USDA United States
Department of
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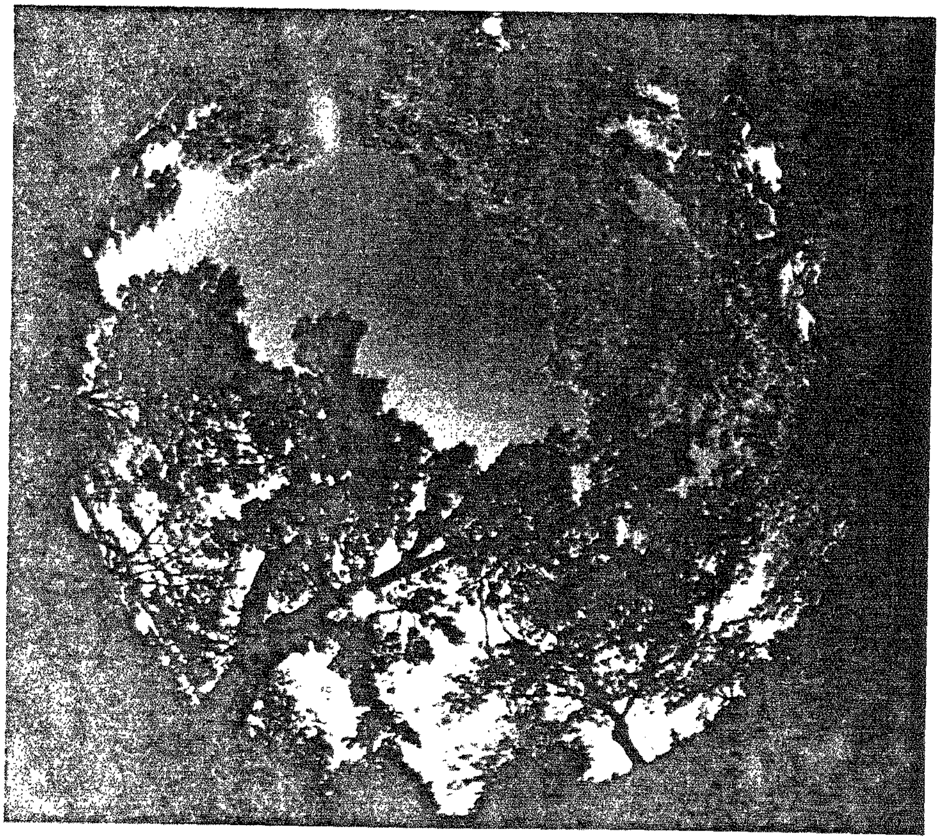
Forest Service

**Northeastern
Research Station**

General Technical
Report NE-268

Ultraviolet Radiation, Human Health, and the Urban Forest

Gordon M. Heisler
Richard H. Grant



Abstract

Excess exposure to ultraviolet (UV) radiation from the sun, particularly the ultraviolet B (UVB) portion, has been definitely linked with adverse effects on human health, including inducement of skin cancers and eye diseases. Also suspected are UVB influences on immune systems and effectiveness of immunizations. Skin cancers are the most common form of cancers among light-skinned people. The skin cancer rate has increased greatly in recent years, largely owing to changes in dress and lifestyle. Increased UV irradiance caused by reductions in stratospheric ozone since the 1970's apparently has also played a role in the increased incidence of various diseases. Trees may prevent even greater disease rates in humans by reducing UV exposure. Trees greatly reduce UV irradiance in their shade when they obscure both the sun and sky. However, at locations where trees obscure the sun but leave much of the sky in view, UV radiation is much more prevalent than is suggested by the appearance of the visible shadow. Recent measurements of leaf optical properties and algorithms describing sky-radiance distributions will provide information for generating computer models of the effect of trees on UV radiation. These models will be useful in estimating the climatology of UV irradiance in urban areas with trees and buildings, and will aid epidemiological studies and in preparing illustrations of shade patterns for use in public education programs.

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Manuscript received for publication 11 September 1997

Published by:
USDA FOREST SERVICE
11 CAMPUS BLVD SUITE 200
NEWTOWN SQUARE PA 19073

February 2000

For additional copies:
USDA Forest Service
Publications Distribution
359 Main Road
Delaware, OH 43015
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Introduction

The news media frequently report warnings of the potential damage to life on Earth as a result of increasing pollution of the stratosphere, which leads to reduced ozone, and consequently to increases in ultraviolet (UV) radiation. Concerns include potential effects of ultraviolet radiation on human health, including skin cancer and cataracts. About 1 million skin cancers are diagnosed in the United States annually (Am. Acad. Dermatol. 1994, Geller et al. 1996; Weary 1996). The UV Index now is included in many TV weather reports.

Just what is UV radiation and what are its effects on human health? Is the UV radiation that people intercept outdoors in their daily routines already a health concern or are its effects exaggerated? Does tree shade provide protection against UV radiation? Can UV damage be ameliorated by careful design of landscapes and management of trees and other vegetation along streets and in residential yards, parks, plazas, and playgrounds? Will the UV problem get worse in the future? What does all of this mean for *urban forest*[1] management and the arboricultural industry?

In this paper we explore these questions by reviewing the scientific literature. Answers are incomplete largely because UV radiation is a highly complex phenomenon (Nunez et al. 1994). We identify some of the reasons for this complexity by examining the methods for and problems related to measuring and predicting UV radiation, and report results of our measurements designed to add to current knowledge of UV radiation in urban ecosystems, including how trees affect UV levels. We also analyze reports of long-term trends in UV irradiance on Earth, as such trends are critical for evaluating the potential importance of urban trees in modifying UV climates for people and for predicting tree effects on future UV climatology.

Beginning in the early 1970's, concern that UV radiation at the surface of the Earth might increase led to a surge in scientific research on UV radiation and its effects on life. Interest was intensified in 1985 when scientists confirmed the existence of an "ozone hole" above the Antarctic. Since that time, the scientific literature has included important symposia, reviews, and assessments of ozone depletion and its implications (U.N. Environ. Prog. 1989, 1991, 1994, 1998; World Meteorol. Org. 1989, 1995; Rowland 1991) and UV radiation and its effects (Biggs and Joyner 1994; Sliney et al. 1994, Tevini 1993; Young et al. 1993; Gallagher and Elwood 1994; Int. Agency for Res. on Cancer 1992).

A wealth of information on ozone and UV radiation is available on the Internet via various search engines. As of this writing, especially noteworthy information was available by locating the home pages for the following organizations and agencies and then searching "ozone" or "ozone depletion": Center for International Earth Science Information Network (CIESIN) and its Socioeconomic Data and Applications Center (SEDAC), National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), and Environmental Protection Agency (EPA). Another Internet source is a set of four "Ozone Depletion FAQ" by professor Robert Parson at www.faqs.org.

In addition to its possible harmful effects on human health, UV radiation may adversely affect components of urban ecosystems, specifically, materials degradation (Andrady 1993; U.N. Environ. Prog. 1991, 1994); wildlife (DeFabo 1994); aquatic systems (U.N. Environ. Prog. 1994; Schindler et al. 1996); pest survival (Coohill 1992); pesticide effectiveness (Yang et al. 1993); and plant growth and competitive ability (Caldwell 1971; Caldwell and Flint 1994; Caldwell et al. 1998; Sullivan 1992, 1993; Tevini 1994). Excess exposure to UV radiation affects many plant species through a variety of interacting mechanisms that may enhance or reduce growth rates (Berkelaar et al. 1996; Grant 1997a). An important interaction is that between UV radiation and photosynthetically active radiation (PAR). Humans also could be affected indirectly by changes in UV radiation climatology should those changes have a negative impact on agriculture or forest production (Longstreth et al. 1994).

Ultraviolet Radiation

The Solar Spectrum

In terms of energy, UV radiation outdoors is a small part of the normal electromagnetic radiation from the sun. This energy varies in intensity with wavelength, and this pattern of energy variation with wavelength defines the *solar spectrum* (Fig. 1). The spectrum is divided into wavelength bands with the shortest in the ultraviolet, then visible, and finally infrared radiation (Fig. 2). The division into bands separates wavelength ranges that differ greatly in transmission through the atmosphere and in their effects on biological systems. Wavelengths with the most influence on biological systems are usually reported in nanometers (nm), or one billionth of a meter. Wavelengths from about 700 to 290 nm are of particular interest. As wavelength decreases, the frequency of radiant energy increases.

From 700 to 400 nm, PAR provides the energy for plant photosynthesis. The PAR band, which encompasses about 75 percent of the sun's energy (Gates 1980), corresponds closely with the visible spectrum, that is, the wavelengths between about 780 and 400 nm that humans can see.

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[1] Terms in italics are defined in the glossary.

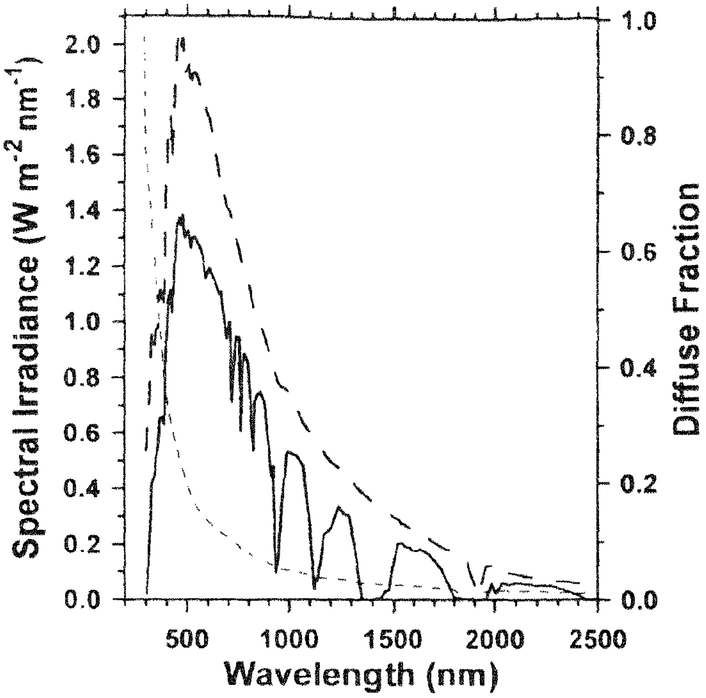

Figure 1.—Solar irradiance versus wavelength above the atmosphere (long dashes) and representative pattern of irradiance on a horizontal surface at ground level with clear skies at noon (solid line). The irradiance on a horizontal surface that is from the sky as a fraction of total irradiance is indicated by the short dashed line and right axis.

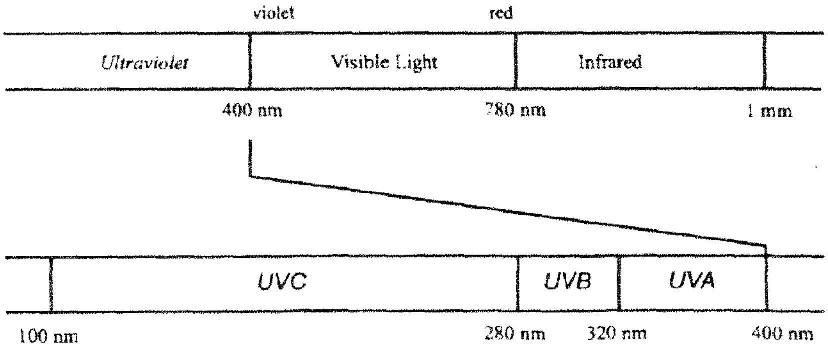

Figure 2.—Wavelength bands in the solar spectrum; data from de Gruijl (1995) and International Agency for Research on Cancer (1992).

The UV wavelengths lie between 400 and about 10 nm (Int. Agency for Res. on Cancer 1992). Within this range, three bands between 400 and 100 nm are of most interest here. Ozone in the *stratosphere* has very different effects on the three UV bands. The UVA band (Fig. 2), usually defined in the United States as the wavelengths between 400 to 320 nm, makes up about 3 percent of the total solar energy at the Earth's surface. This band is not significantly attenuated by ozone. The UVB band extends from 320 to 280 nm in most classification schemes; in Europe, UVB often is divided from UVA at 315 nm. Within the UVB band, ozone absorption increases dramatically, from about 1 percent of the sun's energy at 320 nm being absorbed by atmospheric ozone to nearly 100 percent at 280 nm (Fig. 3). Because of the ozone absorption between 290 and 240 nm and oxygen absorption below 240 nm, essentially no measurable radiation reaches the surface of the Earth below about 290 nm (Wayne 1991). Thus, effective UVB is from 320 nm to about 290 nm (different reports give values for the lower wavelength limit between about 290 and 295 nm). At the surface of the Earth, the UVB band contains less than 0.1 percent of the energy in the total solar spectrum. Below 280 nm, the UVC band extends to 100 nm. UVC energy would be calamitous to life on Earth (de Gruijl 1995) were it not absorbed entirely by ozone and oxygen.

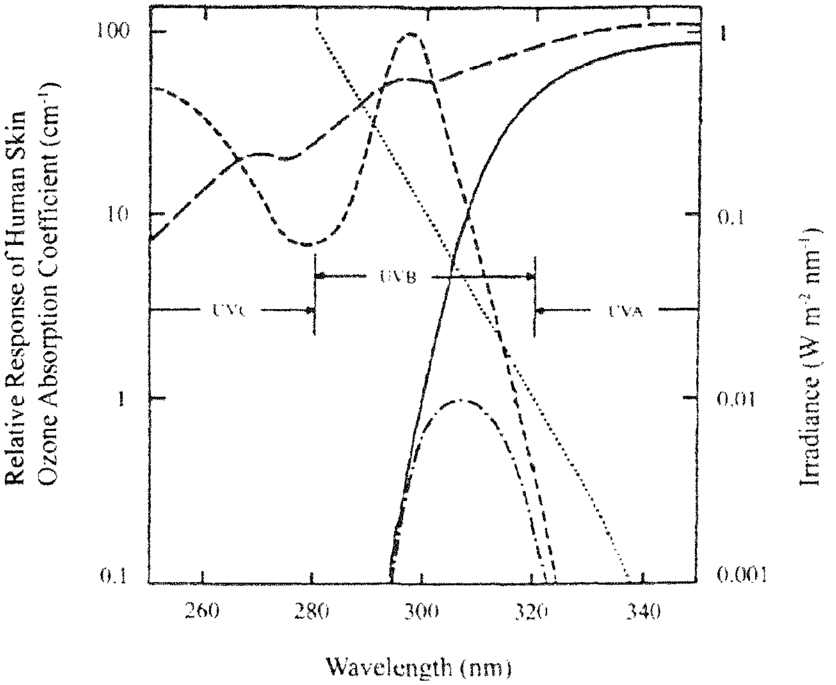

Figure 3.—Relationships important to understanding UVB radiation at the surface of the Earth: (1) Irradiance above the atmosphere (long dashes); (2) Typical pattern of irradiance at the Earth's surface after absorption by ozone (solid line, scale on the right); (3) The ozone absorption coefficient (dotted line, scale on the left); (4) Relative tendency of light-colored human skin to burn (short-dash line); (5) The importance of different wavelengths of radiation in sunburning (dash-dot line) derived by the multiplication of irradiance times burn tendency (modified from Barton and Paltridge 1979).

Atmospheric Processes that Influence Ultraviolet Radiation

The importance of UV in urban ecosystems depends on the annual cycle and long-term trends of *irradiance* and the distribution of energy in specific wavelengths. Cycles, trends, and wavelength distributions depend on atmospheric processes. In the UVB, ozone absorption is especially important. Most of this absorption takes place in the stratosphere, where ozone is at a maximum about 25 km (15 miles) above Earth (Fig. 4). Ozone in the atmosphere often is characterized by the depth that it would take up if it were brought together in a layer at sea-level pressure. The depth, referred to as "total column" ozone, is reported in centimeters or in units equal to 1/1000 of a centimeter, also known as a *Dobson unit* (DU), after the scientist who invented an instrument to measure ozone depth.

About 90 percent of the ozone (O_3) in the atmosphere forms in the stratosphere (Fig. 4), where radiation with wavelengths less than about 240 nm in the UVC splits molecules of oxygen (O_2), leaving two O molecules which can join with O_2 molecules to form O_3. Ozone is not a stable molecule. The quantity of O_3 in the stratosphere is in approximate balance because it breaks down and re-forms continually. Manmade chemicals, particularly chlorofluorocarbons (CFC's), upset this balance by catalyzing O_3 breakdown. The catalytic effect of CFC's also is a function of solar irradiation. Usually stable and nonreactive, these chemicals are split by the intense UV radiation in the stratosphere. After they split, the parts become catalytic and speed the breakdown of O_3.

Even without pollution, stratospheric O_3 depth would vary over the Earth owing to natural processes in the atmosphere. Primary among the natural processes are the differences in solar radiation with latitude and the change of seasons combined with global air-mass circulations. These circulations have a major role in the formation of the polar ozone hole. In the stratosphere over equatorial regions, winds tend to blow in an easterly or westerly direction in a somewhat regular pattern known as the Quasi-Biennial Oscillation (QBO). The QBO causes cycles of stratospheric O_3 levels (Berger 1987; Gleason et al. 1993). The O_3 cycle peaks occur at 23- to 27-month intervals, and UVB irradiance may increase or decrease by as much as 8 percent at some places on Earth (Berger 1987).

The 11-year solar sunspot cycle causes variations in total column O_3 of about 1 percent (John E. Frederick pers. commun.). Higher sunspot activity corresponds to increased solar UV and hence more rapid production of O_3. Recent reports (Hood 1997; Shindell et al. 1999) examine the heights in the stratosphere and troposphere where the sunspot influences on O_3 are greatest, the relationship between sunspot influences on ozone and weather, and the difficulty of separating sunspot influences from effects of volcanic emissions.

Volcanic aerosols seem to reduce stratospheric O_3 (Gleason et al. 1993). Apparently there are reactions in the stratosphere between materials from volcanic eruptions, e.g., sulfur dioxide (SO_2), and chlorine and bromine chemicals from human sources that lead to O_3 destruction (Vogelmann et al. 1992; World Meteorol. Org. 1995). The net

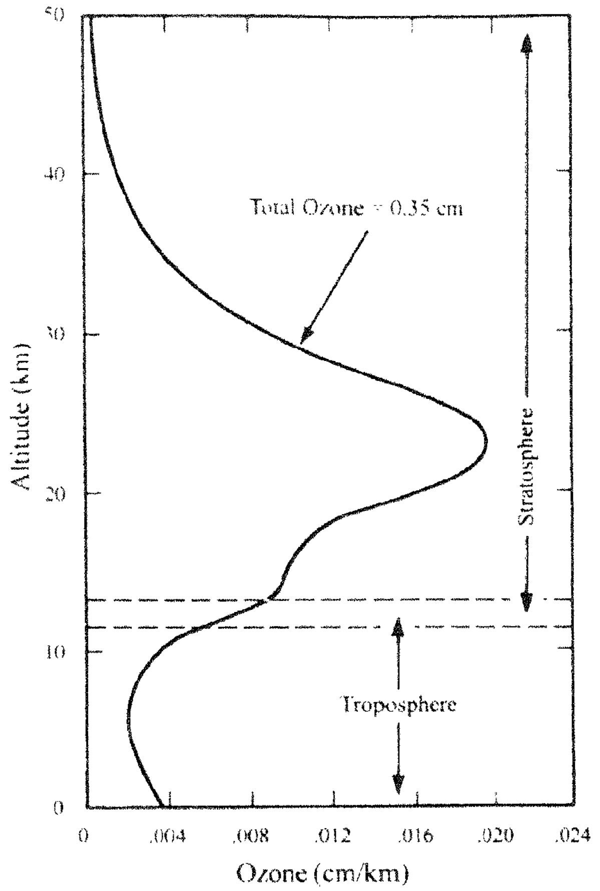

Figure 4.—Typical profile of ozone concentration in the atmosphere (modified from Iqbal 1983). The dashed lines show the approximate midlatitude height of the tropopause, the division between the troposphere and stratosphere.

effect of volcanic eruptions on UVB irradiance at the surface of the Earth is a balance between reductions in O_3 and increased scattering of the radiation by particles. This balance generally results in increased UVB (Vogelmann et al. 1992).

Ozone in the troposphere (Fig. 4) can be significant in absorbing UV radiation, particularly in industrial areas (Lubin and Jensen 1995). Tropospheric O_3 absorbs UV radiation more efficiently than stratospheric O_3 because the greater scattering in the troposphere creates longer effective path lengths (Bruhl and Crutzen 1989). In some areas, increases in tropospheric O_3 due to chemical reactions of pollutants may be large enough to counteract the effect of reduced O_3 in the stratosphere (Bruhl and Crutzen 1989; Stolarski et al. 1992).

In addition to absorption by O_3, UVB irradiance at the surface of the Earth varies with other factors that influence the rest of the solar spectrum—clouds, haze, SO_2 and other pollutants, reflectivity of the surface of the Earth, sunspot cycles, and direct effects of volcanic dust (Bais et al. 1993; Kerr and McElroy 1993; Nunez et al. 1994). Cloud effects on UV irradiance at ground level often are compared to the effects of O_3 on irradiance. In the UVB band, O_3 absorption differs so much with wavelength (Fig. 3) that the impact of O_3 on UV relative to cloud effects on UV differs greatly with wavelength. In the shortest UVB wavelengths (below 300 nm), O_3 scattering reduces irradiance to 10 percent or less of irradiance above the atmosphere (Bais et al. 1993). When the entire UVB band is considered climatologically, irradiance generally is influenced more by variable cloud cover than by variations in O_3 column depth (Blumthaler et al. 1994; Frederick et al. 1993).

Scientists have disagreed on how clouds affect UV versus the longer wavelengths of radiation. Some studies suggest that because of greater scattering of the short UV wavelengths than in the longer wavelengths, cloud cover reduces total solar irradiance to a greater degree than the UV (Blumthaler et al. 1994; Estupinan et al. 1996; Spinhirne and Green 1978). Other researchers have found that relative reductions in irradiance by clouds do not differ for the UVB and total shortwave spectra (Frederick et al. 1993). The effect of clouds on scattering of solar radiation is about the same for all UV and visible wavelengths (John E. Frederick, pers. commun.). For seven half-hour measurements with overcast skies, we found similar attenuation for the UVB and PAR bands. UVB was reduced by an average of 76 percent from clear sky conditions with the same sun angle versus 74 percent for PAR, but the difference was not statistically significant (Grant and Heisler 1997). The thickness of the cloud cover is less important than the fraction of sky covered with clouds (Frederick and Snell 1990). With full-sky coverage by opaque clouds, average reductions in UVB irradiance are much larger than if a small portion of the sky (1/8 or 1/10) is clear (Bais et al. 1993; Barton and Paltridge 1979; Blumthaler et al. 1994).

Cloud cover does not always result in less irradiance at the ground surface. When *cumulus humilis* clouds are present, localized increases in UVB can be as much as 27 percent greater than when skies are clear, particularly when the sun is high in the sky near noon (Estupinan et al. 1996; Mims and Frederick 1994). Such increases can easily last for 30 minutes or more—sufficient time for a person to acquire a severe case of sunburn.

Annual Cycles

In the tropics (0 to 23° N and S latitude), variation in UVB radiation is small because of interacting consequences of relatively constant inputs of solar energy on a horizontal surface at the top of the atmosphere through the year. Likewise, the variation in O_3 throughout the year is small because the variation in O_3-producing solar radiation is small. In the tropics, total column O_3 depth usually is between 250 and 300 DU (0.250 to 0.300 cm) year round (similar to Miami in Figure 5). Ozone tends to be formed over the tropics and then carried to high latitudes by prevailing wind in the stratosphere (Rowland 1991). In midlatitudes,

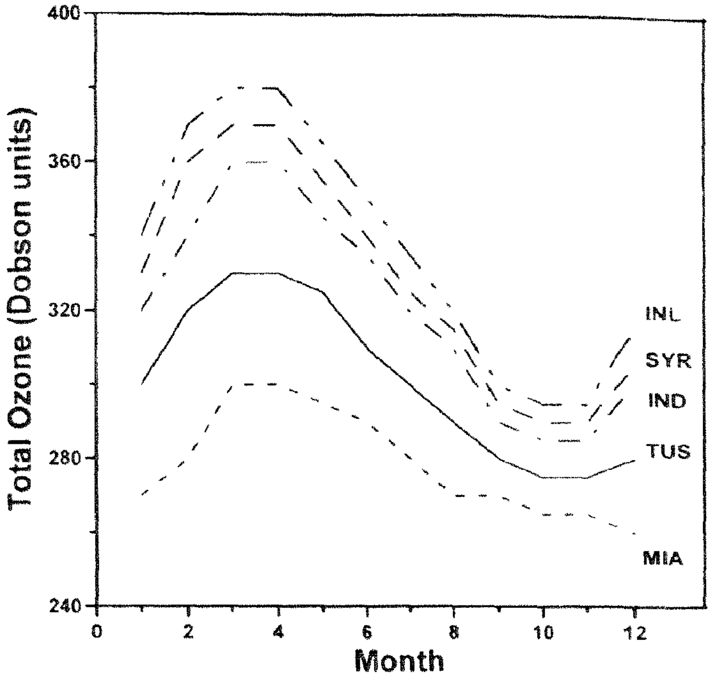

Figure 5.—Annual variability of atmospheric ozone at the latitude of five cities in the United States (International Falls, MN [INL], 49°; Syracuse, NY [SYR], 43°; Indianapolis, IN [IND], 40°, Tucson, AZ [TUS], 32°; and Miami, FL [MIA], 26°). Ozone values are from the World Meteorological Organization (1989), assuming global mean atmospheric ozone content at each city's latitude. Note the larger variability through the year in the north (higher latitudes) than in the south.

where stratospheric O_3 is more variable. O_3 depth ranges from about 250 to 450 DU and there is an annual O_3 cycle, with average depth peaking in early spring and then declining until it is about 25 percent less in midautumn. Ozone depth then gradually returns to spring values (Fig. 5). Superimposed on annual average stratospheric O_3 cycles in midlatitudes are short-term fluctuations of about 100 DU. The durations of these fluctuations are similar to those for the passage of weather systems. Differences from one day to the next can be up to 60 DU at high latitudes.

Ozone is more variable over polar regions than at other latitudes; this is especially true in the Southern Hemisphere. For example, a satellite image from October 6, 1996, shows a range from about 100 DU near the south pole to nearly 450 DU south of Australia (Fig. 6). On average, at least in recent years, total column O_3 has been lower in the Southern Hemisphere than at equivalent latitudes in the Northern Hemisphere (U.N. Environ. Prog. 1994).

A combination of factors contribute to the ozone hole in the Antarctic (Graedel and Crutzen 1993; Rowland 1991; Wayne 1991). Because of the extreme cold during the winter above Antarctica, crystals of ice form in the stratosphere that do not form elsewhere. The cold conditions lead to a vortex circulation of the atmosphere around the Antarctic region that funnels in and traps O_3-destroying chemicals. With the lack of sunshine during the polar winter, the chemicals build up throughout the season. Then, with the coming of the southern polar spring, the sun rises and breaks down these chemicals, forming O_3-splitting catalysts. The crystalline ice enhances the catalytic effect, and the result is a dramatic ozone-sparse hole in the stratosphere over Antarctica (Fig. 6). As spring turns to summer, the vortex breaks up and the O_3-depleted air mixes with air over lower latitudes (Fig. 7), raising concern that UVB will increase in New Zealand, Australia, southern South America, and southern Africa (Burke 1995).

Although the effects of O_3 on UVB irradiance at the surface of the Earth are important, in northern midlatitudes, the annual cycle of UVB irradiance depends mostly on the sun's daily path across the sky. When measured on horizontal surfaces, the usual comparative measure, UVB irradiance at noon with clear skies in U.S. cities is greater at more southern locations (Fig. 8). However, on south-facing surfaces, noon UVB irradiance is similar at all U.S. latitudes between May and September, and the effect of lower O_3 values in autumn is more pronounced (Fig. 9). As shown in Figure 9, the potential for exposure to UV radiation in the United States can be as great at northern as at southern locations depending on the orientation of the surface.

Another factor that may influence exposure to UV radiation is reflection from objects on the ground. Most surfaces reflect only a small percentage of UVB radiation that falls on them. However, reflection of UVB from snow can exceed 95 percent of incident radiation and add greatly to irradiance on nonhorizontal surfaces (Fig. 10).

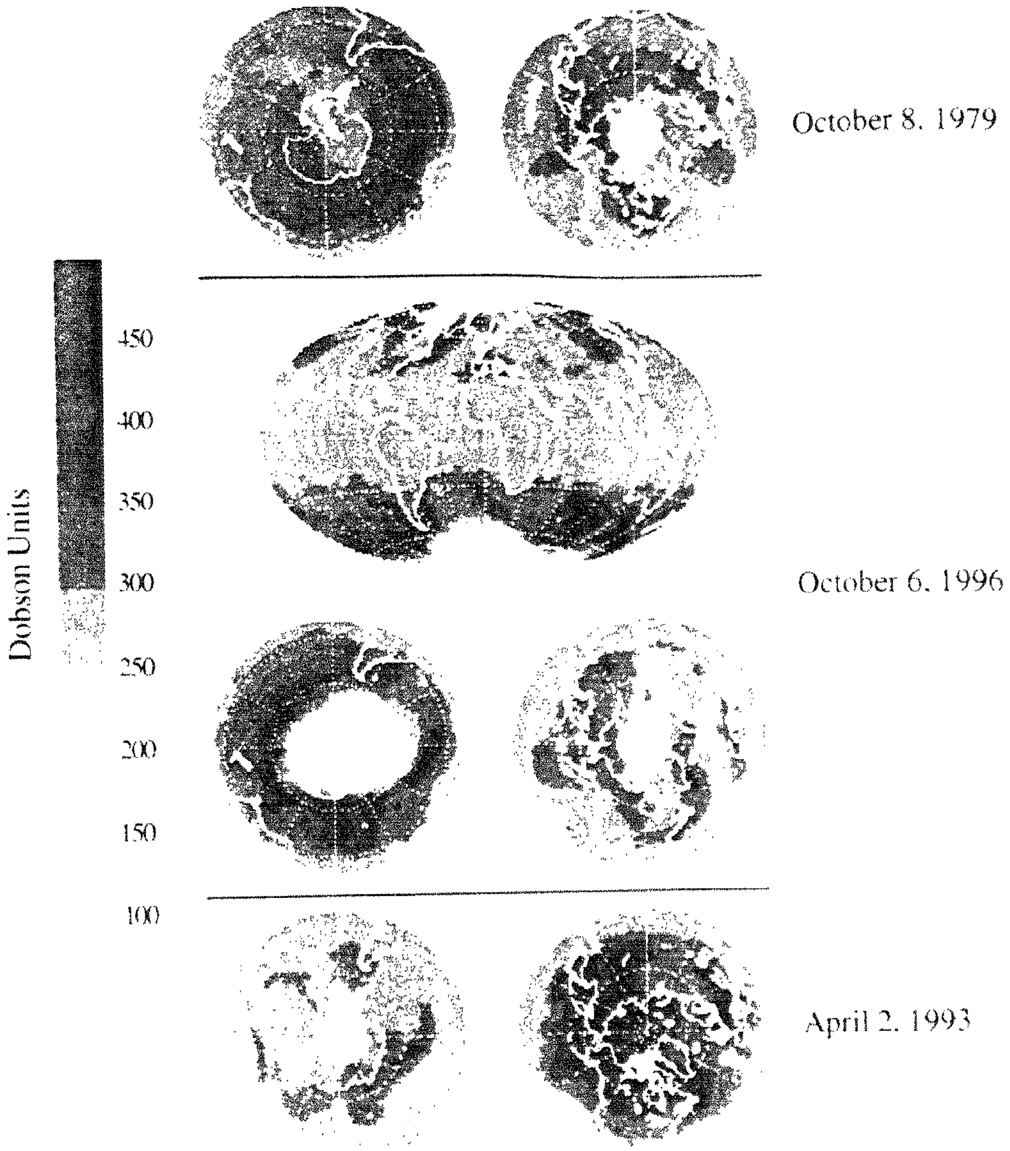

Figure 6.—Satellite images of the distribution of total column ozone derived from NASA Goddard Space Flight Center TOMS satellite images: (top) Southern and Northern Hemisphere ozone depths on a representative day in the first October (Southern Hemisphere spring) of the Nimbus 7 TOMS record. The white circle over the north polar region is in polar night when ozone is not measurable by satellite; (middle) World and hemisphere views of total ozone near the time of the Antarctic ozone minimum in 1996 from ADEOS TOMS. Contrast with the 1979 image. The ozone hole is plainly visible in 1996, though northern hemisphere ozone is similar in the two years; (bottom) The two hemispheres near the time of the Northern Hemisphere ozone maximum in April 1993, the last northern spring in the Nimbus 7 TOMS record. Note the absence of an ozone hole over the north polar region in its spring as contrasted with the south in its 1996 spring. The ozone hole over the Antarctic was slightly larger in October 1993 than in October 1996 (NASA 1996).

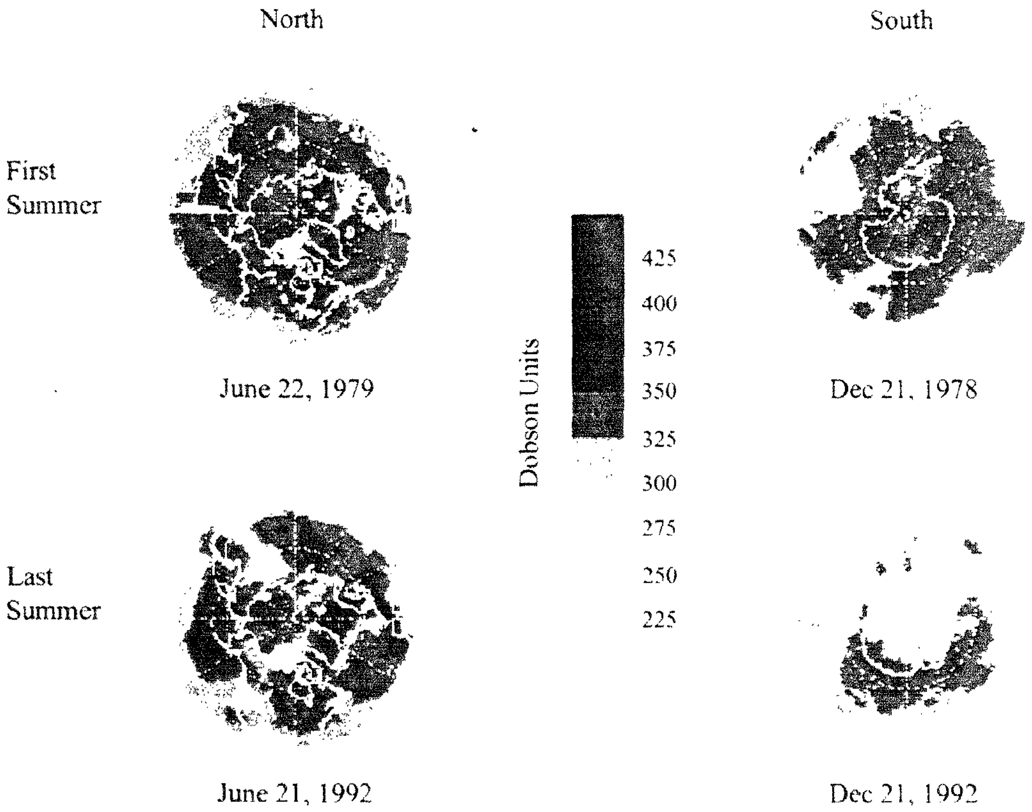

Figure 7.—Samples of ozone patterns from the first and last summers of the Nimbus 7 TOMS series. Note the slightly lighter shading, indicating less ozone in the last summers, particularly for the Southern Hemisphere.

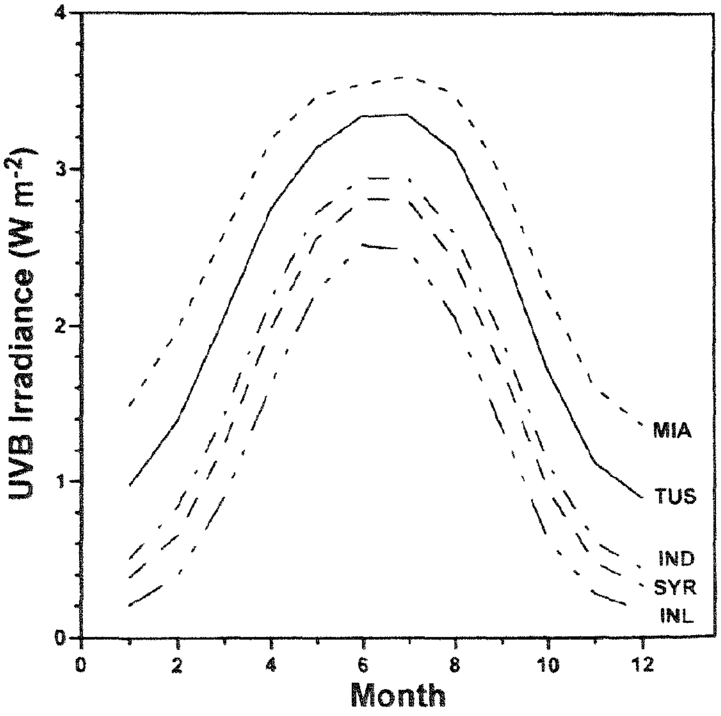

Figure 8.—UVB irradiance on horizontal surfaces with clear skies at solar noon on an average day (Iqbal 1983) of each month for the five cities shown in Figure 5 (from Grant and Heisler 1993). The symmetry of the UV irradiance curves on each side of the month of June is disturbed only slightly by ozone differences through the year (Fig. 5). Irradiance is calculated by the model of Green et al. (1974).

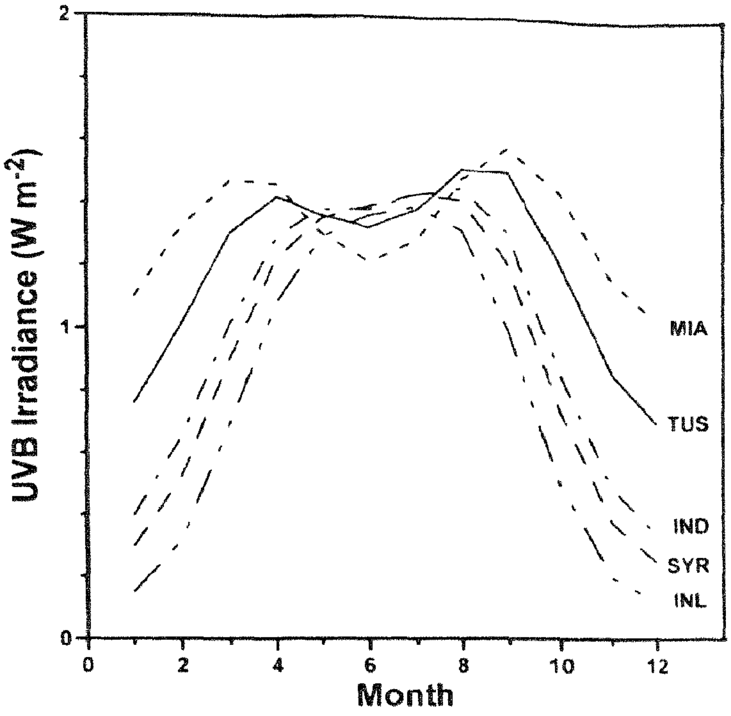

Figure 9.—UVB irradiance on south-facing surfaces with clear skies at solar noon on the 21st of each month for the five cities listed in Figure 5.

Measuring Ultraviolet Radiation and Ozone

Ground-Level Measurements

Measurements of UV radiation are far more complex than measurements of other parts of the solar spectrum that reach the surface of the Earth. Although radiation in the UV can be damaging, especially sensitive radiometers are required for measurement because of low energy levels, particularly in the UVB band. It is difficult to prevent the stray light of longer wavelengths from interfering with UV measurements. Also, detecting long-term trends in UV radiation requires stable instruments that hold their calibration. However, most tend to be unstable because even the most simple instruments have several components that deteriorate with time or use.

Ultraviolet B and O_3 are closely linked in measurements because many methods of measuring atmospheric O_3 rely on measurements of radiation transmission in the UVB band. In the 1880's, it was discovered that there is essentially no radiation at the Earth's surface below a wavelength of 293 nm. At that time it was known that O_3 absorbed very strongly below 293 nm. This suggested the presence of the O_3 layer in the atmosphere. In the 1920's, G.M.B. Dobson adapted existing instruments to derive measurements of total column O_3. His instrument compared the intensity of radiation in a narrow wavelength band within the UVB, which is strongly influenced by O_3 to the intensity of a narrow band in the UVA, which is not influenced by O_3 (Rowland 1991). A worldwide network of Dobson instruments was implemented in the 1920's and 1930's. This technique with several modifications still is used to provide total column ozone measurements against which satellite-based ozone instruments are calibrated (McPeters et al. 1996, Stolarski et al. 1992). Around the world, more than 30 Dobson instruments have operated routinely since 1957 (Gleason et al. 1993; Stolarski et al. 1992).

Instruments that can measure radiation over broad ranges of wavelength but accurately differentiate between measured amounts in different narrow wavelength bands, e.g., 1- or 2-nm band widths, are called spectroradiometers or spectrophotometers (Barnard and Cupitt 1994, Diffey 1987; Josefsson 1993). These instruments are expensive (about $150,000), complex, and difficult to calibrate and use. A spectral instrument commonly used in networks is the Brewer spectrophotometer. More than 90 Brewer instruments are operating around the globe as part of a network that was developed in the early 1980's. Brewer data are archived for the World Meteorological Organization by the Atmospheric Environmental Service of Canada in Toronto (Barnard and Cupitt 1994).

More common are sensors that measure all the radiation within the UVB wavelength band (broadband sensors). These generally are designed with a response that differs with wavelength to represent the response of human skin to sunburn, or erythemal *action spectrum* (Figs. 11 - 13). The unit of measure with these instruments usually is the *minimal erythemal dose (MED)*, which is the lowest radiant exposure (in units of energy per unit area of skin) that will result in noticeable sunburn on light-skinned individuals (Diffey and Elwood 1994).

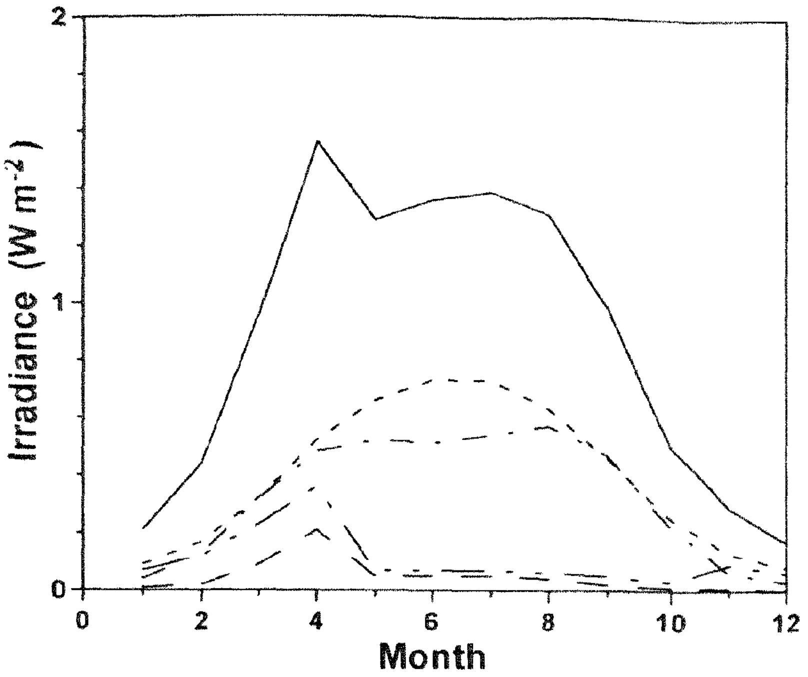

Figure 10.—UVB irradiance on a south-facing surface with clear skies at solar noon on the 21st of each month with snow on the ground during the winter season, at the latitude of International Falls, MN. Total UVB irradiance (solid line) is shown along with contributions to the total from sky radiance (short dash), direct beam from the sun (long-dash short-dash), originating from the sky and reflected to the surface (long-dash short-dash short-dash), and originating from the direct beam and reflected to the surface (long dashes).

The earliest networks of broadband monitors usually used sensors of a type known as Robertson-Berger (R-B) meters (Berger 1976; Nunez et al. 1994; Scotto et al. 1988a). The current version is manufactured by the Solar Light Co.[1] of Philadelphia, PA. The U.S. Department of Agriculture has a national network for monitoring UVB surface irradiance in rural areas (Gibson 1991). The USDA network is using broadband meters manufactured by Yankee Environmental Systems (YES) of Turners Falls, MA, that are similar in principal to R-B meters. The R-B and YES sensors cost about $5,000. The International Light (IL) Co. of Newburyport, MA, manufactures a variety of UV sensors, including some that approximate an erythemal response. An IL sensor and precision ammeter for making readings costs about $2,500, and sensors alone can be purchased for less than $1,000. The IL sensors are designed for laboratory or short-term outdoor measurements rather than long-term monitoring; they do not compensate for temperature. An advantage is that they can operate with only small batteries for power.

Different broadband instruments have slightly different approximations of the erythemal response (Figs. 11 - 12). The R-B meter response (Fig. 11) is greater than the assumed erythema response between 300 and 340 nm (Kennedy and Sharp 1992; Scotto et al. 1988a). Within the UV spectrum, relative energy levels change greatly over a short span of wavelengths (Fig. 3). A small change in the pattern of sensor response with wavelength can result in a large change in total response. Also, as the sun changes position from directly overhead and its rays pass through a greater length of the atmosphere, the shortest wavelengths are increasing absorbed by O_3, thus changing the wavelength distribution during a typical day. The output of broadband UV meters with weighted response functions can be converted to energy units rather than MED, but because the solar spectrum changes with solar zenith angle, the conversion is approximate.

Another common problem associated with broadband UV sensors is that they register less radiation than they should when the angle of incidence of the radiation is not close to perpendicular to the sensor surface, as when the sun is low in the sky (Deluisi et al. 1992; Grant 1996). Without special temperature controls, UV radiometers tend to be sensitive to the temperature of the sensor (Blumthaler and Ambach 1986; Grant 1996). The first R-B meters that were part of the monitoring network developed in the 1970's did not have temperature controls (DeLuisi et al. 1992) and their sensitivity has been measured as increasing by 3 to 8 percent with a temperature change of 10°C (Blumthaler and Ambach 1986, Kennedy and Sharp 1992). Modern R-B meters and YES broadband radiometers used for long-term monitoring are equipped with temperature controls. This generally requires that they be used at sites with access to a power line.

Relatively new instruments that are a compromise between broadband sensors and spectroradiometers have several channels of moderate bandwidth (Dahlback 1996). For example, one instrument (GUV-511) from Biophysical

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[1] The use of trade, firm, or corporation names in this report is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that might be suitable.

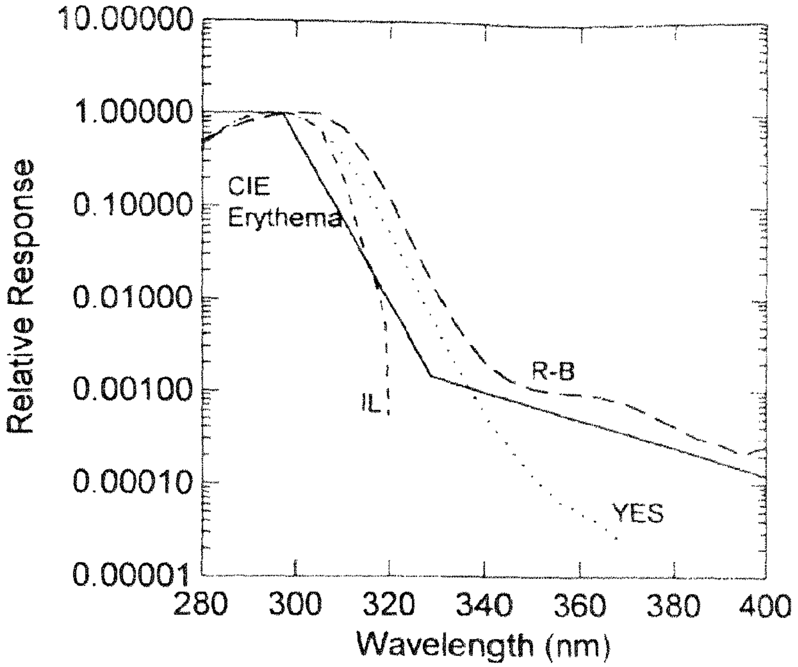

Figure 11.—Responses of the Robertson-Berger (R-B), Yankee Environmental Systems (YES), and International Light with SED/UVB/W filter (IL) UVB meters compared to human sunburn (erythema) by commonly used action spectrum, that of McKinlay and Diffey (1987) for the International Illumination Commission (CIE). Responses normalized to 1.0 at the wavelength of their peak values.

Instruments of San Diego, CA, has UV channels with 10-nm-wide bandwidths centered at 305, 320, 340, and 380 nm, from which the entire UVB and UVA bands may be extrapolated. Data from a channel in the UVB (305 nm) and another in the UVA (340 nm) provide a measure of total column O_3. Calculations can be made of effective UV dose rates for any action spectrum, such as that for erythema. The GUV-511 also has a channel in the PAR, which could be used as an approximation of visible radiation. These instruments cost about $12,000.

Measurements of human exposure to UV radiation have been made by personal dosimeters that people carry as they go about normal activities or experimental routines. One kind of dosimeter uses a film patch treated with a chemical, polysulphone, that gradually becomes less reflective of light when exposed to UV radiation (Diffey 1987, 1989; Diffey and Saunders 1995; Diffey et al. 1996; Gies et al. 1995; Melville et al. 1991). The film is worn like a badge, and after a day to a week it is examined for total UV exposure. A more sophisticated dosimeter uses a solid-state detector and a small recording data logger (Diffey and Saunders 1995). None of these dosimeters match human erythemal response precisely, though relative values are obtained that can be used to approximate erythemal response. Dosimeter measurements have been used in studies of human exposure to UV radiation but not on a large scale. One difficulty is in relating the results to the local UVB irradiance in the open during the measurement period (Nunez et al. 1994).

Satellite Measurements

In the late 1970's, the combination of satellite measurements and computer models of radiation transfer in the atmosphere began providing more information on UV irradiance at the Earth's surface than was being gathered from direct measurement at the surface. If the depth of O_3 is known and skies are cloudless and unpolluted, models can predict UVB irradiance at the surface of the Earth as accurately as irradiance can be measured by surface instruments (Eck et al. 1995; Madronich et al. 1994). The theory on which the models are based is well established, and the effects of O_3 on radiation are well known. Models are essential for predicting UV irradiance as O_3 quantities change in the future. The primary difficulty in predicting UV irradiance occurs with cloudy conditions and for polluted atmospheres (Nunez et al. 1994). Recent analysis techniques (Herman et al. 1996) have included cloud effects in satellite estimates of surface UVB irradiance.

Information on O_3 is available from several types of instruments carried on satellites. The Solar Backscattering Ultraviolet Ozone (SBUV) sensor detects O_3 in the column directly below the satellite by measuring upward reflected radiation at several wavelengths. The SBUV sensor can detect O_3 at different levels in the atmosphere (Long et al. 1996). A previous version operated from 1970 to 1972 (Stolarski et al. 1986). The TIROS Operational Vertical Sounder (TOVS) is another satellite instrument that detects vertical profiles of O_3 (Long et al. 1996). The TOVS sensor also measures temperature and water vapor profiles, but its

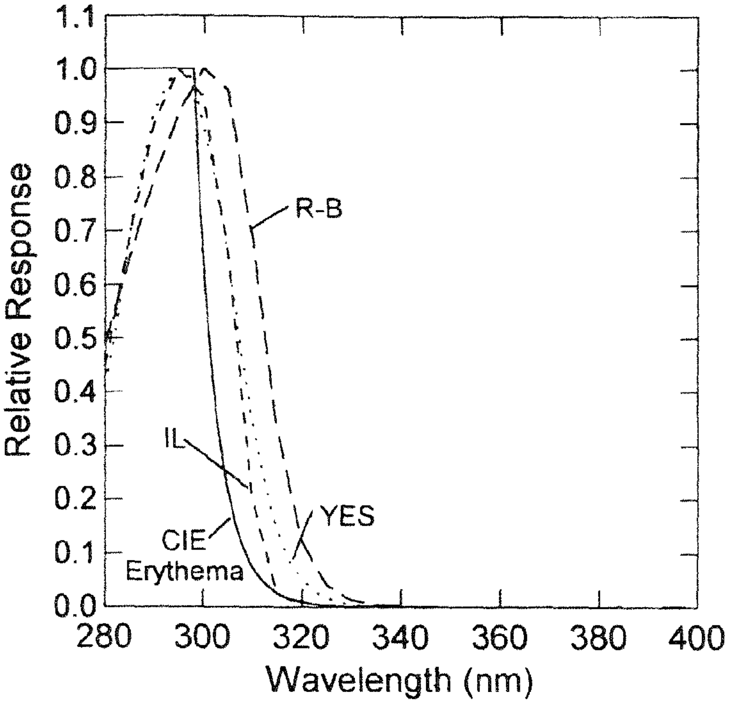

Figure 12.—The data in Figure 11 on a linear scale. The contrast between the two plots illustrates that semi-log plots generally are used because of the wide range of energy levels across the UVB wavelength band.

multifunctional design may make it less accurate for O_3 detection than other satellite sensors (Chen 1985). Both the SBUV and TOVS sensors are currently on board a satellite called NOAA-14; previous National Oceanic and Atmospheric Administration (NOAA) satellites also carried these instruments.

The Total Ozone Mapping Spectrometer (TOMS) was designed to measure the spatial distribution of total O_3. The first TOMS was carried on a satellite called Nimbus 7, which also carried an SBUV instrument that aided in calibrating TOMS. Nimbus 7 relayed information on O_3 depths around the world from November 1978 to May 1993. These data constitute the longest continuous record of O_3 depth around the globe from a single satellite instrument. These data have been analyzed in different ways to garner additional information and to recalibrate the sensor (Herman et al. 1996; Madronich and de Gruijl 1994). The Nimbus 7 TOMS global O_3 data and corresponding estimates of UVB irradiance at the surface of the Earth are available on the Internet from the Goddard Space Flight Center's Web site (currently http://jwocky.gsfc.nasa.gov/index.html) for intervals of 1° latitude by 1.5° longitude.

In 1996, two new NASA TOMS were placed in orbit but one was lost in July 1997. The Earth Probe TOMS (EPTOMS) began returning data on July 25, 1996 from a height of 500 km (310 miles). Two days are required to complete scanning the entire globe, but EPTOMS provides better resolution than other higher satellites. The second TOMS, on the Advanced Earth Observing Satellite (ADEOS) functioned from September 12, 1996 until July 1997, when the satellite was lost. The ADEOS TOMS provided total global coverage each day from a height of 800 km (Fig. 6). Data and images from operating NASA satellites are available via the Internet in nearly real time.

Long-term Trends in Ozone and UVB Irradiance

Trends in UVB irradiance at the surface of the Earth that extend over periods of longer than a year can be caused by (Madronich et al. 1994; Nunez et al. 1994):

- Long-term changes in output from the sun.
- General changes in global climate that might include changes in cloud patterns.
- Changes in O_3 and other pollutants in the troposphere.
- Volcanic activity.
- Oscillations in general air-mass circulation patterns.
- Changes in stratospheric O_3.

The trends in O_3 and UV irradiance have been analyzed from satellite and ground-station data. Figure 14 shows average stratospheric O_3 cycles—in fact, cycles upon cycles—from TOMS data over a 14-year period. There is a general swale in the pattern with the highest years in 1979 and 1990 and the lowest from about 1985 to 1988. However, a downward trend is apparent when a best-fit straight line is drawn through all years. The dashed line shows the predicted values from a statistical analysis for the years 1979 to 1991 (Gleason et al. 1993). The analysis in Figure 14 includes the effects of the QBO and the solar sunspot cycle (see **Atmospheric Processes that Influence Ultraviolet Radiation**). Figure 14 has been simplified

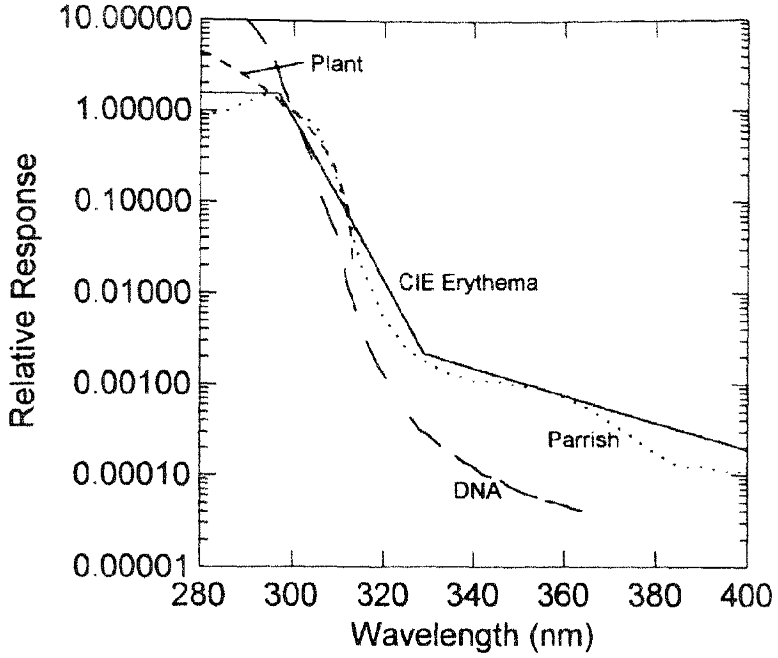

Figure 13.—Action spectra for erythema (CIE and Parrish [Parrish et al. 1982] spectra compared), DNA damage (Setlow 1974), and plant damage (Caldwell 1971; Caldwell et al. 1998). Responses normalized to 1.0 at 300 nm.

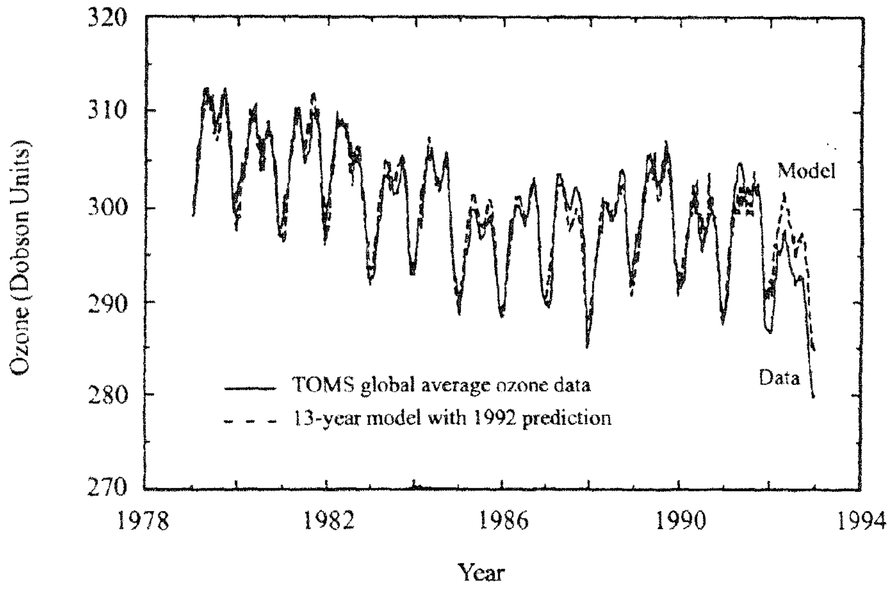

Figure 14.—Measured and modeled cycles of globally averaged ozone from 1979 through 1992 as derived from Total Ozone Mapping Spectrometer data (Gleason et al. 1993).

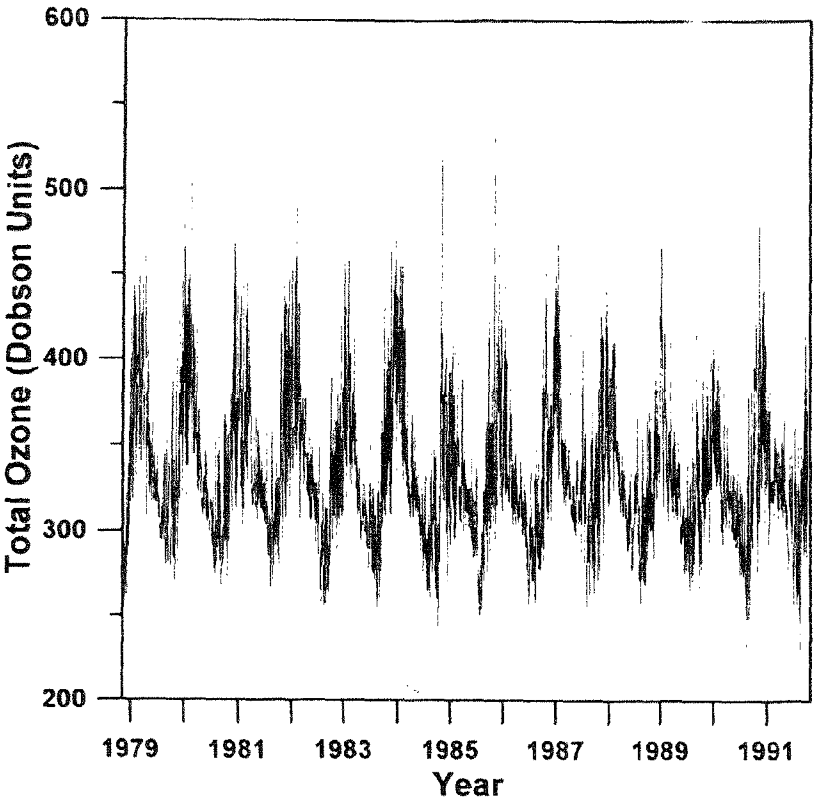

Figure 15.—Total column ozone at Urbana, IL, as measured by the TOMS on Nimbus 7 (data from Goddard Space Flight Center). Tic marks indicate January 1 of the labeled year.

because it consists of a series of weekly average O_3 values over the entire range of 130° of latitude. Latitudes beyond 65° N or S latitude are not included in these long-term averages to avoid the complexity of the polar nights when O_3 cannot be measured by TOMS. The complete pattern for a single location is further complicated by local variations with the passing of air masses as seen in Figure 15, which represents a continuous O_3 pattern for one latitude and longitude.

In Figure 14, O_3 in the last year, 1992, is lower than the predicted trend by about 2 percent. This is interpreted as being largely an effect of the eruption of Mt. Pinatubo in June 1991 (Gleason et al. 1993). In 1992, when large amounts of ash from the Mt. Pinatubo eruption were in the atmosphere (Vogelmann et al. 1992), O_3 levels dropped by 2 to 3 percent below the range of values in any of the preceding 13 years (Gleason et al. 1993; Kerr and McElroy 1993). Hence, trend calculations derived from Nimbus 7 TOMS measurements after June 1991 overestimate long-term O_3 depletions since the start of the satellite record (Chandra et al. 1996; William B. Grant, pers. commun.). Some analysts have regarded volcanic influences on calculated long-term trends of surface UVB as "slight" and included the post-1991 period (e.g., Herman et al. 1996); others have omitted this period (Chandra et al. 1996). The eruption of El Chichon in 1982 also reduced O_3 levels (Rowland 1991).

Figure 16 shows the longest record of O_3 above a single location, which is the Dobson station at Arosa, Switzerland, (47° N latitude), where measurements have been taken nearly every day since 1926 (Rowland 1991; Stolarski et al. 1992). The generally downward trend suggested by the slanting dashed line that departs from the horizontal trend line in the early 1970's is consistent with the trend in the TOMS O_3 data, though there is an offset of about 3 percent in absolute DU values. The magnitude of this discrepancy is typical of other comparisons between Dobson and TOMS data (Gleason et al. 1993).

The loss of stratospheric O_3 by manmade chemicals was first stated as an hypothesis by chemists Mario Molina and Sherwood Rowland (1974) in the early 1970's. Their initial hypothesis was that the greatest O_3 losses would be in the tropics where solar input is greatest. That O_3 loss was actually occurring became evident in 1985 with the publication of a now famous paper by J.C. Farman and colleagues (1985) in "Nature". The paper describes their observations, using Dobson instruments, of the ozone hole over the Antarctic during the Southern Hemisphere spring. They built upon the Molina and Rowland hypothesis by relating the reduced O_3 amounts to increased levels of inorganic chlorine originating from industrial chemicals. They also suggested that the low stratospheric temperatures that prevail in the Antarctic spring abetted the O_3 losses by the chlorine catalysts. The importance of the role of manmade

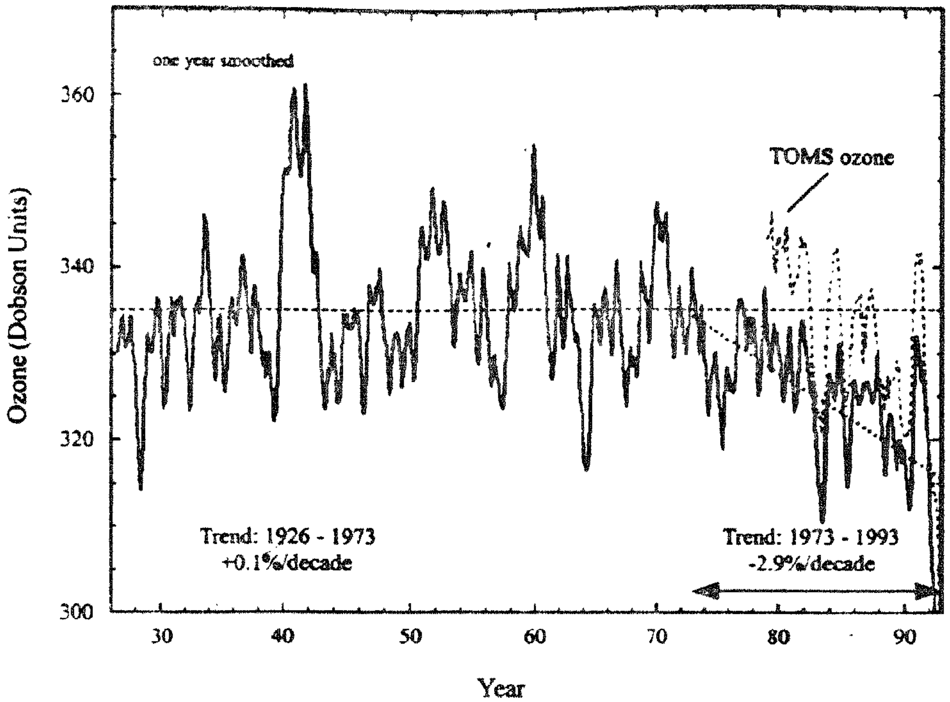

Figure 16.—The longest continuous series of ozone measurements at a ground-based station. Measurements have been made with a Dobson spectrometer since 1926 near 47° latitude at Arosa, Switzerland (data from Swiss Meteorological Institute).

chemicals in the stratosphere is indicated by the award of the Nobel prize in 1995 to three atmospheric chemists, Mario Molina, F. Sherwood Rowland, and Paul Crutzen, for their work in identifying the threat.

Recently, total column O_3 has been less than 50 percent in the "hole" compared to pre-1970's values (Hales 1996). The top left of Figure 6 shows global O_3 distribution near the time of minimum levels in the Antarctic spring in 1979, the first October in the Nimbus 7 TOMS series. Although the trend in O_3 already had started downward, column O_3 levels over Antarctica exceeded 225 DU. The ozone hole intensified during the 1980's. Minimum O_3 levels there routinely dropped below 125 DU during October 1996, as shown in the center part of Figure 6. Between the 1970's and 1993, ground-level measurements showed a doubling of UVB in Antarctica.

In contrast to Antarctica, O_3 remains at relatively high levels in Arctic springs. For example, on April 2, 1993 (the most recent year with Northern Hemisphere spring Nimbus 7 TOMS data), the O_3 column exceeded 425 DU in northern Canada (Fig. 6, bottom right). A sample of TOMS data for Northern and Southern Hemisphere summers (Fig. 7) shows relatively even distributions of O_3, with perhaps small decreases from the beginning to the end of the series of 13 or 14 years, particularly for the Southern Hemisphere.

From the 1978-93 TOMS O_3 measurements, estimates have been made of latitude-averaged erythemal doses of UVB and trends for erythemal, plant, and DNA damage (Gleason et al. 1993; Herman et al. 1996; Madronich and de Gruijl 1994; Madronich et al. 1994). Recent calculations (Herman et al. 1996) include cloud effects and refinements in calibration of the O_3 data. Trend estimates generally are lower than in previous estimates that did not include cloud effects. For example, for 11 of 14 latitude zones, trend estimates of erythemal dose by the United Nations Environmental Programme (1994) are higher than the 1996 Herman estimates, and averages for the other three zones are nearly identical (Fig. 17). Trends for DNA and plant damage are higher than those for erythemal dose, because the action spectra for DNA and plant damage give more weight to the shortest wavelength UV radiation that is most affected by O_3, than the spectrum for erythema (Fig. 13). The top of Figure 17 does show that where erythemal doses are highest, trends for increased UVB were lowest.

Not shown in Figure 17 are large error bars (± 2 standard deviations) that extend below 0 for the erythemal trends for all latitudes within 35° N and S. The analysis in Figure 17 averages over longitude within 10-degree latitude zones. In examining O_3 trend variations with longitude at 40° N, Chandra et al. (1996) found a range of trends for winter months ranging from -3 to -9 percent per decade. Thus,

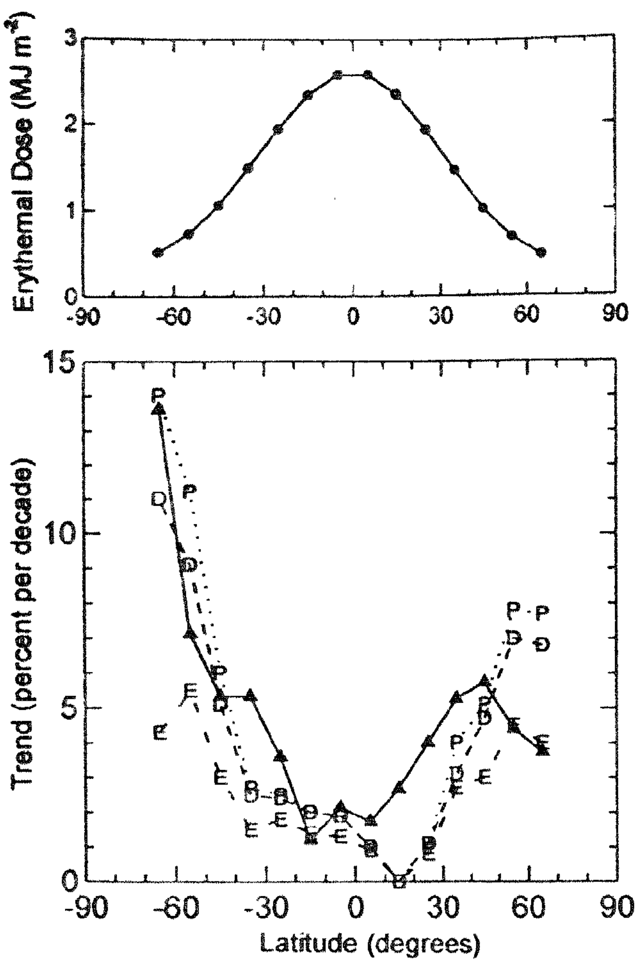

Figure 17.—Top graph shows average annual erythemal dose of UVB radiation (in MJ [million Joules] per square meter) by latitude between 1979 and 1992 from 1994 assessment of ozone depletion (Madronich et al. 1994). The trend in UV irradiance during the same period is shown in bottom graph as calculated by Madronich et al. (1994) for the erythemal actions spectrum (triangles and solid line) and by Herman et al. (1996) for the erythemal (E), DNA damage (D), and plant damage (P) actions spectra. Contrast the 1994 erythema estimates (triangles) with the 1996 estimates (E).

longitudinal variability leads to some of the large uncertainties associated with trend predictions.

While scientists are relatively certain that anthropogenic emissions of chemicals have contributed to dramatic reductions in O_3 and increases in UVB irradiance in the Antarctic, the evidence for increased UVB irradiance in temperate regions is much less apparent. Within the last several years, ground-level measurements of UVB in highly populated regions in midlatitudes may be showing an increasing trend (e.g., Hales 1996; Kerr and McElroy 1993, 1994), or there may be no increase (e.g., Hales 1996; Michaels et al. 1994), depending on how measurements are interpreted. Reports of UVB trends from measurements with Robertson-Berger instruments that began monitoring in the 1970's between 30° and 47° N latitude show a small downward trend in UVB irradiance (Frederick 1992; Frederick and Weatherhead 1992; Scotto et al. 1988a). This is a cause of controversy regarding the scientific evidence for O_3 depletion. If O_3 is decreasing, why do the UVB monitors not show an increase? Part of the reason may be related to the manner in which the R-B meter is calibrated (DeLuisi et al. 1992). Also, the fact that the response of the R-B monitoring instruments is shifted several nm to longer wavelengths than the erythemal action spectrum (Figs. 11 - 12) means that R-B measurements will be less sensitive to reductions in O_3 than measurements from instruments that more closely follow the erythema spectrum (DeLuisi et al. 1992). The action spectrum assumed in the satellite calculations of UVB irradiance gives more weight to shorter wavelengths than the R-B meter.

Another reason why ground-level monitoring may show less UVB irradiance than is estimated from satellite O_3 measurements is that increased tropospheric O_3, SO_2 and other pollutants may be absorbing significantly greater amounts of UVB above the ground-level sites (Bruhl and Crutzen 1989; Frederick 1992; Frederick et al. 1993; Grant 1988; Rowland 1991). As mentioned previously, decreases in UVB irradiance are possible even though the total column of O_3 decreases. Most of the R-B sites are in urban areas with the greatest increases in tropospheric O_3 (Grant 1988), though increases have been noted even in rural areas (Scotto et al. 1988b). Also, the variability in cloud patterns from year to year or over several years causes variations in UVB irradiance (Frederick and Erlick 1995; Frederick and Weatherhead 1992). As a result, the UVB trend estimates are questionable (Frederick and Erlick 1995). Ground-level increases in UVB may become more evident as monitoring networks and instrumentation (Sci. and Policy Assoc. 1992; Thompson and Hobish 1995) improve. The improvements include the addition of measurements of tropospheric ozone and other pollutants at UV monitoring sites (Barnard and Cupitt 1994).

Despite problems associated with measurement and incomplete knowledge of the physical processes in the atmosphere, the scientific evidence for increased UVB irradiance due to the loss of stratospheric O_3 now seems incontrovertible, at least for many regions of the globe. Recent assessments seem to make clear that at northern midlatitudes, O_3 levels have been decreasing at rates ranging from about 1 to 6 percent per decade depending on season and location (Gleason et al. 1993; Hales 1996; Herman et al. 1996; Madronich et al. 1994). It is estimated that a reduction in O_3 of 1 percent causes a surface increase in UVB of about 2 percent (Scotto et al. 1988a).

Increases in UVB are larger in winter than in summer. Predictions from Nimbus 7 TOMS for 1978-92 (Herman et al. 1996) indicate that in the 10° latitude band centered at 45° N, DNA- and erythemal-UV weighted irradiance increased by 8.6 and 5.1 percent per decade in April and 5.3 and 3.6 percent in summer, respectively. Annual average trends for

Table 1.—Modeled UVB and photosynthetically active radiation (PAR) direct and diffuse irradiance and diffuse fractions in open with clear sky and ozone depth of 320 DU (From Grant and Heisler 1996); the smallest zenith angle of the sun at 40° N latitude (New York City) is 23°

Solar zenith angle[a]	UVB			PAR		
	Direct	Diffuse	Diffuse fraction	Direct	Diffuse	Diffuse fraction
	Wm^{-2}	Wm^{-2}		Wm^{-2}	Wm^{-2}	
20°	2.11	1.76	0.45	384.8	69.7	0.15
40°	1.23	1.36	0.52	296.8	64.0	0.18
60°	0.29	0.74	0.72	165.7	52.7	0.24

[a] In solar radiation literature, the vertical position of the sun in the sky usually is given as the angle between the center of the sun and the zenith (directly overhead).

DNA and erythema (Fig. 17) at this latitude are similar to summer values. Again, such estimates might be affected by tropospheric O_3 and SO_2 or changes in average cloudiness at a particular location.

What of the future for O_3 trends? Concerns about the effect of CFC's on stratospheric O_3 caused the United States and other countries to ban the use of aerosol cans with CFC propellants in 1979. The use of CFC's worldwide continued, but the rate of increase in use slowed for several years before it increased again. When the ozone hole over the Antarctic was first observed with certainty in 1985, the cause of the hole was still not fully known. Nevertheless, that year, a number of countries signed the Vienna Convention, an agreement that called for international negotiations to develop a plan for worldwide action to reduce the use of O_3-destroying chemicals. By September 1987, concern about the potential impact of these chemicals was so great that 24 nations signed an agreement known as the Montreal Protocol (U.N. Environ. Prog. 1989). The Protocol provided that by mid-1989, the signers would freeze the production and use of halocarbons at 1986 levels and they would cut production and use in half over the next 10 years (U.N. Environ. Prog. 1994). The agreement also called for periodic assessments of the stratospheric O_3 problem every 4 years. Assessments were carried out in 1989, 1991, 1994, and 1998 (U.N. Environ. Prog. 1998). The Montreal Protocol was strengthened by amendments in 1990 (in London) and 1992 (in Copenhagen).

The 1994 Assessment reported that the provisions of the Protocol have brought about such a marked decrease in the production and use of O_3 depleting chemicals that thinning of the O_3 layer had been slowing and was predicted to stop about 1998 (U.N. Environ. Prog. 1994, 1998; World Meteorol. Org. 1995). However, despite this result, low levels of O_3 were not predicted to return immediately to levels prior to the start of O_3 depletion. While researchers still lack a full understanding of the chemical and air-motion processes governing O_3 abundance and UV radiation transfer (Am. Meteorol. Soc. 1996), best estimates are that, relative to levels before O_3 depletion began, increased UVB irradiance at the surface of the Earth will continue well into the middle of the next century (Hales 1996; U.N. Environ. Prog. 1998) even if the agreements of the most stringent Montreal Protocol amendment adopted in 1992 are fulfilled. The potential consequences of the UVB trends for human health are discussed in **Effects of Ultraviolet Radiation**.

Sky Radiance

Diffuse Fraction

The atmosphere free of dust and clouds scatters shorter wavelengths of solar energy much more than longer wavelengths (Fig. 1). Thus, the short wavelengths of UV radiation, particularly in the UVB, tend to be readily scattered out of the direct rays from the sun to be reflected back to space or to other parts of the sky, and then to reach the earth from a part of the sky far from the sun. Usually, more than half of the UVB irradiance arriving on earth is from this diffuse radiation from the sky (Barton and Paltridge 1979). Table 1 compares direct and diffuse origins of irradiance in the UVB and PAR bands, as calculated by a model of atmospheric radiation transfer. Note that the sky diffuse fraction, especially in the UVB, varies with the angle of the sun above the horizon, and that the fraction that is diffuse is much higher in the UVB than in the PAR. The greater fraction of radiance from the sky has profound implications for the amount of UVB irradiance in urban ecosystems.

Radiance Distributions

Both the amount and the distribution of *sky radiance* are important in determining irradiance in urban ecosystems, where much of the sky often is in view. The radiance distributions are needed for accurate predictions of tree and building effects on irradiance. In analytical modeling of the effects of vegetation or other obstacles on irradiance on surfaces near them, all parts of the sky often are assumed to have equal radiance. This leads to errors even for modeling total solar irradiance in the shadow of a tree (Grant 1985; Grant 1997b; Grant and Heisler 1996).

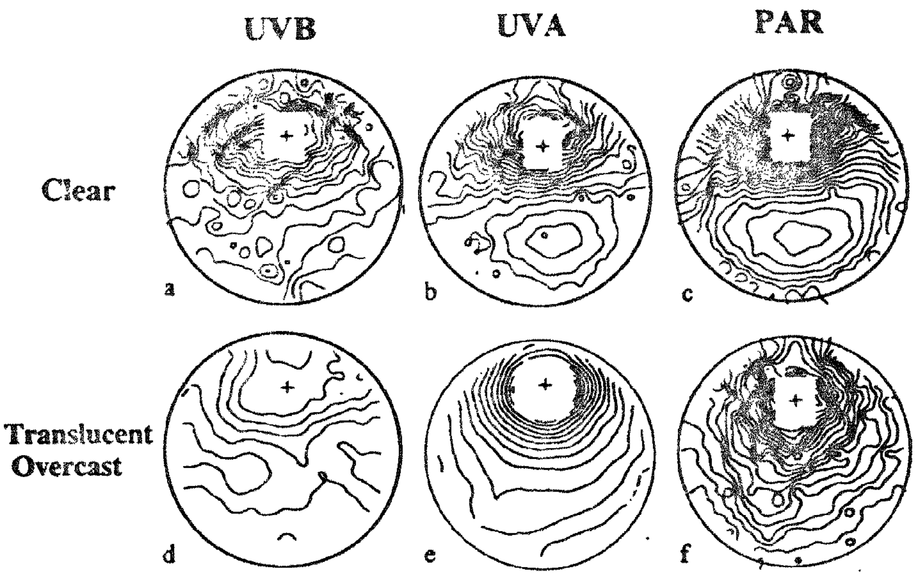

Figure 18.—Measured distributions of relative UVB, UVA, and PAR sky radiance for clear and translucent overcast skies. Contour intervals are 0.02. Parts a and b from Grant et al. (1997a), c and f from Grant et al. (1996b), and d and e from Grant et al. (1997b). Sun locations are marked by + symbols. Data were not collected within 15° of the sun. Closed circles in b and c in the part of the sky opposite the sun represent depressions in radiance. Compare with 19.

Figure 18 shows patterns of sky radiance as measured with a specially designed platform that held and rotated narrow-field-of-view sensors in 360° circles around the sky dome (Grant et al. 1996a,b). In Figure 18, the sun was near a 50° zenith angle; we also measured radiance distributions with solar zenith angles of about 20, 30, 40, 60, and 70°. The distribution for PAR shows a large gradient in radiance in the sun half of the sky and a decided dark portion opposite the sun in the other half. The pattern for UVA is similar to the pattern for the PAR, though the gradient is smaller. The UVB distribution is less regular and shows a generally smaller gradient due to the greater scattering of the energy in this waveband. With translucent overcast skies, the sun is discernible through a veil of thin clouds. Distributions of sky radiance have smaller gradients than when skies are clear, though similar patterns are evident.

We used regression techniques to fit equations to the radiance distributions. Representative results are depicted in Figure 19. For clear skies, the radiance for points in the sky was modeled in the regressions as a nonlinear function of the sky-point zenith angle and the *scattering angle*, the angle between the sun and the sky location (Grant et al. 1996b, 1997a). For translucent overcast skies, radiance distributions were best modeled as functions of sky point zenith angle, solar zenith angle, and scattering angle (Grant et al. 1996b, 1997b; Grant and Heisler 1997). The radiance distribution for skies overcast with clouds too thick for the sun to be seen can be described by equations with sky point zenith angle as the only independent variable (Grant and Heisler 1997; Grant et al. 1996b). Modeling of sky radiance distributions for partly cloudy skies is more difficult and probably will require including a cloud type as an independent variable.

Ultraviolet Radiation and Human Health

In many respects, the effect of UV radiation on life, whether human, animal, or plant, is similar. One similarity is that damage generally occurs at the cellular level with disturbance of DNA function. Another similarity is that the damage per unit dose of irradiance on the organism often is strongly nonlinear, with little damage from small doses but rapidly increasing damage as the dosage increases (Coohill 1994). With respect to the effects of sunlight on the human body, UVB radiation generally is considered the most damaging component (DeFabo 1994), though UVA also is potentially harmful (de Laat et al. 1996; Wong and Parisi 1996).

Human diseases linked to UV radiation as the causative agent or as a factor in susceptibility to disease include several kinds of skin cancer, several eye diseases, and damage to the immune system. It is the UV portion of the solar spectrum that also is responsible for skin aging and wrinkling (Weary 1996). One of the cancers, melanoma, often is lethal. The number of diagnosed cases of all these diseases has increased dramatically since 1980. Some increase in cancer rates has been attributed to increases in UV radiation (Burke 1995; de Gruijl 1995; Madronich and de

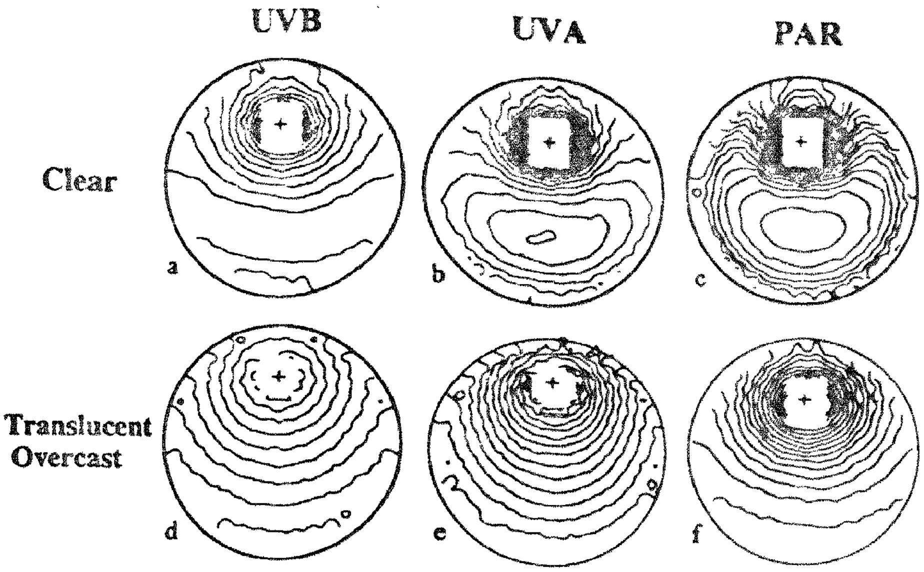

Figure 19.—Modeled distributions of relative UVB, UVA, and PAR sky radiance for clear and translucent overcast skies. Contour intervals are 0.02. Sources are the same as in Figure 18.

Gruijl 1994). Skin cancer is expected to increase by approximately 2 percent for every persistent 1-percent loss in average O_3 concentration (de Gruijl 1995). However, the increases in skin cancer are much larger than could have been caused by increasing UV radiation. Changes in habits of recreation and dress and the increased value placed on a "tan" are cited as largely to blame (Long et al. 1996).

Because of the time lag — apparently, often many years — between excess exposure to sun and evident disease, and because humans usually are not experimented on when the result could be serious illness, cause-and-effect relationships between sun exposure and disease are difficult to establish. Animal surrogates used often in studying the effects of UV radiation include mice, a species of fish (Brash et al. 1991; Nairn et al. 1996), and a South American opossum (Longstreth et al. 1994). Although experiments with animals are instructive in studies of the basic physiology of tumor development, they are of limited use for quantifying the effect of increases or decreases in UV radiation on humans (Longstreth et al. 1994).

Sunburn (Erythema)

The pattern of relative sensitivity of light-skinned humans to sunburning versus the wavelength of the radiation is known as the erythemal action spectrum (see **Ground-Level Measurements**). Wavelengths that have high thermal energy and make us feel warm do not cause sunburn. Different investigators have found somewhat different action spectra for sunburning (Fig. 13). The International Illumination Commission spectrum of McKinley and Diffey (1987) in Figures 11-13 is now used most often in studies of disease prevalence; the short-dash line in Figure 3 is the previously used action spectrum of Parrish (1982).

When action-spectrum values are multiplied by the values from the solar spectrum, a graph can be produced that shows the wavelengths of energy from the sun that are the most responsible for causing sunburn (dash-dot line in Figure 3). At noon on June 22 at 40° latitude and with 300 DU of O_3 above, the sunburn-causing peak is at about 308 nm. The peak wavelength changes as the solar spectrum changes with zenith angle of the sun and total column O_3. The peak in effectiveness moves to shorter wavelengths as O_3 decreases.

Damage to Immune Systems

UVB is strongly absorbed in the skin and in the outer layers of the eye but does not penetrate deeper into the human body. However, it can affect the human immune system because part of the immune system is in the outer layers of skin (de Gruijl 1995). Although the exact mechanisms of solar UVB effects are not fully known, it seems likely that UVB leads to infectious diseases and cancer in part because it affects immune systems (Chapman et al. 1995; DeFabo 1994; Noonan and DeFabo 1994, Weary 1996). One evidence of UV effects on human immune systems is that tissue that has been heavily irradiated loses sensitivity to chemicals placed on it. Normal tissue is said to have contact hypersensitivity, or CHS, which is the cause of the reaction of skin to poison ivy, for example. Irradiation with UVB reduces CHS.

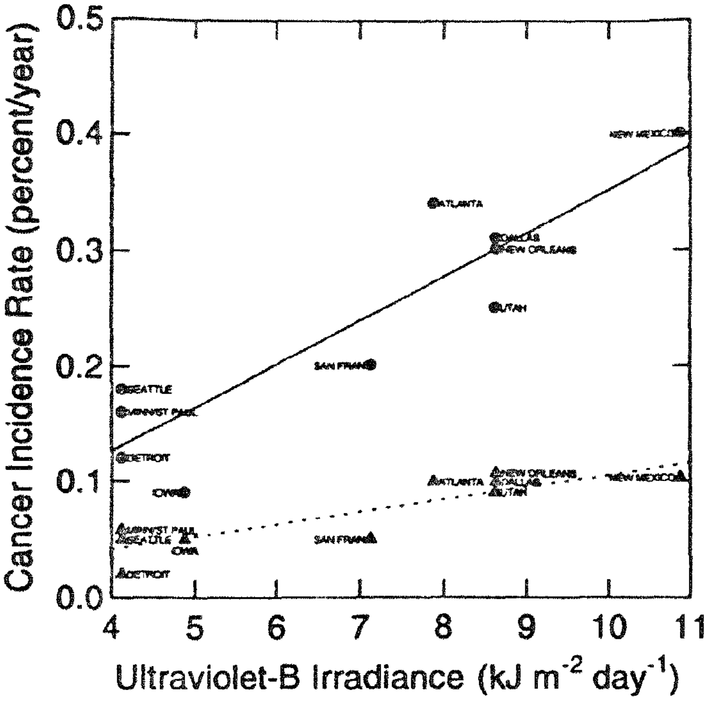

Figure 20.—Skin cancer rates as a function of UVB irradiance in a representative month for different states and cities for squamous cell carcinoma (triangles and dotted line) and basal cell carcinoma (circles and solid line). Data are from Leffell and Brash (1996). We extrapolated irradiance in average kJ (kilojoules) per m^2 per day for July 1992 from a map in the Leffell and Brash paper.

Also, when tumors are transplanted to mammalian tissue, they usually are rejected by the tissue and do not grow. However, tumors tend to grow if the tissue has first been irradiated with UV radiation. This link suggests that certain infectious diseases also may be affected by UV (Chapman 1995; Chapman et al. 1995; DeFabo 1994; Noonan and DeFabo 1994). Another concern is that excess UV radiation may reduce the effectiveness of immunizations against infectious diseases, though additional research is needed to confirm this (Chapman 1995). Excess UVB exposure can suppress immune functions even in people with dark skin (de Gruijl 1995; U.S. Environ. Prot. Agency 1995b).

Nonmelanoma Cancers

The body does have some defense mechanisms against excess UV radiation. When skin is exposed to UVB radiation, it adapts by thickening the outer layer of cells, the epidermis, and by developing pigmentation that shades the more vulnerable and deeper dividing cells. Overly damaged cells self-destruct in a process called apoptosis. However, if the individual is particularly susceptible or UV exposure is intense and of long duration, UVB eliminates the body's natural ability to ward off cancers (de Gruijl 1995). Recent studies show the UV radiation alters humans' p53 tumor suppressor gene; these alterations clearly are linked to human nonmelanoma skin cancers (de Gruijl 1995; Koh and Lew 1994; Ziegler et al. 1994).

Nonmelanoma skin cancers (squamous and basal cell carcinomas— SCC and BCC) are the most frequently diagnosed and most rapidly increasing forms of cancer in Caucasian populations (Int. Agency for Res. on Cancer 1992). BCC has been characterized as the most common cancer in the United States and throughout the world (Chuang et al. 1990). Although BCC and SCC often are grouped for statistical purposes, there is some evidence of different relationships with sun exposure (Vitasa et al. 1990). However, both BCC and SCC are thought to be correlated with cumulative lifetime UV exposure (Lloyd and Im 1993).

It is difficult to gather epidemiological data on nonmelanoma skin cancers partly because these diseases are not always included in cancer reporting registries (Weinstock 1993). It has been estimated that in the United States, 600,000 to 800,000 cases are diagnosed each year, about twice as often in men as in women (Lloyd and Im 1993; Long et al. 1996). The American Cancer Society estimated about 2,100 deaths from nonmelanoma skin cancers in 1995 (Long et al. 1996). Incidence rates of both cancers generally increase with decreasing latitude (Weinstock 1993) and with average cumulated UVB irradiance, particularly for BCC (Fig. 20). The incidence of nonmelanoma skin cancer in Southern United States is about double that in the North (Weinstock 1993).

Squamous cell carcinoma of the skin can progress by stages: sun-damaged epidermis, actinic keratosis (AK), SCC on the skin, and metastasis, that is, spreading to other parts of the body (Ziegler et al. 1994). Actinic keratosis is a condition of precancerous skin that appears as a raised tan or reddish splotch on the skin that increases in size without additional sun exposure. It is generally found on the face, on top of a bald head, and other parts of the body that are frequently exposed to the sun. The AK patches can be treated to greatly reduce the possibility of squamous cell cancer (Fackelmann 1994). Both BCC and SCC are concentrated on skin surfaces that are most exposed to the sun (Weinstock 1993).

By using the relationship between the incidence of skin cancer in different geographic areas with the average ultraviolet irradiance in that area, several investigators have estimated the effect of changing O_3 levels on future cancer rates (Madronich and de Gruijl 1994). One study (Lloyd and Im 1993) calculated the "biologically effective accumulated dosage" of UVB (which the authors call BAD) over days, months, and years. It showed that a small loss of O_3 in the tropics, where UVB already is high, could provide as much additional biologically effective UVB as a much larger loss O_3 at higher latitudes. For O_3 depletions greater than 5 percent, the BAD of UVB increases rapidly (exponentially) with decreasing O_3 levels. Until recently, these kinds of studies (Madronich and de Gruijl 1994) did not take cloud cover into account.

Examining the effect of the Montreal Protocol and its amendments on disease trends, Slaper et al. (1996) concluded that UVB will peak near the end of this century (see **Long-term Trends in Ozone and UVB Irradiance**), but that rates of skin cancer will continue to increase into the middle of the next century when they will be about 10 percent higher than in 1976. By 2100, incidence rates are expected to return to 1976 levels. The authors are assuming that people will not take greater protective measures against excessive exposure to the sun, and that the provisions of the Copenhagen agreement will be fulfilled. According to the authors, if only the less stringent original Montreal Protocol agreement is fulfilled, the increases in cancer rates should continue upward, doubling by 2100. They add that had there had been no international agreements limiting O_3-depleting substances, incidence rates of skin cancer would quadruple by 2100.

Malignant Melanoma

The American Cancer Society estimated that about 34,000 people would be diagnosed with melanoma in the United States in 1995 and about 7,200 would die (Long et al. 1996). As with nonmelanoma skin cancer, rates of cutaneous malignant melanoma (CM) have been rising rapidly for decades, even before increases in UVB due to stratospheric O_3 loss (Koh and Lew 1994). During the 1990's, rates of melanoma have been increasing by 4 percent per year (Weary 1996).

There are similarities and differences between CM and other skin cancer epidemiology. Lower latitudes tend to have higher CM incidence and mortality rates (Koh and Lew 1994), as is the case for nonmelanoma skin cancers. Although sunlight is implicated in malignant melanoma, the parts of the solar spectrum that are responsible are not well known, that is, the action spectrum has not been defined as it has for nonmelanoma (Longstreth et al. 1994). Malignant melanoma can occur on normally unexposed parts of the body. Genetic factors such as a family history of melanoma, skin blemishes, and light skin increase the risk of melanom (Weinstock 1993), complicating the task of sorting out the effects of UV radiation.

The UVA band may be important in melanoma (Setlow 197 Coohill 1994). If so, there are a number of consequences. Some investigators hypothesize that because sunscreens until recently primarily blocked UVB and not UVA, they may have increased the risk of melanoma, partly because UVB causes the body to produce vitamin D, which may protect against melanoma. If the majority of solar-induced melanomas are caused by UVA, then malignant melanoma will not be affected greatly by O_3 loss because UVA radiatio is not absorbed by ozone (Coohill 1994).

Although medical opinions and results of epidemiological studies on the relationship between sun exposure and CM differ (Weinstock 1993), the statement that "it is now well established that sun exposure is one of the probable cause [of melanoma]" (Diffey and Saunders 1995) seems the consensus. Some studies suggest that CM is related to intermittent extreme sun exposure (Koh and Lew 1994; Melville et al. 1991; Weinstock 1993,) rather than to cumulative exposure over long periods. This finding is consistent with the fact that the incidence of melanoma tends to be higher among indoor workers than outdoor workers (Koh and Lew 1994). Some research links blisterin sunburns in childhood or adolescence with increased likelihood of CM later in life (Koh and Lew 1994; Weary 1996). In a study of college graduates, outdoor employment before college was positively correlated with CM incidence (Weinstock 1993).

Sunscreen Effectiveness

Sunscreens provide a high degree of protection against sunburn, depending on their effectiveness number or SPF (*sun protection factor*). However, the effectiveness of sunscreens in reducing disease remains an often studied research topic. There is uncertainty as to whether sunscreens that prevent sunburn are effective in preventing immunosuppressive effects and tumors (Bestak and Hallida 1996; Gorman 1993; Int. Agency for Res. on Cancer 1992). In mice, sunscreens have blocked sunburn but have not always protected against melanoma (Koh and Lew 1994). However, Roberts and coworkers (1996) have pointed out that the apparent lack of sunscreen effectiveness in preventing UV-induced immune suppression might be caused by experimental methods. For example, some studies on immune responses in animals used artificial radiation sources that emitted significant power at wavelengths below 295 nm, that is, below the wavelength of significant solar radiation on Earth. Other studies used unrealistically high UV doses in animal experiments.

Given the uncertainty about the effectiveness of sunscreens some experts are concerned that people will rely too heavily on them and/or abandon other protective measures (Wright 1994), for example, seeking shade at midday and wearing protective clothing.

Eye Diseases

The most common association between UV radiation and eye disease is that between UV and senile cataracts (a clouding of the eye lens), the most common severe and chronic eye disease. Cataracts are treatable only by surgery in which the natural eye lens is removed and replaced with a plastic lens, the most common surgery in medicine (Belkin 1994). Cataracts cause about 53 percent of the blindness in the world (Long et al. 1996). An estimated 1.35 million cataract surgeries are performed annually in the United States at a cost of $3.4 billion in Medicare expenses alone. Although it is not known what percentage of cataract cases are attributable to excess UV exposure, it would seem that many dollars could be saved if people took preventive measures to avoid exposure (Long et al. 1996). Wearing hats and eyeglasses (even with clear lenses) can greatly reduce exposure of eyes to UV radiation (Belkin 1994; Rosenthal et al. 1985).

UV radiation is associated with other eye diseases. There is some evidence that the most common cause of blindness in the developed world, age-related macular degeneration, is related to extensive exposure to solar radiation over many years, though this association may be with longer wavelengths than UV. Forms of malignant melanoma and squamous and basal cell carcinomas, which affect the eye or eyelid, also have been related to sun exposure. A less severe solar radiation-related disease is pterygium, a benign growth on the exposed surface of the eye that causes inflammations and a cosmetic blemish. Yet another disease associated with sun exposure is climatic droplet keratopathy, an accumulation of protein in exposed parts of the cornea that can lead to blindness. Presbyopia, the inability of the eyes to focus at close distances, causing the need for reading glasses, is essentially an universal condition when people approach middle age. The fact that it occurs at earlier ages in countries closer to the equator may indicate an association with sun exposure (Belkin 1994).

Beneficial Effects on Health

Some diseases are alleviated by moderate UVB exposure (van der Leun and de Gruijl 1993). For example, both UVB and UVA are used in the treatment of psoriasis, though some studies have indicated a risk of increased skin cancer associated with prolonged treatment (Stern and Laird 1994).

Humans also benefit from UV radiation for the production of vitamin D. Exposure to UVB is involved in both the synthesis and breakdown of vitamin D by a complex series of photochemical reactions (Long et al. 1996; Webb 1993). These reactions regulate the production of vitamin D so that toxic levels are not reached (Webb 1993). Taking vitamin D as a dietary supplement in the absence of UVB exposure can lead to toxic levels in the body. There is some conflict in the literature as to the role of UVA in the synthesis of vitamin D (Koh and Lew 1994). Only low levels of UVB exposure—far less than 1 MED—are needed in the synthesis process (Webb 1993), suggesting that tree shade may not limit vitamin D production.

There is some controversy in the literature with respect to the possibility that reduction in exposure to UVB is associated with an increased risk of non-cutaneous cancers such as breast and colon cancer. Reduced production of vitamin D with lower UVB usually is suggested as the cause of the increased risk of non-cutaneous cancers (Ainsleigh 1993; Cowley 1991; Lefkowitz and Garland 1994). There is a documented trend of increased incidence of breast cancer from south to north in the United States (Cowley 1991; Sturgeon et al. 1995). This trend has been attributed to a reduction in the production of vitamin D with the lower exposure to UVB in the North, though this geographic variation in breast cancer also is related to demographic patterns. For example, women who give birth to their first child at a young age, which is more common in the South than the North, have a lower risk of mortality from breast cancer than older, first-time mothers (Sturgeon et al. 1995).

UV Indices

The issuance of UV indices began in Australia in the mid-1980's. New Zealand followed in 1987 and Canada in 1992 (Kerr 1994; Long et al. 1996). The United States initiated a UV Index (UVI) in 1994 (Geller et al. 1996; Long et al. 1996). An important goal of the UV indices is to publicize the dangers of being in the sun too long (U.S. Environ. Prot. Agency 1995a,b; Geller et al. 1996). Public education is particularly important because most of the adverse effects of UV radiation, including skin cancers, are preventable (Weary 1996).

The United States' UVI is a collaborative effort between the National Weather Service and the Environmental Protection Agency (Long et al. 1996). The UVI reports predicted UVB irradiance at noon local time for 58 cities using relative units that range from 0 to 10 and 10+ or five exposure categories: minimal (0-2), low (3-4), moderate (5-6), high (7-9), and very high (10 or higher). For each category, protective actions are recommended; for example, for very high exposure use sunscreen with an SPF 15+, protective clothing, and sunglasses, and stay out of the sun between 10 a.m. and 4 p.m. Methods used in UVI predictions and for determining their accuracy are detailed in Long et al. (1996).

Ultraviolet Radiation in Urban Environments

Suggestions have been made in the popular press (e.g., Lemonick 1992) and in public information brochures (U.S. Environ. Prot. Agency 1995a) that tree-shaded spaces be used to protect against excessive UVB radiation. It seems simple enough that where we see the shade of trees, there will be some protection from UVB. However, there can be significant differences between the reductions of the visible portion of the solar spectrum, that is, the shade pattern we see, and reductions of UV by trees and other structures in urban areas. Differences can occur partly because of differences in optical properties of leaves at different wavelengths. Visible and UV shade patterns also differ because of differences in UV and visible radiation in the diffuse fraction of total irradiance, in the distribution of sky radiance, and in the reflectivity of urban structural surfaces.

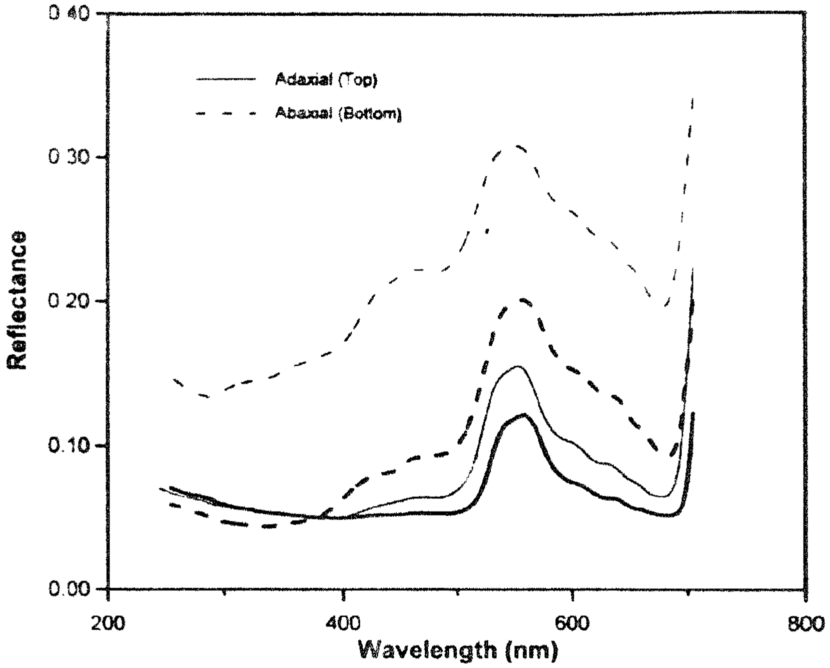

Figure 21.—Reflectance as a fraction of incident radiation for leaves of silver maple (*Acer saccharinum)* [fine lines] and green ash (*Fraxinus pennsylvanica*) [heavy lines] from laboratory measurements (Gao et al. 1996).

UV Reflectivity

Leaf Optical Properties

Because transmission of UV radiation through leaves is negligible for nearly all tree species (Gao et al. 1996; Yang et al. 1995), leaf optical properties are essentially a matter of reflectivity from the leaf surface. Measurements of leaf reflectivity in the UV are not widely available because specialized and relatively expensive instruments are required, especially for the UVB. Table 2 shows the UV reflectivity of seven tree species, all but two of which (hickory and black oak) are commonly planted in urban areas. Compared to PAR reflectivity, which is generally in the range of 10 to 30 percent, UV reflectivity is low (Fig. 21). Measurements of leaves of 19 species with a Perkin-Elmer spectrophotometer (Gao et al. 1996) showed that average PAR reflectance was 1.1 to 3.3 times greater than UVB reflectance. Overall average reflectivity was 5.7 percent for UVB and 5.2 percent for UVA compared to 3.1 percent for UVB and 4.4 percent for UVA in the study by Yang et al. (Table 2).

The different average reflectivities in the two studies may be partly the result of the different species sampled and partly the result of different measurement methods. These studies do confirm that UV reflectance generally is low for all species. Whether the differences in reflectivity between species could be significant for exposure of people to UV radiation remains to be determined by additional measurements of irradiance near tree crowns and sensitivity analyses using mathematical models of tree influences on irradiance.

Other Surfaces in Urban Areas

Apart from leaves, many other surfaces that are good reflectors for visible radiation are poor reflectors of UV (Koller 1965). Average reflectivities in the UVB and for the total solar spectrum for various outdoor surfaces are given in Table 3. Madronich (1993) provided a similar summary of UVB reflectivities from earlier reports. The reflectivity of grass is especially low. New fallen snow has high reflectivity; as shown in Table 3, it is the only surface for which UVB exceeds total solar reflectivity. Blumthaler and Ambach (1988) pointed out that keratitis solaris (snow blindness) occurs because unprotected eyes can experience many times greater UVB exposure (an estimated 16 times greater) with snow than with no snow on the ground.

The radiation environment in urban areas depends partly on the reflectivity of building and paving surfaces. Most clean metals free from tarnish and oxide reflect 30 to 55 percent of incident radiation at 300 nm (Koller 1965), though few of these materials remain clean for long in outdoor environments. For 300-nm radiation, reflection from glass is less than 10 percent with incidence angles up to about 70°, where it increases rapidly to 100 percent at near "grazing incidence." This means that with the sun high overhead, reflection from glass-walled buildings could nearly double the UVB irradiance on a person standing near the building. Water is similar to glass but its reflectivity is a few percentage points higher at low incidence angles (that is, with incidence nearly perpendicular to the surface).

One suggestion for making buildings more energy efficient and cities cooler is to increase the *albedo* of a large

Table 2.—Average reflectance in the ultraviolet as a percent of incident radiation, from top and bottom surfaces of fresh leaves and oak litter (Yang et al. 1995)[a]

Species	UVB		UVA	
	Top (adaxial)	Bottom (abaxial)	Top (adaxial)	Bottom (abaxial)
Oak litter	3.2	3.2	9.2	8.0
Sweetgum (*Liquidamber styraciflua*)	4.6	4.9	4.3	6.7
White oak (*Quercus alba* L.)	3.7	5.8	3.6	6.7
Red oak (*Q. rubra* L.)	2.9	3.7	2.9	3.9
Hickory (*Carya tomentosa*)	2.6	2.8	3.1	4.6
Sugar maple (*Acer saccharum*)	2.5	5.4	2.8	6.1
Norway maple (*Acer platanoides*)	1.5	1.8	1.9	3.1
Black oak (*Q. velutina* Lamarch)	0.9	1.0	3.9	1.6
Average for fresh leaves	2.8	3.5	3.9	5.0
Average, both surfaces, fresh leaves	3.15		4.45	

[a] Measurements by Yang et al. were made with light from a solar simulator that was fed by a fiber optic cable into an integrating sphere that held samples. A spectroradiometer scanned output from the sphere.

proportion of building and paved surfaces in a city (Akbari et al. 1990; Rosenfeld et al. 1995; 1996) by painting them with white- or light-colored materials. Although reflectivity in the UVB is less than in the visible, whitened wall or paving surfaces may significantly increase UVB irradiance on pedestrians and also increase UVB loads on vegetation. For example, if we assume that radiation to the eyes is primarily from the ground (Blumthaler and Ambach 1988), a doubling of surface albedo in the UVB could double UVB radiation into the eyes of pedestrians. Measured UVB reflectivities are not available for most of the materials that are proposed for lightening urban surfaces, but from the data in Table 3 it is reasonable to assume that an increase in asphalt albedo for total solar radiation of 0.25 (or to about 0.36 for dark asphalt, Table 3), as proposed by Rosenfeld et al. (1996), might be accompanied by a doubling in UVB albedo from 0.055 (5.5 percent in Table 3) to 0.11.

If roof or pavement surfaces of a sufficient portion of a city were whitened to increase the general UVB reflectivity of the landscape, UVB irradiance at ground level might be increased by an increase in the radiation that is reflected from ground-level surfaces up to the sky and then back to ground level. This effect could be tested by a sensitivity analysis using radiation transfer models such as that developed by Green and coworkers (1974). This model predicts that for a typical urban aerosol distribution, solar zenith angle of 45°, and relative humidity of 50 percent, an increase in UVB landscape reflectivity from 3 to 20 percent would increase UVB irradiance at ground level by about 3 percent. This might approximate the effect if, as Rosenfeld and coworkers (1995) suggest, the albedo for total solar radiation for some parts of Los Angeles were increased by 35 percent (0.35 fractional) by light-surfaces programs. However, Rosenfeld and coworkers (1996) suggested a plan that would raise the overall reflectivity of the city by only 0.075 for total solar radiation, which probably would have little effect on UVB sky radiance. A sensitivity analysis would require considering the extent of areas to be lightened, measured UVB albedo for the different types of lightened surfaces, and the climatology of O_3 variations, urban aerosol climatology, and changes in solar angles over the course of a year.

Table 3.—Percent reflectivity for some surfaces in UVB waveband and for total solar radiation (sensors and surfaces were horizontal)

Surface	Reflectivity (albedo)[a]		
	UVB (erythemal)		Total solar
	[1]	[2]	[1]
Water	4.8		9.1
Bare field	2.2		11.5
Grassland and corn	1.3		20.7
Lawn grass, summer		3.7	
Asphalt	5.5		10.6
Sidewalk, light concrete		12.0	
Rock, weathered	3.7		14.4
Limestone	11.2		26.5
White paint, metal oxide		22.0	
Aluminum, weathered		13.0	
White fiberglass		9.1	
Beach sand, dry		18.0	
New snow	94.4		87.0
Old dry snow	82.2		79.2

Sources: [1] Blumthaler and Ambach (1988); [2] Sliney (1986).
[a] Albedo is term usually used to indicate ratio of radiation reflected to radiation received by a surface when radiation is from the sun.

Table 4.—Average percent reductions in UVB and PAR irradiance below a street-tree canopy (Grant and Heisler 1996; Heisler et al. 1996)

	No. half-hour measurements	Reduction in irradiance		Percent of view[a]		
	Item	UVB	PAR	Buildings	Trees	Sky
In-leaf						
Shade	3	63	84	—	44	49
Sunlit	2	39	3	—	39	56
Out-of-leaf						
Shade	1	56	73	—	41	53
	1	70	47	23	17	56
Sunlit	2	40	6	—	36	60
	1	59	5	31	13	47

[a]View percentages (buildings + trees + sky) do not add to 100 percent because sky view includes a correction to account for the fact that the effect of a radiance source on irradiance on a horizontal surface varies with the cosine of the angle of incidence.

UV Beneath Vegetation Canopies

Although there are few measurements of the UV environment below extensive vegetation canopies, the pattern that does emerge is consistent with what we know about leaf optical properties and sky radiance in the UV relative to the rest of the solar spectrum. Radiation transfer in crop canopies (Grant 1991, 1993; Grant et al. 1995) is quantitatively different from forest canopies, though it provides useful information about forests because the physics of both canopies are qualitatively the same. For example, reflection from a maize canopy was greater in the visible (PAR) than in the UV (Grant 1991). Different varieties of sorghum crops produced canopies with stalks that differed in optical properties (Grant et al. 1995) such that the transmission of UV radiation through the canopies differed. Results might be similar with trees of different cultivar origins. The distribution of irradiance at points beneath the sorghum did not follow the normal statistical distribution, but was skewed with the median irradiance less than the mean. Thus, analysis of irradiance beneath similar canopies should be based on non-normal statistical methods. Brown et al. (1994) noted the same skewing in measurements made under a variety of forest canopies.

Under dense tropical forest canopies, UVB irradiance may be reduced to essentially negligible levels because the sky is totally obscured by layers of leaves (Brown et al. 1994; Lee and Downum 1991). As we have seen, transmittance of UV radiation through leaves is low for all species for which measurements have been made. Beneath complete, undisturbed canopies of a variety of tropical and in-leaf temperate deciduous forests, one study showed that PAR attenuation was less than UVB attenuation (Brown et al. 1994). In "disturbed" canopies and gaps, the same study showed that UVB attenuation was less than PAR attenuation. Measurements over 2 days of the radiation environment under an oak canopy with a relatively low *leaf-area index (LAI)* of 1.7 showed UVB was attenuated to a greater extent than the PAR (Yang et al. 1993). Measurements under a *Sorghum* canopy with an LAI of 7 showed that UVB is attenuated less than PAR when the solar zenith angle is small (sun nearly overhead), and attenuated more than PAR when the solar zenith angle is large (Grant et al. 1995). Yang and coworkers (1993) found that a simple commonly used equation to describe radiation transmission through media with randomly distributed elements (*Beer's Law*) explained the mean UVB penetration through the oak forest, though they did not address variability about the mean.

UV in the Vicinity of Urban Trees

There have been few measurements of the UV environment in urban areas. UV measurements with a dosimeter that measured mostly in the UVB suggest that "trees can be particularly important" in exposure to UV (Diffey and Saunders 1995). The dosimeter was worn vertically at the waist by a person walking beneath a row of trees and then in the open. The measurements indicated that tree shade reduced erythemal irradiance by nearly 100 percent at times, though the detail of the tree structure was not given. A dense tree canopy with crowns that blocked the sky on the side that the dosimeter was worn probably accounted for these large reductions in UVB irradiance.

The effect of mature deciduous street trees on the PAR and UVB *global irradiance* is shown in Table 4. The trees were typical of trees in older suburban neighborhoods. The table summarizes measurements made at a height of 1.5 m (5 feet) at points near or beneath tree canopies on the campus of Purdue University, West Lafayette, IN. Six conditions are represented: shaded and sunlit points when the tree crowns were in leaf, shaded and sunlit points after leaves had fallen

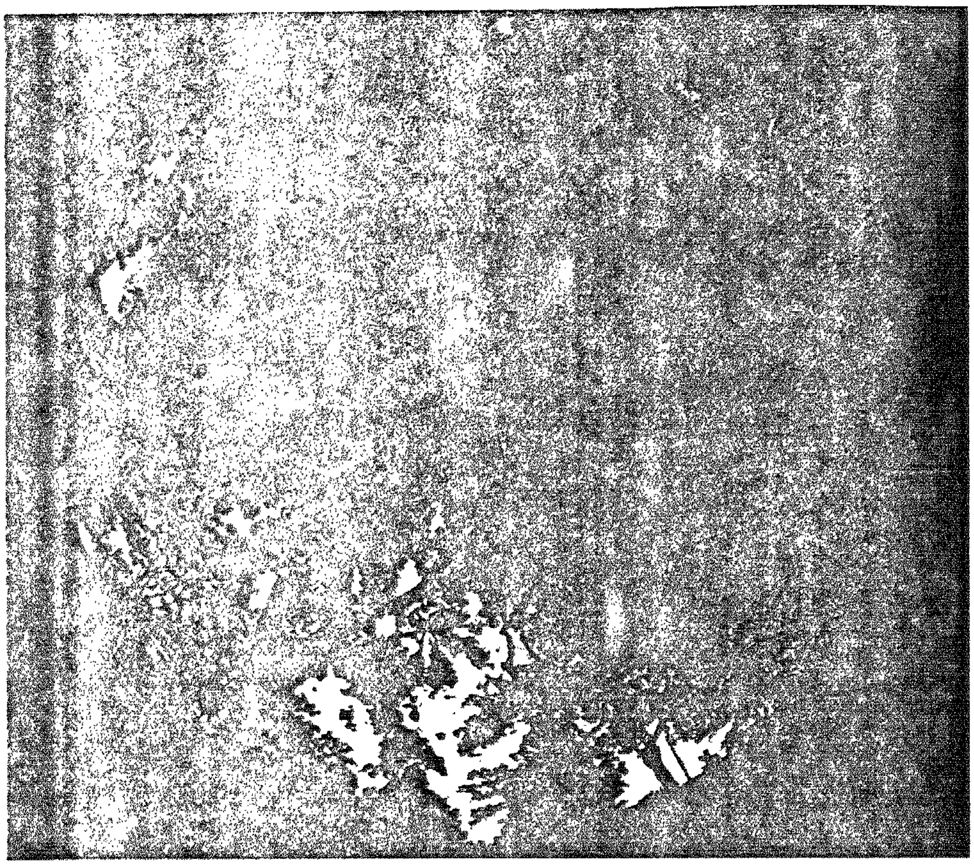

Figure 22.—Hemispherical photograph (180° field of view) taken from irradiance measurement point with trees in-leaf. The center of the photograph is directly above the sensors.

and with no buildings nearby, and shaded and sunlit points after leaves had fallen and with a building wall nearby. Irradiances were averaged over 30-minute periods. Skies were clear for all measurements. Concurrent UVB and PAR irradiances measured at a rural field provided an open-condition reference. The solar zenith angle ranged from 33° to 60° during the measurements. Measurements were made with International Light sensors that respond only in the UVB (Fig. 11).

Slide photos (upward facing, hemispherical view) from each measurement site provided a means of determining the percentage of sky obscured by trees and buildings (Fig. 22). In Table 4, the percentages for building and tree views give equal weight to all solar elevation angles. The sky percentages represent an effective sky view because they are corrected by the relative importance of the sky elevation angle zone as a radiance source for global irradiance. With the effective sky view ranging from 47 to 60 percent, these measurements represent irradiance conditions with fairly large views of the sky.

The results in Table 4 show that the distinction between "shade" and "sunlit" would be much less apparent if our eyes registered UVB rather than a range of wavelengths close to the PAR. In the visible (PAR) shade of trees in leaf, reduction in UVB irradiance was 63 percent compared to 84 percent for PAR. Conversely, at sunlit locations near in-leaf trees, PAR was not reduced appreciably but UVB reductions averaged 40 percent. Reductions in UVB irradiance differed much less between shade and sunlit points (24 percentage points with leaves on trees versus 16 percentage points with no leaves) than in the PAR (81 and 66 percentage points).

Thus, at points with significant view of the sky, UVB shadows can differ greatly from visible shadows. The measurements in Table 4 illustrate the differences in irradiance in the UVB and PAR that can exist largely because of differences in diffuse sky radiation between these two bands (Heisler et al. 1995). Where the sun is obscured by a small tree crown, longer wavelengths are greatly reduced, whereas UV is reduced much less (Grant 1997b).

The difference between UVB and PAR irradiances in tree shade is apparent in Figure 23, which shows relative irradiance (irradiance in tree shade divided by irradiance in the open) as sensors become shaded over a half-hour period. The larger fluctuations in PAR are caused primarily by the much larger importance of direct beam radiation in

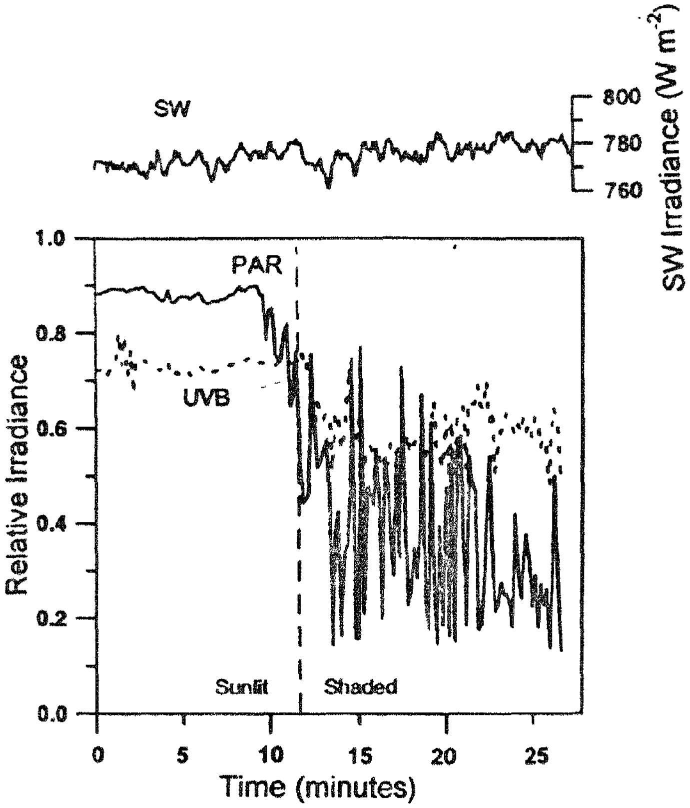

Figure 23.—Relative irradiance in and out of street-tree shade (Heisler et al. 1996). Total shortwave irradiance above the canopy (SW Irradiance) was relatively constant during below-canopy measurements.

the PAR, which increases the difference in irradiance between points in and outside of *sunflecks.*

Differences in sky diffuse fraction are primarily responsible for the different reductions in radiation between UVB and PAR, particularly for sunlit points, though differences in leaf reflectance also contribute. As noted in **Ultraviolet Reflectivity**, leaf reflectance in the UVB is about 0.05 for most species and the ratio of average UVB/PAR leaf reflectance generally ranges from 0.3 to 0.9 (Gao et al. 1996). Thus, tree crowns contribute little scattered UVB to adjacent points, whereas PAR contributions can be more important.

Building Effects

In the survey measurements of UV irradiance on the Purdue campus (Table 4), reflection from a sunlit brick wall led to smaller reductions for PAR at a tree-shaded point than when no wall was present even though sky view at both points was similar. In the UVB waveband, the wall increased the reduction because of low reflectivity in the UVB for the brick surface. The brick wall with some windows reflected about 0.18 of incident visible radiation, whereas it reflected only about 0.03 of the UVB (Grant and Heisler 1996).

Interactions with Other Tree Effects on the Environment

One tenet of urban planning and design is that trees have multiple effects on the environment (Heisler et al. 1995; McPherson et al. 1994; Rowntree et al. 1994; Rowntree 1994). One of the obvious effects is that tree shade reduces heat stress on people. Thus, tree shade as a UV protective feature tends to be self-enforcing because people seek it out to keep cool under the sunniest conditions. This self-enforcing aspect is important because, judging by continued high incidence rates for skin cancer, people often do not take precautions to avoid excessive sun.

Along with considering the effects of trees on UV radiation, optimum planning for trees in urban environments will consider their effects on human comfort by modifying the rest of the solar spectrum (Heisler 1985), wind (Heisler 1990), and humidity and air temperature (Heisler et al. 1995; Simpson et al. 1994; Souch and Souch 1993). Other tree effects to be considered include a complex of interactions with air quality. Trees emit hydrocarbons in varying amounts depending on species, but they also collect chemical pollutants and particulates (Nowak 1995). In turn, tree growth is influenced by air quality and climatic variables, including UV irradiance.

Conclusion

UVB radiation clearly is implicated as the primary cause for nonmelanoma skin cancer and may be a contributing agent or a cause of malignant melanoma skin cancer and cataracts. In the United States, rates of skin cancer have been rising for many years. Nearly a million new cases are reported each year, the majority of which are squamous and basal cell cancers that have been most linked to UV radiation. UVB also may play an important role in other adverse health effects, including damage to the human immune system, which may predispose people to infectious diseases and render immunizations less effective. Although the rising skin cancer rate is caused primarily by changed human behavior or other environmental factors, increased UVB irradiance also may have played a part.

The increase in UVB irradiance is caused by decreasing O_3 in the stratosphere. Although ground-level measurements of UVB irradiance in midlatitudes have shown statistically significant increases in only several locations, calculations of UV at ground level from satellite-monitored O_3 indicate the increases have been more general. Satellite-based UV measurements show increases at middle and high latitudes in both hemispheres, particularly in the winter. More recent studies indicate that average increases in DNA-damaging UVB range from negligible at the equator to 7 percent per decade at 55° N latitude and 11 percent per decade at 65° S latitude. Increases in UVB irradiance greater than 50 percent, relative to the early 1970's, occur during part of the year in the Antarctic, but these large increases are unlikely in north polar regions.

Recent trends in the amount of human-created, O_3-depleting chemicals in the atmosphere and trends in stratospheric O_3 suggest that unprecedented international agreements, which limit production of the chemicals, have been successful in slowing the increase in UVB on Earth. If the provisions of the most recent of agreements are fulfilled, reduced O_3 in the stratosphere and increased UVB at the Earth's surface are expected to peak around 2000. No region is likely to experience maximum UVB levels that are much higher than the maximum found in tropical areas today. However, the increased UVB in midlatitudes may be stressing unacclimatized human populations and life in natural ecosystems, and it may continue to do so. Relative to levels in the 1960's, the increased levels of UVB are expected to continue well into the next century. Because of the long latency periods of UV-induced disease, some scientists suggest that the full effects of increased UVB may not appear in disease registries until the year 2060 in the United States. At that time, the increase in cancer caused by the increase in UVB will be about 10 percent compared to the time before O_3 depletion began.

Although little is known about the current and potential future importance of urban forests in ameliorating UV radiation, the possibility for rapid advances in our knowledge is enticing. Data from satellite measurements of total column O_3 around the globe have been available since 1979. However, the significance of these data, particularly for determining UVB irradiance at ground level, was uncertain due to problems with analysis and calibration techniques. Improvements since 1996 have made the data more useful.

Currently, several federal agencies are implementing new networks of ground-based UV monitoring instruments. These will include measurements of other pertinent atmospheric variables. Progress also is occurring in instrument design and network deployment that will be useful in obtaining information on above-canopy irradiance for field studies of the effects of buildings, trees, and forests on UV radiation.

Research to date has practical implications for work and recreation outdoors. Forested areas with closed tree canopies provide nearly total protection from UVB irradiation. We measured irradiance near and beneath urban trees using broadband sensors for the UVB, UVA, and PAR bands. Differences between PAR and UVB sky diffuse fractions and reflection from leaves and buildings cause major differences in the fractions of visible and UVB radiation components that penetrate to pedestrian levels in urban environments. In visible shade where there is a significant view of the sky, reductions in UVB generally are much less than those in PAR levels. A location just inside the shade pattern of a small-crowned tree in the open provides deceptively less UVB protection than would be expected by the visual depth of the shadow. Just outside visible shade patterns of trees, UVB is reduced much more than PAR. Thus, where many large street-tree crowns block much of the sky, substantial protection from UVB is afforded for pedestrians, even in spots with direct sun. This result argues for the maintenance of large-crowned trees in areas frequented by people, especially children. It also tends to justify the use (where utilities and buildings are not in conflict) of some of the fast-growing, large tree species that often are shunned because of high maintenance requirements.

Accurate models to predict ground-level irradiance under clear skies within the different solar radiation wavebands have been available for many years. For UVB, the column O_3 depth is an important input parameter. These models only predict irradiance on horizontal surfaces in the open. Our current research goals are to use the open irradiance models as the starting point for other models that predict irradiance in urban areas with trees and buildings. Our algorithms for sky radiance distributions and the knowledge of leaf optical properties will be important input to models that predict the effects of trees and buildings on irradiance. Such models will be useful in preparing 3D images of the distribution of UVB irradiance patterns on ground surfaces to illustrate in public information programs the difference between visible and UVB shade patterns.

Models of tree and building effects on UV also will make it possible to determine the climatology—the long-term averages and the ranges—of UV irradiance in urban locations. Another goal is to project the irradiances onto models of human forms so that the results are more meaningful for interpreting the effects of irradiance on people. If successful, this modeling effort will provide important tools for studying human epidemiology. These models will aid in planning the management of urban trees (street trees to complete canopies) as well as the arrangement of facilities, e.g., sitting and play areas and picnic tables, with respect to their influences on UV radiation.

Acknowledgments

We thank Dr. William B. Grant of the NASA Langley Research Center for generously sharing his literature database files and for numerous suggestions on an earlier draft of the manuscript. Comments by Dr. John E. Frederick of the University of Chicago led to improvements to the sections on ozone and UVB cycles, trends, and measurements. Dr. Elizabeth C. Weatherhead of Colorado State University also commented extensively on an earlier draft. Dr. Donald Lyman, of the Chronic Disease and Injury Control Department, Sacramento, CA, commented on sections dealing with human health. The excellent services of the Interlibrary Loan staff of Moon Library at the SUNY College of Environmental Science and Forestry were essential. Michelle Docteur and Joseph Comi assisted with collection of literature and maintenance of the literature database. Sue Sisinni and Michelle Docteur assisted with the preparation of artwork. Wei Gao provided information on leaf optical properties and assisted with sky radiance measurements. Linda Sit assisted with literature collection. This research was partly funded by the USDA Forest Service's Northern Global Climate Change Program.

Glossary

Albedo. The term usually used to indicate the ratio of radiation reflected to radiation received by a surface when the radiation is from the sun (Iqbal 1983).

Action spectrum. The relationship between sensitivity or response to radiation and the wavelength of the radiation, often described by a mathematical equation. Different kinds of responses (e.g., sunburning, damage to DNA) have different action spectra.

Beer's Law. An equation often used to model the gradual extinction of radiation through media with elements (that can be leaves) that are distributed randomly or nearly randomly. In plant canopies, it is of the form $t = \exp^{kL}$ where t is canopy transmission to a given canopy depth, L is the cumulative leaf area index from the top of the canopy down to that point, and k is an "extinction coefficient" to be determined experimentally.

Cumulus humilis. The scattered puffy white clouds common during afternoons with fair weather.

Dobson unit. A measure of total O_3 in the atmosphere above a point on Earth named after G.M.B. Dobson, the scientist who invented an instrument in the 1920's that is still commonly used to measure O_3. One Dobson unit is equivalent to a 0.01-cm depth of ozone if all the ozone were brought together at sea level pressure.

Global irradiance. Radiant energy per unit of area, within the designated wavelength band, that falls on a flat, horizontal surface from all directions above the surface.

Irradiance. Radiant energy falling on a flat surface per unit area of the surface, commonly measured in Watts per square meter, W m^{-2}.

Leaf-area index (LAI). The area of leaf surface per unit of ground area.

Minimum erythemal dose (MED). The UV radiation dose that can cause minimal reddening on untanned average Caucasian skin, as determined by experiment.

Scattering angle. The angle Ψ between a point in the sky and the position of the sun defined by $\cos\Psi = \cos\Theta \cos\Theta^* + \sin\Theta \sin\Theta^* \cos\Phi$, where Θ is the sky point zenith angle, Θ^* is the solar zenith angle, and Φ is the difference between the solar azimuth and the sky point azimuth.

Sky Radiance. Radiance is the electromagnetic energy given off by a surface. The unit of radiance from a surface (or the sky) is energy per unit area of the receiving surface per solid angle of the emitting surface as viewed from the receiving surface (Watt cm^{-2} steradian $^{-2}$). Sky radiance results from scattering of beam solar radiation in the Earth atmosphere.

Solar spectrum. The energy distribution by wavelength for electromagnetic radiation from the sun. The limits of the solar spectrum on Earth are approximately 295 to 3,000 nm.

Stratosphere. The layer of the atmosphere that extends from about 15 to 50 km (9 to 31 miles) above the Earth. The troposphere is the layer from the surface of the Earth to the bottom of the stratosphere (see Figure 4). In the stratosphere, the absorption of solar radiation by ozone and oxygen causes the temperature at the top of this layer to be warmer than the lower part of the layer. With cooler air being overlain by warmer, vertical mixing is limited, an important condition for the chemistry of the stratosphere. The division between the troposphere and stratosphere is called the tropopause. Its height ranges from about 9 to 18 km (6 to 11 mi) depending on the season and latitude.

Sun protection factor (SPF). An index of protection against sun burning by sunscreen lotions. The erythemal radiation that penetrates a specified sunscreen application is proportional to 1/SPF, for example, an SPF of 10 allows penetration of one-tenth of the incident UV radiation that causes sunburn.

Sunflecks. Spots within the shadow pattern of a tree that have distinctly higher irradiance than the rest of the shadow caused by direct beams from the sun coming through gaps in the tree crown.

Urban forest. Generally, the aggregate of trees and forests in locations frequented by people or near human habitations.

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