CHAPTER 7

Surface Ultraviolet Radiation: Past, Present, and Future

Lead Authors:
A.F. Bais
D. Lubin

Coauthors:
A. Arola
G. Bernhard
M. Blumthaler
N. Chubarova
C. Erlick
H.P. Gies
N. Krotkov
K. Lantz
B. Mayer
R.L. McKenzie
R.D. Piacentini
G. Seckmeyer
J.R. Slusser
C.S. Zerefos

Contributors:
U. Feister
V. Fioletov
J. Gröbner
E. Kyrö
H. Slaper

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- **New methods to quantify the aerosol optical properties have been developed.** These properties have important influences on UV radiation. By combining spectral irradiance and radiance measurements, the effective single scattering albedo and optical depth of aerosols can be derived with reasonable accuracy at locations with moderate to high aerosol optical depth. Under low aerosol conditions, accurate determination of the wavelength dependence of the aerosol optical depth in the UV-B is restricted by calibration uncertainties and by the interference of ozone and SO_2.

- **Although the Total Ozone Mapping Spectrometer (TOMS) instrument is no longer available, continuity of satellite-derived global UV data is maintained.** The new Ozone Monitoring Instrument (OMI) onboard the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) Aura spacecraft was launched in July 2004 for continued global monitoring of ozone, other trace gases, and surface UV irradiance.

- **Tropospheric aerosols are responsible for the overestimation of UV irradiance from satellite instruments (e.g., TOMS) that use solar backscattered ultraviolet radiation to derive surface UV irradiance.** Although at clean sites the agreement with ground-based measurements is good, over more polluted locations the bias can be as large as 40% because the lowermost atmosphere containing the absorbing aerosols is not adequately probed. The presence of clouds, and snow or ice cover, can also lead to significant biases. New algorithms have been developed to improve the parameterization of aerosol and snow and ice effects on satellite-derived surface UV irradiance, as well as of cloud effects using Advanced Very High Resolution Radiometer (AVHRR) and METEOSAT images, showing on average good agreement with ground-based UV observations.

- **Further improvements have been made in UV measuring instruments and techniques.** For example, a transportable spectroradiometer was compared with instruments at more than 25 sites in Europe. The uncertainty of well-maintained spectroradiometers, however, could not be significantly reduced in recent years, mainly due to the remaining difficulties with lamp calibrations. Diode array and CCD spectrographs record the entire spectrum in a fraction of a second, allowing for better spectral characterization of cloud effects of UV radiation, but their intrinsic stray-light problem limits their use in the UV-B. Narrowband multifilter radiometers are now used in several networks providing more information than broadband radiometers and are a useful supplement to well-maintained spectroradiometers. Those that include rotating shadow-bands provide, in addition, estimates of the aerosol optical properties.

- **Algorithms have been developed for converting spectral irradiance to actinic flux, which is more relevant to atmospheric chemistry.** This enables us to derive historic actinic fluxes from the 1990s, when the irradiance measurements became widely available. The resulting uncertainties in the actinic fluxes are between 5% and 15% under all sky conditions.

- **Model calculations incorporating only ozone projections show that UV levels will decrease over the next few decades.** These calculations imply that UV irradiance is currently close to maximum and under this scenario they will revert to pre-1980 levels at midlatitudes between about 2040 and 2070, but later at southern high latitudes. However, other factors that influence UV are likely to dominate over these time scales.

- **Climate change will also influence surface UV irradiance through changes induced mainly to clouds and surface reflectivity.** Aerosols and air pollutants are also expected to change in the future. These factors may lead to either increases or decreases in surface UV radiation, through absorption or scattering. If the projections for future ozone are correct, these factors are likely to dominate future changes in UV radiation.

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SURFACE ULTRAVIOLET RADIATION: PAST, PRESENT, AND FUTURE

Contents

SCIENTIFIC SUMMARY

- **Ultraviolet (UV) measurements from some stations in unpolluted locations indicate that the Montreal Protocol is working, because at these locations further increases have not been observed since the late 1990s.** Outside polar regions, increases in UV due to ozone depletion have been relatively small and in many places they are difficult to separate from those due to other causes, such as changes in cloud and aerosol. In unpolluted locations, especially in the Southern Hemisphere, UV irradiances have been decreasing in recent years, as expected from the observed increases in ozone.

- **At most midlatitude stations in the Northern Hemisphere, surface UV irradiance continued to increase at rates of a few percent per decade.** The observed increases and their significance depend on location, wavelength range, and the period of measurements. These increases cannot be explained solely by ozone depletion and could be attributed to a decreasing tendency in aerosol extinction and air pollution since the beginning of the 1990s and partly to decreasing cloudiness, as estimated from satellites. The longest reconstructed series of erythemal irradiance (in Switzerland back to 1920s) revealed that high UV levels occurred in the mid-1940s and early 1960s due to reduction in cloudiness. Increased cloudiness in the mid-1970s resulted in reduced erythemal irradiance over several locations in Europe.

- **In polar regions, high UV irradiances lasting for a few days have been observed, associated with low total ozone episodes.** Erythemal irradiance averaged over several days has been increased by ~70% over southern Argentina during vortex overpasses in October. Instantaneous enhancements up to a factor of 6 have been observed over Antarctica. Over northern Europe and Alaska, the observed enhancements were smaller.

- **At present, clouds generally influence surface UV irradiance more strongly than any other atmospheric variable, including ozone.** Further studies that quantify cloud effects on surface UV irradiance are now available. Under overcast conditions, reductions can exceed 90%. Reductions of UV irradiance by clouds are 15-45% smaller than in the visible part of the spectrum. Recent measurements have shown intermittent enhancements of up to 40% in UV actinic flux over clear-sky values for cloudy conditions when the solar disk is unoccluded, whereas enhancements of 25% were found for irradiance under similar conditions.

- **Cloud variability is the major factor limiting our ability to detect long-term changes in surface UV radiation due to ozone.** At most sites, even if ozone trends were linear, at least 10-15 years of measurements would be needed to detect a trend in UV radiation.

- **The high surface reflectivity (close to unity) in Antarctica can lead to enhancements in clear-sky UV irradiance up to 50%.** Under such conditions, the high albedo compensates the UV attenuation by clouds, resulting in surface irradiance similar to clear skies, while zenith radiance is strongly enhanced (even tripled). For the first time the UV surface albedo was measured in Antarctica with high spectral resolution, confirming that albedo in the UV is slightly lower than in the visible, but still close to unity. New observations in the European Alps showed that a snow-covered terrain may increase the clear-sky erythemal and UV-A irradiance by up to 22% and 15% respectively, with respect to low-albedo conditions. Spatial variations of snow coverage may result in large (up to 40%) variations in sky radiance from different directions. The effect of snow albedo is stronger on tilted surfaces.

- **Air pollutants may counterbalance the UV radiation increases resulting from ozone depletion.** Observations confirmed that surface UV irradiance at locations near the emission sources of ozone (O_3), nitrogen dioxide (NO_2), or sulfur dioxide (SO_2) in the lower troposphere is attenuated by up to ~20%. Air pollution exerts stronger attenuation in UV compared with total solar irradiance.

- **Three-dimensional radiative transfer models have improved the ability to model UV radiation under broken cloud and over complex terrains.** For most measuring sites, these are the prevailing conditions. However, the realization of this improved capability is still limited by the lack of the necessary input parameters.

- **New methods to quantify the aerosol optical properties have been developed.** These properties have important influences on UV radiation. By combining spectral irradiance and radiance measurements, the effective single scattering albedo and optical depth of aerosols can be derived with reasonable accuracy at locations with moderate to high aerosol optical depth. Under low aerosol conditions, accurate determination of the wavelength dependence of the aerosol optical depth in the UV-B is restricted by calibration uncertainties and by the interference of ozone and SO_2.

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7.1 INTRODUCTION

The potential for increased solar ultraviolet (UV) radiation reaching the Earth's surface in response to ozone (O_3) reduction has been a major concern since the first signs of ozone depletion in the early 1980s. Although UV is a small fraction of the total radiant solar energy, it may produce detrimental effects on the ecosystem and degrading effects on materials, and therefore knowledge of its variability in time and space has high priority in scientific research. Oxygen, ozone, and nitrogen molecules in the upper atmosphere absorb the UV-C (wavelength < 280 nanometers (nm)) part of the spectrum effectively, whereas ozone in the stratosphere strongly absorbs the UV-B (280-315 nm) part and consequently determines the spectral shape of UV radiation at the surface. UV-B is of great biological importance because photons in this region may damage deoxyribonucleic acid (DNA) molecules and some proteins of living organisms. On the other hand, UV-B is essential for the synthesis of vitamin D in the human body, which has beneficial health effects and helps in prevention of some diseases. Vitamin D can not be produced in sufficient amounts when incident UV-B radiation is very low. UV-A (315-400 nm) is less affected by ozone and may also contribute to some biological effects, especially if received in high doses. UV in both spectral ranges is important for tropospheric chemistry because it is involved in important photochemical reactions, such as the photolysis of nitrogen dioxide (NO_2), ozone, and formaldehyde. Changes in tropospheric composition induced by UV changes may be important for the stratosphere through interactions between the troposphere and stratosphere. Finally, there are linkages between changes in UV-A radiation and climate change.

Monitoring of UV radiation has been a challenging task because of the great difficulties in conducting accurate measurements and proper quality control, and because UV is highly variable both in time and space. Assessment of the UV levels in the last two decades is addressed through a limited number of measurement records from instruments operating at the ground or onboard satellites.

Most of the unresolved issues that were pointed out in the previous Assessment (Kerr and Seckmeyer et al., 2003) have been further studied. Some progress has been made with respect to the effects of absorbing aerosols on satellite UV retrievals, and different methods have been proposed for determining the aerosol single scattering albedo from radiation measurements and modeling. Improvements have also been made in quantifying the cloud effects and the influence of high surface albedo on the ground-based and satellite-derived measurements. Effects from inhomogeneities in the surface reflectivity of the terrain surrounding a monitoring site have also been studied, although marginal progress has been made in investigating the representativeness of measurements made at a monitoring site for the surrounding areas.

While propagating through the atmosphere, solar UV radiation is influenced by complex processes of scattering and absorption before reaching the Earth's surface. Sufficient understanding and quantification of the effects of these processes, particularly the tropospheric, are essential for the simulation of the UV radiation field and for explaining its variations in time and space. Improvement of our knowledge and more quantitative information on these processes since the previous Assessment (WMO, 2003) are presented in Section 7.2. In particular this section describes effects arising from the Sun-Earth geometry, clouds, atmospheric gases and aerosols, as well as effects from the surface albedo and altitude. Finally, new findings about the transfer of UV under water and ice are also included. Section 7.3 discusses the progress made in instruments and procedures that are used to measure solar UV radiation and other relevant parameters, from the ground and space. The differences between ground-based and satellite-derived surface UV measurements are also discussed in connection with further developments in satellite UV retrieval algorithms. The section also includes developments in radiative transfer (RT) modeling and other modeling approaches. Finally, this section discusses the short-term predictions of surface UV and the use of these predictions to construct the UV index. Changes in surface UV irradiance on different time scales derived from ground-based and satellite instruments, as well as from reconstructed past UV records are discussed in Section 7.4. Particular emphasis is given to long-term changes and to the attribution of these changes to different atmospheric parameters. The link between surface UV and climate change, and prediction of future UV levels in relation to ozone changes, are discussed in Section 7.5. Finally, open issues that need further investigation are outlined in Section 7.6.

7.2 FACTORS AFFECTING UV RADIATION: NEW FINDINGS

The non-uniform distribution of the predominant factors that interact with UV radiation (clouds, ozone, aerosols, and surface albedo) makes detailed calculations of UV radiation a nontrivial task. The impact of these factors cannot always be treated independently, since in most cases they act synergistically (e.g., Kerr, 2005). The following sections describe the progress that has been achieved during the last four years toward understanding and quantifying the role of these factors in modifying the

solar UV radiation received at the surface. Due to the large natural variability of surface UV, ground-based measurements that are made in many locations worldwide provide results that are valid mainly locally, and cannot be easily extrapolated to global scales (see also Figure 7-4). On the other hand, satellite estimates of surface UV radiation provide global coverage, but the sampling frequency is typically only once per day, with a coarse spatial resolution that represents average conditions over large areas. Further, these estimates are based on model calculations that include assumptions that are not always realistic.

7.2.1 The Extraterrestrial Solar Spectrum

UV radiation entering the Earth's atmosphere is primarily controlled by the variations in the Sun emittance and in the orbital position of the Earth. Uncertainties in the spectral solar irradiance at the top of the atmosphere translate directly into uncertainties in the spectral radiance (and irradiance) at all levels in the atmosphere and at the surface due to the linearity of the radiative transfer equation. Thus, accurate knowledge of the solar spectrum at the top of the atmosphere (see Appendix 7B.4) is very important for accurate prediction of the radiation levels at the surface with radiative transfer models.

Variations in the orbit of the Earth, the so-called Milankovitch cycles (obliquity, eccentricity, and precession), have very long periods and produce changes in radiation at the top of the atmosphere of up to ~30% on time scales of hundreds of thousands of years. Shaffer and Cerveny (2004) calculated surface irradiance changes in the UV band 300-325 nm taking into account variations in the extraterrestrial radiation reaching the atmosphere and the solar zenith angle (SZA), but assuming invariant latitudinal ozone concentrations (see example in Figure 7-1). Although over such long time scales there should have been significant changes in oxygen, Segura et al. (2003) showed that even for large changes in oxygen, changes in ozone are relatively small. Variations in surface UV radiation caused by these orbital changes are expected to be very small (less than ~1%) in the next few centuries. Thus solar activity (sunspots, and 11-year and 27-day cycles) is the dominant factor responsible for the variability in the extraterrestrial irradiance spectrum in the near future.

Solar activity in the last 70 years has been exceptionally strong, and the previous period of equally strong activity occurred more than 8,000 years ago, as suggested by Solanki et al. (2004) based on dendrochronologically dated radiocarbon concentrations. This strong solar activity marginally influences the UV radiation that reaches the surface (UV-B and longer wavelengths), but it is important for the UV-C wavelengths that are involved in stratospheric ozone production.

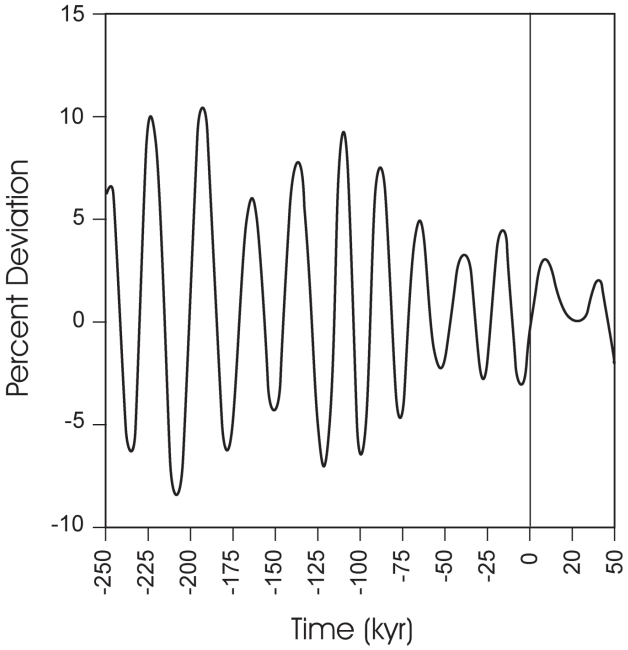

Figure 7-1. Percent deviations in daily near-UV (300-325 nm) solar irradiance on the March equinox at 60°N between 250,000 before present and 50,000 after present, caused by Milankovitch cycles. Larger variations, ranging between about ±30%, have been calculated for different latitudes and for the solstices. Reprinted from Shaffer and Cerveny, 2004, with permission from Elsevier.

Spectroradiometers onboard Earth-orbiting satellites allow investigations of temporal variations of solar irradiance in different wavelength ranges. Two new composite solar irradiance reference spectra extending from 0.1 to 2400 nm were constructed using recent space measurements for two distinct time periods during solar cycle 22 (1985-1997). From data gathered with instruments onboard the Atmospheric Laboratory for Applications and Science (ATLAS) 1 and 2 and the Upper Atmosphere Research Satellite (UARS), the accuracy of the measured solar spectra was determined to be ~3% in the UV and visible ranges (Thuillier et al., 2004). Gurlit et al. (2005) presented a moderate resolution solar irradiance spectrum in the spectral range 316.7-652 nm derived from the azimuth-controlled Limb Profile Monitor of the Atmosphere/Differential Optical Absorption Spectroscopy (LPMA/DOAS) balloon gondola at around 32 km float altitude. This spectrum is in very good agreement with previously reported spectra (Kurucz et al., 1984; Thuillier et al., 1997, 1998; Harder et al., 2000) in the visible, but it

is 1.4 to 6.2% lower in the UV-A. In agreement with Skupin et al. (2003), this study emphasizes that the present level 1 calibration of the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) of the European Space Agency (ESA) is systematically 15% higher in this wavelength range (316.7-652 nm) with respect to all other available solar irradiance measurements, and suggests using the recalibration proposed by the University of Bremen for SCIAMACHY. Finally, a new reference solar spectrum (given in steps of 0.5 nm) was constructed by combining measurements derived from different satellite platforms and from the ground, and this spectrum was compared with historical reference spectra (Gueymard, 2004, 2006). It was concluded that reference solar irradiance spectra in the UV-B and UV-A that were published after 1985 are in very good agreement (within a few percent) and that the ATLAS 3 spectrum is probably the most suitable one for radiative transfer calculations. The latter is in agreement with the conclusion of Bais et al. (2003) that was derived from comparison of measured and modeled surface UV spectra.

The variability of the solar irradiance spectrum for the duration of solar cycle 23 has been investigated using data from different satellites. Several studies quantified the amplitude of the solar cycle in the wavelength band 245-250 nm and found that it ranged between 6% and 8%: DeLand et al. (2004a) used data in the period from March 1985 to May 1997 from the Solar Backscatter Ultraviolet Radiometer 2 (SBUV/2) onboard the National Oceanic and Atmospheric Administration (NOAA) 9 satellite; DeLand et al. (2004b) used data from the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) and the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) instruments aboard UARS; and Floyd et al. (2003) used the SUSIM dataset alone. In the band 200-205 nm, the amplitude is larger (~9%). All three analyses reveal that no irradiance variations due to solar cycle variability could be detected in the UV-B and UV-A ranges at these spectral resolutions. Therefore surface UV radiation is not expected to respond directly to solar variations, but only indirectly through changes in stratospheric ozone induced by the variability of solar irradiance in the far ultraviolet (see Chapter 3, Section 3.4.4). A weaker solar activity will result in less ozone in the stratosphere and thus in more UV-B radiation at the surface, but also in less risk of sudden ozone decreases due to solar flares.

7.2.2 Stratospheric Ozone

The influence of stratospheric ozone on the transmission of UV radiation through the atmosphere is well understood and has been extensively discussed in previous Assessments (Herman and McKenzie et al., 1999). The community now has access to better measurements and radiative transfer models; and the effects of molecular absorptions are now better quantified through field measurements and supporting model calculations (e.g., Burrows et al., 1999; Mohamed-Tahrin et al., 2001). New evidence for increases of surface UV-B radiation due to stratospheric ozone depletion in Antarctica, particularly during the period of the ozone hole in spring, has been reported from observations (Bernhard et al., 2004, 2006). Summertime enhancements of surface UV were reported also at northern high latitudes during episodes of low ozone in the stratosphere caused by chemical destruction and transport processes (Orsolini et al., 2003).

Surface UV radiation depends on the vertical profile of ozone and on the vertical profile of temperature because of the temperature dependence of the molecular absorption cross sections. McKenzie et al. (2003) showed that differences in the shape of the vertical profile of ozone amplify the seasonal differences in UV irradiance between the northern (NH) and southern (SH) hemispheres. The summertime UV irradiance at southern midlatitudes greatly exceeds that at northern midlatitudes. Kazantzidis et al. (2005) quantified the differences in surface UV irradiances that are calculated by RT models when substituting the standard Air Force Geophysics Laboratory (AFGL) ozone and temperature profiles with measured ones. The differences in the UV-B irradiance are ~2-3% at small SZA, increasing by a few percent at larger SZA. Krzyścin (2004) reported that for large SZA, the UV irradiance at the surface is more sensitive to the ozone changes in the midstratosphere than to changes in the lower stratosphere, while the opposite occurs for small SZA. Under the current state of the atmosphere, the dependence of surface UV on the vertical profiles of temperature and ozone is relatively weak, but it might become stronger in the future, if the temperature of the lower stratosphere (where the bulk of ozone resides and most of the UV absorption occurs) changes (see Chpater 5, Section 5.3). Generally, the effect of changes in the ozone profile on surface UV radiation is larger than that of changes in the profile of temperature.

7.2.3 Clouds

Clouds dominate any other atmospheric variable as a source of surface UV variability, resulting in either a reduction or an increase in UV radiation. Indirectly, clouds may affect absorption of UV by other atmospheric constituents, while their variability usually masks the effects of other variables. For example, clouds are the major factor that limits the detectability of ozone-induced trends

in UV radiation (den Outer et al., 2005; Glandorf et al., 2005). The higher the variability of clouds, the longer the record of ground-based UV data required for detecting an ozone-induced trend in UV radiation. Cloud effects on UV radiation are complex, thus restricting our ability to describe and predict accurately the UV radiation field at the ground. In practice, the necessary parameters needed to calculate local cloud effects are rarely available. Even if they were, the complexity of cloud geometry would require three dimensional (3-D) model calculations. Climate modeling suggests that the temporal and spatial distribution of clouds is likely to change in the future (IPCC, 2001 and Section 7.5.2). If ozone changes are small, the anticipated changes in cloudiness will have a much greater impact on UV radiation than changes in ozone. Despite the inherent difficulties in investigating the effects of clouds on surface UV, new case studies have been published and have broadened our understanding.

Results from different studies of cloud effects (e.g., Calbó et al., 2005) can be compared using the cloud modification factor (CMF), which is defined as the ratio between the measured UV radiation in a cloudy sky and the calculated radiation for a cloudless sky. Typical CMF values for overcast skies range from 0.3 to 0.8, depending both on cloud type and characteristics (Cede et al., 2002; Calbó et al., 2005). Den Outer et al. (2005) have investigated the effects of clouds on UV and visible solar radiation in the Netherlands by comparing measurements with model calculations. These studies confirm that clouds attenuate UV radiation by 15-45% less than total solar radiation, as a result of Rayleigh scattering that redirects toward the surface more efficiently the UV part of the radiation reflected by the clouds. Nichol et al. (2003) found a tendency toward greater cloud attenuation with increasing solar zenith angle.

Clouds may also have an enhancement effect, manifested by increased UV irradiance at the surface when the solar disk is unoccluded. Recent studies show enhancements of up to 25% and reconfirm earlier findings that the enhancements are significant (Herman and McKenzie et al., 1999; Kerr and Seckmeyer et al., 2003) and can last for hours (Cede et al., 2002). The enhancements were found to be most pronounced for large cloud cover of 5 to 7 octas (Cede et al., 2002) and were smaller in the UV than in the visible and infrared (Pfister et al., 2003). Simultaneous occurrence of a small solar zenith angle and a cumulus cloud close to the Sun's position in the sky at a high-altitude inter-tropical desert region produces very high erythemal doses. Piacentini et al. (2003) reported mean percentage increases due to the cloud effect of 6% for UV and 12% for total solar irradiance, relative to no clouds near the Sun. Cloud enhancements in UV actinic flux can be up to 40% over clear-sky values when the solar disk is unoccluded (Crawford et al., 2003). When the solar disk is occluded, reductions in actinic flux below the cloud appear to vary inversely with cloud fraction in some instances. Wavelength dependence has been observed under broken clouds, with shorter wavelengths generally exhibiting lower variability in irradiance for both enhancements and reductions (e.g., 20-30% less variability at 320 versus at 420 nm). For actinic fluxes, the wavelength dependence due to clouds is stronger for cloud-induced enhancements than for cloud-induced reductions with respect to clear skies. At large SZA, a wavelength dependence appears to occur even for overcast conditions. The observed behavior (reductions, enhancements, and wavelength dependences) could be explained through the difference in the impact of clouds on the direct and diffuse components of actinic flux. Integration over longer periods results in weaker wavelength dependence, suggesting that differences in wavelength response may be localized phenomena with impacts that are minimized when integrated over the surrounding area.

Simultaneous measurements of actinic flux, irradiance, and aerosol and cloud properties were made from four ground stations and by aircraft (Kylling et al., 2005). The actinic flux above the cloud is increased by between 60-100% when compared with a cloudless sky, with the largest increase occurring for the optically thickest cloud. Similarly, the actinic flux below the cloud is decreased by about 55-65%. Just below the cloud top, the downwelling actinic flux reaches a maximum.

Mie scattering from cloud particles interacts with Rayleigh scattering in the atmosphere and produces a complex wavelength dependence in the top-of-the-atmosphere reflectances measured by satellite instruments that operate in the ultraviolet part of the spectrum (Ahmad et al., 2004). It was also shown that clouds can perturb the absorption by tropospheric ozone in complex ways that cannot be explained by models that treat them as reflecting surfaces rather than as volume scatterers. Winiecki and Frederick (2005) confirmed that the cloud transmission in the ultraviolet decreases with decreasing wavelength as a consequence of increasing absorption by tropospheric ozone in the cloud, and they suggested that this mechanism results in enhanced production of excited-state oxygen atoms, $O(^1D)$.

The UV-B sky radiance distribution under partial and overcast stratified cloud fields was studied using azimuthally averaged radiance measurements at Hobart, Australia (Kuchinke et al., 2004) and modeling. It was shown that inhomogeneities within realistic cloud fields have a significant effect on the radiation distribution at the ground, even on an overcast day.

7.2.4 Aerosol Scattering and Absorption

The influence of aerosols on the transmission of UV radiation has important consequences for stratospheric and tropospheric photochemistry, human and plant biology, remote sensing of column ozone, and surface UV mapping. There is a large variation in aerosol properties in both space and time caused either by natural or anthropogenic activities, and quantifying their effect remains a challenge. Uncertainties in aerosol particle microphysical data, particularly the particle number concentration, cause variability of up to 10% in predictions of actinic flux and UV irradiance (Früh et al., 2003). Advances in quantifying the effect of aerosols are being made from various fronts: laboratory and field measurements of aerosol optical properties in the UV, detection of aerosol amounts and optical properties from the ground and space, and theoretical modeling of scattering and absorption of UV radiation. Detecting and predicting aerosol absorption properties in the UV have received particular attention in recent years.

The optical properties of aerosols in the ultraviolet have been measured for different aerosol types in the laboratory and in the field. Black carbon/soot aerosols were characterized during the Aerosol Interactions and Dynamics in the Atmosphere (AIDA) Soot Aerosol Campaign (Schnaiter et al., 2003) using an optical technique based on the integrating sphere method (Mogo et al., 2005). Biomass burning aerosols were studied using a long path extinction spectrometer (LOPES) (Schnaiter et al., 2005) and fluorescence from a UV lidar (Immler et al., 2005). Desert dust, Arctic industrial pollution, and marine aerosols were investigated by Wetzel et al. (2003). Vaglieco et al. (2002) and Kirchstetter et al. (2004) found that organic carbon from motor vehicles and biomass burning contributes significantly to absorption of UV (and visible) radiation, although Myhre and Nielsen (2004) found that absorption of UV by organic acids is not significant. Kirchhoff et al. (2002) found a wavelength dependence of aerosol optical depth (AOD) in the UV-B that opposes the Angstrom law; they examined the possible influence of additional UV-absorbing species, such as formaldehyde, but found no influences on the AOD retrieval. On the other hand, Arola and Koskela (2004) studied various sources of errors in direct irradiance measurements due to the field of view of Brewer spectroradiometers that can partly explain this behavior. The properties of desert dust in the UV are also under debate. Some measurements have indicated enhanced absorption in the UV compared with the visible (Mattis et al., 2002; Meloni et al., 2004).

The optical properties of aerosol optical depth, single scattering albedo (SSA), and phase function are used to quantify the transmission of UV through turbid atmospheres and may be obtained by both satellite and ground radiometric data. Direct measurements of aerosol absorption present a great challenge even for ground-based remote sensing techniques, and the uncertainties have been recently discussed (e.g., Petters et al., 2003; Bais et al., 2005b; Goering et al., 2005; Krotkov et al., 2005a, 2005b). Using spectral direct irradiance measurements, AOD was retrieved by Lenoble et al. (2002) in the Bavarian Alps with absolute uncertainties of 0.03 to 0.05 and by Gröbner and Meleti (2004) in Ispra, Italy using a Brewer spectrophotometer. During the period 1991-2002, the AOD at 320 nm in Ispra varied between 0.05 and 2, showing a pronounced seasonal variability with high values (~0.6) in spring and summer and low values (~0.3) in winter. The AOD in the UV-A region determined from global and diffuse irradiance in the French Alps showed seasonal variations between 0.05 and 0.2 (Lenoble et al., 2004a). Techniques for retrieval of SSA have been developed using multiangle measurements of sky radiance (e.g., Dubovik et al., 2002; Qin et al., 2002), direct, diffuse, and global irradiance in conjunction with RT models (e.g., Petters et al., 2003; Bais et al., 2005b; Goering et al., 2005; Krotkov et al., 2005a, 2005b), and by combining Raman lidar, total ozone, and UV-B irradiance measurements with a RT model (Balis et al., 2004). The aerosol SSA is reported routinely by the Aerosol Robotic Network (AERONET) but only at visible wavelengths, so SSA at UV wavelengths can only be inferred by extrapolation. Petters et al. (2003) used an ultraviolet multifilter rotating shadowband radiometer (UVMFRSR) and RT model calculations to estimate the SSA, which ranged from 0.65 to 0.91 at 300 nm and 0.80 to 0.99 at 368 nm at Black Mountain, N.C. Bais et al. (2005b) estimated the SSA by combining Brewer irradiance measurements with a RT model and found that the ratio of direct to diffuse irradiance gives the highest accuracy compared with global irradiance, as long as the aerosol optical depth at 340 nm is greater than 0.2. From five years of irradiance measurements, the SSA in Thessaloniki, Greece, was determined to be between 0.85 and 0.99 when the AOD is larger than 0.8, and to cover the entire range from 0.64 to 0.99 for AOD between 0.2 and 0.8 (Bais et al., 2005b). The very low minimum SSA values (~0.65) reported in these two studies may have resulted from additional absorption by atmospheric gases, for example by NO_2 (Krotkov et al., 2005c) that was not taken into account in the retrieval of SSA.

Recently, an inversion technique has been developed to convert the unique Total Ozone Mapping Spectrometer (TOMS) spectral signature generated by the

interaction of molecular scattering and aerosol absorption into a quantitative estimate of AOD and SSA, with accuracies of ±30% and ±0.03 respectively (Torres et al., 2002, 2005).

New studies demonstrated the strong influences of variations in aerosol concentration and composition on long- and short-term variations in surface UV radiation: Chubarova et al. (2002) for Moscow, Russia; Barnard et al. (2003) for California, USA; Palancar and Toselli (2002) for Cordoba, Argentina; Micheletti et al., (2003) for Buenos Aires, Argentina; Ogunjobi and Kim (2004) for Kwangju, South Korea; Latha et al. (2004) for Northern India; Arola et al. (2003b) for Sodankylä, Finland, and Thessaloniki, Greece; Kambezidis et al. (2005) for Athens, Greece, and di Sarra et al. (2002) and Meloni et al. (2003a; 2003b; 2003c; 2005) for the island of Lampedusa in the Mediterranean. Jaroslawski and Krzyścin (2005) showed that aerosol forcing on the erythemally weighted UV at Belsk, Poland, under clear skies is as important as the forcing due to changes in ozone amount, both on long-term and short-term time scales.

The long-term variations of surface UV irradiance, which are discussed in Section 7.4, may strongly be influenced by temporal changes in the optical properties of aerosols, especially the SSA, which defines their absorption efficiency. In addition, the wavelength dependence of the two main aerosol optical properties, AOD and SSA, may result in different long-term variation of surface UV radiation at short and long wavelengths, if the type of aerosols over a particular site changes with time. Apart from their natural sources, aerosols are also a consequence of anthropogenic activities leading to atmospheric pollution, and thus they may change with time, depending on the effectiveness of pollution abatement measures. Finally, a reduction in SSA may result in less scattered radiation available for absorption by atmospheric gases, thus affecting indirectly the photochemistry in the troposphere.

7.2.5 Tropospheric Ozone and Other Gaseous Air Pollutants

UV radiation can be efficiently absorbed by man-made or natural gases in the troposphere, and at the same time it controls the concentration of some of them. For example, tropospheric concentrations of ozone may be significantly affected by changes in photodissociation rates induced by stratospheric ozone changes (Isaksen et al., 2005), which in turn affects the intensity of UV radiation at the surface. Under certain conditions, the concentration of gases resulting from photochemical reactions can increase simultaneously resulting in additional absorption of UV radiation near the Earth's surface. On the other hand, UV radiation is regulated by stratospheric ozone, as well as by the influence of aerosol and cloudiness. Thus, UV radiation interacts with tropospheric gases and aerosols in complex ways through a variety of atmospheric processes.

Tropospheric absorbers of UV radiation include ozone (O_3), sulfur dioxide (SO_2), nitrogen oxides (NO_2, dinitrogen pentoxide (N_2O_5), NO_x), some bromine and chlorine compounds (e.g., chlorine dioxide (OClO), molecular chlorine (Cl_2), dichlorine monoxide (Cl_2O), bromine monoxide (BrO), hypobromous acid (HOBr)), and the oxygen dimer (O_2-O_2) (Atkinson et al., 1997; Sander et al., 2003). In addition, many organic species can also absorb UV radiation, including different types of aldehydes (i.e., formaldehyde, benzaldehyde, acetaldehyde), acetone, peroxyacetyl nitrate (PAN), propanal, glioxal, nitrated aromatics, certain organic acids, and others (Atkinson et al., 1997; Jacobson, 1999; Sander et al., 2003; Myhre and Nielsen, 2004). The abundance of most of these substances in the troposphere usually is not large enough to produce measurable effects on surface UV, except near the sources of emission in polluted areas, or during natural hazards, like forest fires, volcanic eruptions, etc. For example, over large industrial centers on the eastern coast of the United States, the additional photochemically-produced ozone in the lower 2 km was up to 14 parts per billion by volume (ppb) (corresponding to a column contribution of 2.5 Dobson units) (Cooper et al., 2005) and was occasionally much higher (Jacobson, 1999). The content of NO_2 in the lower troposphere over polluted areas can be up to 1-2 DU, or even more (Richter and Burrows, 2002; Richter et al., 2005; Wang et al., 2005a; Cede et al., 2006a). Tropospheric SO_2 can be high in regions with volcanic activity and over industrial areas, with concentrations of 2 DU or more, as revealed from SCIAMACHY and ground measurements (Wang et al., 2005b). Finally, formaldehyde concentrations can exceed 0.6 DU (Heckel et al., 2005). The attenuation of UV radiation at the surface from these gases can be important, particularly if they coexist in the same area. Table 7-1 shows the effects of the main air pollutants in the boundary layer on the attenuation of UV irradiance, expressed by the absorption sensitivity (AS) parameter, defined as the relative change in UV irradiance due to 1 DU change in gas concentration. The absorption sensitivity of NO_2 and SO_2 can be even higher than for O_3 for the same change in concentration.

There is an increased awareness of the possible roles of these tropospheric trace gases on surface UV radiation, particularly in more polluted environments (Chubarova et al., 2002; Koronakis et al., 2002; Palancar

Table 7-1. The absorption sensitivity (AS) of different integrals of UV irradiance due to a 1-DU change in the column of O_3, SO_2, and NO_2 in the lower troposphere. Calculations are for local noon in January and July at 45°N, assuming 300 DU of ozone column (X) above 2 km. For a different ozone column, the absorption sensitivity for O_3 and SO_2 can be approximately estimated from the expression: $AS_X = AS_{300}\frac{300}{X}$, whereas NO_2 is practically unaffected. Adapted from Chubarova (2006).

	Absorption Sensitivity (%/DU)					
	O_3		NO_2		SO_2	
	July	January	July	January	July	January
Erythemal irradiance	−0.6	−0.4	−0.8	−1.8	−1.0	−0.9
UV-B (280 - 315 nm)	−0.3	−0.4	−0.8	−1.5	−0.6	−0.8
UV-A (315 - 400 nm)	Negligible		−1.6	−3.0	Negligible	
UV (280 - 400nm)	Negligible		−1.6	−2.9	Negligible	

and Toselli, 2002; Chubarova, 2004). Monitoring over several years of UV-B and total solar irradiance in Moscow and at a site located 50 km upwind to Moscow has revealed that in more than 75% of the cases, the monthly-mean UV-B values at the rural site are higher, with differences reaching 18% in winter and 9% in summer (Chubarova, 2002). For Moscow conditions, ozone and nitrogen dioxide are the most important gases in tropospheric UV-B absorption. For example, the observed attenuation of UV-B irradiance due to NO_2 is up to 6%, being ~2-3% on the average (Chubarova, 2004). During extremely high pollution episodes caused by forest fires near Moscow in 2002, the UV reduction only due to NO_2 was about 11-14%. Koronakis et al. (2002) reported reductions in UV-A irradiances of similar magnitude due to increased concentrations of tropospheric ozone and nitrogen oxides in Athens, Greece. Progress has also been made, using suites of ground-based instruments, to separate the effects of extinctions by NO_2 and aerosols (Krotkov et al., 2005c).

The future concentrations of tropospheric gases will depend on increased population, international agreements, such as the Kyoto Protocol and its successors, and the continued affordability of fuels. These changes in concentrations can affect UV radiation in various ways. Some gases, such as tropospheric ozone, can have a direct influence through absorption of UV. Others, such as nitrous oxide (N_2O) and methane (CH_4), can influence UV through their role in stratospheric chemistry, which results in changes to ozone concentrations. Further, all the greenhouse gases contribute to cooling of the stratosphere, which affects ozone chemistry, and to warming at the surface. The latter leads to changes in many variables that are capable of modifying directly the UV radiation at the surface. These include changes in glaciation, ice/snow cover, clouds, rainfall, and run-off. Presently it is difficult to predict the future concentrations of tropospheric gases that attenuate UV radiation (Isaksen et al., 2005), and consequently their importance for surface UV in the future. It is clear, however, that UV is reduced under polluted atmospheric conditions and, in some cases, these reductions may balance, to a certain degree, the UV enhancements produced by stratospheric ozone depletion.

7.2.6 Surface Albedo

UV radiation is enhanced by surface albedo, particularly over strongly reflecting surfaces, such as snow, ice, or sand, and even more in the presence of cloud layers that trap the reflected radiation between the clouds and the surface. The wavelength-dependent scattering and absorption processes control the enhancement of UV radiation by surface albedo, and hence they determine the area around a site that can contribute to these enhancements. Changes in surface albedo due to global warming may thus become important for future surface UV radiation, through, for example, reduction of snow- and ice-covered areas, deforestation, or expansion of deserts. New studies have focused on quantifying the effects of high-albedo surfaces on UV irradiance under both clear skies and cloudy conditions, and on estimating surface albedo by combining measurements and modeling. Increases in erythemal irradiance of up to ~20% were reported in these studies.

Variations of erythemal and UV-A irradiances due to surface albedo changes were investigated during 15 cloudless days at Briançon (French Alps) in February 1998 with variable snow cover and a small snowfall in the middle of the campaign. The enhancement of erythemal

irradiance was found to change from 15% to 5% (7% to 5% for UV-A) as a result of changing surface albedo, with a jump to 22% (15% for UV-A) after the snowfall. The corresponding values of the effective surface albedo are respectively 0.4, 0.1, and 0.5 for erythemal, and 0.25, 0.1, and 0.4 for UV-A irradiances (Smolskaia et al., 2003). Measurements at the same station in winter/spring 2002 showed that the enhancement of surface UV irradiance depends more strongly on the snow distribution around the site than on the actual topography. The maximum enhancement of erythemal irradiance (~22%) for clear skies agrees with results of a 3-D RT model, assuming a snow albedo of 0.3 between the snow line and the tree line and of 0.8 above the tree line. Retrieving an effective surface albedo from the enhancement of UV irradiance measurements is challenging, because small uncertainties in the enhancement (e.g., ±2%) lead to large uncertainties (±0.05) in effective albedo (Lenoble et al., 2004b). Quantitative estimates of the enhancement of surface UV irradiance due to surface albedo changes were derived also for Sodankyla, Finland, by analyzing a time series of monthly erythemal dose measurements (Arola et al., 2003b). It has been shown that for this location the enhancement is largest in May, being 21% at its maximum and 7% on average.

The effect of surface albedo on UV sky radiance was investigated at the High Alpine Research Station Jungfraujoch, Switzerland, 3576 meters above mean sea level (amsl), located at the boundary between snow-covered and snow-free terrain (Huber et al., 2004). Toward the northwest, the effect of snow-free terrain causes a significant reduction of UV sky radiance (between 20% and 40% depending on SZA) relative to a modeled simulation assuming a homogeneous snow albedo of 0.4. Finally, at Neumayer, Antarctica, it was found that UV zenith sky radiance may increase by more than a factor of 2, relative to clear sky, due to the combined effect of clouds and high snow albedo (see example in Figure 7-2) (Wuttke and Seckmeyer, 2006). On the contrary, no change has been observed in the total irradiance, which was ~670 W m^{-2}, both for overcast and clear-sky conditions.

Using model calculations, Parisi et al. (2003) estimated the increases in daily erythemal UV exposures on horizontal and on inclined planes over water, concrete, and sand relative to grassland. Under cloud-free skies, the estimated additional daily UV exposure on a horizontal plane was up to 3% higher over sand relative to grassland, while on a vertical plane the enhancement was up to 11%, for the range of SZA in the Australian sub-tropical location of this study.

Finally, measurements of spectral surface albedo from aircraft over flat arable land in East Anglia, Great Britain, show increasing albedo with increasing wavelength, from about 2% in the UV-B to about 5% at 500 nm (Webb et al., 2004). Effects of scattering and absorption within the layer beneath the flight level were removed by nonlinear extrapolation of the airborne albedo measurements to the ground (Wendisch et al., 2004).

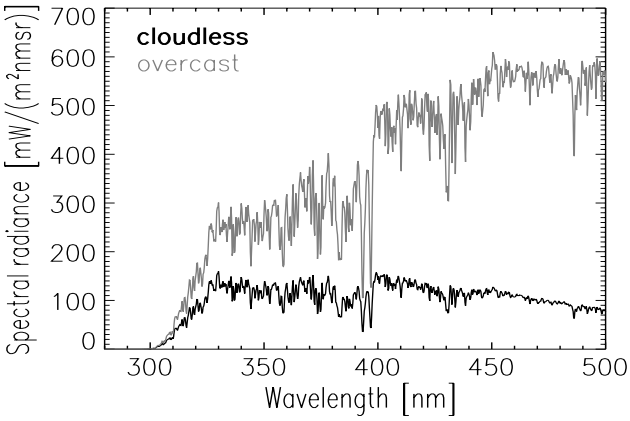

Figure 7-2. Spectra of zenith radiance measured under overcast and cloudless skies at the German Antarctic Neumayer Station (70.65°S, 8.25°W) on 19 December 2003 and 22 January 2004, respectively. The overcast spectrum exceeds the clear-sky spectrum by up to a factor of 10. In addition, the wavelength with maximum radiance is shifted from the UV (330 nm) for the clear-sky case to the visible (450 nm) for the overcast situation. Adapted from Wuttke and Seckmeyer, 2006.

7.2.7 Altitude

UV radiation increases with altitude, because of reduction of scattering and absorption by the less-dense overhead atmosphere, and, at high altitudes, because of additional reflections from the surface and the clouds below. At high altitudes, the surface is usually covered with snow, thus irradiance increases further due to enhanced surface albedo. As these processes are wavelength dependent, the increase of UV radiation varies also with wavelength.

New studies have investigated the altitude effect on UV-B irradiance using simultaneous measurements at different altitudes. The reported increases in erythemal irradiance are 7% per kilometer in Bolivia (Zaratti et al., 2003), 10.7% per kilometer in the Swiss Alps (Schmucki and Philipona, 2002), 7-16% per kilometer in Germany and between 5 and 23% per kilometer at different altitude pairs in Bolivia (Pfeifer et al., 2006), and ~11% per kilometer in the western Himalayas (Singh and Singh, 2004). The latter study also reported increases in direct and dif-

fuse irradiance, respectively, of 17.4 and 8.5% per kilometer. The variability in the estimates derived by these studies confirms that the altitude effect of UV irradiance is not linear, depending strongly on atmospheric and surface parameters, and varies also with wavelength.

Piacentini et al. (2003) measured extremely high values of solar irradiances at Cerro Cruz Azul (3900 m amsl) at the Puna of Atacama high-altitude inter-tropical desert, Argentina, under conditions favoring enhancements from reflections at the cloud edges and from multiple scattering in the cloud layer. The maximum shortwave (300-3000 nm) irradiance was 1528 W m^{-2}, about 8% higher than the solar constant, adjusted to the actual Sun-Earth distance, while the maximum UV irradiance integral (295-385 nm) was 69.5 W m^{-2} at 2.4° SZA.

Seasonal variations of the altitude effect on UV radiation are mainly influenced by changes in solar elevation, albedo, and turbidity. Allen and McKenzie (2005) measured with personal dosimeters the UV exposure of skiers at the ski field of Mount Hutt, New Zealand (2080 m amsl), and found the UV Index maxima greater by ~23% in mid-October and ~30% in mid-September than at sea level at the same time of year. Thus the exposure depends strongly on season.

7.2.8 UV Irradiances on Inclined Surfaces

Erythemal UV irradiance incident on a horizontal surface is not always the best way of estimating the real dose received by humans or animals, which is usually much higher, considering that nonhorizontal parts of their bodies may receive direct solar radiation at smaller angles of incidence. As solar radiation measurements are referenced traditionally on a horizontal surface, often personal UV radiation exposure studies and anatomical distributions of UV radiation relate the measured relative exposures to ambient UV radiation on a horizontal surface. A dataset of more than 3,000 days of irradiance measurements at 27 different orientations and on a horizontal plane reveals that irradiances on inclined surfaces are up to 1.7 times higher at the Schneefernerhaus high-altitude observatory (2650 m amsl) and 1.4 times higher in Munich (530 m amsl) compared with irradiances on a horizontal plane at the same locations (Oppenrieder et al., 2004, 2005). Simulations of these effects with a RT model were found to be in good agreement with measurements (Mech and Koepke, 2004). From clear-sky irradiance measurements with different detector inclinations in the plane of the Sun at Rosario, Argentina, it was found that the highest intensity of erythemal irradiance does not occur when the detector is pointed directly to the Sun, but at an angle larger than the solar elevation (i.e., closer to zenith). This enhancement, which is stronger at large SZA (~30% at 80° SZA) and diminishes at solar zenith angles smaller than ~50°, is attributed to differences in the contribution of diffuse and direct irradiances (Piacentini and Cede, 2004). The irradiance incident on inclined planes depends more strongly on ground reflectivity than irradiance on a horizontal plane (Koepke and Mech, 2005). Maximum increases of 57% in erythemal UV irradiance from horizontal to normal incidence were calculated by Weihs (2002) for altitudes above 3000 m.

7.2.9 UV Under Water, Ice, and Snow

Recent years have seen an expansion of research into UV under water, ice, and snow, along the lines of assessing variability in the context of climate change as well as ozone depletion, and in discovering the wide variability in UV penetration that exists among various types of aquatic ecosystems. Considerable new research has emerged on the dependence of UV in a wide variety of aquatic systems on bio-optical constituents such as dissolved organic matter (DOM), dissolved organic carbon (DOC), which is part of DOM, chromophoric (i.e., optically active) DOM (CDOM), particulate organic carbon (POC), and chlorophyll a, and on inorganic suspended particles. Table 7-2 summarizes many of these new results, listing the transmission depth, Z(1%), of UV-B radiation to 1% of the surface value for several aquatic systems. In addition, satellite methods for globally mapping UV penetration into oceanic waters have progressed from developmental stages to more viable algorithms (Vasilkov et al., 2005).

Häder et al. (2003) emphasize that for polar aquatic ecosystems, factors such as climate warming and changes in the sea ice season, surface albedo, and CDOM, may influence exposure to UV-B radiation even more than the springtime ozone depletion. As one example, Perovich (2002) reported that 10 cm of snow cover reduces UV-B transmittance by a factor of 40, thus protecting biota from UV-B while allowing a substantially larger fraction of PAR (i.e., Photosynthetically Active Radiation) to penetrate. During Arctic spring conditions, Z(1%) for UV-B radiation incident on bare sea ice may be as deep as 1.75 m, but with 5 cm of overlying snow, Z(1%) may be reduced to 30 cm. This implies a risk to non-UV-adapted organisms within and under the ice, if snowmelt were to occur earlier in the spring season as a result of climate warming. Similarly, Cockell and Córdoba-Jabonero (2004), who measured spectral UV transmittances through snow and ice on the Mars Oasis, a deglaciated section of Alexander Island, Antarctica, reported that an overlying snow depth of 4 cm is sufficient to offset a UV-B increase caused by

Table 7-2. Values of the 1% transmission depth ($Z_{UV-B}(1\%)$) for solar radiation at single wavelengths and wavelength bands in the UV spectral region from recent studies in a variety of aquatic systems.

Location	$Z_{UV-B}(1\%)$ (m)	Wavelength Range	Source
N. Michigan stream, DOC = 2.0 mg l^{-1}	0.45	305-320 nm	Frost et al., 2005
N. Michigan stream, DOC = 24 mg l^{-1}	0.04	305-320 nm	Frost et al., 2005
Boreal forest lake, DOC = 3.0 mg l^{-1}	2.00	300-320 nm	Donahue et al., 2003
Boreal forest lake, DOC = 6.7 mg l^{-1}	0.40	300-320 nm	Donahue et al., 2003
Humic lake, Finland, DOC = 5.9 mg l^{-1}	0.32	310-320 nm	Huovinen et al., 2003
Ultraoligotrophic high Arctic lake	7.00	308 nm	Ørbæk et al., 2002
Lake Huron, central	8.40	325 nm	Smith et al., 2004
Lake Erie and Lake Ontario, central	2.50	325 nm	Smith et al., 2004
Lake Huron tributaries	0.19	325 nm	Smith et al., 2004
Oceanic water, Jerlov type OI	30.50	310 nm	Piazena et al., 2002
Oceanic water, Jerlov type OIA	24.70	310 nm	Piazena et al., 2002
Oceanic water, Jerlov type OIB	20.60	310 nm	Piazena et al., 2002
Oceanic water, Jerlov type OII	12.40	310 nm	Piazena et al., 2002
Oceanic water, Jerlov type OIII	6.60	310 nm	Piazena et al., 2002
Atlantic water, Nordic Seas	31.00	310 nm	Aas et al., 2002
Northern Barents Sea	11.80	310 nm	Aas et al., 2002
Northern Greenland Sea	8.80	310 nm	Aas et al., 2002
Norwegian Coastal Current	7.80	310 nm	Aas et al., 2002
Kara Sea	3.60	310 nm	Aas et al., 2002
North Water Polynya, pre-bloom	9.40	320 nm	Vasseur et al., 2003
North Water Polynya, bloom	7.90	320 nm	Vasseur et al., 2003

60% ozone depletion. The penetration depth of UV radiation into snow may have also relevance for photochemical processes, through the release of NO_2 during the photolytic destruction of nitrate anions in the snow pack (Fisher et al., 2005). The expected decrease in snow cover in many areas due to climate warming suggests a strong linkage between climate change and UV-B variability at high latitudes.

Johannessen et al. (2003) have developed an empirical method to parameterize UV attenuation and CDOM absorption in oceanic waters using satellite ocean color measurements (i.e., SeaWiFS (Sea-viewing Wide Field-of-view Sensor) images of normalized water-leaving radiance). Their method is based on in situ measurements from a variety of sources, including the Mid-Atlantic and Georgia Bights, the Bering Sea, and inshore waters of the Delaware and Chesapeake Bays. Vasilkov et al. (2005) developed and validated a method for retrieving the radiation field in oceanic waters that uses backscatter UV (BUV) measurements from TOMS and OMI in conjunction with SeaWiFS data and full radiative transfer computations of irradiance at depth. Ocean Raman scattering, which is a function of absorption by particulate matter and CDOM in the upper water column, contributes to the filling-in of Fraunhofer lines in space-based BUV measurements over cloud-free open ocean (Vasilkov et al., 2002). There is the potential to use BUV measurements to estimate chlorophyll and CDOM concentration for waters, where CDOM and particulate matter are well correlated. A BUV-based method would offer the advantages of (1) good sensitivity at low chlorophyll concentrations, and (2) a high-frequency spectral structure, thus being less affected by uncertainties associated with absolute calibration errors. However, complete development of such a method requires more in situ measurements of UV bio-optical properties throughout the world's oceans than presently exist.

From spectral transmission measurements in relatively transparent oceanic waters (characterized by small concentrations of particulate matter, such as silt, and yellow substance), Piazena et al. (2002) found that UV-B penetrates up to ~25% of the photic zone in these waters, while UV-A penetrates up to 93%. Rasmus et al. (2004) found that Southern Ocean waters are quite transparent to UV-B radiation during January, and that under an unperturbed ozone layer, 305 nm doses influence the first 4.0-

9.5 meters of the upper mixed layer, between 51°S and 65°S. They determined that the levels of UV and PAR were high enough that Southern Ocean phytoplankton is often not light limited.

Aas et al. (2002) synthesized several decades of in situ spectral UV attenuation measurements in Arctic marine waters and found considerable variability, related to particular classes of Arctic surface water, including Atlantic water, polar water influenced by river runoff, or Arctic water found in central gyres. Barron and Barron (2005) studied the waters of Prince William Sound, Alaska, in the context of glacial retreat due to climate warming, and reported that glacial melt water and suspended rock sediment cause a tenfold reduction in UV transmission at depth, compared with waters in the same basin distant from glacial influences.

In freshwater ecosystems, optical properties can vary widely due to factors such as water renewal time, the proportion of wetlands in the catchment, and the influence of tributaries, thus influencing the transmission of UV radiation in the water column (e.g., Frenette et al., 2003; Kjeldstad et al., 2003; Bracchini et al., 2005; Erga et al., 2005). Smith et al. (2004) found for the Great Lakes in the USA, much higher UV attenuation by CDOM in tributaries (89-94% of the attenuation) as compared with the lakes (37-77%). Arctic freshwater ecosystems are often characterized by low nutrient concentration and low DOC, implying particular vulnerability to UV stress (Häder et al., 2003). UV penetration in many boreal lakes is increasing, as DOC concentrations decrease due to influences of climate change and acidification. In Scandinavian humic lakes (60-63°N) and boreal forest lakes, DOC is a strong regulator of UV-B transmission (Donahue et al., 2003; Huovinen et al., 2003). In the shallowest aquatic ecosystems, there appears to be strong attenuation of UV radiation in the water column, correlated with DOM concentrations (e.g., Palen et al., 2002; Frost et al., 2005).

7.3 RESOURCES FOR STUDYING SURFACE UV RADIATION

The variability of surface UV irradiance in time and space is studied using measurements from ground-based instruments, as well as from estimates that are derived from a combination of satellite radiance measurements and radiative transfer modeling. Significant advancements have been reported in the last few years in measurement and calibration procedures of instruments and in algorithms used both in ground-based and satellite-borne platforms. Particular effort has been devoted to the determination and quantification of the errors and uncertainties involved.

7.3.1 Ground-Based Measurements

Quality control and quality assurance procedures have received considerable attention in the last decade, leading to significant improvements in instrument stability and data quality. Many monitoring stations have adapted widely accepted calibration and measurement procedures and protocols. In addition to irradiance, spectrally resolved measurements of actinic flux, direct irradiance, radiance, and polarization are now frequently made.

7.3.1.1 SPECTRORADIOMETERS

Spectroradiometers are still the most reliable type of instruments to measure solar UV radiation at the Earth's surface (Seckmeyer et al., 2001). In most cases, the measured quantity is the global irradiance, but in recent years, spectral measurements of actinic flux and of direct irradiance are gaining particular attention, for more accurate determination of photolysis frequencies, spectral aerosol optical depth, or column densities of different atmospheric constituents (e.g., Hofzumahaus et al., 2002; Webb et al., 2002a; Houët and Brogniez, 2004; Lenoble et al., 2004a; Kazadzis et al., 2005; Kylling et al., 2005).

Empirical and semi-empirical methods have been derived to determine actinic flux and photolysis frequencies from irradiance measurements, in experimental campaigns where the derived products could be validated by measurements (Webb et al., 2002a; Bais et al., 2003; Hofzumahaus et al., 2004; Monks et al., 2004). For clear-sky conditions, the conversion with empirical models agrees better than 10% with measurements (McKenzie et al., 2002; Webb et al., 2002b; Kazadzis et al., 2004; Topaloglou et al., 2005); for cloudy conditions the agreement is within ~15%. Use of model calculations yields a similar agreement under clear and overcast conditions, but is less accurate under broken clouds (Kylling et al., 2003b). A semi-empirical approach that combines measured actinic flux and irradiance spectra with model calculations results in similarly good agreement for all sky conditions (Schallhart et al., 2004). Considering that long-term measurements of actinic fluxes and photolysis frequencies are few and sparse, these methodologies constitute the only way to assess the variability of these quantities and their effects on tropospheric photochemistry in the last 10 to 15 years.

The distribution of actinic flux in the vertical dimension and through a cloud layer was measured during a field campaign and was well described by a RT model (Kylling et al., 2005). The interpretation of such measurements and simulations is important for improving our understanding of the radiative and chemical processes that

occur in the troposphere, especially under and above the clouds.

7.3.1.2 Broadband Filter Radiometers

Broadband radiometers represent instruments that measure integrated irradiance over a large wavelength range, such as UV-A or UV-B, but typically have been designed to measure irradiance weighted by the action spectrum for erythema as defined by the Commission Internationale de l'Éclairage (CIE) (McKinlay and Diffey, 1987). These instruments are suitable for many applications because of their low cost and ease of operation in remote locations, but they do have limitations in terms of quality assurance and quality control (QA/QC). They are a major source of ultraviolet radiation information for larger geographical areas and have been in continual use for longer periods than many other types of UV instruments (Nunez et al., 2002; Hicke et al., 2004; Kimlin et al., 2005). The UV instrumentation working group of the World Meteorological Organization (WMO) prepared a report (Seckmeyer et al., 2005) which describes and defines the specifications of this type of instruments, provides guidelines for their calibration and characterization, and outlines QA/QC procedures based on current understanding of these instruments and UV science objectives. These guidelines have been applied, for example, in the Austrian UV monitoring network (Blumthaler, 2004). A detailed uncertainty analysis of broadband radiometers operating in Norrkoping has been presented by Josefsson (2006).

A new method for calculating correction factors for the non-ideal angular response of the broadband radiometers was developed using actual measurements of the anisotropy of the UV-B sky (Kuchinke and Nunez, 2003). The usual assumption of isotropic sky distribution overestimates the diffuse component by 4-6% for clear skies.

Knowledge of the relative spectral response of erythemal radiometers is essential for correcting their measurements for column ozone and SZA variations. Measurements of the response of a sample of instruments at three different laboratories were found to agree within 20% with typical dynamic ranges of approximately 10^4 (Schreder et al., 2004). The dependence of the output signal of Solar Light Co.SL501 erythemal radiometers on ambient temperature and relative humidity was investigated (Huber et al., 2002, 2003). It was shown that despite the internal temperature stabilization at 25°C, increasing the ambient temperature by 20°C reduced the instrument's spectral response by up to 10% in the UV-B and by a factor of two in the UV-A, depending on the instrument and its internal relative humidity. By varying the relative humidity from 9 to 70%, the instrument's sensitivity was reduced by 5% in the UV-B and by a factor of two in the UV-A. There is yet no evidence that such effects occur also in Yankee Environmental Systems, Inc. (YES) model UVB-1 radiometers that are stabilized above 40°C. The dependence of the SL501 radiometers on the ambient conditions calls for further investigation and quantification of the effects on the actual measurements and of this radiometer's suitability for long-term studies.

7.3.1.3 Narrowband Multifilter Radiometers

Narrowband multifilter radiometers measure solar radiation in several (typically 4 to 7) UV channels with bandwidths ranging from 2 to 10 nm. They provide more information than broadband radiometers and require less maintenance than spectroradiometers. All channels can be measured at high frequency, making the instruments well suited for investigating short-term variation of spectral UV irradiance caused, for example, by rapidly changing cloud conditions (Lovengreen et al., 2005). High sampling rates also allow deployment on balloons for measuring vertical profiles of UV (Kylling et al., 2003a). For accurate calibration, knowledge of the spectral response of the different channels is required (Høiskar et al., 2003; Bernhard et al., 2005; Lakkala et al., 2005) and corrections for the effect of ozone and SZA variation should be applied (Diaz et al., 2005). Methods for proper quality control of Norwegian Institute for Air Research NILU-UV multichannel radiometers, operating under harsh conditions in SH high latitudes, are described by Lakkala et al. (2005), who have also reported large (up to ~35%) drifts in their sensitivity.

Data from multifilter radiometers allow the calculation of secondary data products such as reconstructed high-resolution solar spectra, erythemal irradiance, total ozone, and cloud transmission, with the aid of empirical or RT models (Høiskar et al., 2003). Such products are regularly included in the UV-monitoring programs of Norway (Mikkelborg et al., 2000), the U.S. National Science Foundation (NSF) (Bernhard et al., 2005), and the U.S. Department of Agriculture (Davis and Slusser, 2005). Feister et al. (2005) use a neural network technique to reconstruct solar irradiance spectra. For solar zenith angles smaller than 80°, total ozone derived from multifilter radiometers can have accuracy similar to data obtained from Dobson spectrophotometers (Dahlback et al., 2005). Seroji et al. (2004) demonstrated the feasibility of calculating photolysis rates of O_3, NO_2, and formaldehyde (CH_2O) from filter instrument data.

If the instruments are equipped with an automated shadow band, direct solar irradiance can be retrieved,

which allows the calculation of aerosol optical depth (e.g., Krotkov et al., 2005a) and the optical depth of thin clouds (Min et al., 2004). By combining direct and diffuse measurements, single scattering albedo and other aerosol parameters can be derived (Petters et al., 2003; Goering et al., 2005; Krotkov et al., 2005b).

The improved technical characteristics of these instruments and the possibility to derive additional products constitute their main advantages and make them important supplements to spectral measurements of solar irradiance in the global UV monitoring system.

7.3.1.4 Advancements in Instrumentation

Further progress has been made toward uncovering instrumental errors in solar UV radiation monitoring and in the development of methods for improving the measurement techniques and the quality of the data.

A temperature dependence in the transmission of polytetrafluoroethylene (PTFE), which is a widely used material in the diffusers of UV spectroradiometers, has been quantified by laboratory studies (Ylianttila and Schreder, 2005). At ~19°C, the transmission of most types of PTFE increases abruptly by 2-3%, whereas below and above this point a temperature coefficient of about −0.1%/°C is observed. The influence on UV irradiance was quantified through comparisons of measured and modeled UV irradiances at an unpolluted site in New Zealand, where all necessary modeling input parameters were available (McKenzie et al., 2005). These authors concluded that all data measured at ambient temperatures of less than 15°C are typically underestimated by ~2%. The temperature sensitivity of PTFE diffusers introduces an additional uncertainty in the UV measurements, especially at sites where the ambient temperature fluctuates around this range of temperatures (i.e., ~15-19°C), which may have also a seasonality. It is rather unlikely that long-term variations of surface irradiance at a particular site may be influenced, unless the ambient temperature has changed over a certain period from temperatures below this threshold to temperatures above it. Finally, during the calibration of the instruments, the diffuser is usually heated by the lamp; thus normally its temperature should be above this threshold.

Knowledge of the angular response error of a radiation instrument allows, with the aid of RT modeling, the calculation of correction factors. A transportable unit that was developed in the frame of the Quality Assurance of Spectral Solar UV Measurements in Europe (QASUME) project was used to measure the angular response of 11 spectroradiometers operating in Europe (Bais et al., 2005a), thus allowing back correction of datasets recorded at these sites. Angular response errors of ~2% can now be reached in Brewer spectrophotometers by modifying their entrance optics (Gröbner, 2003), compared with errors of ~10% found in the standard Brewer configuration (e.g., Bais et al., 2005a).

Due to the combined effect of two polarization-sensitive elements, the entrance window and grating, the sensitivity of Brewer spectrophotometers for direct-Sun and sky-radiance measurements changes with solar zenith angle. This introduces systematic errors in Langley extrapolations, aerosol optical depth retrievals, and aerosol single scattering albedo retrievals. The need for appropriate corrections has been shown by Cede et al. (2006b). New methodologies were proposed for improving the measurements of O_3, SO_2, and NO_2 columns with Brewer spectrophotometers (Cede and Herman, 2005; Cede et al., 2006a).

In recent years, diode array and charged-coupled device (CCD) single monochromator instruments have become available, allowing measurement of the full solar spectrum from UV to infrared within seconds or milliseconds (Edwards and Monks, 2003; Jäkel et al., 2005). However, in the UV-B range, these instruments suffer from stray-light contamination, and many attempts are underway to reduce this problem.

7.3.1.5 Data Quality and Databases

The importance of quality assurance of UV measurements has been recognized since the beginning of the measurement records, although procedures for implementing quality assurance were developed later, mainly through intercomparison campaigns (e.g., Bais et al., 2001; Lantz et al., 2002; Metzdorf et al., 2003; Webb et al., 2003). Most of the spectroradiometers deployed today are radiometrically calibrated with tungsten halogen standard lamps that are traceable to standards maintained by National Metrology Institutes (NMI) (e.g., Gröbner and Sperfeld, 2005; Wuttke et al., 2006). Differences between the UV spectral irradiance scales realized and disseminated by different NMIs in the past are one of the most critical problems in UV radiometry (Kübarsepp et al., 2002; Metzdorf et al., 2003). Even standards of the same Institute may disagree beyond their stated accuracy, and deviations exceeding 4% in the UV have been observed (Bernhard and Seckmeyer, 1999; Kiedron et al., 1999; Gröbner et al., 2002). Alternative methods for reducing the uncertainties in the calibration standards and for improving the comparability of the irradiance scales of different NMIs are in progress (Yoon et al., 2002; Metzdorf et al., 2003; Sperfeld et al., 2003; Durak and Samadov, 2004).

In the framework of the QASUME project, a transportable spectroradiometer was developed (Gröbner et al., 2005; Gröbner and Sperfeld, 2005). On-site comparisons with 26 spectroradiometers deployed at various locations in Europe revealed irradiance differences ranging between 4 and 14% (Gröbner and Sperfeld, 2005). Similarly, a new spectroradiometer to act as traveling standard for the Network for the Detection of Atmospheric Composition Change (NDACC) (formerly Network for the Detection of Stratospheric Change, NDSC) was developed (Wuttke et al., 2006).

The uncertainties in UV irradiance measurements vary between different instrument types and stations, depending on the availability of resources for achieving accurate characterization of instruments and for applying proper quality control procedures. These procedures are improving with time following the progress of the relevant technology. It is therefore expected that measurements conducted in early stages of monitoring have larger uncertainties, which in some cases are difficult to quantify. Different studies in the last 5-10 years have reported uncertainties between 5-7% for global or direct spectral irradiance measurements in the UV-B (Bernhard and Seckmeyer, 1999; Bernhard et al., 2004; Kazadzis et al., 2005; Bernhard et al., 2006), which are dominated by the uncertainty of the calibration standards and, for global irradiance, the cosine-error correction.

There are two major databases of spectral UV radiation measurements: the World Ozone and Ultraviolet Radiation Data Centre (WOUDC) in Toronto, Canada (http://www.woudc.org) with spectral irradiance data from 29 stations, and the European Ultraviolet Database (EUVDB) in Helsinki, Finland (http://uv.fmi.fi/uvdb/) containing data from 43 stations. A list of stations and currently available data are given in Appendix 7A. New techniques have been pursued to uncover errors in spectral measurements at the databases EUVDB and WOUDC, and tools have been developed (Slaper et al., 2004; Engelsen and Kylling, 2005) for this purpose. In EUVDB, all data are now automatically checked and flagged for their quality.

Several UV monitoring networks maintain independent UV databases. The U.S. National Science Foundation's UV monitoring network includes quality-controlled spectra measured between 1988 and 2006 at seven high-latitude sites located in Antarctica, South America, Alaska, and Greenland (see Appendix 7A.3). A new data edition named "Version 2" is currently in preparation; it will offer higher accuracy and additional data products such as total ozone, effective albedo, and cloud optical depth (Bernhard et al., 2004, 2006).

7.3.2 Satellite-Derived UV Estimates

Instruments onboard satellites provide global maps of surface UV irradiance by combining backscattered radiance measurements with RT models. The accuracy of the models is limited mostly by uncertainties in input parameters representing the atmosphere and the Earth's surface. Issues that require particular attention are the detection and correction of long-term calibration drifts and the establishment of interpolation methods when combining different satellite datasets.

7.3.2.1 Differences Between Ground-Based and TOMS-Derived UV Irradiances

Surface UV retrievals from the measurements of the Total Ozone Mapping Spectrometer (TOMS) instruments onboard different satellites (1978-2002) is probably the only dataset that has been so extensively compared with ground-based measurements. Recently, the TOMS UV irradiance database (http://toms.gsfc.nasa.gov) has been expanded to include five new products (noon irradiance at 305, 310, 324, and 380 nm, and noon erythemally weighted irradiance), in addition to erythemal daily exposure, allowing direct comparisons with ground-based measurements from UV spectroradiometers (Krotkov et al., 2004).

Since the previous Assessment (WMO, 2003), advances have been made in understanding the factors causing differences between satellite- and ground-based UV data. Sabburg et al. (2002) compared TOMS daily erythemal doses on clear days against measurements at four sites of the Brewer network of the U.S. Environmental Protection Agency, and concluded that TOMS UV retrievals have a positive bias between 1.4 and 12.5%, with an average of ~5%. Fioletov et al. (2004) produced two UV Index climatologies over Canada and the United States for the period 1980-1990 using TOMS data, and these were validated against Brewer UV measurements from several sites. With snow on the ground, TOMS retrievals were up to ~60% lower, due to insufficient treatment of the snow albedo. In summer, the TOMS UV estimates were 10 to 30% higher, caused most likely by air pollution and absorbing aerosols. Differences between daily erythemal irradiances derived by TOMS (version 7 and 8) and by a Brewer spectrophotometer at Lampedusa have been found to increase with increasing aerosol optical depth, often associated with Saharan dust outbreaks (Meloni et al., 2005). Arola et al. (2005) found positive bias of 20-30% by comparing irradiance data over Thessaloniki, Greece, and Ispra, Italy, with TOMS version 8 products.

These studies confirmed that insufficient information on aerosols near the surface is responsible for the observed biases in satellite UV irradiances. Arola et al. (2005) and Krotkov et al. (2005b) have shown that knowledge of the absorbing properties of aerosols may reduce appreciably these biases, and suggested that taking into account even climatological estimates of AOD and SSA would greatly improve the satellite UV retrievals. Aerosol absorption corrections were found to improve TOMS-derived UV over Moscow during the period May-September (Chubarova et al., 2005). Erythemal irradiances recorded at eight stations in Argentina agreed with TOMS estimates, which were first corrected for the effects of aerosols, to within ±10% under snow-free conditions (Cede et al., 2004). These newly reported differences are much smaller than those previously reported (Kerr and Seckmeyer et al., 2003). Therefore the use of satellite-derived UV estimates without accounting for effects from aerosols at locations with large aerosol abundances may lead to false conclusions.

New approaches have been suggested to model the effects of clouds over snow-covered terrain. The method proposed by Arola et al. (2003a) improved the agreement between TOMS-retrieved erythemal daily doses and ground-based measurements over two Finnish and five Canadian sites. Tanskanen et al. (2003) developed a methodology by analyzing the TOMS Lambertian Equivalent Reflectivity (LER) data using a moving time-window technique, accounting also for autumn and spring transitions during snow accumulation and snow melt.

7.3.2.2 UV Retrieval Algorithms and Related Uncertainties

Further studies were devoted to the development of new algorithms for producing global coverage of surface UV irradiances, involving information from other satellite products. Apart from the effect of aerosols (discussed in Section 7.3.2.1), the treatment of the cloud and surface reflectivity by the UV-retrieval algorithms is still a challenging issue.

The influence of clouds is one of the major sources of uncertainty in surface UV irradiances retrieved from satellite instruments, particularly over areas with high surface reflectivity, and different methodologies to parameterize the cloud transmittance have been proposed. Meerkötter et al. (2003) compared two independent approaches using data from the AVHRR instrument onboard the polar-orbiting NOAA satellites and from MVIRI (METEOSAT Visible and Infrared Instrument) onboard the geostationary METEOSAT satellite. The latter offers particularly good temporal resolution, but was expected to be problematic at high latitudes where their study was focused. However, they found that METEOSAT (or the new METEOSAT Second Generation (MSG) satellite) may be used to account sufficiently for cloud effects in UV at latitudes up to 70°. By combining cloud information from METEOSAT, ozone column from TOMS and GOME (Global Ozone Monitoring Experiment), and RT modeling (Surface Irradiation Derived from a Range of Satellite-Based Sensors-SIDES), UV climatologies over Europe from 1984 to 2003 were generated by Verdebout (2004a; 2004b) with spatial resolution of ~5 km. Improvements to the Joint Research Center (JRC) algorithm SIDES were applied (Wuttke et al., 2003), resulting in better agreement with measurements in the UV-B. A new satellite UV algorithm for producing UV-B and UV-A irradiances and the UV Index using the Surface and Atmosphere Radiation Budget (SARB) products of Clouds and the Earth's Radiant Energy System (CERES) was developed (Su et al., 2005). Differences when compared with a high-resolution, multistream radiative transfer code range from −10% to +4% for UV-B and UV-A irradiances, and from −26% to +16% for the UV Index. Ciren and Li (2003) derived a long-term (1983-2000) global climatology of surface UV-B and erythemal irradiance by combining TOMS ozone and International Satellite Cloud Climatology Project (ISCCP) D1 3-hour reflectance measurements, thus accounting more efficiently for the diurnal variability of clouds. On the other hand, Williams et al. (2004) have shown that using the ISCCP climatology for estimating surface UV irradiance results in significant bias, suggesting instead to use the TOMS reflectivity at 360 nm.

The TOMS UV algorithm (Krotkov et al., 1998; Herman and McKenzie et al., 1999; Krotkov et al., 2001) was successfully applied to the new Ozone Monitoring Instrument (OMI) onboard the Aura spacecraft for continued monitoring of ozone, other trace gases, and surface UV irradiance (Levelt et al., 2006; Tanskanen et al., 2006). OMI is a contribution of The Netherlands's Agency for Aerospace Programs (NIVR) in collaboration with the Finnish Meteorological Institute (FMI) to the NASA Earth Observing System (EOS) Aura mission and, among other products, provides global maps of surface UV irradiance (see example in Figure 7-3).

7.3.3 Advancements in UV Radiation Modeling

Considerable progress has been made in radiative transfer modeling, in particular on the interaction between clouds and radiation, the impact of aerosols, and three-dimensional radiative transfer. Important aspects for the ultraviolet spectral region are: (1) the strong Rayleigh scat-

tering and absorption by ozone; (2) the approximately wavelength-independent optical properties of clouds and their negligible absorption unless they are polluted by absorbing aerosol; and (3) the importance of short wavelengths due to the strong biological and chemical effects of UV radiation, despite their small contribution to the total energy.

A variety of radiative transfer codes are freely available (see Appendix 7B.3) (Madronich and Flocke, 1997; Evans, 1998; Ricchiazzi et al., 1998; Key, 1999; Koepke et al., 2005; Mayer and Kylling, 2005; Rozanov et al., 2005). In addition to being useful for calculating irradiance at the surface, most of them can be used to calculate other quantities, such as radiance and actinic flux, also at different altitudes. Some (e.g., LibRadTran) allow calculations throughout the whole solar and thermal spectral range.

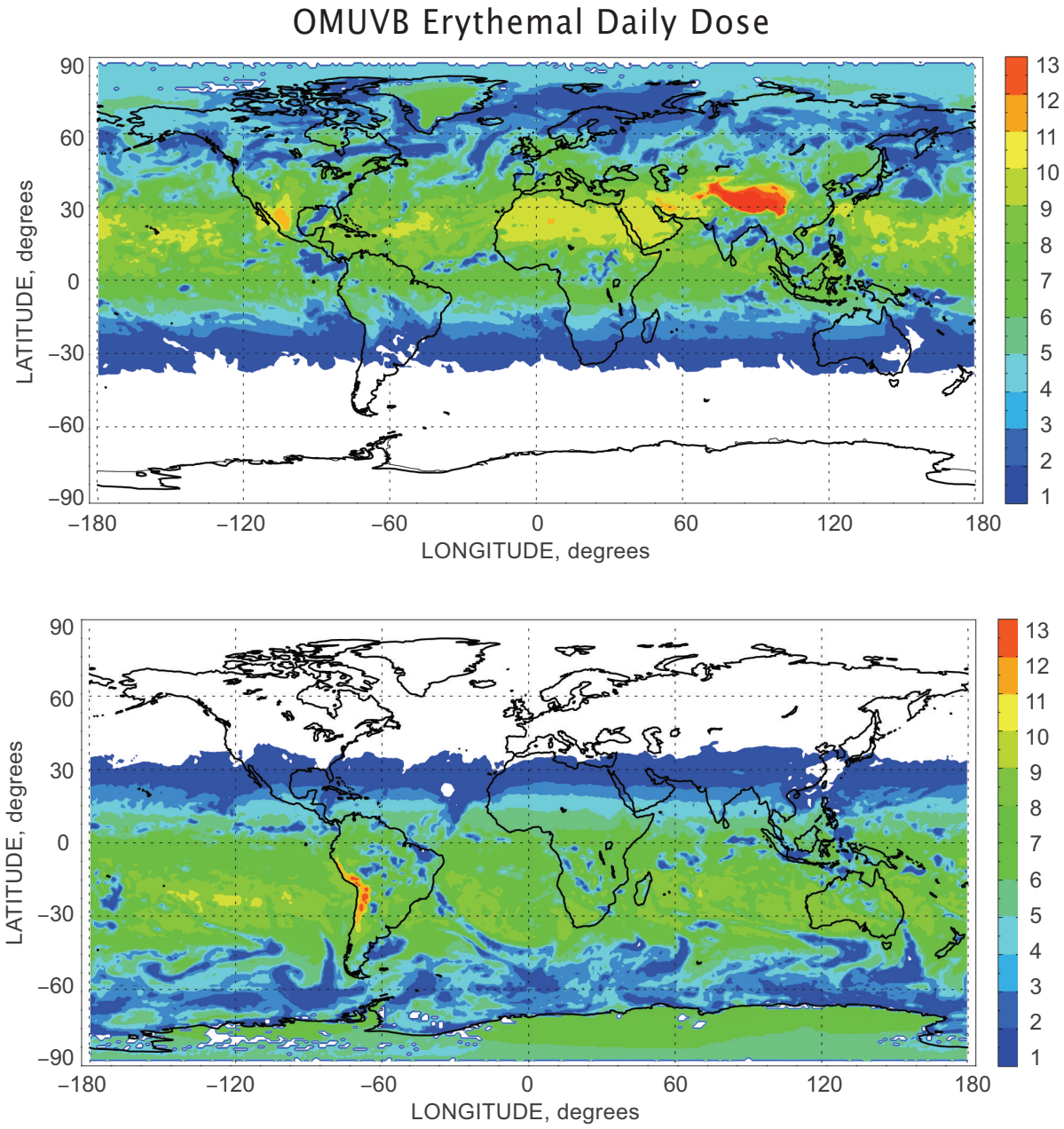

Figure 7-3. Global distribution of the cloud-corrected daily integral of erythemal irradiance in kJ m^{-2} for 28 June 2005 (upper panel) and 28 December 2005 (lower panel) derived from OMI measurements.

Radiative transfer is used in: (1) research applications, such as the interpretation of campaign data, requiring the highest degree of sophistication including, for example, three-dimensional solvers or spherical geometry; (2) routine applications, such as the quality control of observations or provision of cloudless-sky reference data to routinely estimate the influence of clouds from observed spectra; or (3) applications where large numbers of calculations are needed, such as the computation of photolysis frequencies in chemistry-transport models (CTMs) or the calculation of global time series of UV data. For most routine applications, the above-mentioned freely available codes are suitable, although they require significant computational power. The use of fast parameterizations like SMARTS2 (Gueymard, 2001) or lookup-table based approaches like FASTRT (Engelsen and Kylling, 2005) may be more appropriate whenever a large number of modeled spectra are required. The calculation of photolysis frequencies in chemistry or chemistry-transport models is probably one of the most demanding applications, in terms of the number of spectra to be calculated, requiring specially tailored solutions like Fast-J (Wild et al., 2000). Finally, statistical methods have been derived by relating a large number of observations at one or a few sites to a set of ancillary measurements, such as total ozone, cloud cover, or pyranometer observations (e.g., Fioletov et al., 2001; Schwander et al., 2002). While these are usually very good in predicting the radiation for a given location, it may be problematic to transfer the results to other locations or to calculate radiation for time periods other than the one used to build the statistical model.

After numerous model-model or model-measurement intercomparisons, the confidence in the results of radiative transfer codes in the UV is high if the input parameters are chosen carefully. Model-model intercomparisons have shown that different radiative transfer codes may agree to well below the 1% level if they are operated with identical optical properties. This is even true for complex three-dimensional codes, as has been shown in the Inter-comparison of 3-D Radiation Codes (I3RC) (Cahalan et al., 2005), where a core group of radiative transfer codes agreed to within 0.1-1% for a variety of complex cases, neglecting polarization, spherical geometry, and inelastic scattering.

Uncertainty of model calculations can have different sources. First, uncertainties in parameters like extraterrestrial irradiance (Gueymard, 2004) and the absorption cross section of ozone (Orphal and Chance, 2003) translate directly to uncertainties in irradiance. The largest source of uncertainty is usually the lack of knowledge of the actual state of the atmosphere or surface, in particular for cloudy, polluted, or partially snow-covered conditions. Clouds pose the most challenging modeling problem, due to their complex geometry and high variability in space and time. The effect of clouds on radiation is basically understood (at least for spherical droplets) and can be simulated with a 3-D radiative transfer code. For theoretical case studies, various cloud models have been used, including simple geometrical shapes, statistical assumptions (Cahalan et al., 1994), cloud-resolving models (Trautmann et al., 1999; Brasseur et al., 2002), and high-resolution observations by satellites and aircraft (Meerkötter and Degünther, 2001; Scheirer and Schmidt, 2005). However, the simulation of an actual situation is complicated because a sufficiently complete description of the clouds is generally not available. Information such as cloud cover or pictures by sky cameras give a first hint but are not sufficient to simulate the irradiance at the ground. The situation for aerosols is similar; while the optical depth is easily obtained by observations, the irradiance is critically determined by the single scattering albedo, which is not easily measured (see Section 7.2.4). Sometimes, the missing information is replaced by an effective parameter, such as an effective single scattering albedo (Kylling et al., 1998; Kazantzidis et al., 2001; Petters et al., 2003; Bais et al., 2005b). If more observations are available to constrain the actual situation, the concept of effective cloud parameters may fail (Kylling et al., 2005), but enough data are usually not available to verify that.

Three-dimensional radiative transfer effects in the ultraviolet spectral range caused by clouds have been recently studied both experimentally and theoretically (Brasseur et al., 2002; Kylling et al., 2005; Marshak and Davis, 2005). Topography also plays a role. For example, mountains may either block part of the diffuse-sky radiance, or cause an increase by reflection of extra radiation at snow-covered mountain slopes (see Sections 7.2.6 and 7.2.7). Moreover, air or clouds below an observation site enhance the backscattered radiation and lead to further increase in irradiance (McKenzie et al., 2001a). Considerable research efforts are spent on three-dimensional radiative transfer applications, to gain a detailed understanding of the processes that control the interaction of radiation with the atmosphere and the surface. The main objective of the Radiation Transfer Model Intercomparison (RAMI) was to improve understanding of the important interactions between radiation and vegetation (Pinty et al., 2004).

Validation campaigns have mostly concentrated on cloudless conditions. Comparisons of spectral irradiance (e.g., Mayer et al., 1997; van Weele et al., 2000) and actinic flux (Bais et al., 2003; Früh et al., 2003; Shetter et al., 2003; Hofzumahaus et al., 2004) for a cloudless sky

generally found differences of about 5-10% between observations and simulations, which were usually within the combined uncertainty of measurement and model. Comparisons for cloudy sky are rare, due to the difficulty in obtaining cloud parameters independent of the irradiance observations. In the European project INSPECTRO (Influence of Clouds on the Spectral Actinic Flux in the Lower Troposphere), simultaneous observations of radiation and clouds using ground-based, aircraft, and satellite instrumentation provided a first dataset to evaluate three-dimensional radiative transfer calculations. Kylling et al. (2005) showed for a broken cloud case that the one-dimensional approach was not able to simultaneously reproduce the measured enhancement of the actinic flux above the cloud and the reduction below the cloud. Further evaluation of the campaign data is in progress.

In summary, radiative transfer in the ultraviolet spectral range has reached a mature state. If the input parameters are known, the radiation can be simulated with reasonable accuracy for many applications. However, some of these input parameters (e.g., a reasonable description of clouds or the single scattering albedo of the aerosol) are not easily attained. While satellite observations of clouds allow derivation of average radiation levels, they usually fail to provide information about the small-scale variability in space and time, which could be essential for biological systems. While the main aim of research in the ultraviolet spectral region remains the study of irradiance and actinic flux for applications in biology and chemistry, observations of radiance give much deeper insights into the interactions between radiation and the atmosphere or surface (Huber et al., 2004; Kuchinke et al., 2004). It may also help to validate and improve radiation codes and to decide which input parameters are required for specific applications.

7.3.4 Short-Term UV Forecasting

In the four years since the previous Assessment (WMO, 2003), the UV Index (WMO, 1994, 1998) has become the internationally accepted standard for disseminating information on solar UV levels to the general public. Forecasts, as well as measurements of the UV Index, now appear on numerous web-sites in many countries (Appendix 7B.5) and are used by TV, radio, and print media across the globe in an effort to change population behavior and moderate exposure to solar UV radiation. UV Index forecasts are a direct application of the scientific work on understanding the factors such as absorption and scattering affecting the transmission of UV radiation through the atmosphere to the Earth's surface.

Forecasts of the UV Index have been provided by numerous agencies since the 1990s using different computational methods (Austin et al., 1994; Burrows et al., 1994; Long et al., 1995; Burrows, 1997; Rikus, 1997; Bais et al., 1998; Staiger et al., 1998; Lemus-Deschamps et al., 1999; Renwick and McKenzie, 2001; Lemus-Deschamps et al., 2004; Staiger and Koepke, 2005). Forecasting the column ozone amount and estimating the atmospheric aerosol contribution to absorption remain the major difficulties in improving the accuracy of calculating the clear-sky surface UV irradiance and in subsequently forecasting UV indices. Computed UV irradiance for clear-sky conditions is generally overestimated in comparison to measurements (Kalliskota et al., 2000; McKenzie et al., 2001b), mainly due to lack of information on AOD (De Backer et al., 2001). Long-term correlations of aerosols with measured UV irradiance may improve AOD forecasts locally (Krzyścin et al., 2001; Petters et al., 2003; Gröbner and Meleti, 2004; Goering et al., 2005).

Including clouds in UV Index forecasting requires both accurate forecasts of cloud cover and cloud types, as well as more accurate data on cloud UV transmittance. Forecasts of UV Index have used empirical relations between forecast cloud types and measured UV radiation to adjust clear-sky forecasts. More recent approaches use information on cloud and surface albedo provided by numerical weather prediction (NWP) models (Staiger and Koepke, 2005). Work on improving agreement between calculations utilizing clouds and their effects on UV transmittance and surface measurements continues (Arola et al., 2003b; Krzyścin et al., 2003; Lane-Veron and Somerville, 2004; Su et al., 2005).

The major parameter affecting the forecast of the clear-sky UV Index is the estimated ozone amount, which can be determined either using the persistence of satellite-observed ozone or from a range of NWP meteorological variables via statistical regressions (e.g., Plets and Vynckier, 2000). Some forecasting centers such as the National Centers for Environmental Prediction (NCEP), the Koninklijk Nederlands Meteorologisch Institute (KNMI), the European Centre for Medium-Range Weather Forecasts (ECMWF), and the Australian Bureau of Meteorology (BOM) assimilate ozone into their forecast models using satellite data to produce forecasts of the global (or continental) ozone fields a number of days in advance (Lemus-Deschamps et al., 2004). Research validating the results of the BOM numerical weather prediction (NWP) system's forecasts of UV Index continues with comparisons against surface observations (Gies et al., 2004; Lemus-Deschamps et al., 2004) in an effort to improve agreement. This ongoing validation study is coupled with research to improve the presentation of the UV

Index in communications to the public, with the aim of increasing its impact and making it more effective in changing behavior (Dixon and Armstrong, 1999; Dixon et al., 2002; Blunden et al., 2004). A range of different UV Index presentations utilizing the recommendations of the World Health Organization (WHO, 1994; Rehfuess, 2002) is being tested in Australia by the Cancer Councils, with planned follow-up assessments of their impact.

7.4 UV CLIMATOLOGY

Long- and short-term UV variability has been studied extensively during the last few years by analyzing measurements of surface UV irradiance that are now available for more than 10 years at several locations worldwide. Routine spectral measurements started only in the late 1980s and thus long-term changes that are calculated from these datasets should be smaller compared with what they would have been if UV records were available before the beginning of the ozone depletion in the early 1980s. Satellite estimates are also available for long periods (since 1979) and provide global coverage, which allows the derivation of UV estimates for any location on the Earth. However, gaps in the satellite records in the mid-1990s increase the uncertainty and complicate the calculation of long-term changes. In addition to the relative shortness of the UV records, surface UV exhibits a large variability from natural factors, such as clouds, ozone, aerosols, surface albedo, and UV-absorbing atmospheric constituents (e.g., SO_2 and NO_2), which reduce the significance of the estimated long-term changes. Extreme values of UV radiation at the surface as a consequence of these factors have been reported and were discussed in Section 7.2. The attribution of the causes for the observed changes is among the present research priorities, especially as it pertains to the response of surface UV to the recovery of the ozone layer.

7.4.1 Derived from Ground-Based UV Measurements

7.4.1.1 Long-Term Changes

The magnitude and statistical significance of the long-term changes in surface UV irradiance derived from analysis of ground-based measurements are of the order of a few percent per decade, depending on location, season, wavelength range, and the period of measurements. The sign of these changes varies also with location and depends strongly on the length of the measurements series. As measurements suitable for calculation of long-term changes are sparse, there are difficulties in projecting the derived results to other time periods or other locations. An example is shown in Figure 7-4, which presents time series of monthly mean anomalies in noon erythemal irradiance under all-sky conditions at 11 UV monitoring sites distributed worldwide. Linear regressions over the period from the early 1990s to the mid-2000s indicate negative changes at stations in the Southern Hemisphere and in the Arctic. This pattern is especially evident if linear regressions are calculated since 1998, when the first signs of a slowdown in the ozone depletion were observed (see Chapter 3, Section 3.2), suggesting that surface UV radiation has responded to ozone increases, at least at these sites. In the northern midlatitudes, the observed UV irradiance changes are positive. The significance of the calculated changes is affected by the uncertainties of the measurements, which may range between 5% and 10%, depending on the site and the period. Data in the beginning of the records have usually higher uncertainties (see Section 7.3.1.5). Statistically significant linear changes (neglecting the measurement uncertainties) for the entire record of measurements were found only at Lauder and Palmer (−8.4% per decade at the 99% confidence level) and at Barrow (−4.4% per decade at 95% confidence level). Observations in Lauder prior to 1994 were performed only under fair-weather conditions, and this may have influenced the calculated linear changes. Statistically significant positive changes are found at all seasons in the station of Lindenberg, produced by two abrupt changes in UV irradiance that occurred in 1996 and 2003, respectively. The change in 2003 is shown also at Bilthoven. For the spring months the linear changes are insignificant and negative at all stations, except at Thessaloniki, Lindenberg, and Bilthoven. In the summer months, half of the stations show negative and the other half positive changes that are all insignificant, except from Lauder (–8.9% per decade at the 95% confidence level). The UV irradiance changes at these stations are dominated mainly by the variability in cloudiness and, to a lesser extent, by ozone and aerosols. The variability of clouds and aerosols has masked the detection of increases in surface UV irradiance that were expected to result from the observed decreases in total ozone in the early 1990s that were caused by stratospheric aerosols from the Mt. Pinatubo eruption. At most stations, the use of measurements made only under clear skies results in too little data to allow reliable statistical analysis.

Glandorf et al. (2005) analyzed in more detail 12 years of UV measurements at Thessaloniki, Greece, and and 14 years of UV measurements at Sodankylä, Finland, and concluded that no unambiguous upward trend could be constituted at either station, due to the high natural variability of the data. It was suggested that for the given vari-

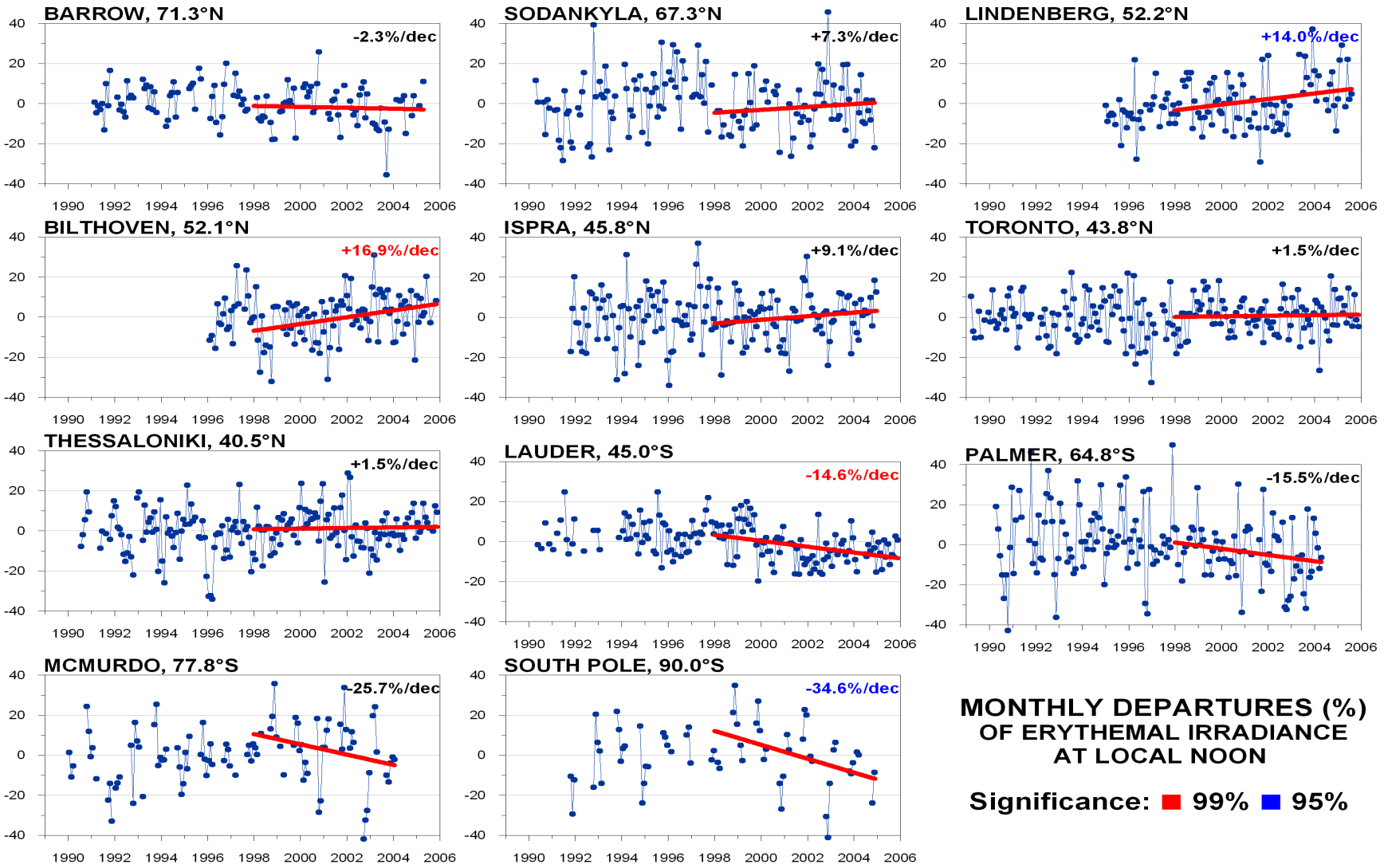

Figure 7-4. Long-term changes in monthly mean erythemal irradiance recorded by UV spectroradiometers within ±1 hour around local noon at 11 sites distributed worldwide, shown as departures from the long-term averages. Linear regressions on the data (red lines) were used to estimate the corresponding linear changes after 1998, when the first indications of a slowdown in total ozone decreases have been observed. The trends are listed in the upper right of each plot, with color-coding to indicate the statistical significance (red = 99%; blue = 95%; black = negligible). This figure was prepared using updated series of published UV datasets. The statistical significance of the changes was calculated from the data variability only, neglecting the uncertainties in the measurements.

ability in total ozone and clouds at the two sites, more than 15 and 12 years of data, respectively, would have been needed for the detection of persistent statistically significant trends in surface UV radiation, in accordance with previous findings by Weatherhead et al. (1998). However, due to the complexity and the self-regulating mechanisms of our climate system, quasi-periodic changes in UV radiation are more likely to occur than long-lasting linear changes. Using two different periods of the Sodankylä dataset (1993-2001 vs. 1990-1997), Lakkala et al. (2003) calculated substantially different linear changes in spectral UV irradiance at 305 nm, even of opposite sign.

At northern midlatitude sites, surface UV irradiance was found to be increasing since the beginning of 1990s, while elsewhere there are signs of leveling. The updated record of clear-sky spectral UV irradiance at 305 nm and 325 nm and at 63° solar zenith angle over Thessaloniki (Kerr and Seckmeyer et al., 2003) indicates that UV has continuously increased since the beginning of the record (1990) at both wavelengths (Figure 7-5). Although not very clear, there are indications that after about 2000, surface irradiance has increased with smaller rates or has even been constant, following the stabilization or a slight increase of total ozone over Thessaloniki. The upward trend during the 1990s at wavelengths unaffected by ozone absorption could only be explained by an increase in atmospheric transmission. Aerosol optical depth and SO_2 column over Thessaloniki have decreased since 1997 (Zerefos, 2002; Kazadzis et al., 2005), while a widespread brightening of the atmosphere has been observed since the late 1980s (Wild et al., 2005). Increasing tendencies of surface UV, unexplained by the total ozone decline alone, were reported also for Hohenpeissenberg, Germany (Trepte and Winkler, 2004). Reduced sunshine duration and increased cloudiness lead to a UV decrease that partially compensates for the UV increase caused by ozone loss in spring; in the autumn, these effects overcompensate for the effect of ozone loss.

The increasing peak values of UV irradiances that were reported in the previous Assessment (Kerr and

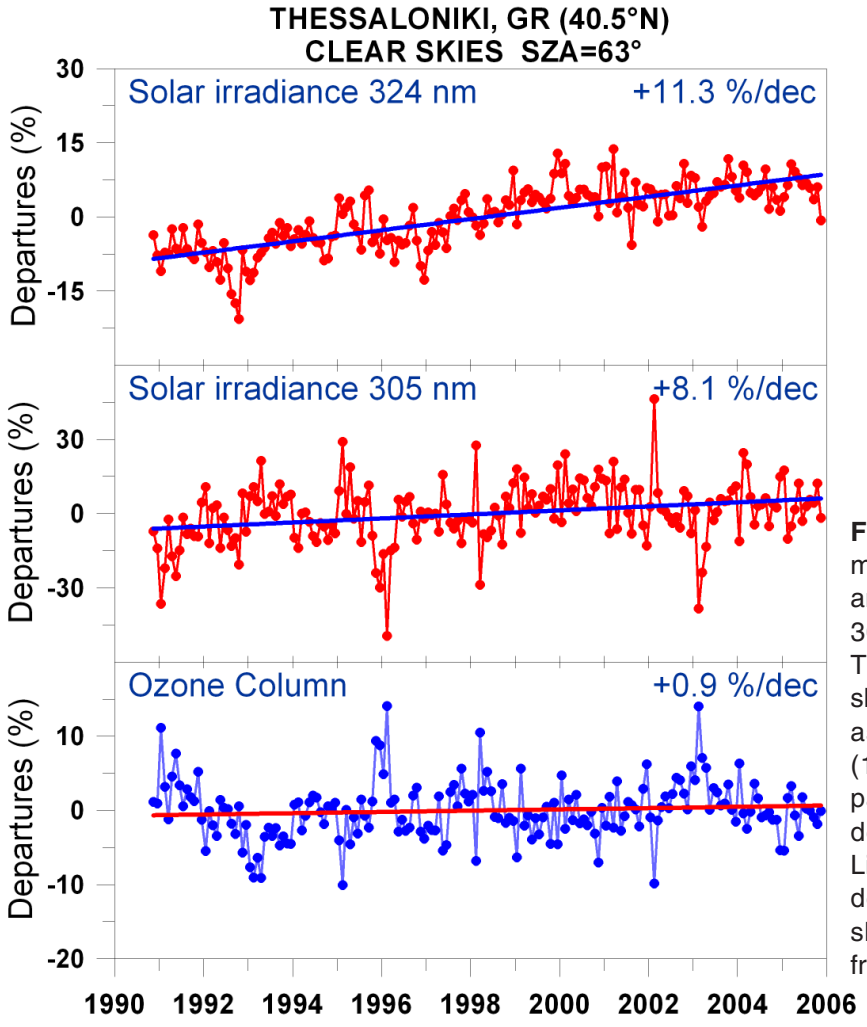

Figure 7-5. Long-term variability in monthly mean solar spectral irradiances at 324 nm (upper panel) and at 305 nm (middle panel) measured at Thessaloniki, Greece, under clear skies at 63° solar zenith angle, shown as departures from the long-term (1990-2006) averages. The lower panel shows the corresponding departures in the ozone column. Linear regressions on the data and the derived trends per decade are also shown for each parameter. Update from Zerefos et al., 2001.

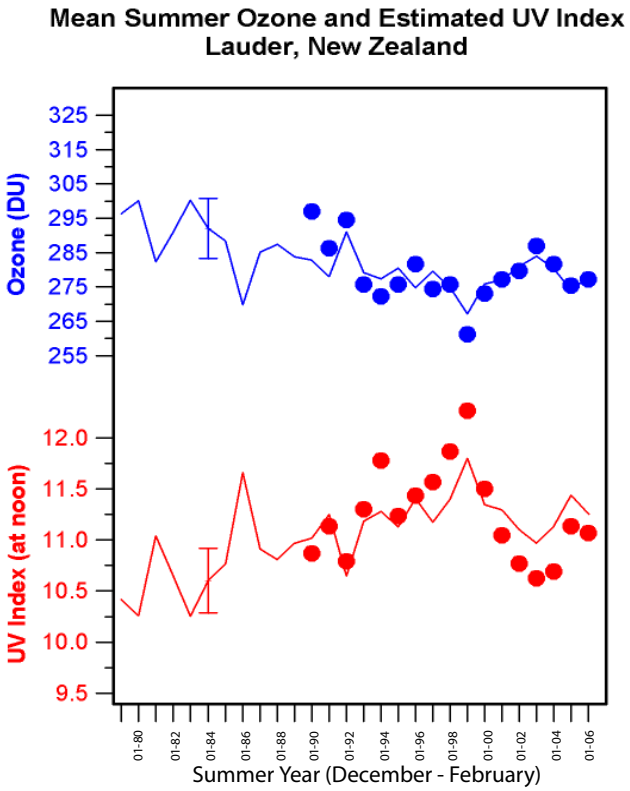

Figure 7-6. Long-term changes in summertime ozone (upper part) and in peak UV Index (lower part) deduced from assimilated ozone data (lines) and from UV spectral measurements at Lauder, New Zealand (symbols). Update from McKenzie et al., 2004.

Seckmeyer et al., 2003) in response to decreasing total ozone at New Zealand show a clear decreasing tendency in the recent four years (Figure 7-6). The magnitude of this decrease is larger than that expected by the increase in total ozone over the area, indicating that aerosol extinction may have also increased during this period. Aerosol data from GOME show increasing aerosol absorption between 45°S and 60°S over the period 1995 to 2000 (de Graaf et al., 2005).

Measurements of surface UV irradiance with broadband radiometers are available for longer periods compared with spectral measurements, although they usually have higher uncertainty (Seckmeyer et al., 2005). Ten years (1990-2000) of solar UV-B irradiance (290 to 320 nm) measurements at Hiratsuka, Japan (35.35°N, 139.27°E), show an increase at a rate of 15.7% per decade (Sasaki et al., 2002). After removing the effect of the Quasi-Biennial Oscillation (QBO) with a 26-month moving average filter, and removing the effect of cloudiness by normalizing with shortwave irradiance measurements, the rate of increase was reduced to 12.2% per decade, corresponding to the observed total ozone changes at the same location. Statistically significant changes of monthly averages are found only for winter (16.7% per decade). Long-term (1968-2003) UV irradiance (300-380 nm) measurements at the Meteorological Observatory of Moscow State University (Figure 7-7) show a distinct interannual variability, with low levels in the 1970s and 1980s and an overall increase from late 1970s toward the late 1990s (Chubarova et al., 2005). This increase is believed to be due to the decrease in cloud amount and aerosol optical depth (since ~1994), with contributions of up to 10% and 2%, respectively. A decline in atmospheric turbidity of 8-10% during the period 1994-2002 as com-

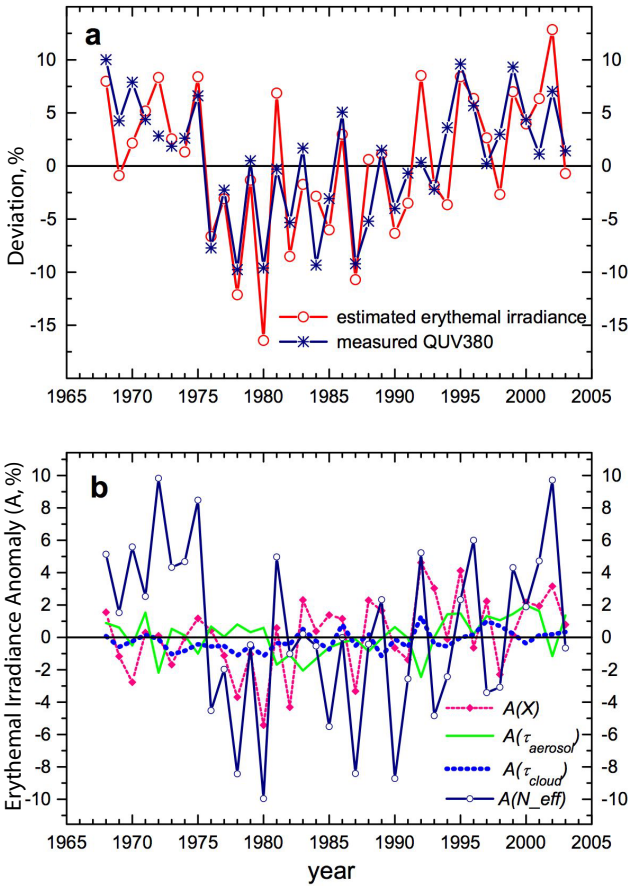

Figure 7-7. (a) Interannual variability of simulated erythemal irradiance and measured irradiance integral from 300 nm to 380 nm (QUV380) for the period May-September in Moscow, Russia, shown as deviations from the 1968-1997 mean. (b) Anomalies in erythemal irradiance (A) due to different atmospheric factors: effective cloud amount *A(N_eff)*, total ozone *A(X)*, aerosol optical thickness $A(\tau_{aerosol})$, and cloud optical thickness $A(\tau_{cloud})$. Adapted from Chubarova and Nezval, 2000; Chubarova et al., 2005.

pared with the 1976-1995 period is observed at many other sites in Russia (Makhotkina et al., 2005). Increases in erythemal irradiance at Norrköping, Sweden, of ~5% per decade were reported by Josefsson (2006) for the period 1983-2003.

Increases in surface UV irradiances during the last decade are evident from several datasets. These changes are attributable to the increasing of atmospheric transmission because of ozone depletion, global reduction of cloud optical thickness, and reduction of the amount or nature of aerosols. Long-term satellite observations (World Climate Research Programme Global Energy and Water Cycle Experiment (GEWEX) International Satellite Cloud Climatology Project, ISCCP) reveal an overall increase of solar irradiance at the surface from 1983 to 2001 (Figure 7-8) at a rate of about 1% per decade, despite the finding that up to about 1990, solar irradiance measured at the surface was decreasing (Pinker et al., 2005). With respect to clouds, Meerkötter et al. (2004) found no significant long-term trend in cloud amount between 1990 and 2003 from the analysis of NOAA/AVHRR data and from Surface Synoptic Observations (SYNOP), although there are indications of decreasing cloud cover after 2000. Decreases in cloud cover of less than 1%/decade, increases in clear-sky days of ~0.6%/decade, and decreases in overcast days of ~0.8%/decade have been observed over most of China during the last half of the 20th century (Qian et al., 2006). For Barrow, Alaska, a statistically significant upward trend in cloud occurrence frequency, from 76 to 82% between 1976 and 2001, was reported (Dutton et al., 2004). Evidently, only in some areas may an increase in atmospheric transmission be attributed to clouds.

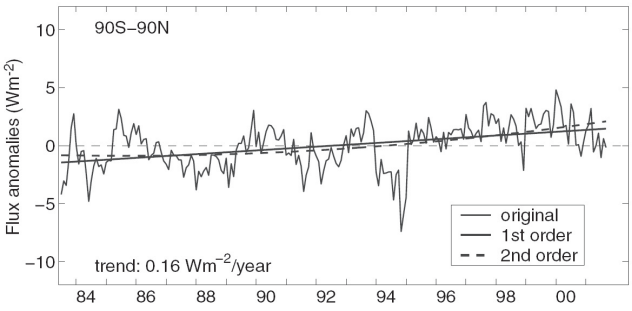

Figure 7-8. Satellite-derived surface solar irradiance (from 1983 to 2001) averaged over the globe, after removal of the mean annual cycle. The linear regression (solid line) on the data reveals a positive trend of ~0.1% per decade. The second-order polynomial (dashed line) indicates a small decrease from 1983 to 1992, with a reversal around 1992. Both fits are significant at the 99% level of confidence. Reprinted with permission from Pinker, R.T., B. Zhang, and E.G. Dutton, Do satellites detect trends in surface solar radiation? *Science*, 308 (5723), 850-854, 2005. Copyright 2005, AAAS.

An indication of cleaning of the atmosphere is supported by the long-term aerosol optical depth data at Uccle, Belgium (Cheymol and De Backer, 2003), which were retrieved from Brewer direct-Sun measurements. They reported a statistically significant negative trend of 24.6 ± 3.7%/decade over the period 1989-2002 for the aerosol optical depth at 306.3 nm; the annual mean was ~0.8 in 1992 and decreased to ~0.6 in 2002. Significant seasonal trends at all wavelengths (in the range 306.3-320.1 nm) were found only in winter months, while in the summer period only at 306.3 nm, a decrease in aerosol optical depth of 12.4 ± 5.5%/decade is significant at the 2σ level. Similarly, Jaroslawski and Krzyścin (2005) reported that aerosol optical depth in Belsk, Poland, shows a decreasing tendency in the beginning of 1990s followed by an increase in surface UV irradiance (UV Index) of about 4%.

7.4.1.2 Short-Term and Spatial UV Variability

Apart from the long-term changes, the variability of surface UV irradiance has been extensively studied using datasets measured all over the globe and at different periods. Some datasets are sufficiently long to be used for the establishment of a UV climatology that is representative for the region around the measurements site(s) (Tarasick et al., 2003; den Outer et al., 2005; Liao and Frederick, 2005). Most of the observed variability is caused by the influence of well-known factors, such as ozone, clouds, aerosols, surface albedo, SO_2, and NO_2, which were discussed in Section 7.2.

A climatology of surface erythemal irradiance, expressed as UV Index, was developed by Tarasick et al. (2003) using spectral measurements from 14 UV monitoring stations, spanning from 82.5°N to 69.0°S, but mainly distributed in Canada. The most prominent feature at all stations is the high degree of variability that is primarily due to clouds and thus is more pronounced at cloudy sites, such as Halifax and Goose Bay, and much less at Mauna Loa. Smaller, positive or negative, variations are due to ozone variability. Also apparent, at most of the Canadian sites as well as San Diego, is that maximum clear-sky UV Index values in the 1990s were higher than those calculated for the pre-1980 period, by about 10%, in accordance with the total ozone decline of about 6-7% during this period. Dramatically higher UV Index values are seen at Syowa during the Antarctic spring, due to the appearance of the ozone hole, with peak values similar to those in June at San Diego.

Liao and Frederick (2005) presented a climatology of erythemal and DNA-damaging solar irradiance at high latitudes in the Southern Hemisphere, derived from data recorded between 1990 and 2001 by four spectroradiometers located between 55°S and 90°S. Monthly integrals show a distortion of the normal annual cycle in irradiance, with enhancements occurring in October and November due to the springtime ozone loss. In some cases, these irradiances exceed those near summer solstice in December. At Palmer Station, near 65°S, the monthly erythemal irradiance in November 1997 was more than double that observed five years earlier. The combined influence of the ozone column and cloudiness variability results in a large interannual variability of surface erythemal irradiance. Monthly averages vary between about ±20 and ±50% for the period from October to December.

Geographical differences in surface UV irradiance were investigated using measurements from multifilter radiometers (Diaz et al., 2006) and from erythemal radiometers (Pazmiño et al., 2005) at stations located at different latitudes from tropical to sub-Antarctic regions. Extremely high UV-B irradiances were recorded when part of the polar vortex with low ozone moved over the measurement sites. McKenzie et al. (2006) have found that peak erythemal UV irradiances in New Zealand are ~40% higher than at locations of similar latitude in North America, as a result of the lower aerosol and ozone amounts in New Zealand and the smaller Earth-Sun separation during the Southern Hemisphere summer.

7.4.2 Estimates from Satellite Data

Global UV climatology and trends based on TOMS data for the period 1979-1991 were reported in the WMO (1999) Assessment, and since then no further studies on UV changes have been conducted using the extended dataset, although inferences can be made on the basis of the leveling off in ozone depletion reported by Reinsel et al. (2005). One of the problems for extending the satellite UV data in the recent years is the gap between Nimbus-7 and EP TOMS. Final EP/TOMS calibrations are not available after 2001, which currently prevents updating global TOMS UV climatology and trends. Updated global satellite UV trends will be a subject of future work, most likely combining TOMS, SeaWifs (Herman, 2004), SBUV/2 (Chapter 3, Appendix A1.1), and the new Ozone Monitoring Instrument (OMI) on NASA Aura spacecraft data (Tanskanen et al., 2006).

However, regional UV climatologies have been developed based on RT modeling and various input parameters. Daily maps of surface UV doses over Europe since 1984 were developed by Verdebout (2004a; 2004b) based on total ozone from TOMS, Total Ozone Vertical Sounder (TOVS) and GOME, and taking into account cloud effects, using METEOSAT/MVIRI images, and effects from tropospheric aerosols, snow cover, and altitude. Fioletov et al. (2004) produced a regional UV climatology by calculating the UV Index over Canada and the United States for the period 1980-1990 using total ozone and reflectivity from TOMS and UV Index derived from ground-based global solar radiation, total ozone, snow, and dew point temperature measurements.

Similar climatologies were derived for Argentina (Luccini et al., 2006), revealing high values of UV irradiances at the northwestern tropical high-altitude Andean plateau. For December-January, the monthly mean UV Index was higher than 18 and the daily erythemal dose was higher than 10 kJ m^{-2}. For most of the continental region, clouds attenuate the clear-sky erythemal irradiance by less than 20% on the average throughout the year.

7.4.3 Reconstruction of Past UV Records

Assessment of UV radiation changes in the past is important because many biological and health-related effects depend on UV dose accumulation during long periods. Because reliable spectral UV measurements are only available since the end of the 1980s, several attempts have been made and various methods have been proposed to reconstruct past UV irradiance records.

Erythemal irradiances or irradiance integrals in other UV spectral ranges are calculated from statistical relationships between actual measurements and various geophysical parameters (e.g., ozone, total solar irradiance, snow cover, etc.) recorded in recent years (e.g., McArthur et al., 1999; Gantner et al., 2000; Fioletov et al., 2001; Diaz et al., 2003; Trepte and Winkler, 2004), or using neural-network techniques (Janouch, 2004). Another hybrid approach uses a radiative transfer model to estimate UV levels under cloud-free conditions, followed by correction for cloud effects based on either total solar irradiance (Kaurola et al., 2000; Bodeker et al., 2002; den Outer et al., 2005), or sunshine duration measurements (Lindfors et al., 2003; Lindfors and Vuilleumier, 2005). Reuder and Koepke (2005) used RT model calculations and algorithms for deriving the required input parameters, total ozone, surface albedo, and clouds from routine observations and aerosol properties from climatological information and the Optical Properties of Aerosols and Clouds (OPAC) database. Chubarova and Nezval (2000) reconstructed UV series by calculating UV anomalies due to different geophysical factors. Coupled Chemistry-Climate Models (CCMs) have also been used for deriving past UV series (Kaurola et al., 2004; Reuder et al., 2005).

In particular, UV trends since 1980 were obtained for the entire globe from the Unified Model with Eulerian Transport and Chemistry (UMETRAC) climate model, including coupled chemistry, and from the FinROSE chemistry-transport model; they demonstrated good agreement with TOMS UV estimates (Kaurola et al., 2004).

Reconstructed UV series allow the assessment of UV trends, as well the estimation of climatic UV irradiances over large areas and long periods. For example, the UV Index climatology over Canada and the United States has been derived from reconstructed UV data combined with TOMS UV estimates (Fioletov et al., 2004). The longest time series to date of UV irradiance reconstructed from total ozone and sunshine duration datasets has been obtained for Switzerland (Lindfors and Vuilleumier, 2005). In the period 1926-2003, distinct interannual changes in erythemal irradiance have been demonstrated, with high values in the middle 1940s, in the early 1960s, and in the 1990s (Figure 7-9). The irradiance changes prior to 1980 are mainly explained by variations in relative sunshine duration, caused mainly by changes in cloudiness, while the increase in the 1990s is due to the negative trend in total ozone. Reconstructed daily UV doses between 1968 and 2001 at Hohenpeissenberg, Germany, show positive changes of 2-5% in the summer months (between March and August) and negative changes of similar magnitude in winter (September to October) (Trepte and Winkler, 2004). The former are due to decreases in cloudiness and in ozone column, whereas the latter are attributable mainly to increases in cloud optical thickness.

Annual integrals of erythemally weighted UV doses were derived for the period 1979-2003 at Bilthoven, The Netherlands, based on model calculations, total ozone, and pyranometer data. These data show increasing UV to the mid-1990s followed by a small decrease, except for a relatively high value in 2003 due to smaller reductions by clouds. Linear regressions over the entire 25-year period revealed increases in UV dose by 3.1% per decade under clear skies and 5.5% per decade under all-sky conditions (den Outer et al., 2005; Lindfors and Vuilleumier, 2005). For the period 1936-2003 in Northern Norway, Engelsen et al. (2004) found trends in monthly reconstructed UV-B doses of 4.5%, 2.8%, and 1.3% per decade, respectively, for March, April, and May. UV-A and PAR doses, which are unaffected by total ozone, reveal smaller trends (1-2% per decade) in March and April, while in May the trend is comparable with that in the UV-B.

The reconstructed UV time series at European observatories in Central and Eastern Europe since the mid-1960s (Krzyścin et al., 2004; Chubarova et al., 2005) demonstrate a pronounced decrease in UV irradiance in

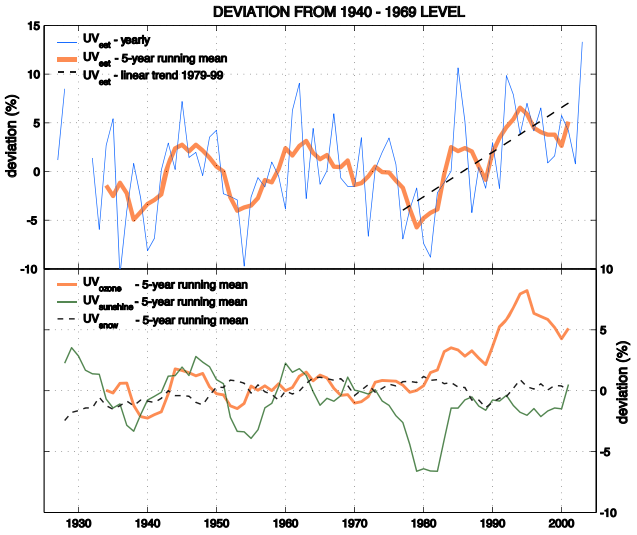

Figure 7-9. Upper panel: Time series of reconstructed erythemal irradiance over Switzerland shown as deviations (changes in %) from the 1940-1969 mean. Lower panel: Percentage contribution of changes in ozone, sunshine duration, and snow depth to the UV variability. Adapted from Lindfors and Vuilleumier, 2005.

the late 1970s and beginning of the 1980s and confirm the increase in the 1990s that is reported from measurement records (see Section 7.4.1). The decreases are mainly explained by negative UV anomalies, up to −10% due to increases in cloud amount, and up to −5% due to total ozone increases (Figure 7-7). It should be noted, however, that sometimes variations of clouds and total ozone are not completely decoupled, both being affected by circulation patterns. In such cases it is difficult to separate their influence on surface UV radiation.

Changes in surface UV radiation during the last century derived from reconstruction methods appear comparable in magnitude to those observed in the 1990s and 2000s. Although short-term UV irradiance variations imposed by different geophysical factors vary between regions, the similarity in the main features of reconstructed erythemal irradiance series confirms the prevalent effect of global processes, such as for example, the changes in atmospheric processes over Europe in the mid-1970s (IPCC, 2001) and the ozone decrease in the midlatitudes of the Northern Hemisphere in the 1990s. Surface UV radiation exhibits high values in the last 30 years, low values in the 1950s and 1960s, and high values again in the 1940s and early 1950s. Most of the past changes have been caused by changes in cloud amount and, to a certain extent, in aerosols; whereas ozone changes have been

responsible for the increases of surface UV only in the 1980s and 1990s.

7.4.4 Polar UV Variability

Studies of polar UV variability have recently benefited from in situ measurement networks becoming more robust (Diaz et al., 2003; Bernhard et al., 2004; Lakkala et al., 2005; Pazmiño et al., 2005; Bernhard et al., 2006) and now provide regionally specific information about the effects of clouds and surface albedo. On the high Antarctic Plateau (Bernhard et al., 2004), most cloud cover is optically thin, and 71% of clouds sampled by the NSF UV Monitor at the South Pole had optical depth less than 1. Due to small optical depth and high surface albedo at the South Pole, the average cloud attenuation of UV radiation was only 5%, and the maximum observed UV cloud attenuation was 23%. This is consistent with radiative transfer studies and measurements by Nichol et al. (2003). Measurements reported by Luccini et al. (2003) for Almirante Brown Station (64.9°S, 62.9°W) show that the average cloud attenuation for erythemal UV was 46% under overcast skies without precipitation, and 73% under clouds with precipitation. Luccini et al. (2003) and Lubin et al. (2002), both studying summertime irradiance levels on the Antarctic Peninsula, show high (short-term) temporal variability for cloud UV attenuation in their measurements.

Liao and Frederick (2005) analyzed the interannual variability in springtime UV-A and UV-B irradiance at all four of the NSF UV monitoring program's high southern latitude sites over 1990-2001, and determined that Palmer Station exhibits the greatest interannual variability in both UV-A and erythemal irradiances due to cloud and albedo effects. They also examined trends in monthly integrated erythemal irradiance, and found upward trends during November and December at McMurdo and South Pole, but no upward trend during October. This result may reflect the springtime ozone decrease already reaching its maximum severity during October over the continent by 1990, but gradually increasing in duration since 1990. Diaz et al. (2003) used the NSF UV monitoring program data to develop an empirical model that allows estimation of historical trends in UV-B if total column ozone and ground-based pyranometer data are available. Their results show increases in UV-B at the South Pole during October since 1983, consistent with the beginning of the anthropogenic springtime ozone depletion.

Lubin et al. (2004) used satellite data to study the multidecadal variability and trends in Antarctic UV-B, in the context of exposure by Southern Ocean phytoplankton. These authors also confirm that elevated UV-B irradiances, related to ozone depletion, had already occurred prior to the ozone "hole" discovery (before 1985), and that these enhanced irradiances had the potential to impact the most sensitive organisms years before dedicated biological field work began and before such damage could be detected. These authors also show that the most frequent occurrences of enhanced UV-B over waters containing significant phytoplankton biomass occurred in the Weddell Sea and Indian Ocean sectors of Antarctic waters, where there has historically been very little related biological field work. These two factors may help explain why reports of ecological impact due to the springtime ozone decrease have been modest compared with initial speculations.

When the polar vortex breaks up, the dilution of ozone-poor air from within the vortex can contribute to ozone decrease over midlatitudes, leading to enhancement of surface UV. Konopka et al. (2003) studied the fate of vortex remnants and the chemistry occurring within them during the spring of 1997 and 2000, using a Lagrangian chemical transport model, and found different behavior in the lower stratosphere and in the midstratosphere. Above 20 km, remnants from the polar vortex (Orsolini, 2001) remain long-lived in the summer westward circulation. Balloonborne in-situ measurements of water vapor and methane (Durry and Hauchecorne, 2005) provided evidence for such vortex remnants in the midlatitude summer stratosphere. Below 20 km, the subtropical jet bounds the meridional propagation of those remnants (Piani et al., 2002), and their lifetimes are considerably reduced due to enhanced stirring by synoptic eddies. Ajtić et al. (2004) noted that despite the regional differences observed in the springtime impact of Antarctic ozone depletion at midlatitudes, when the Antarctic polar vortex breaks down in late December and January, the resulting ozone reduction at southern midlatitudes is essentially zonally constant and decreases toward lower latitudes.

The expansion of the Antarctic polar vortex during the 1990s, both in spatial extent and temporal extent through early summer, has increased the frequency of elevated UV-B episodes over sub-Antarctic populated areas (Casiccia et al., 2003; Pazmiño et al., 2005). These episodes are no longer just small pockets of ozone-depleted stratospheric air coming from the breakup of the polar vortex, but now include occasional excursions of the polar vortex edge over Ushuaia and Punta Arenas. This occurred 44 times in the years 1997, 1998, and 2000 combined, and some episodes lasted 3-4 days. Surface measurements show average erythemal UV increases of 68% over Ushuaia since 1997, and episodic total UV-B increases of up to 80% over Punta Arenas.

Diaz et al. (2003) show that Barrow, Alaska, has experienced UV-B increases related to springtime ozone

depletion in March and April, but these increases are a factor of ten smaller than those observed at the South Pole. Summertime low-ozone episodes in the Arctic also affect surface UV-B irradiances (Orsolini et al., 2003). These summertime events result from gas-phase chemistry involving nitrogen and hydrogen cycles, which become very efficient during the 24-hour insolation that occurs in the Arctic summer. During summer 2000, two low-ozone episodes brought about erythemal UV increases of order 10-15%, each lasting more than five days.

7.5 EXPECTATIONS FOR THE FUTURE

7.5.1 Links with the Recovery of the Ozone Layer

All other UV modulating geophysical variables being stable, it is expected that decreases in stratospheric ozone will lead to increases in UV radiation at the surface. However, in practice it is difficult to detect such changes because of the high variability in UV radiation that is caused by factors other than ozone. During the period of most-rapid ozone decline (from ~1980 to ~1997), the situation was exacerbated by a lack of high-quality calibrated UV data. In recent years, data quality and quantity have improved. However, there are still only a few sites globally with sufficient long-term data to detect the effects of the observed changes in ozone. Spectroradiometric data from unpolluted NDACC sites located in regions of ozone depletion (e.g., Lauder, New Zealand, and Antarctica) offer the greatest hope for detecting these changes over the natural variability caused by clouds and aerosols. However, to date, no studies have clearly demonstrated any reductions in surface UV irradiance that may be attributable to possible increases in ozone since the late 1990s.

The most convincing studies to demonstrate these long-term changes all used some sort of filtering to minimize cloud effects (Calbó et al., 2005). Other confounding factors include systematic changes in surface albedo and air quality (aerosols and tropospheric ozone). Even with modern state-of-the-art equipment at our disposal, it remains a challenge to measure UV radiation to sufficient accuracy to unequivocally detect future changes in UV radiation that may result from future changes in ozone.

At Lauder, New Zealand, the observed increases in peak summer UV irradiance due to ozone depletion have ceased (McKenzie et al., 1999). Since 1999, the summer ozone levels have leveled off or started to increase, and in the most recent published update, it has been noted that the observed peak UV Index values now appear to be diminishing (McKenzie et al., 2004). Others factors may also be important, because the UV reductions in recent years are larger than those expected from changes in ozone alone, and there are apparent reductions in UV-A that cannot be attributed to ozone changes. These reductions may therefore be due in part to increases in absorbing aerosols over this region, which have been inferred from satellite data (de Graaf et al., 2005). Satellite-derived ozone measurements show that the leveling off (or even turnaround) in summertime ozone occurs throughout the midlatitude region of the Southern Hemisphere (McKenzie et al., 2004; Reinsel et al., 2005).

7.5.2 Predictions of UV Long-Term Changes

Several attempts have been made to predict future changes of ultraviolet radiation. Such predictions are often based on radiative transfer simulations considering predicted changes of the relevant input parameters. All predictions made to date have concentrated on the effect of ozone changes, which is considered as the most prominent of these parameters, especially for the lowermost UV-B wavelengths and in the polar regions. One of the first estimates of how ultraviolet radiation might evolve in the 21st century was provided by Slaper et al. (1996), who based their calculations on ozone predictions for different scenarios under cloud-free conditions. Later studies included clouds, which were assumed to be constant in time, in the model calculations (Taalas et al., 2000; Reuder et al., 2001). While calculations including clouds are more realistic, any changes of UV radiation were still due to ozone, which is neither the only, nor the main, factor influencing ultraviolet radiation. Clouds, aerosols, and surface albedo are also very important (see Section 7.2). These are subject to change in a future climate, and they have already changed during the last decades. This is manifested by a worldwide decrease in total solar irradiance of ~4% between 1961 and 1990 (Liepert, 2002), which seems to have been followed by an increase in the 1990s (Wild et al., 2005). These changes are attributed to a modification in cloudiness and aerosol, which also affects ultraviolet radiation. A variation of this magnitude is comparable to the effect of ozone and may thus strongly reduce or enhance ozone-related trends. Based on the A2 and B2 IPCC emission scenarios, Giorgi et al. (2004) predicted decreases in the mean cloudiness over the period 2071-2100 in Europe, with respect to the period 1961-1990. For the summer months, these changes range from approximately −2 to −15%. This would result in an increase in the daily UV dose of ~10% instead of a reduction of ~5% due to the recovery of the ozone layer (Reuder et al., 2005). Another indirect effect on long-term trends in cloudiness

involves ocean plankton and dimethyl sulfide (DMS) production, which feeds back to clouds via production of cloud condensation nuclei (CCN). Cloud formation depends on the availability of CCN, which may be produced locally through sea-to-air ventilation of DMS. PAR is important for DMS production, whereas UV photolysis leads to DMS loss (Deal et al., 2005). If long-term changes of clouds and aerosols cause an increase in surface UV irradiance, then any ozone reductions in the future will become more important for UV radiation levels.

Depending on the application, interest might be in either cloudless sky trends (e.g., if human exposure at the beach is investigated) or in all-sky changes (e.g., if exposure of the biosphere is investigated). Both are affected by changes in aerosol content, and the all-sky calculations must also take into account changes in cloudiness. Future scenario calculations should therefore also include the effect of clouds and aerosols. However, available data must be handled with care because predictions of clouds and aerosols are highly uncertain. In particular, IPCC (2001) states that "as has been the case since the first IPCC Assessment Report in 1990, probably the greatest uncertainty in future projections of climate arises from clouds and their interactions with radiation." In fact, different climate models disagree about the magnitude and even the sign of the changes in cloudiness. As a consequence, the inclusion of clouds in UV predictions would at present add a large uncertainty range to the results. In any case, giving a range for the potential impact of changes in cloudiness on predictions of ultraviolet radiation is better than excluding them completely. If clouds, as predicted by climate models, are included into the analysis, great care must be taken in the UV calculation to treat them consistently with the cloud-radiation parameterization of the respective CCM.

The availability of CCM simulations for ozone column response to Montreal Protocol controls (Chapter 6) allows simulations of the corresponding multidecadal response in surface UV irradiance, assuming that the rest of the atmosphere and surface remain the same. By use of ozone simulations by the Atmospheric Model with Transport and Chemistry (AMTRAC) model (see Chapter 6 for details) as input to a UV radiative transfer algorithm designed for satellite UV mapping (Lubin et al., 1998), it is possible to estimate when biologically active UV irradiances might be expected to peak and to return to levels that existed prior to anthropogenic influences on the ozone layer. AMTRAC is currently the only Chemistry-Climate Model with results up to 2100 (Austin and Wilson, 2006). The ozone losses calculated by this model are larger than observed, especially in the Southern Hemisphere (see the blue dashed curves corresponding to the "AMTRAC" model in Figures 6-10 and 6-12 of Chapter 6), and hence more emphasis is given on the timing of the projected changes of UV radiation, rather than on their absolute magnitude. Figure 7-10 shows an example of predicted erythemal irradiance at local noon for summertime at 45°N and 45°S, where a large part of the Earth's population lives, and for October at 65°S. The UV calculations are based on the average ozone column, respectively, at the latitude bands 35°N-60°N, 35°S-60°S, and 60°S-90°S. Erythemal irradiance increases from a reference value (calculated as the average of the period 1970-1980) for twenty years beginning in 1980, and this increase reaches a maximum during ~2005. The predicted increases in erythemal irradiance are twice as large in the Southern Hemisphere, compared with the Northern Hemisphere. The return of the calculated irradiance to the pre-1980 levels is expected by about 2040 at the Northern Hemisphere and by about 2070 at the Southern Hemisphere, while at the southern high latitudes this return is expected to occur later. These simulations are focused on the effect of future ozone changes on surface UV radiation, thus it was assumed that all other UV-influencing parameters (Section 7.2) remain unchanged since 1980. In reality many other atmospheric variables (e.g., cloudiness, surface albedo, aerosols, and temperature) are expected to change during the period of study, as a result of climate change. Changes in the vertical profiles of ozone and temperature are also expected to influence the solar UV irradiance received at the surface. Therefore the changes shown in Figure 7-10 could be different in magnitude and shape when predictions of the other parameters become available and are included in the UV calculations.

7.5.3 Factors Related to Climate Change

If the ozone layer in the next ~50 years returns to its normal state, as predicted by models (in Chapter 6, see Figure 6-10 and Section 6.6), then climate change will likely dominate the surface UV variability in the future. While most of the discussion of climate forcing generally involves visible and infrared wavelengths, where most of the Sun's energy lies, there are a number of linkages between ultraviolet radiation and climate change. Included among the elements that force the Earth's climate on different time scales is the total solar irradiance incident at the top of the atmosphere, which varies by 0.08% or 1.1 W m^{-2} in annual mean over the 11-year solar cycle (Section 6.11.2.1 in IPCC, 2001). The amplitude of variability in UV-C radiation is even higher, while in the UV-B and UV-A, only isolated spectral lines are modulated by the solar activity (see also Section 7.2.1). Such variations in UV irradiance cause a number of climate-

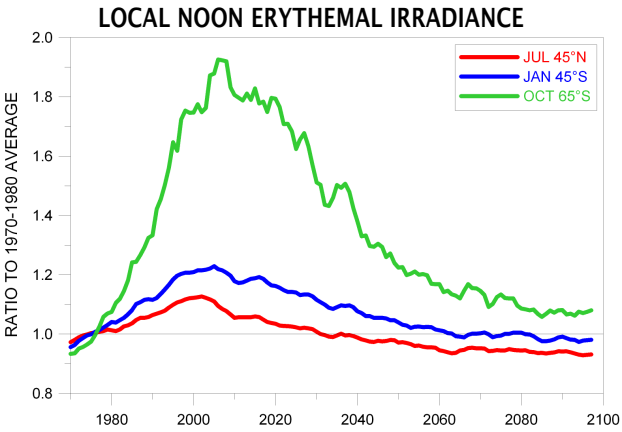

Figure 7-10. Estimated changes in erythemally weighted surface UV irradiance at local noon in response to projected changes in total column ozone for the period 1970-2099, using zonal-averages in total ozone in the latitude bands 35°N-60°N, 35°S-60°S, and 60°S-90°S, and the solar zenith angle corresponding to 45°N in July, 45°S in January, and 65°S in October, respectively. At each latitude, the irradiance is expressed as the ratio to the 1970-1980 average. The results have been smoothed with a 5-year running mean filter to remove some of the year-to-year variability in the ozone predictions in the model. The ozone losses calculated by this model are larger than observed, especially in the Southern Hemisphere (in Chapter 6, see the blue dashed curves corresponding to the "AMTRAC" model in Figures 6-10 and 6-12). Therefore, the corresponding increases in the calculated UV irradiance are overestimated. Surface UV irradiance is predicted to peak between about 2000 and 2010 and is expected to return to the pre-1980 levels between 2040 and 2070 at midlatitudes, but later at the southern high latitudes.

related changes: a change in downward shortwave flux at the tropopause; a change in stratospheric heating (Larkin et al. (2000) estimated the additional UV heating to be a factor of 8-10) leading to a change in downward infrared flux; or a change in ozone concentration (e.g., Tourpali et al., 2003; Egorova et al., 2004; Langematz et al., 2005) affecting also the balance of absorption of solar UV radiation in the troposphere. A change in the stratospheric heating may also affect stratospheric zonal wind structure and in turn affect vertically propagating planetary waves in the winter hemisphere. Such anomalies in zonal wind structure can propagate down into the troposphere in the same fashion as anomalies arising from heating in the lower stratosphere due to volcanic aerosol (e.g., Stenchikov et al., 2004). All of this may lead, for example, to shifts in the positions of the sub-tropical jets in the troposphere. A change in ozone concentration feeds back on the downward shortwave flux at the tropopause and may thus force further changes in tropospheric dynamics (e.g., Shindell et al., 2001; Haigh, 2003; Labitzke and Matthes, 2003; Shindell et al., 2003) or may affect the lifetime of reactive greenhouse gases (IPCC/TEAP, 2005).

Soon et al. (2000) suggested that the climate may be particularly sensitive to changes in UV irradiance. They found a stronger climate response to an imposed UV radiative forcing, preferentially absorbed in the layer above 250 hPa, than to the radiative forcing induced by increases in CO_2 or total solar irradiance. The strong climate response to UV forcing is a coupled feedback involving vertical static stability, tropical thick cirrus ice clouds, and stratospheric ozone.

As discussed in Sections 7.2.3, 7.2.4, 7.2.5, and 7.4.4, forcing occurs in the other direction as well. Variations in atmospheric aerosols, air pollutants in urban areas (e.g., NO_2 and SO_2), and cloud content over long time scales, as well as variations in ozone concentration as a result of chemical processes, lead to significant variations in UV irradiance at the surface (see also Meloni et al. (2003c; 2004) and Hatzianastassiou et al. (2004a; 2004b) for radiative forcing by aerosols at UV wavelengths). Extreme UV irradiances that are expected in tropical high altitude regions are often mitigated by overcast skies in summertime during the rainy season. Changes of climate patterns in those regions linked to a decrease in cloud density, as it happens sometimes during El Niño-Southern Oscillation (ENSO) events, may become important for future surface UV radiation levels.

An indirect effect on the climate that works in this direction involves ocean plankton. Increased UV penetration to the troposphere also leads to increases in the concentration of tropospheric hydroxyl radicals (OH) and hence to decreases in the lifetime of CH_4, which influences ozone (IPCC, 2001). Such changes may play a role in future CO_2 and CH_4 trends and consequently in global warming due to greenhouse gases (e.g., Coale et al., 2004). Moreover, changes in UV radiation are inducing changes in biogenic emissions, some of which are important drivers of climate change. The overall scheme of such interactions is complicated, and our understanding of the effects on UV is still poor (EC, 2003). Although several mechanisms that couple UV radiation variations with climate variations can be identified, it is hard to determine the importance and magnitude of these couplings. Progress in simulating past and future UV radiation levels may be achieved through the combined use of CCMs, RT models, and measurements.

7.6 REMAINING QUESTIONS AND UNCERTAINTIES

Despite the progress in the last four years, there are still open issues related to the transfer of UV radiation through the atmosphere and to interaction of UV radiation with climate change. These include:

- using assumptions in modeling aerosol effects on surface UV radiation (e.g., asymmetry parameter or phase function of aerosols);
- quantifying the effects of inhomogeneous clouds and inhomogeneous topography on UV irradiance and actinic flux at the surface;
- investigating the role of UV from the perspective of introducing changes in tropospheric photochemistry and, thus, indirectly affecting the stratospheric composition;
- advancing the state of knowledge concerning interactions of climate change and UV radiation in time and space, for example through changes in surface albedo (deforestation, decrease of snow-ice cover, etc) and cloudiness, which have not been extensively studied so far;
- developing a better understanding of the UV light penetration into the water, which may be underlying partially snow-covered ice, and is important for marine ecosystems;
- defining better the interaction of radiation and the surface, in particular the reflection of radiation by vegetation and the penetration into canopies; and
- better understanding and quantifying the effects of pollutant gases and aerosols on surface UV radiation.

With respect to tools and technological issues, research on UV radiation is expected to progress through further development in:

- three-dimensional radiative transfer modeling, which is becoming available but is not yet in widespread use and requires substantial computing resources and input parameters that are usually not available;
- more accurate UV radiation measurements that can help to validate radiative transfer models and satellite-derived UV estimates, while establishment of new stations, especially in the tropics, would provide better coverage;
- radiative transfer studies for large solar zenith angles and viewing angles, which are required for calculations for high latitudes and for the interpretation of remote sensing observations;
- retrieval of trace gas amounts and the optical properties of aerosols using combinations of measurements and modeling;
- correct consideration of polarization, which is important for the interpretation of radiance measurements; and
- quality control procedures of broadband and multichannel narrowband radiometers deployed worldwide, which are not as good as required for addressing long-term changes and for studying radiative processes in detail.

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Appendix 7A
SPECTRAL DATA AVAILABLE FROM DATABASES

7A.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	31.58	130.56	01/01/1991
12	Sapporo	Brewer	Japan	JMA	43.06	141.33	01/01/1991
14	Tateno / Tsukuba	Brewer	Japan	JMA	36.06	140.10	01/01/1990
18	Alert	Brewer	Canada	MSC	82.50	-62.32	09/06/1995
21	Edmonton / Stony Plain	Brewer	Canada	MSC	53.55	-114.10	19/03/1992
24	Resolute	Brewer	Canada	MSC	74.72	-94.98	14/03/1991
31	Mauna Loa	Brewer	United States	MSC	19.53	-155.57	24/03/1997
31	Mauna Loa	Brewer	United States	MSC-MLO	19.53	-155.57	01/01/1998
65	Toronto	Brewer	Canada	MSC	43.78	-79.47	01/03/1989
67	Boulder	Brewer	United States	EPA_UGA [c]	40.08	-105.25	01/01/1997
76	Goose Bay	Brewer	Canada	MSC	53.30	-60.36	01/01/1997
77	Churchill	Brewer	Canada	MSC	58.75	-94.07	30/03/1992
95	Taipei	Brewer	Taiwan	CWBT	25.02	121.47	06/03/1992
101	Syowa	Brewer	Japan	JMA	-69.00	39.58	01/01/1993
190	Naha	Brewer	Japan	JMA	26.20	127.68	01/01/1991
241	Saskatoon	Brewer	Canada	MSC	52.11	-106.71	01/01/1991
290	Saturna Island	Brewer	Canada	MSC	48.78	-123.13	03/10/1990
301	JRC Ispra (Varese)	Brewer	Italy	JRC_EU	45.80	8.63	01/01/2001
306	Chengkung	Brewer	Taiwan	CWBT	23.10	121.36	02/01/1992
307	Obninsk	Brewer	Russia	IEM-SPA	55.12	36.30	06/05/1993
315	Eureka	Brewer	Canada	MSC	80.04	-86.17	10/02/2001
319	Montreal (Dorval)	Brewer	Canada	MSC	45.48	-73.75	06/03/1993
320	Winnipeg	Brewer	Canada	MSC	49.90	-97.24	06/07/1992
321	Halifax (Bedford)	Brewer	Canada	MSC	44.70	-63.61	01/07/1992
331	Poprad-Ganovce	Brewer	Slovakia	SHMI	49.03	20.32	01/01/1994
332	Poyang	Brewer	Korea	KMA	36.03	129.38	27/01/1994
338	Bratts Lake (Regina)	Brewer	Canada	MSC	50.20	-104.70	01/01/1995
353	Reading	Optronic	United Kingdom	UMIST	51.45	0.93	27/01/1994
377	Research Triangle Park	Brewer	United States	EPA_UGA [c]	35.89	-78.87	10/09/1996
379	Gaithersburg	Brewer	United States	EPA_UGA	39.13	-77.21	01/01/1996
380	Atlanta	Brewer	United States	EPA_UGA	33.75	-84.41	30/05/1996
382	Riverside	Brewer	United States	EPA_UGA	34.00	-117.34	01/01/1996
383	Big Bend	Brewer	United States	EPA_UGA	29.31	-103.18	20/02/1997
384	Great Smokey Mountains	Brewer	United States	EPA_UGA	35.60	-83.78	03/01/1997
385	Canyonlands	Brewer	United States	EPA_UGA	38.47	-109.82	31/07/1997
386	Glacier	Brewer	United States	EPA_UGA	48.51	-113.99	18/09/1997
387	Everglades	Brewer	United States	EPA_UGA	25.39	-80.68	24/02/1997
388	Shenandoah	Brewer	United States	EPA_UGA	38.52	-78.44	05/03/1997
389	Acadia	Brewer	United States	EPA_UGA	44.38	-68.26	04/03/1998
390	Denali	Brewer	United States	EPA_UGA	63.73	-148.97	04/10/1997

391	Virgin islands	Brewer	Virgin Islands	EPA_UGA	18.34	-64.79	25/05/1998
392	Rocky Mountain Natl. Park	Brewer	United States	EPA_UGA	40.03	-105.53	30/05/1998
393	Olympic	Brewer	United States	EPA_UGA	48.14	-123.40	11/12/1997
402	Theodore	Brewer	United States	EPA_UGA	46.90	-103.38	29/09/1998
463	Sequoia	Brewer	United States	EPA_UGA	36.49	-118.82	20/08/1998
465	Kilauea	Brewer	United States	EPA_UGA	19.42	-155.29	18/02/1999

[a] Website: http://www.msc-smc.ec.gc.ca/woudc/

[b] JMA, Japan Meteorological Agency; MSC, Meteorological Service of Canada; EPA_UGS, Environmental Protection Agency, University of Georgia, Athens, USA; CWBT, Central Weather Bureau of Taiwan; JRC_EU, Joint Research Centre of the European Union; IEM-SPA, Institute of Experimental Meteorology-Scientific Hydrometeorological Institute; SHMI, Slovakian Hydrometeorological Institute; KMA, Korean Meteorological Administration; UM, University of Manchester.

[c] The Brewer spectrophotometers operated by EPA have ceased operation after 2004.

7A.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	Feb. 98
3	Uccle Brussels	Jobin Yvon	Belgium	IASB	50.80	4.36	Mar. 93
4	Hradec Kralove	Brewer	Czech Republic	CHI	50.19	15.83	Jan. 94
5	Jokioinen	Brewer	Finland	FMI	60.81	23.50	Mar. 95
6	Sodankylä	Brewer	Finland	FMI	67.37	26.63	Apr. 90
7	Briançon	Jobin Yvon	France	USTL	44.90	6.65	Sep. 99
8	Villeneuve d.Asq	Jobin Yvon	France	USTL	50.37	3.01	May 97
9	Neuherberg	Bentham	Germany	BfS	48.22	11.58	Mar. 00
10	Offenbach	Bentham	Germany	BfS	50.10	8.75	Jan. 00
11	Hohenpeissenberg	Brewer	Germany	DWD	47.80	11.02	Jan. 95
12	Lindenberg	Brewer	Germany	DWD	52.22	14.12	Jan. 95
13	Potsdam	Brewer	Germany	DWD	52.36	13.08	Jan. 95
14	Garmisch-Partenkirchen	Bentham	Germany	IFU	47.48	11.07	Apr. 94
15	Zugspitze	Bentham	Germany	IFU	47.42	10.98	Jul. 97
16	Thessaloniki	Brewer	Greece	LAP	40.52	22.97	Oct. 89
17	Lampedusa	Brewer	Italy	ENEA	35.50	12.60	Jan. 98
18	Ispra	Brewer	Italy	JRC	45.81	8.63	Aug. 91
19	Rome	Brewer	Italy	URO	41.90	12.52	Feb. 92
20	Andøya	Bentham	Norway	NILU	69.48	16.02	Feb. 98
21	Oesteraas	Bentham	Norway	NRPA	59.92	10.75	Jun. 99
22	Trondheim	Optronic	Norway	NTNU	64.43	10.47	Aug. 97
23	Tromsø	Brewer	Norway	UT	69.66	18.93	May 95
24	Belsk	Brewer	Poland	IGFPAS	51.83	20.78	Jan. 93
25	Azores Island	Brewer	Portugal	IM	38.66	−27.22	Jul. 92
26	Funchal (Madeira Is.)	Brewer	Portugal	IM	32.64	−16.89	Jan. 90
27	Lisbon	Brewer	Portugal	IM	38.77	−9.15	Jan. 90
28	Penhas Douradas	Brewer	Portugal	IM	40.42	−7.55	Oct. 94
29	Izana	Brewer	Spain	INM	28.49	−16.50	Jan. 95
30	Norrköping	Brewer	Sweden	SMHI	58.58	16.15	Sep. 91
31	Vindeln	Brewer	Sweden	SMHI	64.23	19.77	Jul. 96
32	De Bilt	Brewer	Netherlands	KNMI	52.10	5.18	Jan. 94
33	RIVM (Bilthoven)	Dilor XY-50	Netherlands	RIVM	52.12	5.20	Jan. 96
34	Reading	Optronics	United Kingdom	UM	51.45	0.93	Jan. 93

Only permanent stations are listed; campaign data are not included.

[a] Website: http://uvdb.fmi.fi/uvdb/index.html

[b] BOKU, Universität für Bodenkultur Wein; IASB, Institut d'Aéronomie Spatiale de Belgique; CHI, Czech Hydrometeorological Institute; 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 Union; URO, University of Rome; NILU, Norsk Institutt for Luftforskning; NRPA, Norwegian Radiation Protection Authority; NTNU, Norges Teknisk-Naturvitenskapelige Universitet; UT, University of Tromsø; IGFPAS, Institute of Geophysics, Polish Academy of Sciences; IM, 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; UM, University of Manchester.

7A.3 U.S. National Science Foundation UV Monitoring Network [a]

No.	Station Name	Instrument	Country	Institute [b]	Lat. (°N)	Long. (°E)	Start Date [c]
1	Arrival Heights	Biospherical	Antarctica	NSF	−77.83	166.67	13/12/1989
2	Palmer	Biospherical	Antarctica	NSF	−64.77	−64.05	14/03/1990
3	South Pole [d]	Biospherical	Antarctica	NSF	−90.00	80.00	31/01/1991
4	Ushuaia	Biospherical	Argentina	NSF	−54.82	−68.32	13/09/1990
5	San Diego	Biospherical	United States	NSF	32.77	−117.20	28/10/1992
6	Barrow	Biospherical	United States	NSF	71.32	−156.68	14/01/1991
7	Summit	Biospherical	Greenland	NSF	72.58	−38.46	15/08/2004

[a] Website: http://www.biospherical.com/NSF/

[b] Stations 1-6 are equipped with SUV-100 spectroradiometers. Station 7 (Summit) is equipped with a SUV-150B spectroradiometer.

[c] Date from which date data are available. Instruments may have been installed before this date.

[d] The system at the South Pole was relocated by approximately 200 m in January 1997. Due to the proximity of the instrument to the geographic South Pole and the movement of the polar ice cap over the bedrock, the azimuth position of the instrument has changed from 84.5°E in January 1997 to 72.5°E in January 2006.

Appendix 7B
INTERNET ADDRESSES FOR UV SITES

7B.1 General UV Information

WMO UV radiation page	http://www.srrb.noaa.gov/UV/
TOMS (ozone and UV satellite data)	http://toms.gsfc.nasa.gov/
OMI (Ozone Monitoring Instrument)	http://aura.gsfc.nasa.gov/instruments/omi/index.html
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.niwascience.co.nz/services/uvozone/
EPA, U.S.	http://www.epa.gov/uvnet/
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	http://sedac.ciesin.columbia.edu/ozone/
World Radiation Centre	http://wrdc-mgo.nrel.gov/

7B.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-726)	http://i115srv.vu-wien.ac.at/uv/COST726/Cost726.htm
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/
Stratospheric-Climate Links with Emphasis on the Upper Troposphere and Lower Stratosphere (SCOUT-O_3)	http://www.ozone-sec.ch.cam.ac.uk/scout_o3/index.html
UV Index & UV dose based on GOME (TEMIS)	http://www.temis.nl/uvradiation/

7B.3 Radiative Transfer Codes

Tropospheric Ultraviolet Visible (TUV) (Madronich and Flocke, 1997)	http://cprm.acd.ucar.edu/Models/TUV/
Library for Radiative Transfer (libRadTran) (Mayer and Kylling, 2005)	http://www.libradtran.org/
System for Transfer of Atmospheric Radiation (STAR) (Koepke et al., 2005)	http://www.meteo.physik.uni-muenchen.de/strahlung/uvrad/Star/starprog.html
Fast and Easy Radiative Transfer (FASTRT)	http://zardoz.nilu.no/~olaeng/fastrt/fastrt.html
Santa Barbara Discrete-Ordinate Atmospheric Radiative Transfer (SBDART) (Ricchiazzi et al., 1998)	http://arm.mrcsb.com/sbdart/
Streamer model (Key, 1999)	http://stratus.ssec.wisc.edu/streamer/streamer.html
SCIATRAN code (Rozanov et al., 2005)	http://www.iup.physik.uni-bremen.de/sciatran/
3-D Spherical Harmonics Discrete Ordinate Method (SHDOM) model (Evans, 1998)	http://nit.colorado.edu/~evans/shdom.html

7B.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/
McMath/Pierce at Kitt Peak	ftp://ftp.noao.edu/fts/fluxatl/
The New Synthetic Gueymard Spectrum (Gueymard, 2004)	http://rredc.nrel.gov/solar/spectra/am0/special.html#newgueymard

7B.5 Internet Sites with UV Information

Argentina	http://www.conae.gov.ar/uv/uv.html 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.uv-index.at/
Belgium	http://ozone.meteo.be/uv/index.php
Brazil	http://www.master.iag.usp.br/ind.php?inic=00&prod=indiceuv
Canada	http://www.msc-smc.ec.gc.ca/education/uvindex/forecasts/ index_e.html
Catalonia	http://www.meteocat.com/marcs/marcos_previsio/marcs_uvi.htm
Chile	http://www.meteochile.cl/
Czech Republic	http://www.chmi.cz/meteo/ozon/o3uvb-e.html
Denmark	http://www.dmi.dk/vejr/index_sol.html
European Commission (JRC)	http://ecuv.jrc.it/
Finland	http://www.fmi.fi/research_atmosphere/ atmosphere_2.html
France	http://www.soleil.info/main.php
Germany (DWD)	http://www.uv-index.de/
Germany (BfS)	http://www.bfs.de/uv
Greece	http://www.uvnet.gr
Hong Kong	http://www.hko.gov.hk/wxinfo/uvfcst/uvfcst.htm
Israel	http://www.ims.gov.il/en2.htm#1
Italy	http://www.lamma.rete.toscana.it/previ/eng/uvhtm/uvnew0.html
Japan	http://www.jma.go.jp/en/uv/index.html
Luxembourg	http://www.restena.lu/meteo_lcd/
Netherlands	http://www.temis.nl/uvradiation/index.html
New Zealand	http://www.niwascience.co.nz/services/uvozone/
Norway	http://uvnett.nrpa.no/uv/
Poland	http://www.imgw.pl/wl/internet/zz/index.html
Portugal	http://www.meteo.pt/en/previsao/uv/prev_uv_d0.jsp
Slovenia	http://www.rzs-hm.si/zanimivosti/UV.htm
South Africa	http://www.weathersa.co.za/uv/uv.jsp
Spain	http://infomet.am.ub.es/uv_i_ozo/uvi.html
Sweden	http://www.smhi.se/weather/uvindex/index.htm
Switzerland	http://www.uv-index.ch/de/home.php
Taiwan	http://www.epa.gov.tw/monitoring/1-1/uv.htm
Uunited Kingdom	http://www.m-office.gov.uk/weather/uv/
United States (NOAA)	http://www.cpc.ncep.noaa.gov/products/stratosphere/uv_index/
United States (EPA)	http://www.epa.gov/sunwise/uvindex.html
World Health Organization (WHO)	http://www.who.int/mediacentre/factsheets/fs271/en/index.html
Intersun (WHO)	http://www.who.int/uv/en/