recent decades. Thus it can be concluded that UV increases due to ozone are partly masked by the increased cloudiness in some regions.

- Uncertainties of ground-based UV measurements are now found to be greater than those estimated in the previous Assessment. A rigorous uncertainty analysis for spectroradiometric solar UV measurements has been performed. For a typical well-maintained instrument it has been shown that uncertainties are as high as ±12.7% at 300 nm and

±6.3% for erythemally weighted irradiance. Major reasons are uncertainties related to calibration standards and wavelength uncertainties. Deviations of about 5-10% between well-maintained instruments and between measurements and models have been seen at recent intercomparisons. In general, broadband instruments have even higher uncertainties than spectroradiometers.

- Better calibration methods have been developed that result in smaller deviations among spectroradiometers. New instruments have been developed and existing instruments have improved with regard to stability, wavelength alignment, and angular response.

- The extraterrestrial solar UV spectrum can be retrieved by Langley plot analysis of ground-based measurements at very clean sites. New studies have shown that these retrievals agree with space-based measurements to within 3%.

5.1 INTRODUCTION

A major concern regarding a decrease in stratospheric ozone is the consequential increase of solar ultraviolet (UV) radiation passing through the atmosphere and reaching the Earth's surface. Ozone absorbs radiation strongly in the UV, and the presence of ozone and oxygen in the stratosphere results in the absorption of nearly all solar radiation below 290 nm. Thus virtually all UV-C radiation (200-280 nm) does not reach the troposphere or the Earth's surface. Solar UV-B radiation (280-315 nm) is significantly absorbed by atmospheric ozone, whereas only a small fraction (less than 3%) of UV-A radiation (315-400 nm) is absorbed by ozone. Accurate measurement of spectral UV has historically been a difficult task. The fact that irradiance varies by many orders of magnitude over a relatively short wavelength range (290-320 nm) requires that useful instruments have a wide dynamic range and a high degree of spectral purity and accuracy. Also the long-term stability of UV instruments and their absolute calibration standard are still difficult to maintain. Consequently, good quality routine spectral measurements did not start until the late 1980s, and these longer records are few in number.

Solar UV radiation that reaches the ground is influenced by many complicated scattering and absorption processes in the atmosphere and at the Earth's surface. These processes must be understood in order to describe fully the characteristics of the current climatology of surface UV radiation on a global scale and to project it to the past and future. Section 5.2 presents findings since the previous Assessment (WMO, 1999) that have improved the understanding of radiative transfer (RT) processes defining the magnitude, wavelength dependence, and angular distribution of UV radiation at and above the Earth's surface and under water or ice. Section 5.2 also discusses the UV Index, a direct application of our understanding of the processes defining surface UV. Section 5.3 discusses resources that are applied to understand and quantify RT processes. These resources include ground-based measurements of surface UV radiation and other pertinent variables; satellite-based measurements of extraterrestrial solar flux, ozone, cloud cover, and reflectivity; RT computer models; and statistical models that quantify dependencies of UV radiation on scattering and absorption. Assessment of the effectiveness and accuracy of these resources (also Section 5.3) includes intercomparisons of different ground-based instruments, intercomparison of RT models, and comparisons of the surface measurements with satellite estimates and RT model results.

In addition to an assessment of recent findings described in the scientific literature, this chapter provides the link between ozone depletion as assessed in earlier chapters of this report and the impacts of increases of surface UV radiation that are assessed in the most recent United Nations Environment Programme (UNEP) "Effects Panel" report (UNEP, 2002). In general, aquatic and terrestrial biological systems (including human beings), material degradation, and pollution photochemistry are sensitive to UV radiation, and in most of the cases the sensitivity increases with decreasing wavelength. The wavelength dependence of the sensitivity of a particular biological system to UV radiation is defined by an action spectrum, and the erythemal (sunburning) action spectrum as standardized by the Commission Internationale de l'Éclairage (CIE; McKinlay and Diffey, 1987) is often used. Studies on impacts of UV radiation require knowledge of the present UV climatology (including average and extreme values) and any changes that have occurred in the past. Results of studies showing that there have been past changes in UV (caused by changes in ozone as well as changes in other variables such as clouds, aerosols, and snow cover) are given in Section 5.4. Section 5.5 presents estimates of future surface UV radiation determined from predictions of ozone changes given in earlier chapters. Effects of other climatological changes, as determined and discussed in the recent Intergovernmental Panel on Climate Change (IPCC) report (IPCC, 2001), that may directly influence surface UV radiation in the future are also discussed in Section 5.5.

5.2 CURRENT UNDERSTANDING OF FACTORS AFFECTING SURFACE UV RADIATION

Since the previous Assessment (WMO, 1999), available resources have been applied to advance our understanding of processes that affect surface UV radiation and have recently been reviewed (e.g., Taalas et al., 2000a; Blumthaler and Taalas, 2001). New research results regarding the dependencies of UV on geophysical variables are presented in Section 5.2.1. Following that is a discussion on the UV Index forecast (Section 5.2.2), which is a direct application of our knowledge and resources. Validation of these daily forecasts allows an ongoing opportunity to assess the accuracy of our resources. Finally, Section 5.2.3 briefly summarizes aspects regarding surface UV radiation that we do not fully understand.

5.2.1 Dependence of UV on Geophysical Variables

One of the main objectives for making good quality measurements of surface UV radiation is to understand the dependencies of UV on absorption and scattering processes that occur in the atmosphere and at the Earth's surface. In principle, if the spatial distribution of all absorbers and scatterers within the atmosphere and at the Earth's surface were fully known, it would be possible to determine the wavelength dependence and angular distribution of surface UV radiation by model calculations. In practice, the complicated distribution of the predominant variables (clouds, ozone, aerosols, and surface albedo) and their interactive impact on UV irradiance makes detailed calculations on a global scale an extremely difficult task.

5.2.1.1 The Extraterrestrial Solar Spectrum

Accurate knowledge of the solar spectrum is important for studying surface UV, since it is used in RT models that are ultimately compared with measurements. At the time of the previous Assessment (WMO, 1999) several satellite measurements were available showing agreement to within ±3% (Cebula et al., 1996). Appendix 5B (Section 5B.4) lists Internet sites that provide information on measured extraterrestrial spectra.

Knowledge of the stability of solar irradiance at UV wavelengths is important because it drives many geophysical processes, including the formation of stratospheric ozone. It could also be used as a reference standard for UV measurements. Changes in solar irradiance from 1700 to present were determined by Fligge and Solanki (2000). Their model assumes that solar irradiance variations on time scales from days to centuries are due only to the changing distribution of solar surface magnetic features. The study determined an increase of solar spectral irradiance at solar activity cycle minimum since the Maunder minimum (year 1700) of 3.0% for wavelengths less than 300 nm and 1.3% for the band 300-400 nm. The total (all wavelengths) and the visible irradiance showed an increase of about 0.3%. Rozema et al. (2002) note that a past long-term increase in solar UV-C radiation would lead to an increase in the production of stratospheric ozone that would reduce surface UV-B irradiance.

5.2.1.2 Dependence of UV on Ozone and Other Trace Gases

The effects of the absorption of atmospheric ozone on surface UV radiation were well understood at the time of the previous Assessment (WMO, 1999), and there has been no major change in our knowledge since then. The wavelength dependence of the sensitivity in UV irradiance to ozone had been fairly well established both by observations and comparison of observations with RT models (e.g., Fioletov et al., 1997; Bodhaine et al., 1998), and these relationships continue to be confirmed (e.g., Bartlett and Webb, 2000; Casale et al., 2000; Cho et al., 2000; Miyauchi et al., 2000). Further work has been done regarding the effects of variations of the vertical distribution and the temperature of ozone (Sabziparvar et al., 1998; Krzyścin, 2000; Lapeta et al., 2000). These effects could influence surface UV should there be a long-term change in the vertical profile or effective column temperature of ozone; however, the effects are relatively small compared to past or expected future long-term changes in total ozone.

The effects of sulfur dioxide on surface UV were shown to be negligible on a global scale but could be significant at sites near local pollution sources or continuous volcanic activity (Fioletov et al., 1998), or over wider areas in the aftermath of major volcanic eruptions. Other gases that absorb in the UV (e.g., nitrogen dioxide, nitric acid, and formaldehyde) are not significant under natural conditions, but could be significant under heavy pollution situations.

5.2.1.3 Dependence of UV on Clouds

Clouds have more influence on surface UV irradiance than any other atmospheric variable. Although important, cloud effects on UV irradiance are difficult to quantify. The effect of clouds on UV is understood in principle. However, in practice the necessary parameters used to calculate local cloud effects are rarely available, and if they were, the complexities of cloud geometry need to be specified in sufficient detail and require the use of three-dimensional (3-D) model calculations.

Under overcast conditions, clouds decrease the irradiance measured at the surface (Josefsson and Landelius, 2000; Renaud et al., 2000). However, enhancements of up to 25% can occur under broken cloud conditions (Estupiñán et al., 1996; Sabburg and Wong, 2000; Weihs et al., 2000), or if there are reflections from cloud decks below high-altitude observation sites such as Mauna Loa Observatory (McKenzie et al., 2001b). Even for large cloud fractions, the reduction in irradiance can be small if the clouds do not obscure the direct beam. Thus, one of the most important parameters is whether or not the Sun is obscured (Grant and Heisler, 2000; Schwander et al., 2002). For individual sites, this poses difficulties for satellite products. When a histogram of cloud transmission is plotted as a function of cloud amount, a bimodal distribution typically results (e.g., Seckmeyer et al., 1997; McKenzie et al., 1998b; McKenzie et al., 2001b), with a lower peak resulting from conditions when cloud obscures the Sun, and a higher peak corresponding to conditions where clouds do not block the Sun. Since the Sun can be unobscured even for large cloud fractions, or obscured even for small cloud fractions, the quantification of cloud effects can become problematic (e.g., Udelhofen et al., 1999; Matthijsen et al., 2000). There are also complications when the scattering of radiation by clouds enhances effects such as absorption by ozone (e.g., Fioletov et al., 1997, 2002) or scattering by aerosols (e.g., Erlick et al., 1998; Mayer et al., 1998b) within the cloud.

The presence of scattered or broken clouds poses difficulties for comparisons between ground-based measurements and satellite estimates of surface UV irradiance. In this situation direct solar radiation is either obscured or not obscured by a cloud at the ground-based measurement site, whereas the satellite measures an average cloud amount over its footprint.

Ground-based measurements of cloud cover are now available at several sites using automated all-sky imagery (Sabburg and Wong, 2000). Although in some cases high thin clouds may not be distinguishable in all-sky images, these continuous records of the spatial distribution of clouds used in parallel with UV irradiance measurements offer the potential to understand and quantify cloud effects more accurately.

5.2.1.4 Dependence of UV on Aerosol Scattering and Absorption

Aerosols are highly variable over space and time. They attenuate UV flux through the atmosphere to an extent that is mostly described by the aerosol optical depth (AOD) and the average column value of the single scattering albedo (ω_o), which is the ratio of scattering to extinction (where extinction = scattering + absorption). The wavelength dependence of the AOD is generally assumed to be proportional to $\lambda^{-\alpha}$, where λ is wavelength, and α is the Angstrom coefficient. Measurements of AOD at visible and UV-A wavelengths using sunphotometry are routinely carried out (e.g., Schmid et al., 1997, 1999). Currently the worldwide Aerosol Robotics Network (Holben et al., 1998) is the best source of information on aerosol particle size, optical depth, and single scattering albedo. Significant progress has been made recently in the measurement and quantification of the effects of aerosols at UV-B wavelengths.

One of the objectives of the Photochemical Activity and Solar Ultraviolet Radiation (PAUR) campaign held in Greece during June 1996 and the PAUR II campaign in Greece and Italy during May-June 1999 was to study the optical properties of aerosols. The AOD in the UV was shown to be approximately inversely proportion to wavelength (i.e., $\alpha = 1.0 \pm 0.5$), and values of ω_o between 0.84 and 0.98 were determined by comparing model results with the measurements (Marenco et al., 1997; Kazantzidis et al., 2000; Kylling et al., 1998). A variety of atmospheric gaseous and particulate concentrations were measured with radiative and optical characteristics of the atmosphere during the PAUR II campaign (Zerefos et al., 2002). Kouvarakis et al. (2002) found that the AOD and single scattering albedo correlated well with surface measurements of ammonium sulfate, indicating the key role that this gas plays in radiative forcing in the area. Variations of calcium originating from the Sahara also correlated well with AOD measurements. The campaigns also studied how changes in stratospheric ozone might influence tropospheric photochemistry through changes in the UV environment (Jonson et al., 2000; Zerefos et al., 2001; Balis et al., 2002; Hofzumahaus et al., 2002; Zanis et al., 2002). These impacts are discussed in the Effects Panel report (UNEP, 2002).

Wenny et al. (2001) studied the variations in AOD at 317, 325, 332, and 368 nm from July through December 1999 using a multifilter radiometer near Asheville, North Carolina, and found the mean optical depth was 0.33 at 368 nm and increased to 0.40 at 317 nm, indicating a value of about 1 for α. The study used an RT model to investigate the reduction in erythemal UV irradiance relative to a baseline case with AOD = 0.2 and $\omega_o = 1.0$. When the AOD was increased to 1.3, maximum reduction in UV was 44% for $\omega_o = 0.75$, 29% for $\omega_o = 0.90$, and only 18% for $\omega_o = 1.0$. Vermeulen et al. (2000) have developed a method for retrieving the scattering and microphysical properties of atmospheric aerosols (including ω_o) from measurements of solar transmission, aureole, and angular distribution of the scattered and polarized sky light in the solar principal plane.

It has been shown by ground-based measurements that large reductions of UV-B occur under absorbing aerosols such as smoke from biomass burning (e.g., Ilyas et al., 2001; Kirchhoff et al., 2001), forest fires (e.g., McArthur et al., 1999), or desert dust (di Sarra et al., 2002a). Recent work suggests that anthropogenic aerosols that absorb in the UV region may play a more important role in attenuating UV irradiances than has been assumed previously (Jacobson, 2001).

Comparisons between satellite-derived UV and ground-based spectral measurements have revealed inconsistencies in satellite-derived UV that are probably related to the inability of the satellite sensors to correct for boundary layer extinctions. Ground-based estimates of regional UV irradiances suffer from a similar inability to correct for horizontal inhomogeneities in boundary layer extinction as well as inhomogeneities in the troposphere and stratosphere. Only at the cleaner sites is there good agreement within the experimental errors. At continental sites in the Northern Hemisphere, the satellite-derived UV estimations are too large (McKenzie et al., 2001a; Fioletov et al., 2002).

Gröbner et al. (2001) made a comparison of AODs determined by seven Brewer spectrophotometers and a Li-Cor spectrophotometer at Huelva, Spain, between 1 and 10 September 1999. For all instruments, measurements of AOD at 306, 310, 313.5, 316.7, and 320 nm agreed to within ±0.03 over a range of AOD between 0.2 and 0.6 at 306 nm. These results suggest that the existing Brewer network can be used to determine UV AODs, an important consideration for extending the coverage of ground-based measurements for studying scattering/absorption processes and long-term trends. Routine measurements of AOD in the UV using Brewer instruments have been reported (e.g., Meleti and Cappellani, 2000; Kerr, 2002).

5.2.1.5 Dependence of UV on Surface Albedo

The presence of snow cover surrounding an observing site increases UV irradiances (McKenzie et al., 1998a; Minschwaner, 1999; Herman and McKenzie et al., 1999; Krotkov et al., 2001; Chubarova et al., 2002; Fioletov et al., 2002), even when the snow is several kilometers away (Degünther et al., 1998; Degünther and Meerkötter, 2000b; Weihs et al., 2001). Recently developed RT models have shown that certain snow distributions can cause significant (defined as being >5%) increases of surface UV irradiance even if the snow is farther than 40 km from a site (Degünther et al., 1998; Ricchiazzi and Gautier, 1998; Smolskaia et al., 1999; Lenoble, 2000; Mayer and Degünther, 2000). Models have also been used to study the complicated interactions between snow enhancements combined with atmospheric scattering and absorbing processes (Aoki et al., 1999; Renaud et al., 2000; Krotkov et al., 2001).

Snow enhancements between 8% and 39% for surface UV at 324 nm were reported in the previous Assessment (Herman and McKenzie et al., 1999). Increases are greater at Arctic sites surrounded by uniform snow cover and less at urban sites or sites near open water (Fioletov et al., 2002). Site-specific enhancements are attributable to increases in the “regional” albedo, which represents a spatial average around the site. The regional albedo may be determined from the snow enhancement values (Schwander et al., 1999; Krotkov et al., 2001; Chubarova et al., 2002) and is a function of the age and depth of snow as well as the terrain and other features around the site. Measurements of UV irradiance (320-325 nm) made at Syowa, Antarctica (Aoki et al., 2000), were compared with those made at four Japanese sites (Sapporo, Tsukuba, Kagoshima, and Naha) for the same values of total ozone and solar zenith angle (SZA). Values at Syowa were observed to be about 60% higher than the upper limit of values seen over Japan (Takao et al., 1999), making the albedo enhancement an important consideration when combined with low total ozone values seen under the Antarctic ozone hole.

Information regarding the average albedo in the satellite field of view is important for space-based estimates of surface UV (Krotkov et al., 2001). When snow depth information is used as input to estimate regional albedo, better agreement between ground-based measurements and satellite estimates is achieved, particularly under cloudy conditions (Arola et al., 2002; Krotkov et al., 2002). However, day-to-day knowledge of regional albedo on a global scale remains a challenge.

Combining measurements with RT model results can be used to derive estimates for unknown input parameters by statistical fitting procedures. When aerosol optical depth is relatively low (and thus the effect of inaccurately known optical characteristics of aerosols is small), regional albedo of partly snow-covered terrain can be derived (Schwander et al., 1999; Gröbner et al., 2000; Weihs et al., 2001). Values of regional surface albedo in the range of 0.3 to 0.9 were determined, depending on local conditions of topography and snow coverage.

5.2.1.6 Dependence of UV on Altitude

Since the previous Assessment (WMO, 1999), the dependence of UV irradiance on altitude has been further quantified. In practice the altitude dependence of UV irradiance is itself dependent on differences in surface albedo, boundary layer extinctions by aerosols, and tropospheric ozone concentrations. Therefore the dependence is not represented by a single value (Seckmeyer et al., 1997). Even when these effects are ignored, it has been found that at higher altitude the dependence of UV irradiance on SZA and wavelength changes. In general, for erythemally weighted UV, irradiances in clean conditions increase between 5 and 10% per kilometer (McKenzie et al., 2001b; Zaratti et al., 2002; Schmucki and Philipona, 2002), with the greatest increase occurring at SZA ~ 60-70°. To model the dependence correctly at Mauna Loa Observatory, it was necessary to consider the effects of sky irradiance scattered from below the observatory (McKenzie et al., 2001b). In mountainous regions the vertical gradient in some instances can be larger (up to 50% per kilometer) because of local effects such as increasing albedo with altitude and high concentrations of ozone or aerosols in the lower troposphere (Seckmeyer et al., 1997). Larger altitude gradients in the free troposphere have also been measured from aircraft under polluted situations over Greece (Varotsos et al., 2001).

5.2.1.7 Angular Dependence of UV

Ground-based measurements of UV irradiance are generally made with a horizontal diffuse surface that would ideally follow a response proportional to the cosine of the angle from normal (vertical) incidence. In many cases the collection efficiency of the diffuser falls below the cosine function for large SZA, and calculations are made to adjust (usually increase) the measured irradiance (Bais et al., 1998a; Chubarova and Nezval, 2000; Fioletov et al., 2002). The adjustments depend on the angular distribution of incident radiation and are complex functions of SZA, wavelength, total ozone, ozone distribution, aerosol, and cloud amounts. The relationships of measured to adjusted values are corrected by use of RT models.

For many biological and photochemical processes, actinic fluxes rather than cosine-weighted irradiances are more appropriate. However, such measurements have not been generally available until quite recently (Hofzumahaus et al., 1999, 2002; Shetter and Müller, 1999). Recent progress has been made in converting irradiances to actinic fluxes, offering the prospect of deriving historical changes of actinic flux from the extensive existing database of irradiance measurements (Kazadzis et al., 2000; McKenzie et al., 2002; Webb et al., 2002). It was found that the most important parameters defining the relation between actinic flux density and global UV irradiance are the ratio of direct to global irradiance, whether or not the Sun is obscured, and the description of the angular distribution of the diffuse radiation. Under clear skies, retrieved spectral actinic flux densities agree with model calculations to within ±5% for a variety of aerosol conditions. The assumption of an isotropic distribution of the diffuse radiation can lead to a wavelength-dependent overestimation of actinic flux densities from 10 to 15%, depending on SZA, especially in atmospheres with high aerosol content (Kazadzis et al., 2000).

A campaign to measure spectral global UV irradiance and actinic flux at the ground, supported by ancillary measurements used to characterize the atmosphere, was carried out in August 2000 at Nea Michaniona, in northern Greece (Webb et al., 2002). It was established that the ratio of actinic fluxes (F) to horizontal irradiance (E) is between 1.4 and 2.6 for UV wavelengths. This ratio is a function of wavelength, SZA, and the optical properties of the atmosphere. Both the wavelength and SZA dependency of the ratio decrease when the scattering in the atmosphere increases and the direct beam proportion of global irradiance decreases, as expected.

5.2.1.8 Dependence of UV Under Water

The underwater UV environment is an important consideration for studies of the sensitivities of aquatic (both freshwater and saltwater) species to UV radiation (de Mora et al., 2000). These effects are discussed extensively in the UNEP Effects Panel report (UNEP, 2002). There have been recent spectral measurements of UV under fresh water (e.g., Sommaruga and Psenner, 1997; Laurion et al., 1997; Bukaveckas and Robbins-Forbes, 2000; Markager and Vincent, 2000) and salt water (e.g., Booth and Morrow, 1997; Kuhn et al., 1999). Measurements of UV penetration into seawater using a biochemical deoxyribonucleic acid (DNA) dosimeter combined with a spectroradiometer have been reported (Boelen et al., 1999). In general, these measurements show that there is wavelength-dependent absorption by water in the UV that increases with decreasing wavelength. The underwater absorption has strong dependence on the abundance of dissolved organic matter that has wide temporal and spatial variability. A sensitivity study conducted by RT modeling has shown that the main parameters controlling levels of the most harmful UV-B radiation underwater for clear-sky conditions are the SZA, seawater bio-optical properties, and total ozone amount (Vasilkov and Krotkov, 1997). Attenuation of UV-B irradiance and DNA dose rate with water depth is primarily controlled by the total seawater absorption coefficient and its spectral dependence.

Estimates of UV radiation penetration into the ocean waters are now available on a global scale by combining Total Ozone Mapping Spectrometer (TOMS) satellite estimates of UV irradiance at the ocean surface with the SeaWiFS (Sea-viewing Wide Field-of-view Sensor) satellite ocean-color data and using a model to define seawater optical UV properties (Vasilkov et al., 2001). Weekly maps of underwater UV irradiance and DNA-weighted exposure are calculated using monthly-mean SeaWiFS chlorophyll and diffuse attenuation coefficient products, daily SeaWiFS cloud fraction data, and daily maps of TOMS-derived surface UV irradiance. The final products include global maps of weekly-average UV-B irradiance and DNA-weighted daily exposures at depths of 3 m and 10 m, and depths where the UV-B irradiance and DNA-weighted dose rate at local noon are equal to 10% of their surface values.

Global mapping of underwater UV radiation creates many new challenges. The challenges are mostly related to larger uncertainties in physical input parameters caused by biological processes within the oceans. Vasilkov et al. (2002) discuss the problems encountered in the assessment of the underwater UV irradiance from space-based measurements, and propose approaches to overcome the difficulties by combining different satellite datasets (TOMS, SeaWiFS, and Moderate Resolution Imaging Spectroradiometer (MODIS)). Both SeaWiFS and MODIS provide some estimate of seawater optical properties in the visible. Currently, the problem of accurate extrapolation of visible data to the UV spectral range is not solved completely, and there are only a few available measurements. Vasilkov et al. (2002) propose to parameterize UV absorption by oceanographic constituents empirically by using bio-optical measurements from a variety of ocean waters. Another problem is the lack of reliable data on pure seawater absorption in the UV. Laboratory absorption measurements of the middle UV for both pure water and pure seawater are required (Fry, 2000).

The transmission of UV radiation through sea ice is reduced by absorption and scattering processes that occur within and on top of the ice. UV radiation is strongly absorbed by both colored dissolved organic matter and particulate organic matter, including ice algae. Scattering occurs above the ice by snowcover, within the ice, and from interstitial brine (Vasilkov et al., 1999). Consequently, the transmission changes during the season, either declining by an order of magnitude as a highly scattering turbid brine layer develops on top of the ice, and as ice algal communities bloom (Trodahl and Buckley, 1990; Perovich et al., 1998), or increasing if snow melt ponds form on top of the ice, thereby reducing albedo and scattering (Belzile et al., 2000). In the latter case, the under-ice spectrum becomes enriched in UV-B relative to photosynthetically active radiation, and may exacerbate UV-B effects.

5.2.2 Daily Forecasting of Ozone and UV

Forecast of the UV Index is a direct application of the resources used to study UV radiation and the knowledge of the dependencies of surface UV on absorption and scattering processes. Forecast values of total ozone are used as input to RT models or statistical models. Most of the agencies that currently produce forecasts of the UV Index had been doing so by the time of the previous Assessment (WMO, 1999) in accordance with the international definition and standardization (WMO, 1994, 1997). Although many agencies provide UV Index forecasts on their web pages, only a few have published their methodology (Burrows et al., 1994; Long et al., 1996; Burrows, 1997; Bais et al., 1998b; Lemus-Deschamps et al., 1999). Many countries have adopted and/or modified the above methodologies to produce their own UV Index forecasts. Further information regarding the UV Index can be found on Internet sites listed in Appendix 5B (Section 5B.5).

With the increase of computing speeds, more countries moved from empirical forecasts of the UV Index to using RT models that can be very specific or can make several assumptions to increase output speed. These models provide the UV irradiances at the surface under clear skies with known column ozone amount and aerosol type and content. The difficulty in the forecast of UV Indices lies in the forecast of the ozone amount and the transmission of UV radiation through the atmosphere in the presence of clouds and aerosols. Our inability to estimate accurately the aerosols at a specific location introduces further uncertainty in UV Index calculations, and a recent study by Krzyścin et al. (2001) has addressed this issue. Comparisons of model predictions with measured UV Indices under cloudless conditions (De Backer et al., 2001) showed that models generally overestimate the UV Indices, owing to lack of aerosol information. Inclusion of clouds in UV forecasts is a double problem, because clouds must be accurately forecast and their transmittance properties must be accurately known.

There have been two approaches to address the cloud problem. In the absence of a comprehensive weather forecasting model, empirical relations between forecast cloud types and observed UV amounts provide the necessary means of producing a UV Index forecast. These relations may include variable amounts of aerosols and the inherent elevation of the site, thus making the relationships unique to a particular site. The second approach is to use a numerical weather prediction model (NWP) such as that from National Centers for Environmental Prediction (NCEP), the United Kingdom Meteorological Office (UKMO), or the European Centre for Medium-Range Weather Forecasts (ECMWF). These models provide the necessary cloud parameters, shortwave radiation information, and snow cover (i.e., albedo) information to derive a better estimate of the UV Index forecast. Research must be conducted to make sure that the NWP's cloud fields and transmittances are validated by observations.

The forecasts of ozone used to produce the UV Index forecasts have been determined using two methods: persistence of satellite-observed ozone amounts, and using NWP meteorological variables to make ozone forecasts via statistical regressions (Bais et al., 1998b; Plets and Vynckier, 2000). The former procedure works well for one-day forecasts year round in the tropics and during summer poleward of the tropics. The latter method is required when ozone variability is large and statistical correlations between ozone variations and variations in the meteorological parameters are greater.

Recently, forecasting centers (e.g., NWP mentioned above and the Koninklijk Nederlands Meteorologisch Instituut (KNMI)) have been assimilating ozone into their forecast models. These models require a much better depiction of ozone in the atmosphere for their radiation calculations. At NCEP, the Solar Backscatter Ultraviolet Spectrometer (SBUV2) ozone profile and total column information is assimilated into the global NWP model. Accurate forecasts of the global ozone field are available out to 5 days. Ozone forecasts are useful for forecasting UV, as well as for the a priori ozone estimates (total and profile) required by ozone retrieval algorithms. The quality of this a priori value greatly affects the derived value (Bhartia et al., 1996). Thus positive feedback between observation and model forecast is created.

5.2.3 Remaining Questions and Uncertainties

Remaining uncertainties in our understanding of the radiative transfer processes that define surface UV radiation include the following:

- A lack of knowledge of aerosol absorbing and scattering processes that results in observed differences between some of the satellite estimates and ground-based measurements of surface UV irradiance.
- A lack of knowledge of aerosol optical depths and aerosol single scattering albedo values on a global scale. Differences in these variables from one geographic location to another may lead to differences in the bias between ground-based measurements and satellite estimates from one site to another.
- The extent to which inhomogeneities of terrain, surface reflectivity, or persistent geophysical features surrounding an individual site influence ground-based measurements. The inhomogeneities also affect how well a single point measurement is representative of an extended region (Chubarova et al., 2002; Fioletov et al., 2002). These uncertainties, plus the fact that the geographic distribution of ground-based sites is not uniform, make the determination of global UV climatologies and long-term trends solely from ground-based networks a difficult, if not impossible, task.
- The combined effects of clouds and surface albedo in the derivation of satellite estimates of surface UV.
- The combined effects of clouds, aerosols, and tropospheric absorbing gases on ground-based and satellite measurements. Some of these processes have been established in case studies, but their importance is not quantified on global and regional scales.

5.3 AVAILABLE RESOURCES FOR STUDYING SURFACE UV RADIATION

Surface UV radiation is studied by using several types of resources that have been developed and applied by many research groups. These resources include ground-based instruments, RT models, satellite instruments, and statistical models. Ground-based instruments that measure surface UV irradiance include spectroradiometers, broadband radiometers, and narrowband multifilter instruments. RT models calculate surface UV using a model atmosphere with the solar spectrum and several scattering and absorbing geophysical parameters as input. Satellite instruments measure geophysical variables and use RT models to calculate surface UV irradiance on a global scale. Statistical models are used to determine dependencies of surface UV irradiance on scattering and absorbing variables.

5.3.1 Ground-Based Measurements

The measurement of solar UV radiation received at the Earth's surface is technically demanding. Usually, the quantity measured is the irradiance on a horizontal surface using a detector with a cosine response. This means, for example, that radiation at 60° from the zenith has only half the weighting of that from the zenith direction.

Three categories of UV sensors are in widespread usage: (1) spectroradiometers designed to measure the spectrum of UV at UV-A (315-400 nm) and UV-B (280-315 nm) wavelengths at spectral resolutions of 1 nm or better, (2) broadband sensors designed to measure biologically weighted UV irradiance, in most cases the erythemally weighted (or "sunburning") UV irradiance, and (3) multifilter instruments where the irradiance is measured through several narrowband (~2- to 10-nm bandwidth) filters and the full spectrum can be recovered using RT models.

5.3.1.1 Spectroradiometers

Since the previous Assessment (WMO, 1999) there have been a number of developments on UV spectroradiometers with the introduction of new instrument types and improvements of existing UV instrumentation. A dual-prism spectrograph (UV-rotating shadowband spectroradiometer) that makes continuous and nearly simultaneous spectral measurements of direct, diffuse, and total horizontal irradiance using an array detector has recently been introduced (Harrison et al., 1999; Lantz et al., 2002). Compared with conventional scanning spectroradiometers, these array instruments measure spectra much faster, thus creating new opportunities to investigate fast-changing atmospheric variables such as clouds. Also a high-resolution (0.1 nm) 1-m Czerny-Turner double grating spectroradiometer with 10^{-10} out-of-band light rejection has been developed and is in operation in the U.S. Department of Agriculture (USDA) monitoring network (Bigelow et al., 1998; Lantz et al., 2002).

The need to correct for the cosine error (McKenzie et al., 1992; Seckmeyer and Bernhard, 1993; Gröbner et al., 1996) is now more widely recognized. More spectroradiometers have been equipped with diffusers that represent the cosine response better than previously used collectors (Bernhard and Seckmeyer, 1997; Bais et al., 2001a). In addition, methods to correct measurements made by instruments with known angular response have been developed and applied to existing data records (Bais et al., 1998a; Fioletov et al., 2002).

Wavelength shifts in measured spectra can contribute significantly to the overall error budget, particularly at wavelengths less than 300 nm where the spectral gradient is large from absorption by ozone. Emphasis has been given in recent years to develop improved wavelength drives with increased thermal stability and reproducibility (e.g., Gröbner et al., 1998). With the implementation of these developments, the wavelength scale of many spectroradiometers can be aligned to within ±0.02 nm, which is acceptable for long-term trend detection. Also methods for post-correction of wavelength shift by correlating the Fraunhofer structure in measured spectra with the same structure in reference spectra have been further refined and tested (Bais et al., 2001a; De la Casinière et al., 2001).

The temperature dependence of the responsivity of Brewer instruments in the U.S. Environmental Protection Agency (EPA) network has been characterized (Weatherhead et al., 2001). It was shown that temperature dependence varies from instrument to instrument and can result in errors up to ±10% in some cases. However, with knowledge of the temperature dependence it is possible to partly correct existing data records.

A comprehensive list of spectroradiometer specifications based on requirements of UV research is given by Seckmeyer et al. (2001). This report contains guidelines for instrument characterization such as spectral sensitivity, stray light determination, wavelength alignment, angular response, and other parameters that influence the quality of data measured by spectral UV instruments. The dominating factors in the uncertainty budget of spectroradiometers are uncertainties related to the radiometric calibration (e.g., uncertainty of calibration standards), deviation from the ideal angular response (the cosine error), instrument drift, and wavelength misalignment (Bernhard and Seckmeyer, 1999). Uncertainties arising from an instrument's spectral bandpass (the slit function) and stray light, which were historically a problem, are of less importance with state-of-the-art instruments that use high-quality double monochromators and a resolution smaller than 1 nm.

5.3.1.2 Broadband Filter Radiometers

Instruments that measure irradiance over a wide wavelength range (>10 nm) are called broadband instruments. Many of these instruments are designed to measure the erythemally weighted irradiance as defined by the Commission Internationale de l'Éclairage (CIE) (McKinlay and Diffey, 1987). From measurements of the erythemally weighted irradiance, the UV Index (WMO, 1994) can be directly calculated. Since the previous Assessment (WMO, 1999) research efforts have focused on the calibration of these instruments and the analysis of data, with little instrument development.

No broadband instrument precisely matches the erythemal spectrum. Examinations of broadband instruments by independent laboratories have revealed that variation of individual instruments from the specifications offered by manufacturers can result in calibration errors between 10 and 20% (Bodhaine et al., 1998; Leszczynski et al., 1998; Landelius and Josefsson, 2000). The conversion from individual detector-based units to standardized units (e.g., the UV Index) depends on the wavelength dependence of the radiation, and at the Earth's surface this dependence is characterized mainly by the SZA and total ozone. Thus, the absolute calibration of a broadband detector depends on these parameters. Often this dependence is determined using RT model results to convert from detector weighted units to erythemally weighted units or by comparing measurements of a broadband detector for a considerably long time with a co-located spectroradiometer (Mayer and Seckmeyer, 1996; Blumthaler, 1997; Bodhaine et al., 1998; Lantz et al., 1999).

Significant changes in the responsivity of broadband detectors have been noted during routine operation (Weatherhead et al., 1997; Silbernagl and Blumthaler, 1998; Borkowski, 2000). These changes are difficult to detect without careful examination of the instruments (Lantz et al., 1999; di Sarra et al., 2002b). Furthermore, it was found that changes of internal relative humidity or temperature are responsible for short-term variations of sensitivity by more than 10% in some instruments (Huber et al., 2002). Therefore, stability for these instruments (as well as for other UV instrument types) should be verified by careful, periodic characterization and calibration.

5.3.1.3 NARROWBAND MULTIFILTER RADIOMETERS

Narrowband multifilter radiometers are less expensive and require less maintenance than spectroradiometers, yet, if well calibrated, can produce valuable information. Their bandwidths range from about 2 nm to 10 nm, and some are equipped with an automated shadowband to retrieve direct Sun irradiance. As with any radiometric measurement, regular calibrations are essential. Recent repeat measurements of the spectral response of 34 multifilter radiometers before and after 6 to 12 months of field use revealed mean spectral shifts of less than 0.04 nm for all channels (Gao et al., 2001). Multifilter radiometers measure all wavelengths (typically from four to seven channels) in less than 1 second as opposed to scanning spectroradiometers that usually require several minutes to complete a scan. This rapid and nearly simultaneous sampling of all wavelengths is useful for studying variations in UV irradiance caused by rapidly changing cloud and aerosol conditions. Radiometers that measure direct Sun can retrieve aerosol optical depth (Wenny et al., 2001; Slusser et al., 2002) as well as track the instrument's radiometric stability in the field (Bigelow and Slusser, 2000). Radiometers that measure global irradiance only, as well as those measuring global and direct Sun irradiances, can retrieve column ozone (Slusser et al., 1999; Gao et al., 2001). Several methods have been successfully implemented to construct a complete spectrum from multifilter measurements (Fuenzalida, 1998; Min and Harrison, 1998). Combining multifilter measurements with concurrent measurements of a scanning radiometer allows the derivation of spectra at high temporal resolution, thus blending the strengths of both instrument types (Thorseth and Kjeldstad, 1999); however, rigorous intercomparisons with spectroradiometers are still sparse.

5.3.1.4 DATA QUALITY AND DATABASES

Scientific objectives, such as the detection of trends in UV radiation and investigations into radiative transfer processes, require UV data of known quality that are attainable only with carefully maintained and well-characterized instruments. The improvement of data quality has remained a vital goal in recent years, and progress has been made toward achieving this since the previous Assessment.

Many new stations have started regular spectral UV observations since the previous Assessment. However, the geographic distribution of these stations is weighted more toward continents in the Northern Hemisphere and less over oceans and large regions of the Southern Hemisphere. The existing nonuniform distribution is not adequate to make measurements of long-term trends that are representative of global coverage.

Currently there are two major databases where interested scientists can obtain data: the World Ozone and Ultraviolet Radiation Data Centre (WOUDC) operated by the Meteorological Service of Canada (MSC) in Toronto, Canada, and the European UltraViolet DataBase (EUVDB) in Helsinki, Finland (called Scientific UV Data Management (SUVDAMA) in the previous Assessment). Appendix 5A gives a list of stations and data that are currently available. Since the contents of these databases are rapidly changing, the interested reader is referred to the database websites given in Appendix 5A as well as other websites listed in Appendix 5B.

Most of the spectroradiometers deployed today are radiometrically calibrated with tungsten halogen standard lamps that are traceable to standards maintained by national standards laboratories. The calibration uncertainty of these lamps is still one of the most prominent sources of error in solar UV radiometry. Standard lamps can abruptly change by up to 1% in the radiation output at unpredictable intervals (Bernhard and Seckmeyer, 1999). In addition, irreversible changes of 10% or more have been seen by several investigators. These are connected to visible changes in the lamp's filaments. Such lamps can no longer be used for calibration purposes. Lamp comparisons further suggest that even standards of the same calibration laboratory may disagree with each other beyond their stated accuracy, and deviations exceeding 4% have been observed at UV wavelengths (Bernhard and Seckmeyer, 1999; Kiedron et al., 1999). National standards laboratories usually provide calibration points in increments of 5 to 50 nm, and interpolation to wavelengths between these points may lead to errors of the order of 0.5 - 1%. New interpolation procedures have recently been developed to reduce this effect (Huang et al., 1998). In order to diminish uncertainties related to transportation of radiometers between calibration in the laboratory and deployment on site, new field calibration units have been developed in recent years (Seckmeyer et al., 1996, 1998; Early et al., 1998; Bais et al., 2001b).

Assessment of the comparability of lamp standards currently used at different stations in Europe has been initiated by the Joint Research Centre (JRC) of the European Commission. A set of carefully selected and seasoned lamps is circulated among the nine participating institutes, which report their spectral irradiance output based on comparative measurements with the local calibration standards. The results of the first round indicate differences of up to 9% between the calibration standards of different laboratories (Gröbner et al., 2002). The average root mean square (rms) difference of all the lamps to the mean is 2.0, 1.8, and 1.7% at 300, 330, and 360 nm, respectively, which is within the expected uncertainty estimates of the lamp calibration certificates. A series of measurements with the same stationary spectroradiometer of JRC proved that the lamps were stable to within 0.6% during the entire period of the exercise, giving confidence to the differences encountered and to the feasibility of the method.

As an alternative to standard lamps, it has been proposed that the Sun can be used as a long-term reference to monitor instrument stability and as a calibration source, since its irradiance is stable to within ±0.5% at UV-A and UV-B wavelengths. This is done with the Langley plot technique using instruments that are able to perform both direct and global measurements at clean sites where the diurnal variability of ozone and aerosol extinction is small (Bais, 1997; Slusser et al., 2000; Gröbner and Kerr, 2001; Kerr, 2002). Ground-based measurements of direct solar irradiance (using absolute lamp-based calibrations) are extrapolated to zero air mass and compared with an extraterrestrial solar spectrum (e.g., Cebula et al., 1996). It has been shown that lamp-based Langley extrapolation measurements of the solar spectrum performed with a Brewer spectrophotometer under ideal conditions at Mauna Loa Observatory (3397-m altitude) are consistent with satellite measurements to the 2-3% level for wavelengths greater than 305 nm (Gröbner and Kerr, 2001). A similar comparison of Langley and lamp-based calibrations was performed at the same observatory with a UV multifilter rotating shadowband radiometer. Differences between 0 and 7% were found, with largest deviations at the shortest wavelengths (Slusser et al., 2000), and drifts in sensitivity of the instruments of the order of 1% per year were detected (Bigelow and Slusser, 2000). An important prerequisite for these extrapolation measurements is that atmospheric conditions remain constant. Therefore such calibrations can only be performed at very clean sites, where aerosols do not influence UV irradiance. Also reliable calibrations cannot be made at wavelengths less than 305 nm, where the signal is strongly attenuated by ozone.

New techniques have been pursued to uncover errors in spectral measurements. For example, analyzing ratios of spectra sampled throughout a day enables the detection of errors in the data acquisition of instruments and the determination of wavelength shifts (Bernhard et al., 1998; Seckmeyer, 2000). Standardized methods to mark data with reduced accuracy or to flag scanning spectral UV measurements that are distorted by clouds have been developed (Vasaras et al., 2001). The WOUDC now flags data before adding them to the database, and other data centers are currently developing data-flagging algorithms for the detection of spectral distortion, wavelength error, and the presence of clouds.

Since the previous Assessment, more systematic work to determine the uncertainty of UV measurements has been completed. Bernhard and Seckmeyer (1999) present a general procedure to calculate the uncertainty budget of spectroradiometers depending on instrument specifications, calibration uncertainties, and atmospheric conditions. The method can be applied to most types of spectroradiometers deployed worldwide. For well-characterized spectroradiometers, erythemal irradiance can be measured within an uncertainty of ±6% (±2σ). A substantial reduction in this uncertainty would require more accurate calibration sources and improved methods to correct for instrument drifts. Below 300 nm, the most important sources of error are typically wavelength misalignment and photon noise. Thorough uncertainty estimates for actinic flux spectroradiometers (i.e., instruments with isotropic rather than cosine-weighted angular response) have also been performed recently (Hofzumahaus et al., 1999). According to Hofzumahaus et al. (1999), the total uncertainty of photolysis frequencies due to uncertainties in the measurement of the spectral actinic UV flux lies in the range of 5-7% and is dominated by the ±4% (±2σ) uncertainty of the irradiance standard. This result is similar to the uncertainty estimate for global irradiance measurements.

In 1994, WMO established a scientific advisory group to provide guidance for UV measurements performed within the Global Atmosphere Watch program. Guidelines for site quality control of UV monitoring (Webb et al., 1998) and recommended specifications for spectroradiometers measuring solar ultraviolet radiation (Seckmeyer et al., 2001) have been drafted. Both publications are considered as working documents that will evolve when new technologies or new objectives for UV spectroradiometry emerge.

5.3.1.5 Instrument Intercomparisons

Since the beginning of the 1990s, periodic intercomparisons of spectroradiometers from different organizations have become an international practice for assessing the quality of UV radiation measurements. Although the stability and the absolute accuracy of individual instruments can be sufficiently maintained using various calibration methods, intercomparison with other independently maintained instruments is an important method that provides uniform quality assurance and data quality. Intercomparisons also provide the opportunity for effective interaction between participating scientists in order to exchange new ideas and findings.

Results of three intercomparisons have been reported since the previous Assessment. The SUSPEN (Standardization of Ultraviolet Spectroradiometry in Preparation of a European Network) intercomparison held in Greece in July 1997 (Bais et al., 2001a) included 19 spectroradiometers from 15 countries. In August 1997 an intercomparison of 10 spectroradiometers operated in Germany (Seckmeyer et al., 1998) took place. In September 1997 the fourth North American Intercomparison of Ultraviolet Monitoring Spectroradiometers (including narrowband filter radiometers) was held near Boulder, Colorado. It included 11 instruments from 9 U.S. agencies (Lantz et al., 2002). Results of these intercomparisons showed that agreement of about ±5-6% (1σ) was typically achieved, with some dependence on wavelength, zenith angle, and observing conditions. Agreement improves with the application of corrections (e.g., wavelength shift and cosine error) to the data and is generally better at longer wavelengths.

The descriptions above represent gross summaries only. The behavior of the individual instruments can only be judged from more detailed information found in the references. Although the intercomparisons have shown that a considerable number of instruments still show large deviations, overall improvement has been achieved as a result of the knowledge gained through the intercomparison exercises.

Previous comparisons and assessments of the operation of broadband instruments have shown the need to examine their performance regularly (e.g., Johnsen and Moan, 1991; DeLuisi et al., 1992; Weatherhead et al., 1997). In this context an intercomparison campaign involving 39 erythemal radiometers and two well-calibrated and maintained spectroradiometers was organized in 1999 at the University of Thessaloniki, Greece (Bais et al., 2001b). The campaign was combined with laboratory investigation of the spectral and angular response of the participating instruments. From the comparisons of broadband with the spectroradiometric measurements, new calibration factors were derived, with differences from the original values ranging between –10% and +25%. For about half of the instruments the differences were smaller than about ± 10%, but only a few agreed with the spectroradiometer to better than ± 5%. These deviations depend on the time elapsed between the two subsequent calibration checks and on the individual characteristics of each instrument. The large deviations found for many of the instruments suggest that the calibration of broadband detectors should generally be checked more frequently, either in comparison with a spectroradiometer, or against another instrument of similar type.

5.3.2 Radiative Transfer Models and Model Validation

Radiative transfer (RT) models allow the calculation of radiation fluxes (direct, global, sky radiance distribution) as functions of geophysical variables and SZA. Most common models are one-dimensional (plane-parallel or pseudo-spherical) with scattering on spherical particles and polarization effects neglected. Several of these models are freely available for public use (Internet sites given in Section 5B.3 of Appendix 5B): the “library for Radiative transfer” (libRadtran, formerly known as uvspec) (Mayer et al., 1997; Kylling et al., 1998); the Tropospheric Ultraviolet Visible (TUV) model (Madronich and Flocke, 1997); the Santa Barbara Discrete-ordinate Atmospheric Radiative Transfer (SBDART) model (Ricchiazzi et al., 1998); the Streamer model (Key, 1999); and the System for Transfer of Atmospheric Radiation (STAR) model (Ruggaber et al., 1993, 1994). However, these one-dimensional models cannot be used to study situations with nonuniform spatial distributions of scattering or absorbing parameters.

Comparison of measurements of spectral UV surface fluxes with numerical RT simulations greatly facilitates the interpretation of measurements. Also, the quality and internal consistency of measurement methods may be checked using numerical simulations. In addition, RT calculations are required for estimating surface UV radiation from satellite data and for making forecasts of spectral surface UV radiation and the UV Index. In order to use RT simulations for these purposes, the validity of the simulations must be assured. However, validation of UV RT models for real atmospheric cases is a complicated task. At best the validation includes a model intercomparison in combination with observations for some well-defined cases. This combined approach has been pursued in the Scientific UV Data Management (SUVDAMA) project (van Weele et al., 2000).

The SUVDAMA model intercomparison (with 12 participating codes) established benchmarks for six real cloud-free atmospheric cases with different ozone column, air density profile, SZA, aerosol loading, surface albedo, and location. The benchmarks give the spectral surface UV irradiance between 295 and 400 nm with 0.5-nm steps and with a standard deviation of 2% between the modeled spectral irradiances. For cases with the Sun close to the horizon and for the shortest wavelengths, the relative standard deviations are somewhat higher (5%), but then irradiance is very small. Remaining differences between model results relate to the translation of the ancillary data and other fixed input parameters into the optical properties that are needed in the RT algorithms. Examples include the parameterization of aerosol optical properties, interpolation of the ozone absorption cross section as a function of wavelength and temperature, and the discretization of the atmosphere into vertical homogeneous layers. Comparison of the benchmarks with the observations showed differences, within ±13% over the whole spectral UV range for four out of six cases, mainly due to uncertainty in the input parameters and assumptions on instrument characteristics such as slit function and wavelength alignment.

Atmospheric and ground parameters are usually horizontally inhomogeneous, especially for cloudy cases. These nonuniformities must be addressed by using three-dimensional (3-D) models, which require significant computational time and are therefore restricted to a subset of conditions only. In recent years, 3-D RT models have become available, which use either the Monte Carlo method (e.g., Cahalan et al., 1994) or the spherical harmonics discrete ordinate method (Mueller and Crosbie, 1997; Evans, 1998). These models allow the study of effects of three-dimensional clouds (O'Hirok and Gautier, 1998a, b; Marshak et al., 1999; Degünther and Meerkötter, 2000a; Meerkötter and Degünther, 2001) or of inhomogeneous surface albedo (Degünther et al., 1998; Degünther and Meerkötter, 2000b; Kylling et al., 2000).

The first intercomparison of 3-D radiation codes has been performed. Differences between the 3-D model calculations are in the range ±5-10%, which is comparable with the uncertainties typically associated with UV measurements. However, such a complete description of the atmosphere is usually not available when UV measurements are to be compared with results of model calculations. Therefore, the uncertainty of the calculated irradiance is much higher, even under clear-sky conditions (Weihs and Webb, 1997a, b; Schwander et al., 1997). For well-characterized conditions, agreement to within about ±5-10% can be obtained between observations and model calculations. When some input parameters are not known, differences higher than ±20% are found (Koepke et al., 1998; De Backer et al., 2001).

5.3.3 Satellite Estimates and Validation

The understanding of RT processes forms the scientific basis for estimating surface UV irradiance from satellite measurements. Since the previous Assessment (WMO, 1999), advances have been made in our understanding and application of the required processes. The Total Ozone Mapping Spectrometer (TOMS) UV algorithm (Eck et al., 1995; Herman et al., 1996; Krotkov et al., 1998) has been modified to improve cloud attenuation estimates and to introduce the enhancement of surface irradiance caused by the high albedo of snow (Herman et al., 1999; Krotkov et al., 2001, 2002). The method has been adapted to the Global Ozone Monitoring Experiment (GOME), the European UV spectrometer on the second European Remote Sensing Satellite-2 (ERS-2) (Peeters et al., 1998). Li et al. (2000) have proposed an alternative parameterization for deriving surface irradiance from TOMS total ozone and TOMS 380-nm reflectivity or Advanced Very High Resolution Radiometer (AVHRR) visible data. Mayer et al. (1998a) have modified the TOMS UV algorithm to estimate the surface actinic flux giving photolysis rates for atmospheric chemistry models.

Polar-orbiting UV spectrometers (e.g., TOMS, GOME) are able to make measurements of atmospheric properties at a given location once per day. This together with a relatively coarse spatial resolution affects their ability to estimate the total daily exposure to UV radiation because of the high temporal and spatial variability of cloud cover. It has been shown that for accurate retrievals, several cloud images per day are required (Martin et al., 2000; Meerkötter and Bugliaro, 2002; Verdebout and Vogt, 2002). Different methods have been proposed that draw cloud transmission information from other satellites or datasets with higher spatial and/or temporal resolution. Lubin et al. (1998) used Earth Radiation Budget Experiment (ERBE) hourly cloud and surface albedo data resolved at 100 km to determine a 5-year climatology; Matthijsen et al. (2000) generated a multiyear dataset over Europe using the International Satellite Cloud Climatology Project (ISCCP) dataset (~15 km, every 3 hours); and Verdebout (2000) retrieved cloud optical thickness and surface albedo from METEOSAT (~5 km over Europe, half-hourly) to generate UV maps over Europe. AVHRR data (between one and five images per day with ~1-km resolution) have been used to map the surface UV radiation over Antarctica (Lubin et al., 1994), the Moscow region, Russia (Rublev et al., 1997), and parts of Europe (Meerkötter et al., 1997) as shown in Figure 5-1 (from Simon et al., 2000). These methods use the TOMS, GOME, or Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) derived total column ozone and various ancillary information such as digital elevation models, aerosol climatologies, or gridded surface visibility observations as inputs to RT models that estimate surface UV irradiance.

Accurate knowledge of cloud transmittance is critical for satellite UV estimates. The TOMS and GOME instruments can measure UV cloud reflectivity, R, and estimate cloud transmission, C_T, by the simple expression $C_T \sim 1 - R$, with a correction for ground reflectivity (Eck et al., 1995; Herman and Celarier, 1997; Herman et al., 2001a; Krotkov et al., 2001). Alternately, C_T for plane-parallel

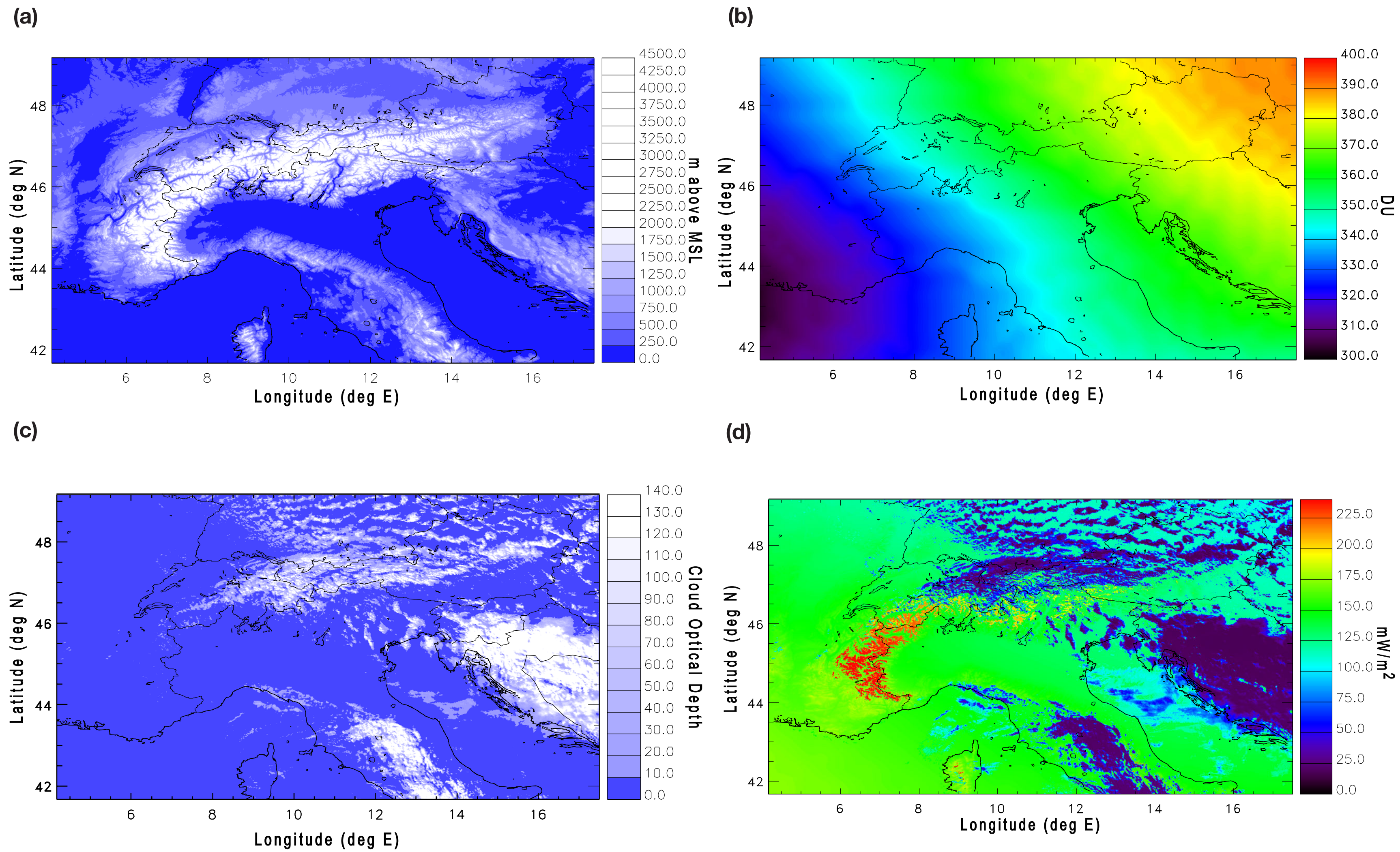

Figure 5-1. A region in Central Europe including the Alps: (a) surface elevation in meters above mean sea level, (b) horizontal distribution of the GOME (Global Ozone Monitoring Experiment) total ozone column amount in Dobson units (DU) on 15 April 1997, (c) horizontal distribution of cloud optical depth as derived from NOAA/AVHRR (Advanced Very High Resolution Radiometer) data on 15 April 1997, and (d) high-resolution map of the erythemal dose rates in milliwatts per square meter (mW m^{-2}). From Simon et al. (2000).

cloud can be estimated by radiative transfer inversion of the satellite-measured "top of atmosphere radiance." The latter approach is applicable to UV, visible, and infrared sensing instruments, since the C_T spectral dependence is included in the RT model (Meerkötter et al., 1997; Krotkov et al., 2001; Verdebout, 2000). There have been a number of studies where satellite estimates of C_T compared with ground-based measurements often show good agreement, but reveal systematic errors in the presence of snow (Kalliskota et al., 2000; Arola et al., 2002). A method to improve satellite cloud reflectivity estimates with snow on the ground has been developed by including snow depth information (Krotkov et al., 2002), and this method is to be considered for future satellite algorithms.

Under cloud-free conditions the accuracy of satellite UV data is limited mainly by an imperfect knowledge of the highly variable aerosol properties. TOMS UV two-channel reflectivity data are used to correct for absorbing aerosols at a known altitude by forming the aerosol index (AI; Krotkov et al., 1998). The effect of aerosols on satellite UV estimates over large areas is largest in tropical regions where there are major dust plumes (e.g., the Saharan plume) and smoke plumes (e.g., Africa and South America) from biomass burning. There the reductions in surface UV irradiance are frequently as much as 50% (Herman et al., 1999). However, the TOMS AI technique does not have the sensitivity to detect absorbing or non-absorbing aerosols close to the ground that are often present in urban atmospheres (Dickerson et al., 1997; Torres et al., 1998; Herman et al., 1999; Jacobson, 1999). When the aerosol effects are estimated using measured optical depths and single scattering albedos between 0.95 and 0.98, the clear-sky differences are usually reduced to within the instrument uncertainty. However, when near-surface atmospheric visibility data are used, UV irradiance reductions as large as 10% are found in some parts of Europe (corresponding to visibility values of ~10 km) (Verdebout, 2000), and even higher reduction could be expected in some cases. Simultaneous measurements of aerosol optical properties and surface UV irradiance are required to quantify local satellite biases for such areas. The aerosol problem is smaller at midlatitudes in the Southern Hemisphere because of clearer air compared with the same latitudes in the Northern Hemisphere (McKenzie et al., 2001a).

The accuracy and precision of satellite estimates have been assessed through comparisons between satellite and ground-based data and are reported either in papers describing the satellite-based methods or in dedicated publications (Kalliskota et al., 2000; Wang et al., 2000; Herman et al., 2001b; McKenzie et al., 2001a; Arola et al., 2002; Chubarova et al., 2002; Fioletov et al., 2002; Slusser et al., 2002, Wuttke et al., 2002). The observed differences of noontime irradiance values between ground-based measurements and TOMS satellite estimates can be ±20-30% rms and are caused by temporal and spatial cloud variation. However, the rms differences are reduced for daily integrals averaged over longer periods (e.g., ±4% for May, June, July, and August monthly mean values at Toronto; Fioletov et al., 2002). McKenzie et al. (2001a) compared ground-based measurements from cross-calibrated spectrometers with UV estimated from TOMS instruments over several years at four midlatitude sites. There is reasonable agreement in the day-to-day variability of UV derived by both methods; however, the TOMS data overestimate monthly erythemal doses by about 15% in Toronto, 24% in Thessaloniki, and 38% in Garmisch-Partenkirchen. At the pristine Southern Hemisphere site, Lauder, New Zealand, the average agreement is within 3%. Fioletov et al. (2002) reported similar comparisons at 10 sites in Canada. At 9 of the 10 sites TOMS overestimates the ground-based measurements from 7 to 16%. The only site with agreement to within 2% is at Saturna, located on the Canadian west coast where there is predominantly clean maritime air. Chubarova et al. (2002) showed that TOMS estimates are about 10% larger than a long-term (1979-2000) record of broadband measurements made at Moscow State University. The reasons for the large differences at northern midlatitudes may be attributed to absorption in the lower troposphere by aerosols and/or other pollutants that are not properly considered in the TOMS retrievals.

Part of the observed differences reflects the fact that the estimates and measurements are not of the same thing. There is always a mismatch between satellite-based and ground-based data acquisition. The satellite-derived value represents a single large-area average compared with the near-continuous local irradiance measured by a ground-based instrument. Lubin et al. (1998) have shown that daily doses can be estimated from satellite data obtained only at local noon with knowledge of the course of the SZA throughout the day. For all cloud cases Martin et al. (2000) have shown that the uncertainty in daily doses reconstructed from a single ground-based near-noon measurement is at least ±25%, and reduces to ~±5% for monthly doses.

Another important consideration is that there are site-specific biases caused by the persistence of local geophysical variables (McKenzie et al., 2001a, b; Chubarova et al., 2002; Fioletov et al., 2002). These include variations in altitude around the site, the persistence of local cloud patterns, or persistent patterns of nearby albedo. The 38% bias between TOMS and Garmisch-Partenkirchen ground-based UV data (reported by

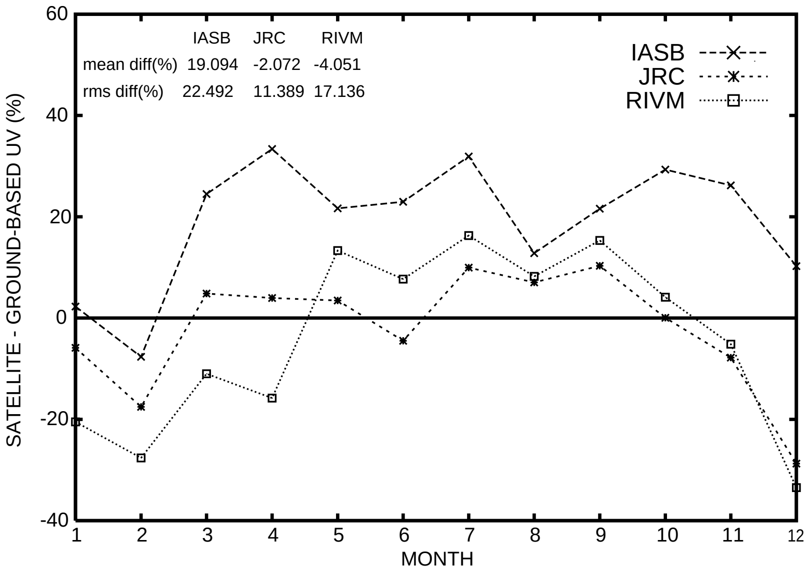

Figure 5-2. Percentage difference between ground-based and satellite-based monthly erythemal irradiance in 1997 predicted by three different satellite algorithms: from the Institut d'Aéronomie Spatiale de Belgique (IASB), the European Commission Joint Research Centre (JRC), and the National Institute of Public Health and the Environment of the Netherlands (RIVM). The algorithm of IASB shows a systematic bias with respect to ground-based data, whereas the algorithms of JRC and RIVM show improved agreement for the mean erythemal yearly dose. However, the latter two algorithms show a seasonal dependence, which is not well understood yet. Adapted from Arola et al. (2002).

McKenzie et al., 2001a) was not seen when METEOSAT or AVHRR data were used (Arola et al., 2002). The algorithm developed by the Institut d'Aéronomie Spatiale de Belgique (IASB) uses TOMS data, but shows a mean difference of 19% (Figure 5-2). The reason for the difference between the original TOMS algorithm and the IASB algorithm is not known. The algorithm of JRC based on METEOSAT and GOME data, and the algorithm of RIVM (National Institute of Public Health and the Environment, Netherlands) based on TOMS ozone and ISCCP data, show a smaller difference between satellite estimates and ground-based measurements at Garmisch-Partenkirchen as well as other sites (Figure 5-2). This leads to the conclusion that some satellite algorithms give better estimates of surface erythemal UV radiation than others. In addition there are systematic seasonal variations between satellite and ground-based results that are not understood yet. A novel method to understand such differences better has been proposed by Wuttke et al. (2002). It has been shown that the use of the full spectral information of both the satellite algorithm and the ground-based measurements helps to identify the reasons for deviations. Such an improved understanding has been used to develop an improved algorithm that shows less deviation when compared with ground-based measurements.

5.3.4 Statistical Modeling

The main geophysical variables that affect surface UV radiation are ozone, clouds, aerosols (both absorbing and nonabsorbing), and surface albedo. Total ozone measurements and ancillary data have been used with measurements of surface UV irradiance to develop statistical relationships that define the dependence of UV on the scattering and absorbing variables. Previous applications of statistical models include the UV Index forecast (e.g., Burrows et al., 1994) and the derivation of total ozone from UV measurements (Fioletov et al., 1997).

Recent studies (Krzyscin, 1996; Fioletov et al., 1997, 2001; McArthur et al., 1999; Bodeker et al., 2000; Kaurola et al., 2000; Gantner et al., 2000; den Outer et al., 2000; Diaz et al., 2000, 2002; Chubarova et al., 2002) have shown that surface UV radiation can be estimated by using measurements of total ozone (ground-based or satellite) with other ground-based data (such as global solar radiation measured with pyranometers). Total ozone values determine the spectral absorption features in the UV-B, and the ancillary data quantify the scattering processes that have weak wavelength dependence (clouds, aerosols, and surface albedo).

There have been a number of approaches for the use of statistical models. In some of these models, daily integrals of wavelength interval or erythemally weighted UV irradiance are statistically related to measurements of global radiation and other atmospheric variables (Diaz et al., 2000, 2002; Gantner et al., 2000); in others (Kaurola et al., 2000; den Outer et al., 2000) the daily integrals are compared with model results. Relationships as functions of total ozone, SZA, and other variables allow hour-by-hour comparisons (Bodeker et al., 2000; Fioletov et al., 2001). The neural network technique has also been applied to datasets of total ozone, global pyranometer information and other weather observations (Janouch, 2000; Schwander et al., 2002).

Good-quality spectral UV irradiance measurements have been available for about 10 years. These data are used with total ozone and ancillary data taken over recent years to establish statistical relationships that determine the dependence of ground-based spectral UV radiation on total ozone and the ancillary data. The statistical relationships are then used with measurements of total ozone and ancillary data to estimate UV radiation at other sites and at times when spectral UV radiation was not measured. These estimates can be extrapolated backward in time to as early as the 1960s, prior to the onset of ozone depletion. Figure 5-3 shows an example of statistical model results compared with ground-based spectral UV irradiance measurements and TOMS UV satellite estimates for summer months at Toronto (Fioletov et al., 2002). This figure demonstrates the good agreement between the ground-based estimates and spectral measurements for the overlap period (1989-1997). Also, the year-to-year variability of the ground-based estimates extended backward is similar to that of the satellite estimates, although there is a bias between satellite and ground-based results as discussed earlier.

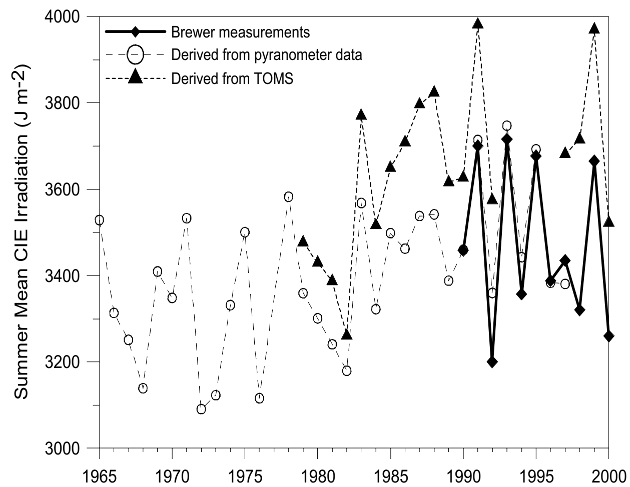

Figure 5-3. Time series of Toronto summertime (May-August) mean daily ground-based and satellite-based erythemal irradiation estimates compared with ground-based measurements. The estimated values using ground-based total ozone and pyranometer data agree very well with the measurements during the overlap period (1989-1997). The satellite estimates follow the year-to-year variability of the ground-based measurements; however, there is a bias as discussed in the text. Similar year-to-year variability is captured by both the satellite-based and ground-based estimates extrapolated backward in time. Adapted from Fioletov et al. (2002).

5.4 UV CLIMATOLOGY, TEMPORAL CHANGES, AND TRENDS

The main objectives for taking long-term systematic measurements of surface UV radiation are to establish a global climatology of UV, both average and extreme values, and to quantify any long-term changes that may have occurred as a result of changes in stratospheric ozone or other variables. This information is of interest to members of the "effects" community, who focus research studies on the response of biological systems (including human beings), materials, and pollution photochemistry to changes in the UV environment. Some ground-based spectral datasets are available to establish average values and variability of UV at specific sites; however, these datasets are relatively short in duration and have sparse and nonuniform spatial coverage over the globe. They are also representative of areas that are small in size and defined by specific local conditions. Understanding and quantifying the radiative transfer processes (Section 5.2) has allowed the extension of these datasets, both in time and space, with a good degree of certainty. Global coverage has been achieved by the use of satellite data, and the temporal extension backward in time has been achieved by using satellite measurements with RT models, as well as ancillary ground-based data with RT and statistical models.

5.4.1 Ground-Based UV Measurements

Difficulties involved in the routine operation and maintenance of accurately calibrated ground-based UV instruments have limited the length of reliable data records to about the past 10 years. It is recognized that 10-year records are not of adequate length to carry out long-term trend analyses (Weatherhead et al., 1998, 2000) because of a combination of variability and autocorrelation in datasets. However, some recent studies have used ground-based measurements to identify shorter term changes in surface UV radiation (McKenzie et al., 1999; Frederick et al., 2000; Zerefos, 2002). Also there has been some work done in using the data to develop specific climatologies of UV radiation at some sites (Ilyas et al., 1999; Cede et al., 2002).

An increase in peak UV values in response to decreasing ozone at Lauder, New Zealand, is shown in Figure 5-4 (from McKenzie et al., 1999, 2000). The trend has not continued in the last two austral summers, and ozone amounts at this site have been slightly higher than in the summer of 1998/99. Furthermore, both summers were rather cloudy over the period that is most critical for this analysis. It should be noted that year-to-year variability in cloud cover can have a significant effect even for peak irradiances and that the analysis of peak values cannot be automatically transferred to average values.

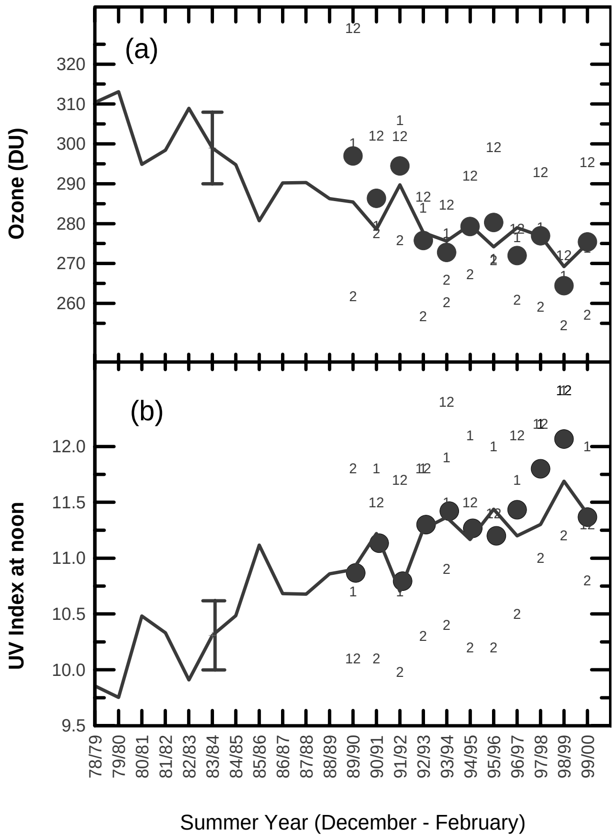

Figure 5-4. (a) Mean total ozone and (b) noontime UV Index at Lauder, New Zealand, for summers (December to February) from 1978/79 to 1999/2000. The solid line in (a) shows observed summertime ozone values that have occurred since the 1970s, and the solid line in (b) shows the expected values of clear-sky UV. The symbols (from 1989/90 on) show measured summertime values of ozone and peak UV Index, both derived from spectral UV irradiance measurements. The plot also shows the values from each contributing month, labeled by the month number. Two-sigma error bars are shown for reference. Adapted from McKenzie et al. (1999, 2000).

Data analysis for the summer of 2000/01 has not yet been finalized because of uncertainties in the National Institute of Standards and Technology (NIST) irradiance scale provided by the irradiance standards laboratories involved. It is likely that the entire dataset will eventually be reanalyzed taking historical changes in lamp irradiance scales into account better. However, it is not expected that the conclusions of the paper will change as a result of that reanalysis.

Routine spectral ultraviolet irradiance measurements made at Reading, England, since 1993 (Bartlett and Webb, 2000), along with total ozone measurements from a nearby site, demonstrated the inverse relationship between ozone and UV-B. Global radiation measurements suggest that from 1993 to 1997 cloud conditions did not change systematically. A decline in ozone of 5.9% and a corresponding increase in erythemal UV of 4.3% were seen, although these changes should not be considered statistically significant trends. Also, solar UV irradiance spectra (290-325 nm) have been measured at Rome and Ispra, Italy, since 1992 (Casale et al., 2000). Correlation coefficients between irradiance at 305 nm and total ozone at Rome were –0.61 (SZA = 47°) and –0.75 (66°) and at Ispra, –0.55 and –0.76. Seasonal analysis showed higher negative correlation with short-term ozone changes (related with weather patterns) during spring and winter, while in summer the long-term changes (time period greater than 2 years) and seasonal changes (between 2 years and 1 month) in ozone were dominant.

Time series of UV irradiance at 305 and 325 nm for Thessaloniki, Greece, for 1990-1997 were reported in the previous Assessment (Zerefos et al., 1997, 1998; Herman and McKenzie et al., 1999) for low-cloudiness (2/8 cloud cover) conditions. These series have been updated to 2001 (Zerefos, 2002) and are shown in Figure 5-5. Both ozone and sulfur dioxide (SO_2) have decreased during the 1990s (Zerefos et al., 1998). However, the observed increase in irradiance of 16.3% per decade at

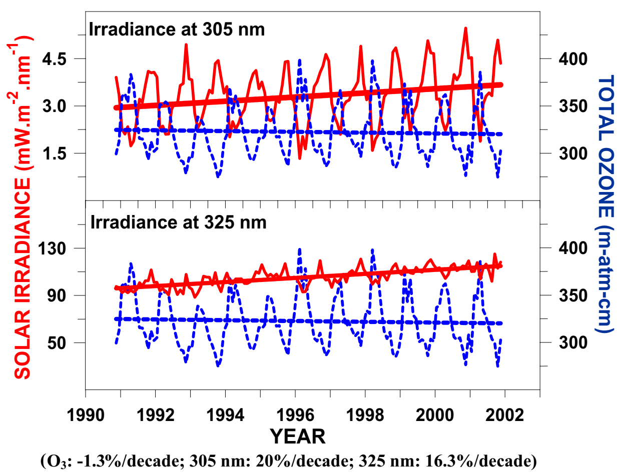

Figure 5-5. Time series of low-cloudiness (2/8 cloud cover) monthly mean values of total ozone and solar UV irradiance (63° SZA for 305 and 325 nm) measured at Thessaloniki, Greece (40°N), between 1990 and 2001. These time series are extensions of those reported in the previous Assessment (Herman and McKenzie et al., 1999; Zerefos et al., 1997). The observed temporal increase at 325 nm is attributable to causes other than ozone, because ozone absorbs weakly at this wavelength.

325 nm cannot be caused by the decrease of these gases, since they both absorb weakly at this wavelength. The increase must be caused by long-term changes in other factors, such as aerosols that are associated with the decrease in SO_2 at the observing site.

The spectral UV irradiance records of the U.S. National Science Foundation (NSF) UV radiation monitoring network operating at Ushuaia (Argentina) and Palmer, McMurdo, and South Pole (Antarctica) have increased in length and are now more than 10 years long. Recent analyses of the records have been carried out (Sobolev, 2000; Booth et al., 2001; Diaz et al., 2001). Although the NSF dataset spans roughly 10 years, it is still too short for statistically robust trend detection. At all Antarctic sites, changes in erythemal and DNA-weighted UV are generally positive for the months from September to December, with largest increases typically observed in November. However, trends in monthly averages of daily erythemal and DNA-weighted doses are not significant at the 2-sigma level because of the large year-to-year variability in total column ozone, related to the interannual variability of the ozone hole. Compared with ozone variability, the year-to-year fluctuation in other factors such as cloud cover is of minor importance for interannual UV changes at Antarctic network sites.

The highest UV levels on record observed at McMurdo, Palmer Station, and the South Pole by the NSF network instruments occurred in the austral spring of 1998. UV levels in 1999, 2000, and 2001 were generally lower. The record-size ozone hole in 2000 led to enhanced UV levels at all austral network sites during September, and some extreme events at Ushuaia during October. The observed increases during September are small in absolute terms because of the low solar elevations prevailing during this month. At all austral network sites, UV values in November 2000 were close to the minimum values on record because of the early closing of the ozone hole.

Yearly maximum erythemal UV levels at austral network locations were observed during recent years in November and early December, 1 to 2 months after the period of maximum ozone depletion. This pattern is explained by the combination of smaller SZA later in the year and the relatively low stratospheric ozone concentrations that still prevail in November. Figure 5-6 demonstrates that peak levels of daily erythemal UV dose in November and December at austral sites exceed those seen during the summer at San Diego (Booth et al., 2001). The large enhancements in November and December suggest that changes in the duration of the ozone hole have a greater influence on biologically relevant UV levels than does the depth of minimum total ozone typically observed at the end of September and beginning of October (Diaz et al., 1994).

5.4.2 Estimates from Satellite Data

The UV trends calculated from the Nimbus-7 TOMS satellite data (1979-1992) were reported in the previous Assessment (Herman et al., 1996; Herman and McKenzie et al., 1999; Ziemke et al., 2000). Follow-on TOMS missions (Meteor-3, Advanced Earth Observing Satellite (ADEOS), and Earth Probe) have extended the TOMS UV record, with an 18-month gap in 1995-1996 (Herman et al., 1999). Extensions of the trends calculated on a global scale and presented in the previous Assessment are not yet available.

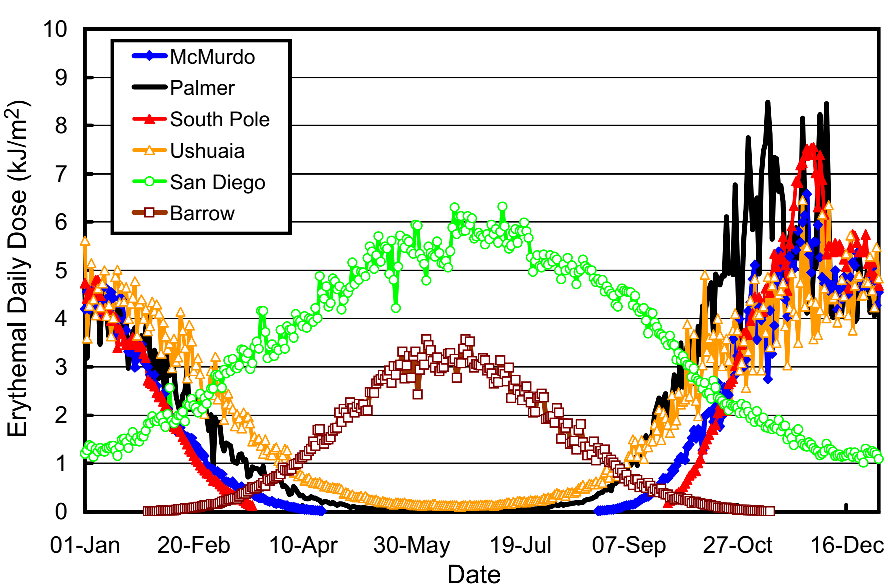

Figure 5-6. The maximum daily dose of erythemal irradiance (in kilojoules per square meter) measured at stations in the National Science Foundation (NSF) UV monitoring network. Peak values occur at austral sites in middle to late spring when the combination of higher Sun angles and low values of total ozone still prevail from an extended breakup of the Antarctic ozone hole. The peak values at these high-latitude sites exceed those at significantly lower latitudes during summer (e.g., San Diego).

Both the TOMS-derived and TOMS/ERBE-derived global UV climatologies have documented the seasonal surface UV variability in different regions in the world caused by cloudiness, ozone, UV-absorbing aerosols, and surface albedo (Lubin and Jensen, 1995; Lubin et al., 1998; Herman et al., 1999, 2001a, b). In addition, interannual variability associated with the quasi-biennial oscillation has been observed (Herman et al., 2000). These datasets permit us to identify the areas and periods where particularly high levels of UV radiation can be expected in cases of low ozone events and low amounts of cloud cover (e.g., parts of South America, Africa, and Australia). Year-to-year variations of UV values in March are up to ±35% over Europe because of highly variable ozone and cloudiness. There have also been changes in UV irradiance associated with long-term systematic changes in cloudiness (Herman et al., 2001a), with large regions of cloud-induced increases over Europe and parts of North America, as well as some small but well-defined regions of UV decrease over the oceans near South America and Antarctica. This represents significant progress in understanding since the previous Assessment (WMO, 1999). At that time the decrease of UV due to the increase in cloudiness over Europe was identified from ground-based measurements of total (pyranometric) radiation but was not found in the satellite estimates.

Trends in snow cover and/or albedo can also affect UV trends at high latitudes. The effects of these forcings on UV trends are significant, but their relative contribution varies geographically and seasonally. Vinnikov et al. (2002) found a statistically significant decrease in sea ice cover over the Northern Hemisphere, whereas sea ice cover has increased in the Southern Hemisphere. Thus it is expected that UV irradiance has decreased in some areas of the Northern Hemisphere and has increased in some areas of the Southern Hemisphere. These conclusions can be drawn from our understanding of the radiative transfer, but ground-based observations are lacking, especially over oceans. Satellite estimations of UV in these areas and seasons are complicated by the difficulties in distinguishing between snow/ice and cloud albedo.

Whereas the effects of UV-absorbing aerosols on surface UV irradiance have been investigated (Krotkov et al., 1998; Herman et al., 1999), their effects on UV-irradiance trends have not been estimated. In some situations, there are indications that aerosol effects are an important source of error (McKenzie et al., 2001a). In the tropics, there does not appear to be a long-term trend in dust aerosol amounts, even though biomass burning in South America has caused some increases in smoke (Herman et al., 1997), which considerably absorbs UV radiation. Absorbing aerosol trends at middle and high latitudes may be affected by industrial activity. If so, they would contribute to long-term changes in UV amount. The current TOMS UV algorithm accounts for absorbing and scattering aerosol effects, and could be used for extended trend estimates by combining the Nimbus-7/TOMS and Earth-Probe/TOMS data.

5.4.3 Estimates from Radiative Transfer Models

Sabziparvar et al. (1999) have calculated the climatology of surface UV radiation using the discrete-ordinate RT model of Stamnes et al. (1988) modified by Forster (1995). Calculations were made for daily doses of UV-B (280-315 nm) and UV-A (315-400 nm), and weighted with various biological action spectra. Calculations were performed for the four midseason months: January, April, July, and October. Clear-sky and aerosol-free irradiance values were calculated using TOMS total ozone averages as input. All-sky conditions were calculated using average cloud distributions measured by the International Satellite Cloud Climatology Project (Rossow and Schiffer, 1991) and aerosol optical depth of 0.1 at 400 nm. Figure 5-7 shows the annual average of daily dose calculations for erythemally weighted UV irradiance.

The same RT model was used by Sabziparvar et al. (1998) to calculate changes in surface UV radiation due to changes in ozone (both stratospheric and tropospheric) and tropospheric aerosols since preindustrial times (1850). Decreases in erythemally weighted irradiance of up to 9% were calculated for tropical regions as a result of increases in tropospheric ozone. Decreases in erythemally weighted irradiance of 4-8% from increased tropospheric ozone were calculated north of 20° in the Northern Hemisphere during July. Increases of erythemal irradiance of 70% at southern high latitudes in October and 10% at northern high latitudes were calculated as a result of stratospheric ozone depletion. Effects of increases in absorbing aerosols and sulfate aerosols were also considered, and it was concluded that an increase in aerosols has decreased erythemally weighted UV by up to 7% locally and 2% on a global average. The study does not include long-term changes in cloud cover or surface albedo.

5.4.4 Estimates from Ground-Based Ancillary Data

Gantner et al. (2000) reconstructed noontime irradiance values at 300, 305, 310, and 320 nm for clear-sky and no-snow conditions at Hohenpeissenberg going back to 1968. Statistical dependencies of irradiance on total ozone were determined from measurements taken

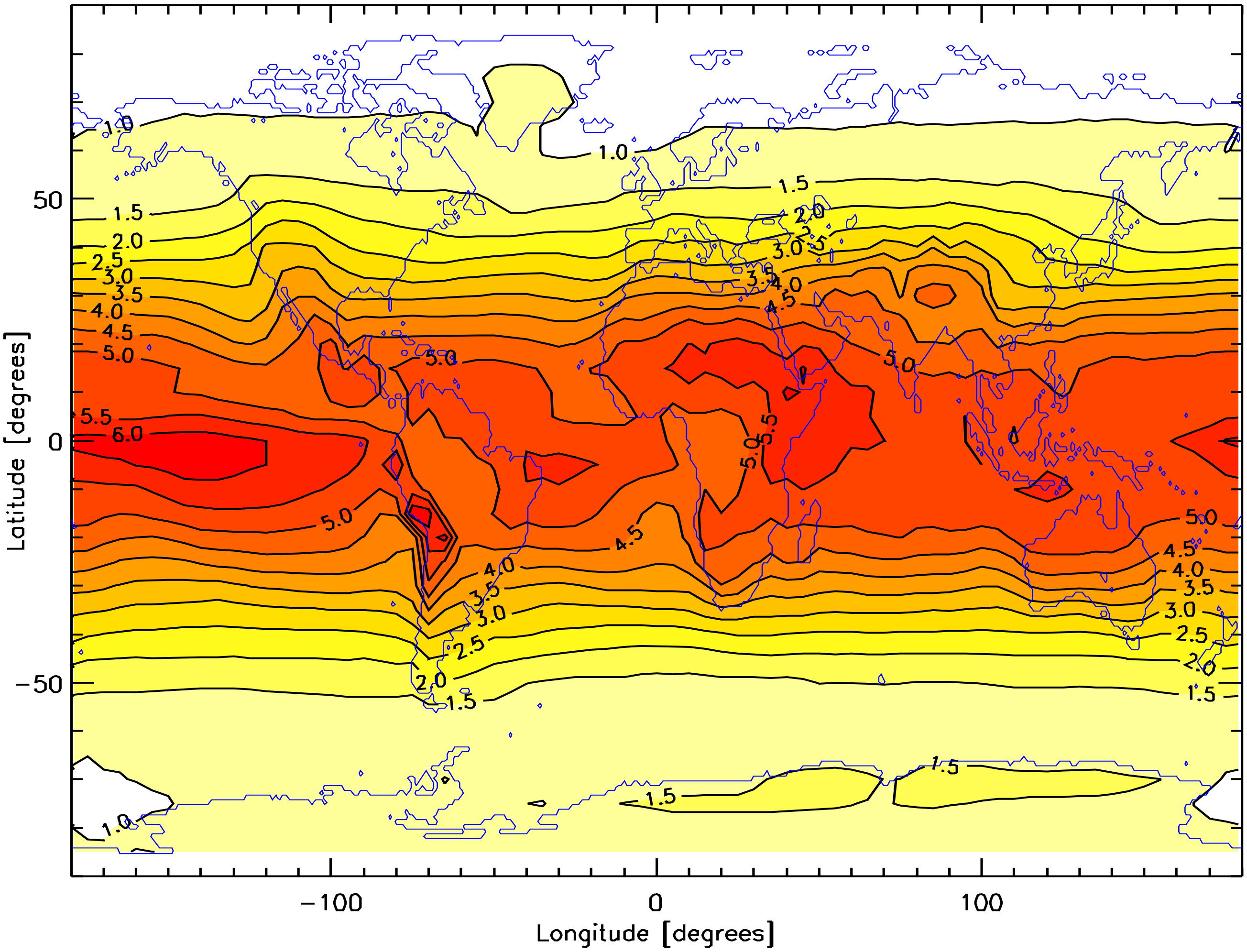

Figure 5-7. Climatology of annual average erythemal dose (in KJoule/(m^2 day)). Values are computed from total ozone and cloud satellite data. Adapted from Sabziparvar et al. (1999).

between 1990 and 1997 when spectral UV, total ozone, and global and diffuse radiation data are available, and the relationships were used to extrapolate estimates of UV irradiance backward in time. For all months between March and September, statistically significant long-term increases in clear-sky noontime values of UV were found that increase with decreasing wavelengths.

The studies by Kaurola et al. (2000) (using data from Norrkoping, Sweden; Jokioinen, Finland; and Belsk, Poland) and den Outer et al. (2000) (using data from Bilthoven, Netherlands) took another approach to reconstruct past UV data that includes effects of clouds and other scattering processes. RT models were used to calculate clear-sky daily integral values of erythemally weighted UV irradiance and global solar irradiance (280-4000 nm) using total ozone, other meteorological data, and the daily variation of SZA as input. The ratio of the daily integral of pyranometer measurements to the modeled clear-sky integral was used to quantify scattering processes that are related statistically to variations in UV observed in recent years. The relationships were used to estimate daily UV values under all weather conditions backward in time to 1979 using pyranometer data and satellite total ozone data, or to the 1960s if ground-based total ozone measurements were available. In general, the reconstructed datasets show that erythemally weighted UV has increased since the 1970s and that the increases and year-to-year temporal variations are consistent with satellite estimates for the same sites (Kaurola et al., 2000).

Diaz et al. (2000, 2002) demonstrated a method that calculates the daily integral of UV radiation (at specific wavelength intervals, broadband or biologically weighted irradiance) from daily average total ozone, daily average SZA (for daylight hours), and the daily integral of broadband measurements (UV-B, biologically weighted UV, or global solar pyranometer). A multilinear regression model was used to fit the daily UV values as a function of the three measured independent variables, and regression coefficients were determined using data from South Pole, Antarctica; Ushuaia, Argentina; and San Diego, U.S. It was shown that monthly averages of UV irradiance between 303 and 308 nm can be predicted to an accuracy of 4-5% using broadband radiation data. The method was applied to TOMS total ozone data and pyranometer data from South Pole and Barrow, Alaska. The regression was determined using data from 1993 to 1998, and results of the regression were used to estimate UV radiation (303-308 nm) back to October 1979. Significant increases (~300%) were found for the month of October at South Pole and lower values (between 90% and 120%) for April at Barrow between 1979 and 1996.

Results of statistical models described by Fioletov et al. (1997, 2001) and McArthur et al. (1999) establish empirical dependencies of UV radiation (both at individual wavelengths and spectral intervals) on SZA, total ozone, global solar radiation, dewpoint temperature, and snow cover. The relationships were determined from observations at six sites in Canada (Edmonton, Winnipeg, Churchill, Toronto, Montreal, and Halifax) where total ozone, spectral UV irradiance, and global solar irradiance (pyranometer) measurements have been made since the early 1990s. It was shown that monthly mean values of erythemal irradiance for summer months (May-August) can be estimated from the ancillary data with a standard error (1-sigma) of 4.2%. The statistical relationships have been used to estimate hourly UV irradiance values dating back to the mid 1960s at Toronto, Churchill, and Edmonton when both total ozone and pyranometer data are available (Fioletov et al., 2001). The hourly values were integrated to make daily total and noontime (within 1 hour of noon) values, and monthly averages of the daily and noontime values were determined. Monthly average daily UV doses for summer months (May, June, July, and August) predicted from the ancillary data agree with simultaneous spectral measurements with an rms difference of 3.3%. This agreement is better than the 4% rms difference for summer monthly ground-based spectral measurements and satellite estimates (Fioletov et al., 2002). Trends in UV for individual wavelengths and weighted spectral intervals were determined for the period from 1979 to 1997 and are shown in Figure 5-8. It is of interest to note that trends in the daily integrated values and noontime values are essentially the same. The annual trend values at wavelengths of 310 nm or less and for the erythemally weighted UV are all statistically significant to the 2-sigma level.

In addition to the estimation of past hour-by-hour UV irradiance, the ancillary data can be used to quantify and distinguish between trends in UV that are caused by factors other than long-term changes in total ozone. Figure 5-8 shows that Churchill had statistically significant trends at all wavelengths, including those with insignificant ozone absorption (325 nm). The positive trend of about 7% per decade at 325 nm is due to the combined effect of an increase of days with snow cover (causing an increase in UV irradiance by about 2% per decade) and a decrease in hours of cloudiness (causing an increase of about 5% per decade) that occurred at Churchill over the period (1979-1997). The 11% per decade increase of erythemally weighted irradiance was found to consist of +2% per decade from increasing snow cover, +5% per decade from decreasing clouds, and +4% per decade from decreasing ozone.

A continuous UV time series made up of irradiance measurements from recent years (1990s) and of irradiance estimates using ancillary data from earlier years (as early as the mid-1960s) is useful to quantify extreme events that are pertinent to some biological studies. Fioletov et al. (2001) demonstrated that the incidence of extreme events has increased since 1970 by showing that the number of hours per year the UV Index is above a threshold value has increased at Toronto, Edmonton, and Churchill (Figure 5-9). This is in accordance with the findings for an alpine site (Seckmeyer et al., 1997), which concluded the same with the support of the ancillary measurements made at Hohenpeissenberg.

5.5 EXPECTATIONS OF UV IN THE FUTURE

Just as the climatology of surface UV radiation has changed in the past, there will likely be changes over the next several decades. The future evolution of UV irradiance will depend on changes in total ozone as well as other atmospheric variables that are influenced by changes in climate. Quantification of predicted changes in total ozone, influenced both by halogen chemistry as well as other climate variables, is discussed and presented in previous chapters in this Assessment. Here we address the changes in UV irradiance that are likely to occur over the next 50 years, both as a result of the expected recovery of the ozone layer (Section 5.5.1) and variations driven by other variables influenced by climate change that directly affect surface UV irradiance (Section 5.5.2).

5.5.1 Links with the Recovery of the Ozone Layer

It is well known that a reduction in total ozone column leads to increased levels of surface UV irradiance if other factors remain constant. This relationship has

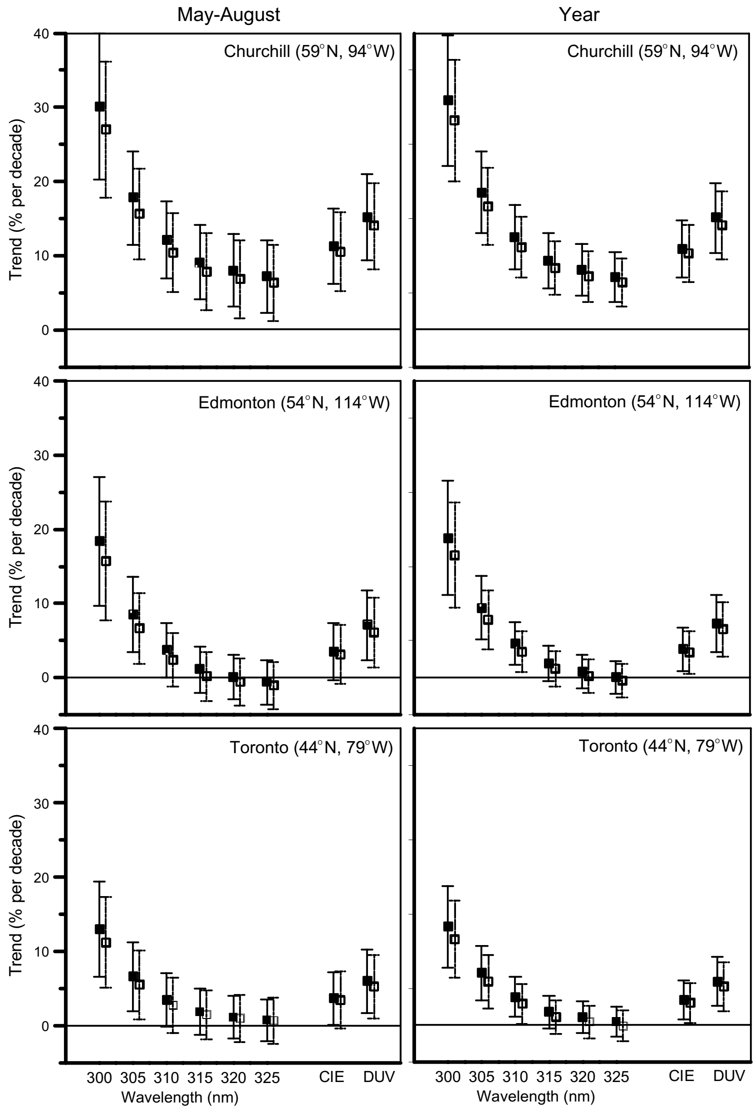

Figure 5-8. Trends in UV irradiance at 300, 305, 310, 315, 320, and 325 nm, and trends in erythemally (CIE) and DNA weighted irradiance for 1979-1997, for May-August and year-round, at Churchill (58.75°N), Edmonton (53.55°N), and Toronto (43.75°N), with 2σ error estimates indicated. Solid squares are trends in daily integrals, and open squares are trends from values within ±1 hour of solar noon. Adapted from Fioletov et al. (2001).

been clearly demonstrated and reported in previous Assessments (WMO, 1992, 1995, 1999).

There has been a significant amount of work done to predict the future of the ozone layer based on considerations of the reduction of atmospheric chlorine and bromine compounds as well as the interactions with climate change. Previous chapters in this Assessment discuss these future ozone scenarios in detail. Future UV levels as a result of changes in ozone have been predicted (Taalas et al., 2000b; Reuder et al., 2001), but, because surface UV radiation is dependent on the many complex scattering and absorbing processes discussed previously in this chapter, prediction of future UV radiation is more difficult and leads to deviating results about the probable UV levels over the coming decades.

Chapter 4 of this Assessment presents results of several two-dimensional (2-D) models that simulate the decline of total ozone between 1979 and 2000 and project its recovery using several halogen and climate change scenarios between 2000 and 2050. The derived ozone projections do not include polar effects (e.g., increased occurrence of polar stratospheric clouds) and their influence at higher latitudes. The results have been used with RT model calculations to estimate future UV irradiance over the next 50 years. Monthly values of total ozone at 5° latitude intervals were averaged from the output of seven 2-D model runs for the MA2 scenario (described in Chapter 4) and used as input to the RT model used by NASA to estimate surface UV irradiance from TOMS satellite data (Herman et al., 1996, 1999; Krotkov et al., 1998, 2001). Monthly values for noontime erythemal irradiance were determined using the total ozone from Chapter 4, and noontime SZA at the middle of each month, for clear skies and low (3%) albedo. Figure 5-10 shows

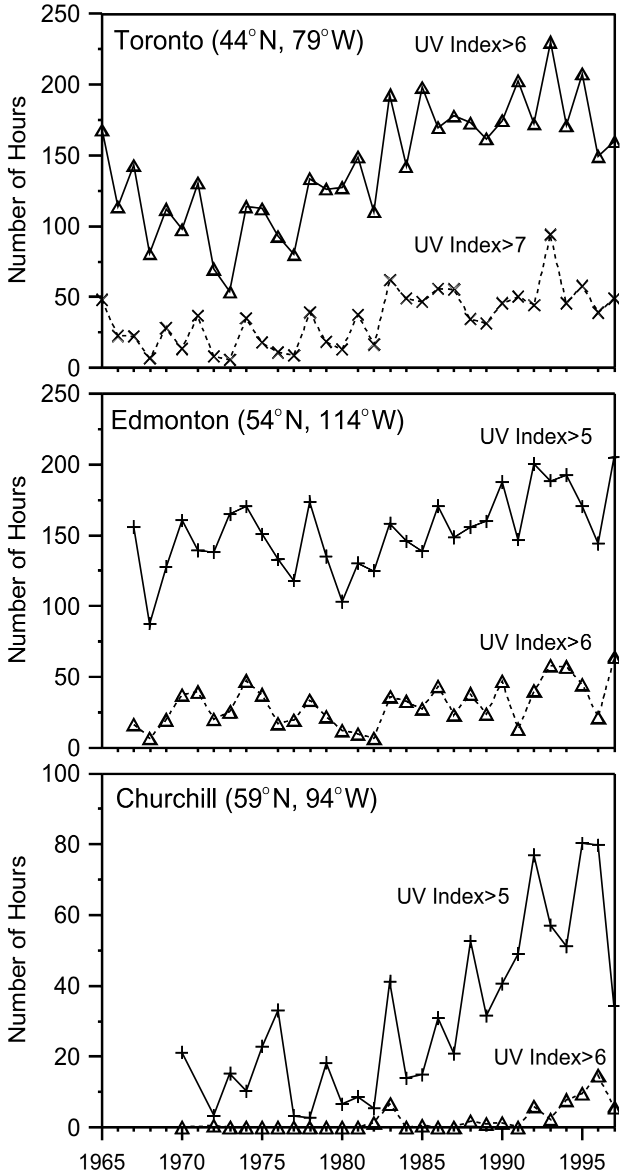

Figure 5-9. The number of hours per year that the UV Index exceeded 6 and 7 at Toronto, 5 and 6 at Edmonton, and 5 and 6 at Churchill. These numbers are determined from reconstructed erythemal UV irradiance determined from total ozone and other ancillary data. Adapted from Fioletov et al. (2001).

the departure (in percent) of these clear-sky calculations of noontime erythemally weighted UV from the 1980 mean values for the period from 1979 to 2050 for the months of January, April, July, and October.

Results of the 2-D model calculations (Figure 5-10) indicate that generally there will be small changes in UV radiation over the next decade. However, in the longer term (next 50 years) UV levels will return to values similar to those that were present in 1980, provided that all other factors (clouds, snow cover, aerosols, etc.) are assumed to remain constant. It should be stressed that this assumption is an unlikely scenario. Past changes of surface UV that are associated with changes other than total ozone have occurred at some sites, as illustrated in Figure 5-5 (Thessaloniki) and Figure 5-8 (Churchill). It should further be emphasized that there have been many surprises in the occurrence of extreme events in the past due to the complex and nonlinear behavior of the atmosphere. These surprises cannot be included in such a projection.

Impacts of greenhouse gases and halogenated species on future UV levels have been studied by Taalas et al. (2000b). The UV scenarios are based on ozone predictions from 3-D chemistry-climate calculations carried out by three different models that were discussed in Chapter 3: the Goddard Institute for Space Studies (GISS; Shindell et al., 1998) model, the U.K. Meteorological Office (Austin et al., 2000) model, and the German Aerospace Institute model.

Figure 5-11 shows results of future erythemal UV levels relative to 1979-1992 averages calculated using the GISS model ozone predictions for April in the Northern Hemisphere and October in the Southern Hemisphere (from Taalas et al., 2000b). For the Northern Hemisphere in April there are enhancements up to 90% at 70°N calculated for the 2010-2020 time period that reduce to <25% in 2040-2050. For the Southern Hemisphere in October the enhancements are up to 100% over Antarctica for the 2010-2020 period and reduce to <50% by 2040-2050. Maximum increases in the annual (not shown) northern high-latitude UV doses were estimated to be up to 14% in 2010-2020, and reduce to 2% in 2040-2050 because of the expected recovery of the ozone layer. At southern high latitudes, 40% annual maximum enhancements are expected during 2010-2020 that reduce to 27% by 2040-2050.

The following points should be noted regarding the rather large deviations stated above, particularly for the Arctic. First, the above values (Figure 5-11) are relative to the period 1979-1992. Since the models indicate that we are nearing minimum ozone values in 2002 (Chapter 3), deviations relative to today's values are appreciably less than those stated above for the 2010-2020 period and are negative for the 2040-2050 period. Second, the deviations are spatially dependent, and the values stated above are at places where the maxima are predicted to occur. When UV levels are averaged from 60°N to 90°N, the GISS model agrees reasonably well with other models (Taalas et al., 2000b). Finally, the GISS prediction of minimum UV levels for the Northern Hemisphere would be higher than those of other 3-D models, since the GISS

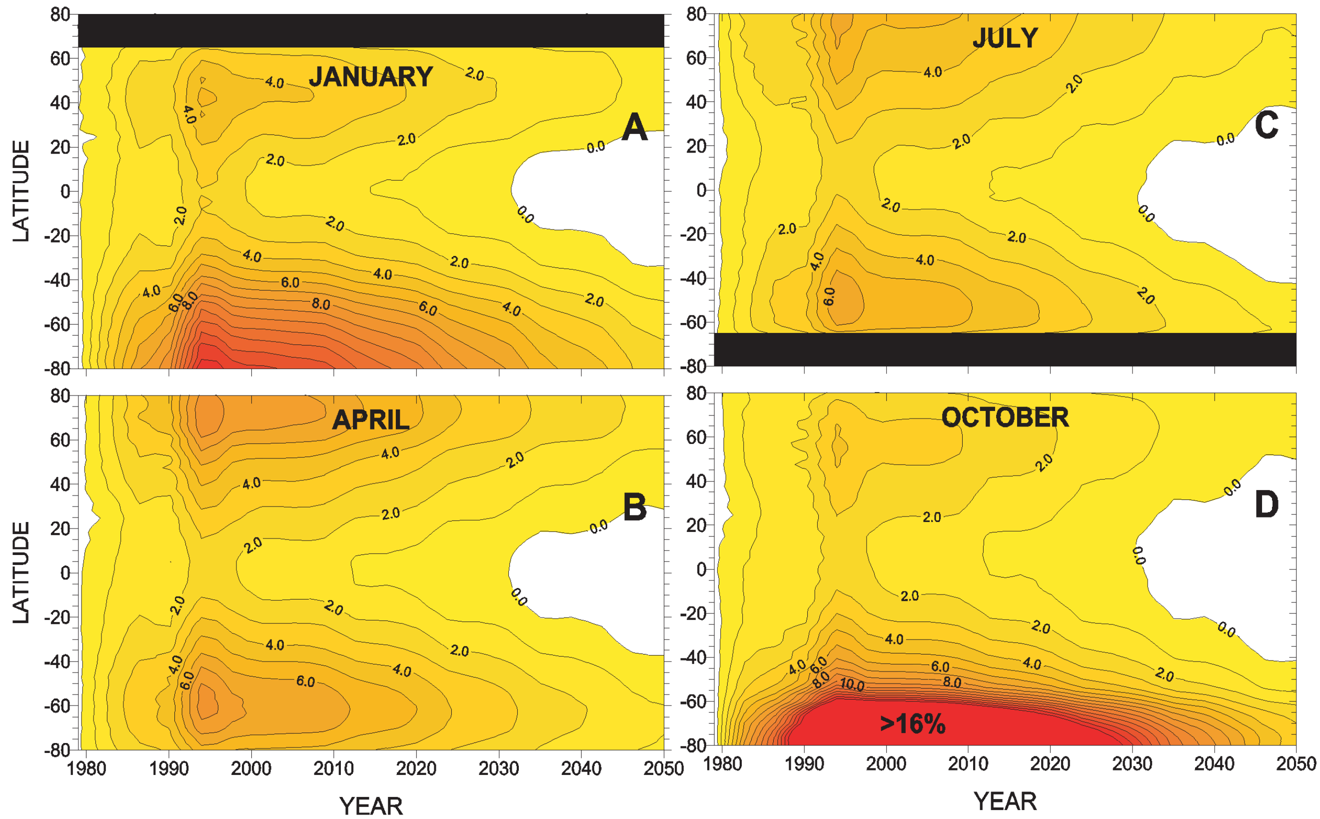

Figure 5-10. Calculations of the departures (in percent) from 1980 UV noontime clear-sky irradiance levels between 1979 and 2050 for the months of (a) January, (b) April, (c) July, and (d) October. The average of seven model runs calculating total ozone from the MA2 scenario discussed in Chapter 4 were used as input to the TOMS radiative transfer model (Herman et al., 1996, 1999; Krotkov et al., 1998, 2001). These results show that UV levels will have insignificant variation over the next 10 years and will return to nearly the same levels as those present in 1980 by 2050. It should be stressed that these calculations assume all variables other than total ozone remain constant, which is unlikely.

model predicts the lowest ozone levels for the Arctic (Chapter 3).

5.5.2 Factors Related to Climate Change

The effects of climate change on surface UV radiation are twofold. The first (indirect) effects are caused by changes in climate that affect total ozone. The consequential changes in total ozone are addressed in Chapters 3 and 4 of this Assessment, and the impact of these changes on surface UV radiation are discussed in Section 5.5.1 above. The second effects of climate change on UV are direct effects (e.g., changes in clouds, aerosols, snow cover, etc.) and those are discussed in this section.

The recent IPCC report (IPCC, 2001) lists many factors that are likely to change due the increased emission of greenhouse gases. Many of these factors have already started to change or are likely to have changed in the past. In addition to these feedbacks that are already discussed in previous chapters (e.g., the higher likelihood of polar stratospheric clouds and their associated role in enhancing the chemical destruction of ozone), there are other factors related to climate change that are directly influencing UV irradiance at the Earth's surface.

In Section 5.2.1.5 it is discussed that snow albedo leads to a significant enhancement of UV irradiance above the surface due to multiple scattering. The IPCC report (IPCC, 2001) states that the sea ice cover in the Northern Hemisphere has reduced significantly and is likely to reduce more in the future. In addition, the snow cover and the extent of glaciers in mountainous areas have been decreasing. Consequently, it can be predicted that UV irradiance above the surface will decrease in these areas for seasons where snow cover or sea ice is reduced. Although UV irradiance above the surface is enhanced by snow-covered areas, a decrease in sea ice and snow cover will result in an increase of UV dose for organisms living under water and on land areas previously covered by snow. According to the IPCC report (2001), the largest reductions of snow albedo will be at high latitudes in spring and summer, and consequently surface UV irradiance will likely be reduced by the decrease in albedo at high latitudes in spring and summer in some areas of the Northern Hemisphere.

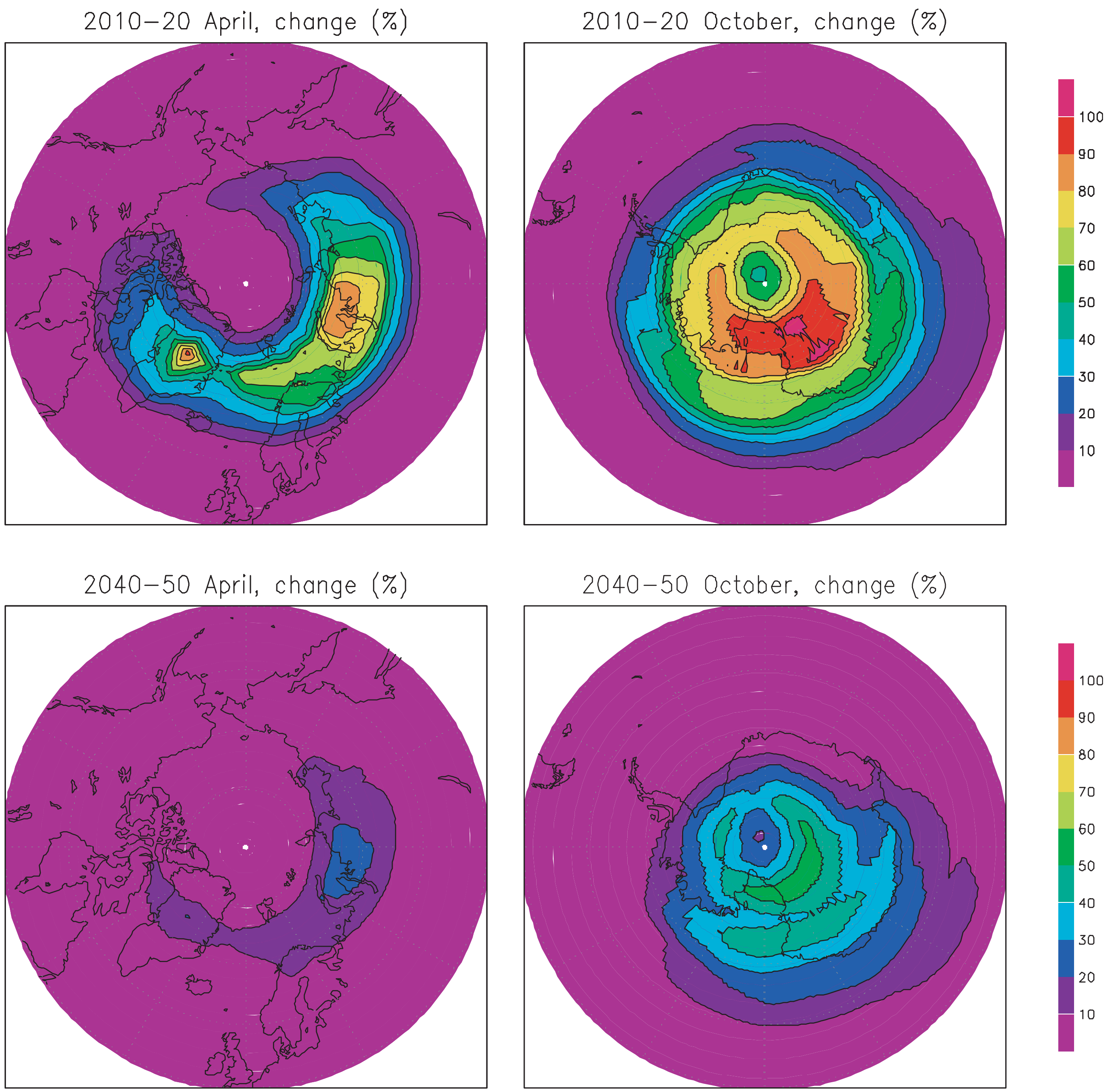

Figure 5-11. Results of erythemal UV changes due to ozone changes predicted by the Goddard Institute for Space Studies (GISS) 3-D chemistry-climate model for April in the Northern Hemisphere and October in the Southern Hemisphere. Future increases of greenhouse gases are expected to delay the recovery of the ozone layer (Chapter 3), and the resulting enhanced UV values at high latitudes are predicted to persist for about two more decades. The indicated changes are relative to the time period 1979-1992, so the changes relative to present-day levels are less than those shown for 2010-2020 and would likely be negative for 2040-2050. Adapted from Taalas et al. (2000b).

Table 5-1. Factors related to climate change that influence UV irradiance at the surface globally. Regional changes are expected to be over a much larger range than the numbers given here. Also the relative importance of the factors may be different in different regions (e.g., snow cover would become a major factor in mountainous areas). It should be emphasized that there have been many surprises in the occurrence of extreme events in the past due to the complex and nonlinear behavior of the atmosphere. These surprises cannot be included in such a projection.

	Correlation with UV Change	Predicted Change in Globally Averaged Erythemal UV from Present	
		2010	Long Term
Major Factors			
Stratospheric ozone	Negative	0 to –3%	Figure 5-10
Cloudiness	Negative	±1%	Negative
Aerosols	Negative	±3%	Negative
Tropospheric ozone	Negative	±1%	–2 to +7%
Minor Factors			
Aviation (IPCC, 1999)		±1%	±1%
Ozone profile		±1%	±1%
Stratospheric temperature	Negative	Positive	Positive
Snow cover and sea ice	Positive	Negative in some areas and seasons	
Tropospheric temperature	Negative	Negative	Negative
Weather extremes		Positive peak values	

Another statement of the IPCC 2001 report has an impact on surface UV: it is thought that cloudiness has increased by about 2% over the past century and is likely to continue increasing in the future. The effects of clouds on UV irradiance depend both on their amount and type. The observed increase of cirrus clouds in the Northern Hemisphere is likely to reduce UV irradiance slightly. However, this increase would lead mainly to a redistribution of UV radiance from the direct beam to diffuse. More important is the likely increase of overall global cloudiness over the next century. The effect of this increase will lead to a reduction of surface UV globally. However, it should be noted that it is very likely that cloudiness will increase in some regions and decrease in others. Recent results by Chen et al. (2002) and Wielicki et al. (2002) demonstrate unexplained decreases in cloud cover in the tropics. These changes will have a great influence on the UV irradiance locally, possibly exceeding those caused by changes in ozone.

Weather extremes may occur more frequently than they have in the past century. In the future, climate episodes of high precipitation might alternate with extremely dry episodes in many parts of the Earth. Higher UV irradiance can be expected during dry spells than during wet spells, and this may be problematic for some biological species. At present it is not possible to predict these changes quantitatively. Nevertheless the biological impact of these changes might exceed those caused by the expected changes in stratospheric ozone.

Aerosol effects on surface UV radiation may be larger than previously thought, and may affect large areas of the globe because of the following:

(1) Many anthropogenic aerosols absorb in the UV (Jacobson, 1999).
(2) Altitude gradients of UV irradiance are generally larger than expected (Lenoble et al., 2002; McKenzie et al., 2001b; Seckmeyer et al., 1997). The relatively high altitude gradients could be partly explained by the attenuation of UV irradiance by aerosols near the ground.
(3) Satellite estimates of surface UV-B irradiance are too large over large areas of the globe, possibly caused by a widespread influence of the aerosols that is not accounted for in the satellite estimates (McKenzie et al., 2001a; Fioletov et al., 2002).

Over the first half of the 20th century, aerosol extinction increased (Liu et al., 1991; Sabziparvar et al., 1998). In recent years aerosol extinction has started to decrease with a cleaner troposphere in some areas (e.g., Krzyścin and Puchalski, 1998; Zerefos et al., 1998). What might happen in the future is open to conjecture, depending on the disparate forcings of increased population, increased awareness of environmental issues, and reduced reliance on fossil fuels. However, it is now likely that UV radiation at the ground will increase in the coming years, before the expected recovery of the ozone layer might take place.

The IPCC report on impacts of aviation on the atmosphere (IPCC, 1999) considered changes in UV that could result from increased aviation activity both in the upper troposphere and lower stratosphere. These changes were generally found to be less than ±1% due to effects that influence UV negatively or positively.

Table 5-1 shows a summary of factors related to climate change that influence UV irradiance at the surface on a global scale. An attempt has been made to quantify changes that may occur both in the shorter term (next 10 years) and longer term (to 2050). It should be emphasized that the UV changes are expected to be larger in certain areas under specific situations (e.g., by changing pollution, cloud cover, or surface albedo).

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Appendix 5A
SPECTRAL DATA AVAILABLE FROM DATABASES

5A.1 World Ozone and Ultraviolet Radiation Data Centre (WOUDC) [a]

Station	Name	Instrument	Country	Institute [b]	Lat. (°N)	Long. (°E)	Start Date
7	Kagoshima	Brewer	Japan	JMA	31.5	130.5	1/01/91
12	Sapporo	Brewer	Japan	JMA	43.02	141.3	1/01/91
14	Tateno	Brewer	Japan	JMA	36.02	140.07	1/01/90
18	Alert	Brewer	Canada	MSC	82.47	–62.35	6/09/95
21	Edmonton (Stony Pl.)	Brewer	Canada	MSC	53.52	–114.13	3/19/92
24	Resolute	Brewer	Canada	MSC	74.69	–95.01	3/14/91
31	Mauna Loa	Brewer (double)	United States	MSC	19.5	–155.6	1/01/98
31	Mauna Loa	Brewer	United States	MSC	19.5	–155.6	3/24/97
31	Mauna Loa	Bentham	United States	NIWA	19.5	–155.6	11/01/97
65	Toronto	Brewer	Canada	MSC	43.75	–79.5	3/01/89
76	Goose Bay	Brewer	Canada	MSC	53.15	–60.51	1/01/97
77	Churchill	Brewer	Canada	MSC	58.72	–94.1	3/30/92
95	Taipei	Brewer	Taiwan	CWBT	24.99	121.49	3/06/92
101	Syowa	Brewer	Japan	JMA	–69.03	–39.55	1/01/93
111	Amundsen-Scott	Biospherical [c]	Antarctica	NSF	–89.96	–24.8	1/01/91
190	Naha	Brewer	Japan	JMA	26.17	127.65	1/01/91
199	Barrow	Biospherical [c]	United States	NSF	71.32	–156.6	1/01/91
239	San Diego	Biospherical [c]	United States	NSF	32.45	–117.11	1/01/92
241	Saskatoon	Brewer	Canada	MSC	52.08	–106.74	1/01/91
256	Lauder	Bentham	New Zealand	NIWA	–45.03	169.68	1/01/94
261	Thessaloniki	Brewer	Greece	AUTH	40.52	22.97	10/01/89
268	Arrival Heights	Biospherical [c]	Antarctica	NSF	–77.83	166.67	1/01/89
290	Saturna Island	Brewer	Canada	MSC	48.75	–123.16	10/03/90
292	Palmer	Biospherical [c]	Antarctica	NSF	–64.75	–64.05	1/01/91
301	Ispra	Brewer (double)	Italy	JRC-EC	45.8	8.63	1/01/01
306	Chengkung	Brewer	Taiwan	CWBT	23.07	121.34	1/02/92
307	Obninsk	Brewer	Russia	IEM-SPA	55.09	35.97	5/06/93
319	Montreal (Dorval)	Brewer	Canada	MSC	45.45	–73.78	3/06/93
320	Winnipeg	Brewer	Canada	MSC	49.87	–97.27	7/06/92
321	Halifax (Bedford)	Brewer	Canada	MSC	44.65	–63.67	7/02/92
331	Poprad-Ganovce	Brewer	Slovakia	SHMI	49	20.29	1/01/94
332	Pohang	Brewer	Korea	KMA	36	129.35	1/27/94
338	Bratts Lake (Regina)	Brewer	Canada	MSC	50.18	–104.74	1/01/95
339	Ushuaia	Biospherical [c]	Argentina	NSF	–54.85	–68.31	1/01/90
353	Reading	Optronic	United Kingdom	UMIST	51.42	0.96	1/27/94

[a] Website: http://www.msc-smc.ec.gc.ca/woudc/
[b] JMA, Japan Meteorological Agency; MSC, Meteorological Service of Canada; NIWA, National Institute of Water and Atmospheric Research; CWBT, Central Weather Bureau of Taiwan; NSF, National Science Foundation; AUTH, Aristotle University of Thessaloniki; JRC-EC, Joint Research Centre-European Commission; IEM-SPA, Institute of Experimental Meteorology-Scientific Production Association; SHMI, Slovak Hydrometeorological Institute; KMA, Korea Meteorological Administration; UMIST, University of Manchester Institute of Science and Technology.
[c] Data from Biospherical Instruments are also available via the website http://www.biospherical.com/nsf

5A.2 European Ultraviolet Database (EUVDB) [a]

No.	Station Name	Instrument	Country	Institute [b]	Lat. (°N)	Long. (°E)	Start Date
1	Sonnblick	Bentham	Austria	BOKU	47.05	12.97	Feb. 96
2	Vienna	Bentham	Austria	BOKU	48.23	16.35	Mar. 98
3	Uccle, Brussels	Jobin & Yvon	Belgium	IASB	50.80	4.36	Mar. 93
4	Jokioinen	Brewer	Finland	FMI	60.81	23.50	Apr. 95
5	Sodankylä	Brewer	Finland	FMI	67.37	26.63	Apr. 90
6	Villar St. Pancrace	Jobin & Yvon	France	USTL	44.90	6.65	Sep. 99
7	Villeneuve d'Asq	Jobin & Yvon	France	USTL	50.37	3.01	Apr. 97
8	Neuherberg	Bentham	Germany	BfS	48.22	11.58	Jan. 01
9	Offenbach	Bentham	Germany	BfS	50.10	8.75	Jul. 01
10	Hohenpeissenberg	Brewer	Germany	DWD	47.80	11.02	Jan. 95
11	Lindenberg	Brewer	Germany	DWD	52.22	14.12	Jan. 95
12	Potsdam	Brewer	Germany	DWD	52.36	13.08	Jan. 95
13	Garmisch-Partenkirchen	Bentham	Germany	IFU	47.48	11.07	Apr. 94
14	Zugspitze	Bentham	Germany	IFU	7.42	10.98	Apr. 94
15	Thessaloniki	Brewer	Greece	LAP	40.52	22.97	Oct. 89
16	Lampedusa		Italy	ENEA	35.50	12.60	Feb. 98
17	Ispra	Brewer	Italy	JRC	45.81	8.63	Jan. 92
18	Rome	Brewer	Italy	URO	41.90	12.52	Feb. 92
19	Andøya	Bentham	Norway	NILU	69.48	16.02	Feb. 98
20	Trondheim	Optronic	Norway	NTNU	64.43	10.47	Mar. 97
21	Tromsø	Brewer	Norway	UT	69.66	18.93	May 94
22	Belsk	Brewer	Poland	IGFPAS	51.83	20.78	Jan. 93
23	Azores	Brewer	Portugal	MI	38.66	–27.22	
24	Funchal (Madeira Is.)	Brewer	Portugal	MI	32.64	–16.89	Jan. 97
25	Lisbon	Brewer	Portugal	MI	38.77	–9.15	Jun. 00
26	Penhas Douradas	Brewer	Portugal	MI	40.42	–7.55	
27	Izana	Brewer	Spain	INM	28.49	–16.50	Jan. 95
28	Norrkoping	Brewer	Sweden	SMHI	58.58	16.15	Sep. 91
29	Vindeln	Brewer	Sweden	SMHI	64.23	19.77	Jul. 96
30	De Bilt	Brewer	Netherlands	KNMI	52.10	5.18	Jan. 94
31	LSO (Bilthoven)	Dilcon	Netherlands	RIVM	52.12	5.20	Jan. 96
32	Reading	Optronics	United Kingdom	UMIST	51.45	–0.93	Jan. 94

Only permanent stations are listed; campaign data are not included.
Data from Neuherberg, Offenbach, Lampedusa, Andoya, Azores, and Penhas Douradas will be submitted in the coming months.

[a] Website: http://www.muk.uni-hannover.de/EDUCE
[b] BOKU, Universität für Bodenkultur Wein; IASB, Institut d'Aéronomie Spatiale de Belgique; FMI, Finnish Meteorological Institute; USTL, Université des Sciences et Technologies de Lille; BfS, Bundesamt für Strahlenschutz; DWD, Deutscher Wetterdienst; IFU, Atmosphärische Umweltforschung; LAP, Laboratory of Atmospheric Physics; ENEA, Ente per le Nuove Technologie l'Energia e l'Ambiente; JRC, Joint Research Centre, European Commission; URO, University of Rome; NILU, Norsk Institutt for Luftforskning; NTNU, Norges Teknisk-Naturvitenskapelige Universitet; UT, University of Tromsø; IGFPAS, Institute of Geophysics, Polish Academy of Sciences; MI, Institute of Meteorology, Portugal; INM, Instituto Nacional de Meteorologia; SMHI, Swedish Meteorological and Hydrological Institute; KNMI, Koninklijk Nederlands Meteorologische Instituut; RIVM, Rijkinstituut voor Volksgezandheid en Milieu; UMIST, University of Manchester Institute of Science and Technology.

Appendix 5B
INTERNET ADDRESSES FOR UV SITES

5B.1 General UV Information

WMO UV radiation page	http://titan.srrb.noaa.gov/UV/
TOMS (Ozone and UV satellite data)	http://toms.gsfc.nasa.gov/
NSF UV monitoring network, U.S.	http://www.biospherical.com/NSF/
USDA UV-B monitoring and research program	http://uvb.nrel.colostate.edu/
NIWA, New Zealand	http://www.niwa.co.nz/services/uvozone/
EPA, U.S.	http://www.epa.gov/uvnet/ and http://oz.physast.uga.edu/
EPA SunWise School Program	http://www.epa.gov/sunwise/
WMO Ozone Bulletins	http://www.wmo.ch/web/arep/ozone.html
Center for International Earth Science Information Network (CIESIN), U.S.	http://sedac.ciesin.columbia.edu/ozone/
Atmospheric Sciences Research Center, U.S.	http://uvb.asrc.cestm.albany.edu/
World Radiation Centre	http://wrdc-mgo.nrel.gov/

5B.2 International UV Projects

World Ozone and UV Data Center	http://www.msc-smc.ec.gc.ca/woudc/
European Cooperation in the field of Scientific and Technical research (COST-713)	http://159.213.57.69/uvweb
SUVDAMA, European Commission	http://www.ozone.fmi.fi/SUVDAMA/
EDUCE, European Commission	http://www.muk.uni-hannover.de/EDUCE/
Thematic Network For Ultraviolet Measurements	http://metrology.hut.fi/uvnet/
QASUME, European Communities	http://lap.physics.auth.gr/qasume/

5B.3 Radiative Transfer Codes

Tropospheric Ultraviolet Visible (TUV)	http://www.acd.ucar.edu/TUV/
library for Radiative Transfer (libRadtran)	http://www.libradtran.org/
System for Transfer of Atmospheric Radiation (STAR)	http://www.meteo.physik.uni-muenchen.de/strahlung/uvrad/Star/STARinfo.htm
Fast and Easy Radiative Transfer (FASTRT)	http://zardoz.nilu.no/~olaeng/fastrt/fastrt.html
Santa Barbara DISTORT Atmospheric Radiative Transfer (SBDART)	http://arm.mrcsb.com/sbdart/

5B.4 Extraterrestrial Spectra

Solar Ultraviolet Spectral Irradiance Monitor (SUSIM)	http://wwwsolar.nrl.navy.mil/susim_atlas_data.html
Solar Stellar Irradiance Comparison Experiment (SOLSTICE)	http://lasp.colorado.edu/solstice/ and http://www-uars.gsfc.nasa.gov/cdrom_main.html
McMath/Pierce at Kitt Peak	ftp://ftp.noao.edu/fts/fluxatl/

5B.5 General UV Index Information

"UV-Index for the public," COST-713	http://www.bag.admin.ch/strahlen/nonionisant/pdf/e/dossier-cost.pdf
EPA, U.S.	http://www.epa.gov/sunwise/uvindex.html
NOAA/EPA, U.S.	http://www.cpc.ncep.noaa.gov/products/stratosphere/ uv_index/index.html
University of Vienna, Austria	http://www-med-physik.vu-wien.ac.at/uv/uv_online.htm
The UV Index Sun Awareness Program, Canada	http://www.msc-smc.ec.gc.ca/uvindex/index_e.html
World Health Organization (WHO)	http://www.who.int/inf-fs/en/fact133.html
Intersun/WHO	http://www.who.int/peh-uv/

5B.6 Internet Sites with UV Information by Country

Argentina	http://www.conae.gov.ar/caratula.html and http://www.meteofa.mil.ar
Australia (BOM)	http://www.bom.gov.au/info/about_uvb.shtml
Australia (ARPANSA)	http://www.arpansa.gov.au/is_uvindex.htm
Australia (SunSmart)	http://www.sunsmart.com.au/
Austria (University Vienna)	http://www-med-physik.vu-wien.ac.at/uv/uv_online.htm
Austria (University Innsbruck)	http://www.uibk.ac.at/projects/uv-index/
Canada	http://www.ec.gc.ca/ozone/
Czech Republic	http://www.chmi.cz/meteo/ozon/o3uvb-e.html
European Commission (JRC)	http://ecuv.jrc.it/
Finland	http://www.fmi.fi/research_atmosphere/atmosphere_2.html
France	http://www.securite-solaire.org/
Germany (DWD)	http://www.uv-index.de/
Germany (BfS)	http://www.bfs.de/uvi/index.htm
Greece	http://lap.physics.auth.gr/uvindex/
Italy	http://www.lamma.rete.toscana.it/previ/eng/uvhtm/uvnew0.html
Japan	http://www.shiseido.co.jp/e/e9708uvi/html/
Mexico	http://www.sima.com.mx/t1msn_valle_de_mexico/uv-index.asp
New Zealand	http://www.niwa.co.nz/services/uvozone/
Norway	http://uvnett.nrpa.no/uv/
Poland	http://www.imgw.pl/
Portugal	http://www.meteo.pt/uv/uvindex.htm
Spain	http://infomet.am.ub.es/uv_i_ozo/uvi.html
Sweden	http://www.smhi.se/weather/uvindex/sv/uvprog.htm
Switzerland	http://www.bag.admin.ch/strahlen/nonionisant/uv/d/index.php
United States	http://www.cpc.ncep.noaa.gov/products/stratosphere/uv_index/