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UV Radiation in Global Climate Change

Measurements, Modeling and Effects on Ecosystems

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With 176 figures

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全球气候变化中的紫外线辐射：观测、模拟及其对生态系统的影响

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内 容 简 介

大量研究指出紫外线（UV）辐射对生物有机体有害，并且危害人类健康。对地表UV-B辐射强度增加的研究极大地促进了地基和空基相关观测项目的发展；人们还需要进一步对UV辐射的观测、建模和影响进行深入研究。本书各章描述了过去30年来世界范围内与UV辐射相关的研究工作，涉及的领域有：① UV辐射的当前与预测水平及其对生态系统、人类健康、经济与社会的影响；② UV 辐射观测仪器的最新发展，地基和空基观测仪器定标进展情况以及观测方法，建模与有关应用；③ 全球气候变化对紫外线辐射的影响。

对于涉及全球气候变化、气象学、气候学、环境科学、生物学和农林科学的大专院校高年级本科生、研究生和教师，本书是一本很有价值的参考书。相关领域的科学家、决策者和普通公众亦能受益于此书。

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Preface

Over the past three decades, the scientific community has realized the urgency of obtaining a better understanding of the interaction between the earth's atmosphere/biosphere and the sun's radiant energy. Most of the research has focused on the radiant energy balances in the solar and infrared regions of the spectrum, and the way these energy flows affect the climate. During this same time frame, in a related arena, a smaller group of dedicated individuals has concentrated on the role of ultraviolet (UV) radiation as it affects the overall welfare of the planet. Although comprising only a small fraction of the radiation balance that may play a role in global climate change over the next centuries, UV radiation has the capacity to cause direct and more immediate harm to virtually all living organisms and especially to human health. Cumulative high doses of UV radiation are considered a major causal factor in the development of skin cancer and cataracts. Ultraviolet radiation can weaken the human immune system, and can also affect crop production and ocean bio-productivity.

Concerns about the increased levels of UV-B radiation reaching the earth's surface have led to the development of ground- and space-based measurement programs to provide long-term records of its levels. Accurate long-term measurements are difficult to obtain, especially when limited to the bandwidth regions that contain the most harmful solar photons. A core of concerned scientists from across the globe realizes that much work is needed in quantifying the harmful radiation levels and defining their adverse effects. In assessing the effects of UV-B radiation, it is important to realize the complexity of the interactions of living organisms that cause adverse responses with radiant energy directly, as well as in combination with other climate stressors, such as drought, increased temperatures, and CO_2.

This book addresses work that has been conducted throughout the world over the past three decades, such as: (1) current efforts for establishing a climatology of UV radiation; (2) modeling the UV component and its impact on ecosystems, human health, and related economic and social implications; (3) new developments in

UV instrumentation, advances in calibration (ground-based and satellite-based) measurement methods; and (4) the effects of global climate change on UV radiation. All chapters, including the review chapters, have been solicited from renowned scientists in their research fields of UV radiation, meteorology, the environment, and ecosystems. They have presented their work based on research at the global scale, taking into consideration possible future developments. Many new techniques and methods developed from space-ground measurements, mathematical modeling, and remote sensing have recently become available, yet have not previously been presented. This book will be a useful source of reference for undergraduate and graduate students who are involved in the study of global change, environmental science, meteorology, climatology, biology, and agricultural and forest sciences. It will also benefit scientists in related research fields, as well as professors, policy makers, and the general public.

As editors of this book, we wish to express our great appreciation for the contributions of many individuals. We are indebted to the over 50 authors and co-authors within the scientific community who have shared their expertise and contributed much time and effort in the preparation of the book chapters. We also wish to give credit to the numerous funding sources promoting the scientific research performed, and thus the valuable findings shared by the authors. We express our appreciation to the many reviewers and expert scientists who took the time to offer valuable comments and suggestions for the improvement of the book chapters. We acknowledge the management and editorial assistance of Laurie Richards and the technical support of Jonathan Straube of the Natural Resource Ecology Laboratory, Colorado State University and Tsinghua University Press and Springer-Verlag. We especially want to express our appreciation for the support of the Cooperative State Research, Education and Extension Service (CSREES) of the U.S. Department of Agriculture, and the USDA UV-B Monitoring and Research Program at Colorado State University. The efforts of many individuals including Drs. John Moore, John Davis, Steve Liu, Ni-Bin Chang, Mr. George Janson, and Ms. Rita Deike are appreciated.

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1 A Climatology of UV Radiation, 1979 – 2000, 65S – 65N

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Abstract Solar ultraviolet (UV) radiation reaching earth's surface is of interest because of its role in the induction of various biological and chemical processes, including skin cancer. We present climatological distributions of monthly mean surface-level UV radiation, calculated using the Tropospheric Ultraviolet-Visible (TUV) radiative transfer model with inputs of ozone column amounts and cloud reflectivities (at 380 nm) measured by satellite instruments (Total Ozone Mapping Spectrometers (TOMS), aboard Nimbus-7, Meteor-3, and Earth Probe). The climatology is averaged over the years 1979 – 2000 for UV-A (315 nm – 400 nm), UV-B (280 nm – 315 nm), and radiation weighted by the action spectra for the induction of erythema (skin-reddening), pre-vitamin D_3 synthesis, and non-melanoma carcinogenesis. Coverage is global, excluding the poles.

Comparisons with concurrent ground-based UV radiation measurements archived at the World Ozone and Ultraviolet Data Center show agreement at the 10% – 20% level, except at high latitudes where the large surface albedo of snow and ice invalidates the use of satellite-observed reflectivity in estimating cloud cover. The climatology may be useful in epidemiological studies that assess the role of long-term environmental exposure to UV radiation.

Keywords UV climatology, erythema, vitamin D synthesis, TUV model

1.1 Introduction

Solar ultraviolet radiation transmitted through the atmosphere to earth's surface is known to induce various biological and chemical processes, many of which are harmful to living tissues and some materials (see UNEP, 2006, for a review). Examples of processes relevant to human health include skin-reddening (erythema), synthesis of vitamin D within skin, and induction of various skin cancers. The long-term geographical distribution of surface UV radiation is of considerable interest towards understanding these effects. However, environmental UV levels are highly variable due to daily and seasonal cycles at different latitudes, and to variations in atmospheric transmission (mainly attributable to variations in ozone, clouds, and aerosols) and surface reflections. Ultraviolet radiation measurements by ground-based instruments are too few, and their record relatively short, to construct a unified picture of its average global distribution.

An alternative method of estimating surface UV levels with long-term global coverage relies on satellite-based observations of earth's atmosphere and surface, combined with a computer model of the propagation of UV radiation through the atmosphere. This methodology is already in use on a NASA website (http://jwocky.gsfc.nasa.gov/ery_uv/ery_uv1.html, which uses data from the TOMS ozone-monitoring satellite instruments to generate maps of erythemal UV for specific days. Other applications of the technique have illuminated interesting aspects of the problem, i.e., estimation of zonal mean irradiances at different UV wavelengths, of trends due to ozone changes, of cloud effects, and of geographical distributions based on monthly averaged ozone and clouds (e.g., Frederick and Lubin, 1988; Madronich, 1992; Eck et al., 1995; Frederick and Erlick, 1995; Herman et al., 1996a; Lubin et al., 1998; Herman et al., 1999; Sabziparvar et al., 1999; Herman et al., 2000; McKenzie et al., 2001). Here we use satellite-based observations of atmospheric ozone and clouds to derive a climatology of erythemal UV radiation with nearly global coverage (excluding the polar regions), averaged over the years 1979 – 2000. We developed a fast method for the explicit calculation of UV daily doses for each day of the whole time period. Averaging daily UV doses, rather than calculating monthly doses on the bases of monthly-averaged cloudiness and ozone, reduces possible uncertainties connected with the non-linear relationship between atmospheric parameters (e.g., total ozone and clouds) and surface UV radiation. Comparisons with long-term measurements at 22 UV monitoring stations allow some assessment of the reliability of this technique. Climatologies such as those presented here can be useful in epidemiological studies that assess the role of long-term environmental exposure to ultraviolet radiation, such as those discussed in Chapter 2 (McKenzie and Liley).

1.2 Method

UV broadband irradiances (W m^{-2}) are computed as integrals over wavelength λ (nm) of spectral irradiances $E(\lambda)$ (W m^{-2} nm^{-1}) weighted by appropriate spectral functions $S(\lambda)$ (typically unit-less):

$$\text{Irradiance} = \int S(\lambda)\, E(\lambda)\, \mathrm{d}\lambda$$

$E(\lambda)$ is a function of solar zenith angle (SZA) and surface elevation, as well as optical depth profiles of atmospheric absorbers and scatterers (e.g., ozone and clouds). The values of $S(\lambda)$ are unity for UV-A and UV-B in the respective wavelength ranges of 315 nm – 400 nm and 280 nm – 315 nm, and zero outside these ranges. Figure 1.1 shows the wavelength dependence for three action spectra with relevance to human health: (1) erythema (McKinlay and Diffey, 1987), (2) pre-vitamin D_3 production in human skin (Holick et al., 2006, after MacLaughlin et al., 1982), and (3) photocarcinogenesis of non-melanoma skin cancers (CIE, 2006). The erythema action spectrum has been accepted for the calculation of the instantaneous UV index (defined as the UV_{ery} irradiance multiplied by 40 (ICNIRP, 1995; WMO, 1997)), and the time-integrated standard erythemal dose (SED = 100 J m^{-2} (CIE, 1998)). In practice, use of this CIE spectrum emphasizes the ozone-sensitive region of 295 nm – 320 nm, peaking near 305 nm with minor contributions from longer wavelengths (Madronich et al., 1998; Micheletti et al., 2003). The other two functions are somewhat similar, in that they maximize at around 305 nm wavelength, and decrease by several orders of magnitude by 330 nm.

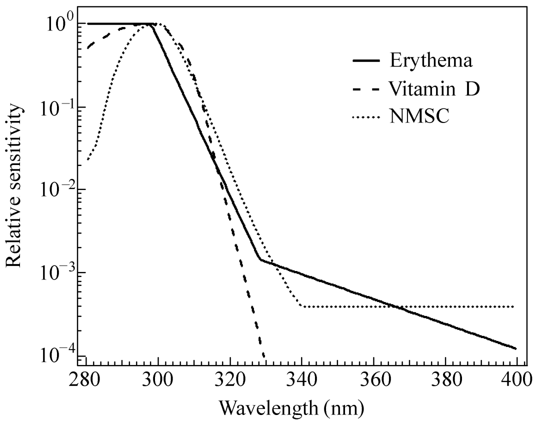

Figure 1.1 Spectral functions for erythema: solid line (McKinlay and Diffey, 1987); synthesis of pre-vitamin D3: dashed line (MacLaughlin et al., 1982; Holick et al., 2006); and non-melanoma carcinogenesis: dotted line (CIE, 2006)

Compilation of a global UV climatology is computationally intensive, requiring the calculation of $E(\lambda)$ at all relevant wavelengths, at each geographical location, and over diurnal cycles for each day of each year. To reduce computational time, we used the TUV model (Madronich and Flocke, 1997) to pre-tabulate values of weighted UV irradiances as a function of SZA (0° to 96° in 1° steps), ozone column (43 DU – 643 DU in steps of 10 DU), and surface elevation (0, 3, and 8 km above sea level), for cloud-free and aerosol-free conditions. The omission of UV absorption by aerosols can lead to overestimates of irradiance for polluted locations; this limitation will be discussed in more detail later. $E(\lambda)$ at earth's surface was computed at 1 nm steps from 280 nm – 400 nm. The spectral irradiance incident at the top of the atmosphere was taken from the Atlas3/SUSIM measurements (D. Prinz, pers. comm., 1998). Vertical profiles (appropriate for mid-latitude, annual average conditions) for air density, temperature, and ozone were taken from the U.S. Standard Atmosphere (USSA, 1976) with, however, the ozone profile re-scaled to the actual ozone column (see below). The propagation of solar radiation through the atmosphere was computed with a 4-stream discrete ordinates method (Stamnes et al., 1988), with pseudo-spherical correction for improved accuracy at low sun conditions (Petropavlovskikh, 1995). A Lambertian surface albedo of 5% was assumed at all wavelengths.

The atmospheric ozone column and cloud reflectivity at 380 nm (R) were taken from the TOMS data from three satellites: (1) Nimbus-7, Level 3/Version 8 (McPeters et al., 1996), Nov. 1, 1978 to Dec. 31, 1992; (2) Meteor-3, Level 3/Version 8 (Herman et al., 1996b), Aug. 22, 1991 to Dec. 11, 1994; and (3) Earth Probe, Level 3/Version 8 (McPeters et al., 1998), July 7, 1996 to June 30, 2000. The geographical resolution of the measurements was 1.25° longitude by 1.00° latitude. For each grid point, only one satellite overpass per day occurred (*ca*. local noon). We therefore assumed constant ozone and reflectivity values for the entire day. Local values of the ozone column, SZA and surface elevation were used to compute the clear-sky irradiances at 30-minute intervals over half days by interpolation of the pre-tabulated values. Assuming symmetry about local noon, these data were integrated over 24 hours to obtain the daily UV-A, UV-B, and erythemal doses. A correction for variations in the earth-sun distance was applied as a function of date. A reduction factor F for cloud cover, identical to that used by Eck et al. (1995), was then applied:

$$1/F = \begin{cases} 1-(R-0.05)/0.9, & R \leqslant 50\% \\ 1-R, & R > 50\% \end{cases}$$

For cloud-free and aerosol-free conditions, total reflectivity at 380 nm is dominated by Rayleigh scattering and surface reflections, the latter being rather small at UV wavelengths unless snow or ice is present. The TOMS algorithm attributes excess reflectivity to clouds or scattering aerosols, without distinguishing between the two. When high surface albedo is encountered (e.g., snow or ice), this method erroneously interprets the high surface reflectivity as cloud cover, thus artificially reducing surface UV irradiance. Polar regions are therefore excluded from our analysis. For non-polar regions, including mountainous regions, we did not attempt to correct for snow cover. The calculated UV doses for such areas should therefore be considered as lower limits.

The calculation of UV doses should in principle be carried out for each location and each day over the satellite record (ca. 1979 – 2000). However, gaps in the satellite record exist, so that for some days and/or locations, no doses could be computed. These missing days require some consideration to avoid biases in any long term averages and trends. For each location, monthly averaged doses were calculated for each of the 247 months in the combined dataset, but were considered valid only if at least half of the days in that month had data. No attempt was made to discriminate between the months in which data gaps typically occurred during the early part of the month and when they typically occurred during the latter part of the month. In some cases, measurements for the same location and days were available from two different satellites; in such cases, monthly means for each satellite were computed, then averaged together to obtain a single mean for that month.

Climatological monthly values were computed for each location by averaging all valid values for that month over multiple years (e.g., climatological January is the mean of all valid January values over 1979 – 2000, etc.). For most of this chapter, we consider averages over the full 22 years (1979 – 2000), but for some of the discussion below, we also considered the time periods 1979 – 1989 and 1990 – 2000 separately. Climatological annual values were computed as the mean of all valid climatological monthly values, specifically (mean of all Jans. + mean of all Febs. + ··· + mean of all Decs.) / 12.

The second period (1990 – 2000) is missing some data (all of 1995, Jan – Jun 1996, Jul – Dec 2000). We tested the effects of these missing data on the calculated changes by temporarily removing the analogous months from the 1979 – 1989 record and comparing the resulting climatology to that of the complete 1979 – 1989 period. Differences of $< \pm 0.2\%$ were obtained. This is on the order of ~1/10 of the clear sky changes between the two periods 1979 – 1989 and 1990 – 2000, and on the order of <1/10 of the changes in the “all sky” values between these two periods.

For a comparison with the satellite-derived estimates, we used measurements of UV irradiances by ground-based spectroradiometers, obtained from the World Ozone and UV Data Center archive (WOUDC; data downloaded June 2002). Measured UV_{ery} doses are reported as daily integrals of spectral observations integrated over wavelength with the McKinlay and Diffey (1987) erythemal action spectrum weighting. The archives include 22 non-polar stations; 10 in Canada (Meteorological Service of Canada, MSC); 4 in Japan (Japan Meteorological Agency, JMA); 2 in the Taiwan region (“Central Weather Bureau of Taiwan, CWBT”), and 1 each in Obninsk, Russia (Institute of Experimental Meteorology-Scientific Production Association (IEM-SPA)), Poprad-Ganovce, Slovakia (Slovak HydroMeteorological Institute (SHMI)); Mauna Loa, HI (MSC); San Diego, CA; Ushuaia, Argentina; and Palmer Station, Antarctica (all US National Science Foundation (NSF) sites). The NSF sites operated double monochromators (Biospherical Instruments, Inc), while all other sites operated Brewer single monochromators. Our satellite-based irradiance values for station locations were derived for the locations and altitudes of the ground-based stations.

1.3 Results

1.3.1 Satellite-Derived UV Climatologies

The geographical distributions of daily UV radiation doses at earth's surface, averaged over the entire time period of (Nov. 1, 1978 – June 30, 2000) are shown in Figs. 1.2 – 1.6. The upper panel in each figure shows values calculated by considering the effects of both ozone and clouds, as estimated from TOMS data, and are thus assessed to be nearest to the actual values experienced over this time period. The lower panels show climatological distributions estimated for hypothetical cloud-free skies (i.e., estimated from the ozone distributions without correcting for the presence of clouds).

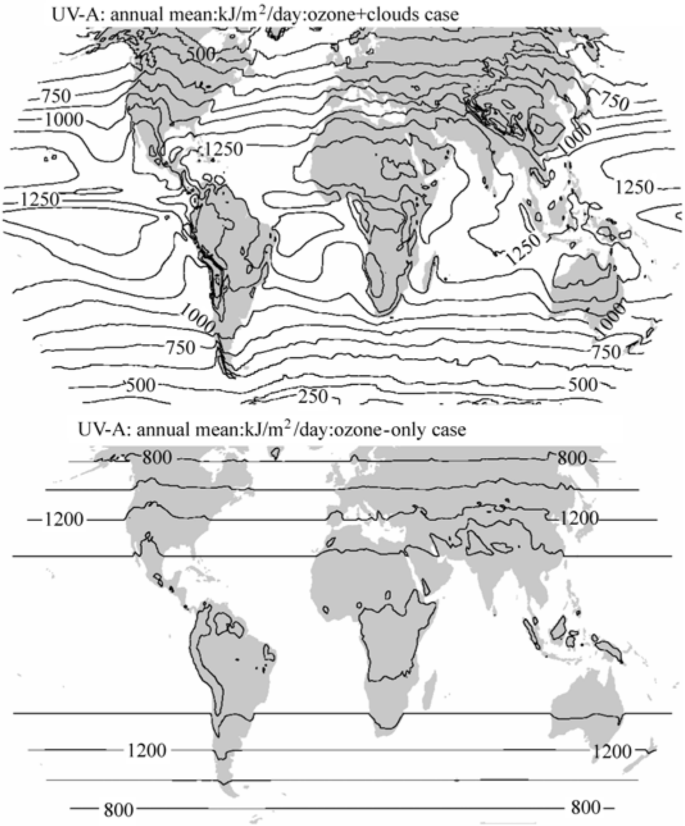

Figure 1.2 Climatological daily doses of UV-A at earth's surface, derived from satellite (TOMS) observations of the atmospheric ozone column and cloud reflectivity at 380 nm and averaged annually over Nov 1, 1978 – June 30, 2000, with (upper) and without (lower) correcting for the presence of clouds

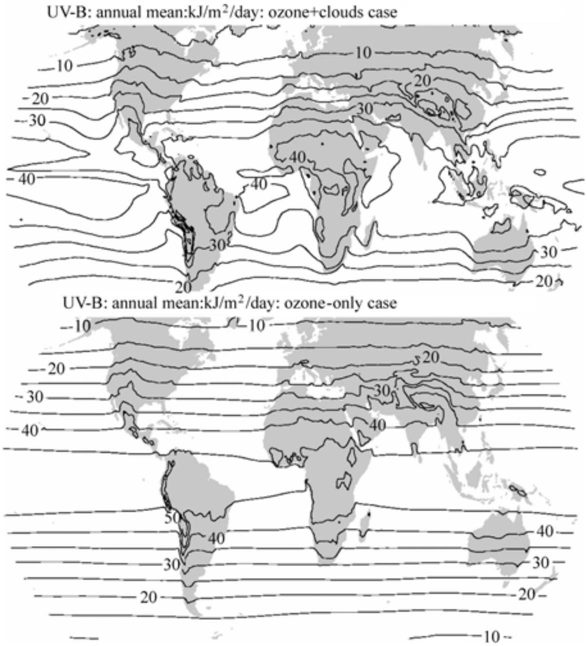

Figure 1.3 Climatological daily doses of UV-B at earth's surface, as Fig. 1.2

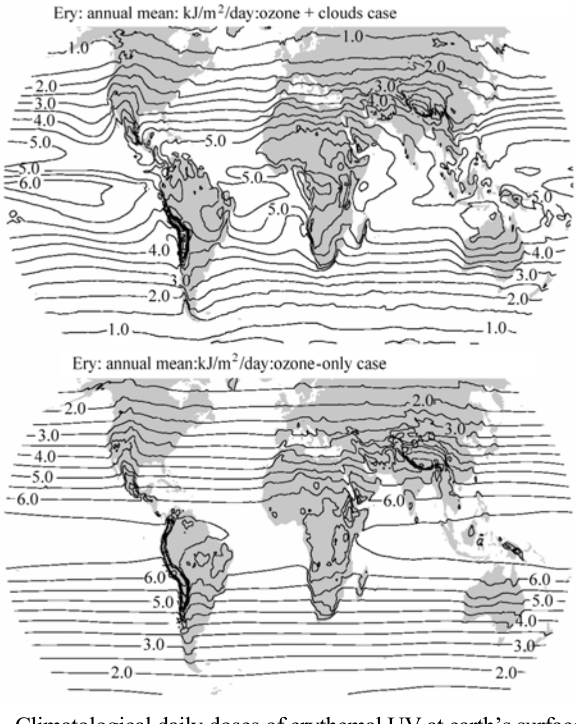

Figure 1.4 Climatological daily doses of erythemal UV at earth's surface, as Fig. 1.2

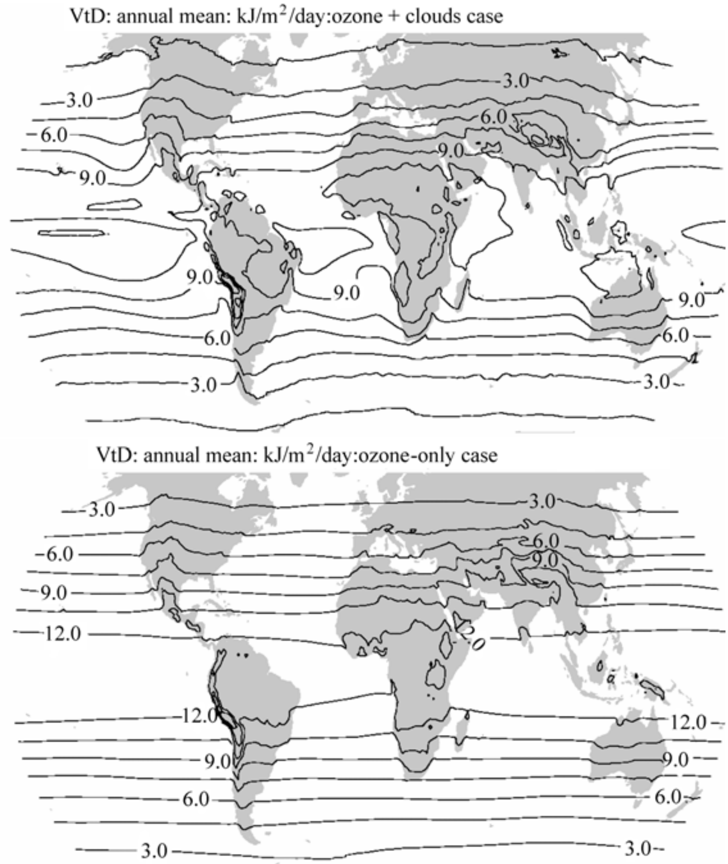

Figure 1.5 Climatological daily doses of UV weighted for pre-vitamin D_3 synthesis at earth's surface, as Fig. 1.2

The zonally homogeneous distribution of UV-A calculated for cloud-free conditions shows almost exclusive dependence on solar position, with only small variations due to surface topography. Ozone column variations induce additional zonal variations in the distributions of cloud-free UV-B and UV weighted for either erythema or other biological response functions. However, the strongest longitudinal variations in the surface UV dose rate distributions are caused by climatological cloud distributions.

As expected, the highest doses are generally seen in the tropics, up to ca. 6 kJ m^{-2} day^{-1} (60 SED day^{-1}) for erythemal UV in the eastern Pacific and eastern Africa, but with substantial cloud-related reductions over western South America, parts of West Africa, and just north of the equator in the eastern and central Pacific. Middle latitudes of both hemispheres show a general pole-ward decrease from about 5 to 1 kJ m^{-2} day^{-1}, with some regional highs associated with higher elevations, smaller ozone columns, and infrequent cloudiness (e.g., the Andes

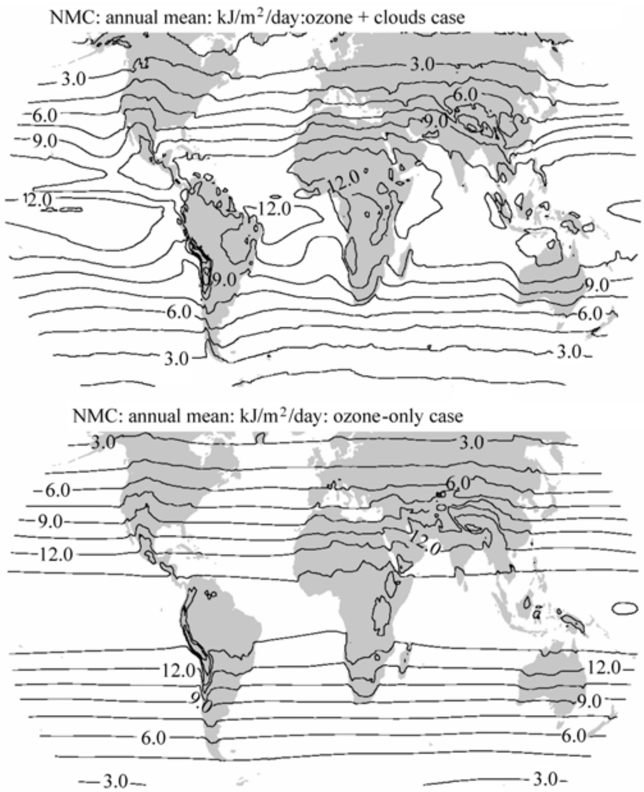

Figure 1.6 Climatological daily doses of UV weighted for non-melanoma carcinogenesis at earth’s surface, as Fig. 1.2

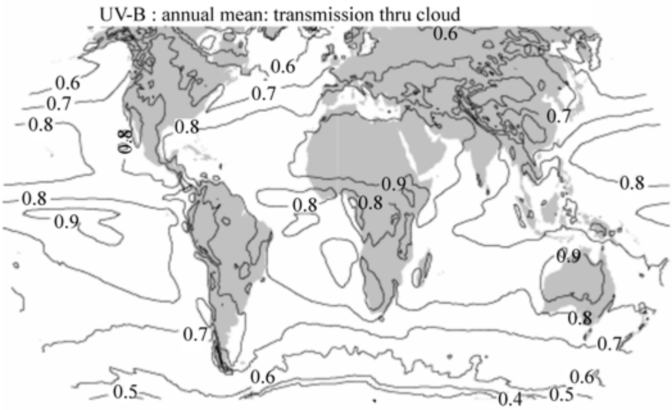

Figure 1.7 Climatological annual mean cloud-related UV reduction factors for daily doses of UV-A derived from satellite (TOMS) observations of the atmospheric ozone column and cloud reflectivity at 380 nm for Nov 1, 1978 – June 30, 2000. Cloud-related UV reduction factors for the other UV functions discussed in this chapter are similar

Mountains, the Tibetan Plateau, central Mexico, and the southwestern U.S.). Lower values for those latitudes are noted for East Asia and the coastal eastern Pacific, associated with more frequent cloud cover. Figure 1.7 shows the cloud-related UV reduction factor, calculated as the ratio of the cloud-corrected climatological daily UV dose (upper panels of Figs. 1.2 – 1.6) to the climatological daily dose before cloud-correction (lower panels of Figs. 1.2 – 1.6).

The seasonal variations of the 22-year UV dose climatologies are shown in Figs. 1.8 – 1.11. (The seasonal variability of UV weighted for non-melanoma carcinogenesis is similar in magnitude and distribution to that of UV weighted for pre-vitamin D3 synthesis, so it is not shown.) The latitudinal distributions are generally consistent with the annual variation of the subsolar point in the tropics, giving strong seasonal variations at temperate latitudes (out of phase by six months between the two hemispheres).

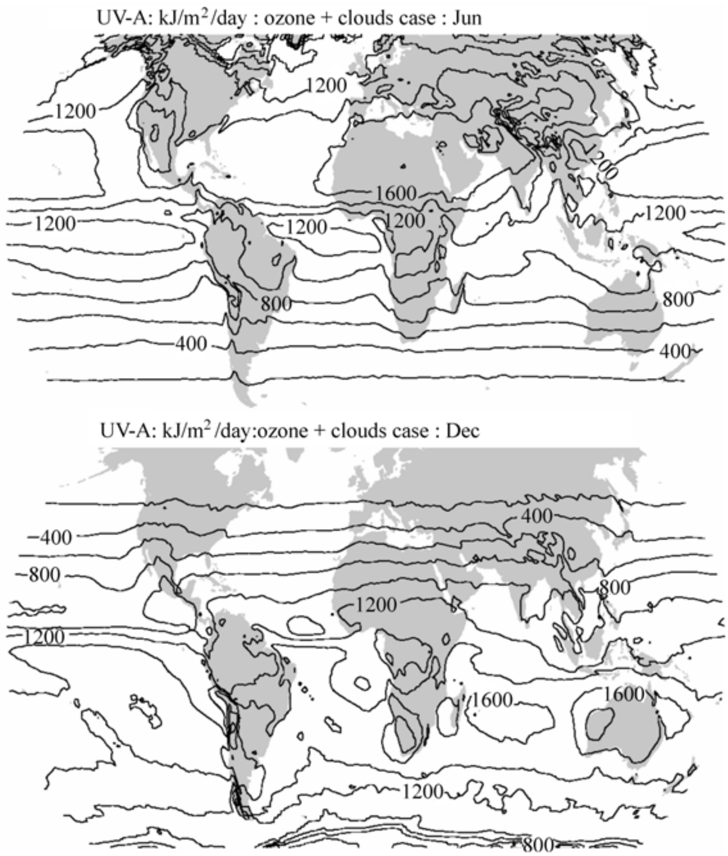

Figure 1.8 Seasonal variability of daily doses of UV-A. The figure shows the daily doses averaged over the period Dec. 1, 1978 – June 30, 2000 for the months of June (upper) and December (lower)