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Biologically Effective Ultraviolet Radiation: Surface Measurements in the United States, 1974 to 1985

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Recent reports of stratospheric ozone depletion have prompted concerns about the levels of solar ultraviolet radiation that reach the earth's surface. Since 1974 a network of ground-level monitoring stations in the United States has tracked measurements of biologically effective ultraviolet radiation (UVB, 290 to 330 nanometers). The fact that no increases of UVB have been detected at ground levels from 1974 to 1985 suggests that meteorological, climatic, and environmental factors in the troposphere may play a greater role in attenuating UVB radiation than was previously suspected.

Recent reports of stratospheric ozone depletion (*1*), as much as 40% over parts of Antarctica during its spring month of October (*2*), suggest that greater amounts of solar ultraviolet radiation will reach the surface of the earth. In 1974 a collaborative study of ground-level measurements of biologically effective, nonionizing solar radiation was implemented (*3*). We report trends in the annual amounts of biologically effective ultraviolet radiation (UVB, 290 to 330 nm) that reach the earth's surface at several locations within the United States. Solar ultraviolet radiation can produce skin erythema (sunburn) in humans and skin cancer in laboratory animals (*4*) and would be expected to increase if ozone is depleted. A 1% decrease in stratospheric ozone could cause about a 2% increase in the amount of UVB that would pass through this shield (*5*). The increases vary according to specific waveband, season, and zenith angle of the sun (*6*).

Photosensitive meters [Robertson-Berger (R-B) meters] were installed at various National Weather Service stations (usually airports) and have been monitored and maintained continuously since 1974 (Table 1). The locations span a latitude range from 30° to 47°N and a longitude range from 75.2° to 122.2°W. Radiation in the UVB range is monitored by a magnesium tungstate sensor and weighted according to an action spectrum that parallels that for skin erythema. The most effective biological wavelength for producing erythema on typical Caucasian skin is 297 nm (*7*). The biological effectiveness of UVB decreases logarithmically within the UVB range; at 330 nm it is less than 0.1% as effective as at 297 nm. The R-B meter integrates the weighted amounts of UVB and provides counts in "sunburn units" (SU) (*8–10*). Quality control checks included an evaluation of diurnal, daily, and monthly readings at specific locations to verify that SU counts agreed with meteorological data.

To assure that the R-B meter measurements were comparable among stations, each meter was checked annually against two standardized meters, which were checked every other week against a calibrating light source (*11*). Calibration factors (CFs) (obtained for each year from 1974 to 1983 for each station) varied in absolute value among stations, but no significant annual trends in CF were noted for the stations reported here. Data presented for 1984 and 1985 were adjusted according to the most recent CF at each field station. The outputs from R-B meters have been compared with those from Dobson spectrophotometers (presently used for measuring total ozone) that were modified to provide measures of erythemal UVB energy reaching the earth's surface at two stations, Bismarck, North Dakota, and Tallahassee, Florida (*12*). The correlation coefficients were reported to be 0.96 and 0.98, respectively, at these locations, and provided an estimate for the conversion of R-B meter readings to energy units (2.8 counts equal 1 J/m^2).

Table 2 shows annual R-B measurements from the period from 1974 to 1985 at each station, arranged according to increasing latitude. The intensity of UVB at each station (Table 2) could have varied according to geographic factors, such as latitude, longitude, and altitude, and physical or meteorological factors, such as the water content of the atmosphere, turbidity, and cloudiness of the day. Solar UV flux generally decreases as latitude increases and as the zenith angle increases. However, Tallahassee, the southernmost station, received less solar UV than either Albuquerque, New Mexico, or El Paso, Texas. This difference reflects the effect of the higher altitude and less turbid and cloudy conditions at the southwestern stations compared to the Florida station, which has greater amounts of sky cover and humidity.

Average annual R-B counts for two consecutive 6-year periods (1974 to 1979 and 1980 to 1985) show a negative shift at each station, with decreases ranging from 2 to 7% (Table 2). Figure 1 (semi-logarithmic plot) shows that there are no positive trends in annual R-B counts for 1974 to 1985. The logarithm of the annual R-B counts is used as the dependent variable in regression analyses to obtain an estimate of the average annual percentage change. The estimated average annual change varied from −1.1% at Minneapolis, Minnesota, to −0.4% at Philadelphia, Pennsylvania (Table 2). For all the stations the R-B counts dropped an average of 0.7% per year since 1974. Three of the individual station trend coefficients were not statistically significant, however.

Although we rule out changes in instrumentation and monitoring techniques, it is unclear whether abrupt meteorological changes such as atmospheric aerosol scatter-

Table 1. Geographic locations and meteorological measures for the eight stations used.

Site number	Location	Latitude (°N)	Longitude (°W)	Elevation (m)	Average sky cover
1	Tallahassee, FL	30.4	84.4	2	0.58
2	El Paso, TX	31.8	106.4	1194	0.39
3	Fort Worth, TX	32.8	97.0	164	0.52
4	Albuquerque, NM	35.0	106.6	1619	0.44
5	Oakland, CA	37.7	122.2	2	0.48
6	Philadelphia, PA	39.9	75.2	9	0.62
7	Minneapolis, MN	44.9	93.2	255	0.64
8	Bismarck, ND	46.8	100.7	502	0.63

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ing from recent volcanic eruptions, for example, El Chichón in 1982, could influence these trends.

These results are consistent with earlier reports that used R-B data for a shorter time period from 1974 to 1979 (*13*) and Dobson meter total column ozone data for the period from 1970 to 1982 (*14*). Although recent measurements of stratospheric ozone from satellite instruments indicate that total column ozone is being depleted during the 1980s, anticipated resultant increases in solar UVB were not evident for the same time period at certain geographic locations in the United States (between 30° and 50°N).

Monthly trends of estimated UVB levels showed consistent decreases at each field station. The seasons with the greatest relative decreases were the fall (October, November, or December) and winter (January, February, or March). Analysis of peak daily UVB measures for each of three 10-day periods within each month showed that the peak day, which is usually cloudless, also had consistent downward trends for the 12-year period. The data were also analyzed with annual calibration factors excluded and the findings remained unchanged.

The R-B meter provides a direct measure of UVB flux reaching the earth's surface and thus incorporates certain effects of meteorological conditions, such as cloud cover and turbidity caused by aerosol particles in the atmosphere, which are difficult to model with the use of theoretical calculations based on ozone data at specific geographical locations. However, because the transmission of energy through its filters does not decrease with increasing wavelength as rapidly as the skin erythema action function, the effect of ozone depletion, which is greater for the shorter UVB wavelengths, may be understated. Thus, although a 1% change in total ozone results in about a 2% opposite change in erythemal solar radiation (*5*), the R-B meter's response to ozone changes may be somewhat reduced. Nevertheless, the R-B meter can measure changes in UV solar radiation associated with ozone changes if all other factors remain unchanged.

Our study suggests that the role of physical and meteorological factors in the troposphere may be greater than expected, and that there may be prevailing conditions that diffuse solar energy and thus reduce the amount of UVB radiation reaching the earth's surface. These results suggest that two-dimensional models for estimating and predicting ozone changes may be appropriate. Unlike one-dimensional models, which provide global total column ozone estimates and trends, two-dimensional models account for variability in season and latitude and indicate that the greatest relative changes in ozone depletion occur at the poles, with smallest changes at the equator.

It has been suggested that the temporal patterns of sunspot activity may be associated with variations in R-B readings and measures of total global ozone at specific locations in the United States (*15*). With respect to biological effects, variations in the incidence of skin melanoma, which may be related to short-term and high-intensity UVB exposure (*16*), were also found to correlate with sunspot activity (*17*). Although we expect that the long-term effects of increased UVB exposure from stratospheric ozone depletions will cause large increases in the incidence of nonmelanoma skin cancer (*18, 19*), we should not be surprised to see an earlier response for skin melanoma incidence (*20*), especially at locations close to the polar region.

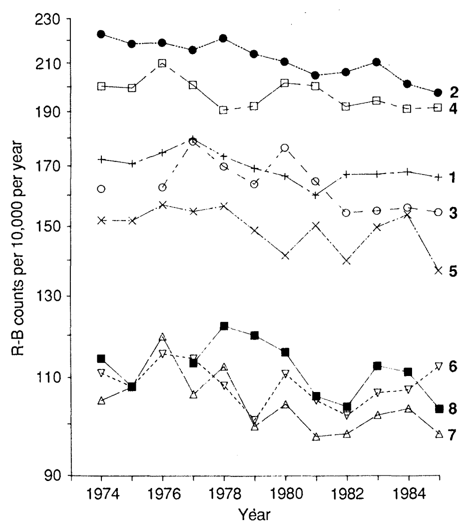

Fig. 1. Solar ultraviolet (UVB) trends and annual R-B counts at the eight field stations listed in Table 1, 1974 to 1985.

Table 2. UVB measurements from R-B meters at the eight locations listed in Table 1 (shown in order of increasing latitude). Counts are given per 10,000; standard errors are given in parentheses. Trend evaluation is described in the text and is the average annual percentage change. NA, data not available.

Year	Location							
	1	2	3	4	5	6	7	8
1974	172.3	222.9	162.1	200.3	151.9	111.1	105.0	114.4
1975	170.8	218.4	NA	199.6	151.8	108.0	107.9	108.0
1976	174.7	218.9	162.6	209.9	156.9	115.5	119.7	NA
1977	179.6	215.5	178.7	200.7	154.7	114.3	106.3	113.2
1978	173.3	220.7	169.7	190.5	156.4	108.1	112.4	122.1
1979	169.1	213.8	163.6	192.1	148.7	100.8	99.5	119.8
1980	166.4	210.2	176.3	201.3	141.2	110.7	104.1	115.7
1981	160.0	204.5	164.6	200.1	150.2	104.9	97.5	105.8
1982	166.9	205.8	154.2	191.8	139.7	101.7	98.0	103.5
1983	166.9	209.9	154.8	194.1	149.6	106.5	101.8	112.5
1984	167.7	200.9	155.8	190.9	153.6	107.2	103.2	111.1
1985	165.8	197.2	154.3	191.3	136.8	112.4	98.0	103.1
				Mean values				
1974–79	173.3	218.4	167.3	198.9	153.4	109.6	108.5	115.5
1980–85	165.6	204.8	160.0	194.9	145.2	107.2	100.4	108.6
1974–85	169.5	211.6	163.3	196.9	149.3	108.4	104.5	111.7
	(1.5)	(2.4)	(2.6)	(1.7)	(1.9)	(1.3)	(1.9)	(1.9)
				Trend				
1974–85	−0.5*	−1.0**	−0.8†	−0.5*	−0.7*	−0.4†	−1.1*	−0.7†

$^{*}P \leq 0.05$. $^{**}P \leq 0.01$. †Not significant.

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Capture of Atmospheric Ammonium by Grassland Canopies

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Air pollution can cause a decline in species through acidification of the habitat. New data suggest that the decline may be due to eutrophication rather than acidification. In Western Europe, eutrophication largely results from atmospheric ammonium deposition. The amount deposited on vegetation is a function of its canopy structure. Deposition on grasslands has been underestimated, and a significant amount of the deposited ammonium appears to be assimilated by the plant canopy. These quantities are sufficient to initiate changes in the competitive relations among the plant species.

THE TWO ENVIRONMENTALLY MOST damaging air pollutants in Western Europe are sulfur dioxide and ammonia or ammonium. They are deposited on surfaces at rates that vary with the structure of that surface. Forests were often shown to receive high amounts of air pollutants because of their rough canopy structure (*1*). Grasslands and croplands were thought to have rather smooth canopy structures and to capture much smaller amounts. Measurements inside grassland canopies are rare, however. Our data show that grassland canopies, depending on their structure, can capture as much air pollutants as forests.

Environmental acidification as a result of SO_2 pollution was shown to lead to declines in species abundance both in aquatic and terrestrial ecosystems, particularly in nutrient-poor sites (*2–4*). The main source for SO_2 is industry. Eutrophication largely results from atmospheric NH_x deposition, originating from the liquid manure used in great quantities in the intensive farming systems in Western Europe (*4–6*). Wind tunnel experiments have shown that the two pollutants are co-deposited (*7*). Amounts of bulk deposition (the sum of wet deposition and dry sedimentation) are relatively unaffected by the characteristics of the surfaces on which they are deposited, but amounts of dry deposition resulting from impaction, phoresis, and diffusion (*8*) are strongly determined by the roughness length of the deposition surface (*9*). Vegetation is the most widespread deposition surface. Forests have been shown to possess surface structures that highly promote deposition (*1, 10*). Deposition of pollutants on plant canopies is measured by comparing the composition of throughfall and bulk precipitation. So far, nearly all field measurements to correlate throughfall with canopy structure have been done in forests (*10, 11*) because it has proved difficult to measure in herbaceous vegetation without disturbing its canopy structure. Besides, herbaceous vegetation was presumed to have a relatively smooth canopy structure (*9*). However, forests cover only limited areas in the densely populated parts of Western Europe. In the Netherlands forests cover less than 9% of the country, whereas grasslands and croplands cover 70%. We investigated the effects of structurally different grassland canopies on deposition. In grasslands, leaf area index (LAI, the sum of the surface area of all leaves in a stand of vegetation per unit ground area) is correlated with other variables describing vegetation structure (*11, 12*).

We developed a technique to measure throughfall in grassland canopies without disturbing the structure, using a system of slanting half-open channels (diameter 15 mm, capturing surface 165 cm^2) covered by polythene gauze (mesh size, 0.02 mm) to prevent contamination with litter and insects (*13*). Bulk deposition was measured above the vegetation. Bulk and throughfall precipitation were gathered in dark bottles dug in the ground to prevent chemical changes (*14*). Measurements were carried out in five replicates in each of two adjacent, homogenous grassland plots in a nature reserve amidst open agricultural land at Deil, about 30 km south of Utrecht, the Netherlands, from 15 June to 26 September 1986. During that period the plants grew up to a maximum of 80 cm. One plot was mown on 7 July to alter its canopy structure. The dark bottles were collected fortnightly. Samples were analyzed for SO_4^{2-} and NH_4^+ (spectrophotometrically, with a continous flow Skalar autoanalyzer). To measure canopy structure, once a month the vegetation was clipped at ground level in five replicate quadrates of 15 by 50 cm in each plot. In these samples LAI was determined with the use of a LiCor leaf area meter. Data were summarized for 28-day periods and statistically analyzed by analysis of variance (*15*). In the undisturbed plot, LAI increased until August and was lower again in September as leaves had started to die off (Table 1). The mown plot showed the same rhythm but LAI values obviously were much lower here during the growing season as a result of the mowing.

As reported previously for the Netherlands (*4*), the amount of SO_4^{2-} in bulk

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