A CLIMATOLOGY OF SUNBURNING ULTRAVIOLET RADIATION

DANIEL S. BERGER* and FREDERICK URBACH

The Center for Photobiology, Skin and Cancer Hospital, Temple University School of Medicine, Philadelphia, PA 19140, USA

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Abstract—Data are presented from 14 sites where continuous measurements of the sun's shortest ultraviolet radiation reaching the earth's surface have been made for four or more years. Average daily dose per month and its variability from year to year is shown for each station. Some of the many influences affecting these measurements can be discerned by station intercomparisons. No consistent long term change in solar UV-B radiation reaching the ground is evident.

INTRODUCTION

The high energy, short wavelength portion of the solar electromagnetic spectrum (wavelengths of ultraviolet radiation shorter than 320 nm: UV-B) is potentially very detrimental to living cells and tissues. A low concentration of ozone formed in the stratosphere absorbs the majority of the photons of UV-B and shorter radiation and thus prevents most of them from reaching earth. However, even in the presence of this ozone layer, which varies in thickness at various latitudes and in different seasons, a biologically significant amount of UV-B reaches the surface of the earth.

Concern has arisen that anthropogenic alteration of the stratospheric ozone layer by aircraft effluents, chlorofluorocarbon emission etc. could significantly decrease ozone concentration with consequent sizeable increases of solar ultraviolet radiation (UVR)† reaching man, animals and plants (National Academy of Sciences, 1979; Impacts of Climatic Change on the Biosphere, 1975).

In order to determine the effect of various man-made chemical emissions on intensity and dose of UV ground level radiation, a network of recording UVR meters was developed and deployed in various areas, initially in response to the needs of the Climatic Impact Assessment Program of the U.S. Department of Transportation, and later under the auspices of the National Oceanic and Atmospheric Administration with support from the Environmental Protection Agency.

The data accumulated with these UVR recording meters from 14 stations operating for four or more years are presented here.

METHODS

The UVR meter used in this study has been described in detail (Robertson, 1972; Berger, 1976). Briefly, it detects the shortest end of the solar UVR below 330 nm with a response which rises sharply with decreasing wavelength. The meter's spectral response resembles the skin's erythema action spectrum (EAS) (Fig. 1). Since the meter response is wavelength dependent, its output cannot be dimensioned in terms of absolute energy. The meter output can generally be considered indicative of erythemal effectiveness. However, since the spectral response of the meter is not identical to the human EAS and has some response in the longer, biologically relatively ineffective UVR, significant errors can result, primarily at large zenith angles, where the total UV-B component is minimal. However, at small zenith angles (the sun overhead) the meter indicates the erythemal effectiveness accurately. For these reasons the dimension chosen to present the data has been named the "Sunburn Unit".

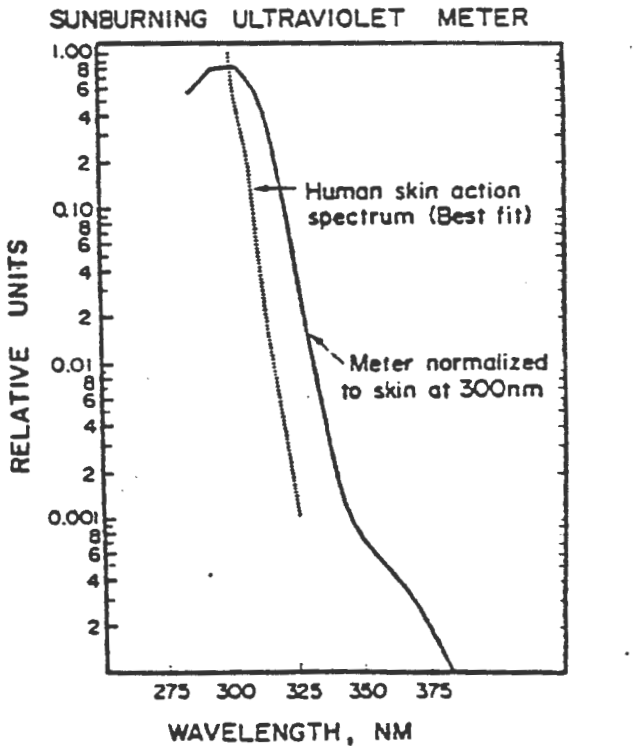

Figure 1. Erythema action spectrum and sunburn ultraviolet meter spectral response.

*To whom all correspondence should be addressed.

†*Abbreviations*: EAS, erythema action spectrum; MED, minimal erythema dose; SUV, solar UV radiation; UVR, ultraviolet radiation.

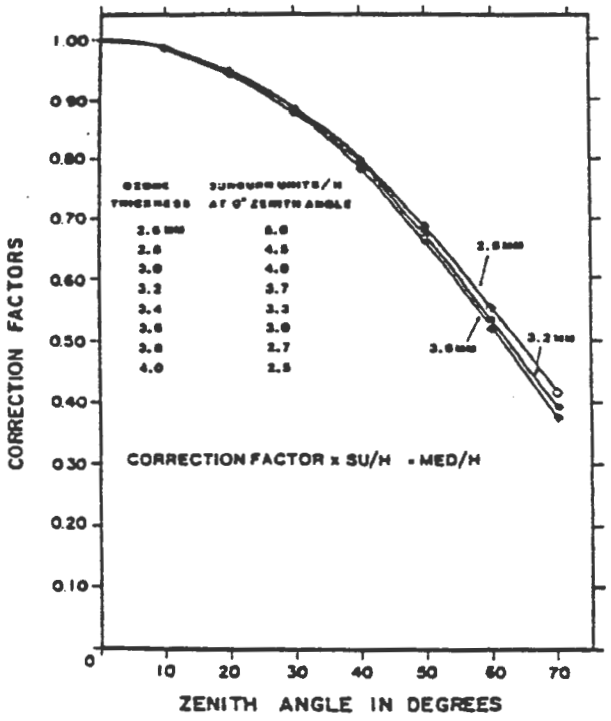

Figure 2. Correction factors allow an accurate estimation of the erythemal effect of global radiation from the meter reading. Note that ozone concentration has only minimal effect on the correction factors.

The sunburn unit (SU) is defined as equal to a minimal erythema dose (MED) when untanned human skin is exposed to a vertical tropical sun; the dose rate of UVR under these conditions is 5 MED per h or 1 MED in 12 min, the maximum erythema intensity found on the earth's surface. This assumes average untanned Caucasian skin, sea level, overhead sun in a clear sky and stratospheric ozone of 2.6 mm thickness.

As the sun's position changes from overhead, that is, as its zenith angle increases, the solar spectrum as well as UVR intensity changes. The shortest wavelengths are reduced most rapidly at increasing solar zenith angles. Since the EAS is influenced more than the meter response by shorter wavelengths there is a greater reduction in erythemic response than of meter response with increasing zenith angle. Using a correction factor based on sun angle, the meter output can be corrected to predict efficacy relative to any biologic action spectrum confined to wavelengths below 330 nm (Fig. 2). Even without correction, however, the meter response is a reasonable guide. Note in Fig. 2, for example, that the sensitivity to ozone thickness is small. Moreover, it should be borne in mind that the majority of a day's dose is received during the period when the sun is at the lowest zenith angles, a period when the correction factor changes fairly slowly. For these reasons, the uncorrected daily meter responses are good relative indicators of the actual daily erythemally effective irradiances and are used in this paper.

The sunburn unit has been standardized with a quartz-halogen calibration source. A pair of detectors in Philadelphia are periodically checked with the calibration source to maintain their accuracy. These detectors are the standard for the entire network. Other detectors used to calibrate station meters are compared regularly against these standards and then shipped to each station annually where they are run for a few days next to the station meter. A correction factor for each station is thus determined.

The UVR dose data from each meter is printed each half hour on paper tape. A month's tape at a time is mailed to the Philadelphia central station. Another source of data is the daily total recorded each day by station personnel. This serves as backup data as well as a data source which can be easily evaluated for monthly and average daily dose. The data from these totalizer cards serve as the basis for the information presented in this report.

RESULTS

Table 1 lists the 14 stations for which the UV insolation is presented. For these stations 4 or more complete years of data and calibration information are available.

Figure 3 shows the geographic distribution of the 14 stations. Unnumbered dots show other stations in the network with too few years of operation to be reported here.

The percent of captured data in respect to the maximum possible is 96% of possible days. Months were discarded when 10 days were missing, and resulted in 97.5% of all possible months in this report. The average annual change in meter sensitivity has been found to be 2%.

Table 2 shows the mean daily dose (in sunburn units) for each month of the year, averaged for as many years as there are data. The number of years of

Table 1. The latitudes and altitudes of 14 sites measured

Station	Latitude	Altitude*
1. MLO = Mauna Loa, Hawaii	19.5°N	3.38 km
2. TLH = Tallahassee, Florida	30.4°N	
3. ELP = El Paso, Texas	31.8°N	1.14 km
4. FTW = Fort Worth, Texas	32.8°N	0.25 km
5. ABQ = Albuquerque, New Mexico	35.0°N	1.51 km
6. OKD = Oakland, California	37.7°N	
7. MLB = Melbourne, Australia	38.0°S	
8. PHL = Philadelphia, Pennsylvania	40.0°N	
9. HNY = Honey Brook, Pennsylvania	40.1°N	0.21 km
10. DSM = Des Moines, Iowa	41.5°N	0.29 km
11. MNP = Minneapolis, Minnesota	44.9°N	0.25 km
12. BIS = Bismarck, North Dakota	46.8°N	0.51 km
13. DAV = Davos, Switzerland	46.8°N	1.58 km
14. BSK = Belsk-Duzy, Poland	51.8°N	

Table 2. Sunburn units per day* ±1 SD

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MLO	13.9 ± 1.8 (6)	17.6 ± 3.1 (5)	20.1 ± 2.8 (7)	21.6 ± 1.1 (5)	23.2 ± 2.7 (6)	25.3 ± 1.9 (6)	24.4 ± 2.8 (6)	23.9 ± 1.7 (6)	22.8 ± 1.7 (4)	16.9 ± 0.9 (5)	14.0 ± 1.2 (6)	12.7 ± 0.8 (7)
TLH	4.6 ± 0.5 (7)	6.9 ± 1.2 (7)	10.1 ± 0.7 (7)	14.3 ± 1.4 (6)	15.1 ± 0.5 (5)	16.1 ± 0.7 (6)	14.6 ± 1.2 (6)	14.0 ± 1.5 (6)	11.8 ± 0.4 (5)	9.3 ± 0.4 (7)	6.0 ± 0.4 (7)	4.3 ± 0.3 (7)
ELP	5.1 ± 0.5 (6)	8.4 ± 0.7 (7)	12.7 ± 0.8 (7)	17.3 ± 1.0 (6)	20.2 ± 0.8 (6)	22.8 ± 1.0 (6)	20.4 ± 1.3 (6)	19.1 ± 0.6 (6)	14.8 ± 1.0 (6)	10.8 ± 0.7 (7)	6.7 ± 0.7 (7)	4.8 ± 0.5 (7)
FTW	3.2 ± 0.5 (6)	5.3 ± 1.0 (6)	8.7 ± 0.7 (6)	11.6 ± 1.1 (6)	14.2 ± 1.4 (5)	18.3 ± 0.6 (5)	17.0 ± 1.6 (5)	14.8 ± 1.2 (6)	11.2 ± 1.6 (6)	7.5 ± 0.5 (7)	4.4 ± 0.2 (7)	3.3 ± 0.4 (7)
ABQ	4.1 ± 0.4 (7)	6.7 ± 0.5 (7)	10.4 ± 0.4 (6)	15.6 ± 1.0 (7)	18.4 ± 1.3 (7)	21.7 ± 1.0 (7)	20.8 ± 1.0 (6)	18.5 ± 1.2 (5)	14.8 ± 0.8 (6)	10.0 ± 0.6 (6)	5.7 ± 0.5 (7)	3.8 ± 0.1 (7)
OKD	2.7 ± 0.4 (7)	4.3 ± 0.5 (7)	7.3 ± 0.9 (7)	11.5 ± 1.1 (7)	14.9 ± 1.5 (7)	16.9 ± 0.9 (7)	17.3 ± 0.8 (6)	14.6 ± 0.7 (5)	11.0 ± 0.6 (5)	6.7 ± 0.5 (6)	3.7 ± 0.5 (6)	2.4 ± 0.1 (7)
MLB	2.2 ± 0.2 (6)	3.4 ± 0.3 (6)	6.2 ± 0.7 (6)	10.2 ± 0.8 (6)	14.9 ± 0.8 (6)	18.2 ± 1.0 (6)	18.9 ± 0.9 (5)	16.6 ± 0.8 (6)	11.1 ± 1.1 (5)	5.8 ± 0.3 (5)	3.1 ± 0.3 (5)	1.9 ± 0.02 (5)
	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
PHL	1.6 ± 0.2 (7)	3.0 ± 0.3 (7)	5.3 ± 0.9 (7)	8.6 ± 0.9 (7)	10.4 ± 1.1 (7)	12.3 ± 0.9 (7)	12.9 ± 1.1 (7)	10.8 ± 0.6 (7)	8.1 ± 0.5 (8)	4.7 ± 0.4 (8)	2.5 ± 0.2 (8)	1.4 ± 0.1 (8)
HNY	1.6 ± 0.2 (6)	3.2 ± 0.5 (6)	5.6 ± 0.6 (6)	8.5 ± 0.8 (6)	11.1 ± 0.8 (6)	13.2 ± 1.0 (6)	13.3 ± 1.1 (4)	12.0 ± 0.5 (6)	8.3 ± 1.2 (5)	4.7 ± 0.5 (5)	2.4 ± 0.3 (5)	1.4 ± 0.2 (6)
DSM	1.6 ± 0.3 (6)	3.0 ± 0.4 (6)	5.3 ± 0.8 (6)	8.5 ± 0.7 (6)	11.7 ± 0.8 (6)	15.4 ± 0.8 (6)	16.1 ± 0.7 (7)	12.6 ± 0.8 (7)	9.2 ± 1.0 (6)	5.1 ± 0.7 (7)	2.1 ± 0.1 (6)	1.4 ± 0.2 (6)
MNP	1.2 ± 0.1 (7)	2.4 ± 0.1 (7)	4.4 ± 0.6 (7)	7.4 ± 1.1 (7)	11.3 ± 1.1 (7)	13.7 ± 1.1 (7)	14.6 ± 1.4 (7)	11.0 ± 1.7 (7)	7.4 ± 0.9 (6)	3.9 ± 0.3 (7)	1.6 ± 0.2 (6)	0.9 ± 0.1 (7)
BIS	1.2 ± 0.1 (7)	2.5 ± 0.2 (7)	5.0 ± 0.9 (7)	7.6 ± 1.6 (7)	11.9 ± 1.5 (7)	15.3 ± 1.0 (7)	16.0 ± 0.5 (6)	12.5 ± 1.5 (6)	8.5 ± 1.1 (6)	4.0 ± 0.2 (6)	1.6 ± 0.2 (7)	0.9 ± 0.1 (7)
DAV	1.4 ± 0.2 (6)	3.3 ± 0.5 (6)	6.2 ± 0.6 (6)	9.5 ± 1.1 (6)	11.8 ± 1.6 (6)	12.2 ± 1.4 (5)	11.9 ± 1.2 (5)	9.4 ± 1.4 (5)	7.5 ± 0.7 (5)	4.4 ± 0.3 (5)	2.0 ± 0.2 (6)	1.2 ± 0.1 (6)
BSK	0.4 ± 0.03 (5)	1.0 ± 0.2 (5)	2.3 ± 0.3 (5)	4.4 ± 0.4 (5)	8.1 ± 1.0 (6)	9.9 ± 1.5 (6)	9.7 ± 1.2 (5)	7.6 ± 1.4 (5)	4.5 ± 0.8 (5)	1.9 ± 0.4 (5)	0.6 ± 0.1 (5)	0.3 ± 0.02 (5)

*For these meters, 440 counts represent 1 sunburn unit.
Number of years averaged in parentheses.

Table 3. Sunburn units per year

	MLO SU/yr	TLH SU/yr	ELP SU/yr	FTW SU/yr	ABQ SU/yr	OKD SU/yr	MLB SU/yr
1974	6650	3860	4991	3598	4480	3397	
1975	7567	3850	4884		4446	3392	3402
1976	6885	3918	4882	3503	4668	3555	3456
1977	7035	3962	4829	3793	4464	3457	3480
1978	6999	3765	4985	3581	4537	3523	3186
1979	7329	3593	4765	3440	4471	3234	3414
Avg SU/yr	7078 ± 326 ± 4.6%	3825 ± 132 ± 3.5%	4889 ± 88 ± 1.8%	3583 ± 133 ± 3.7%	4511 ± 83 ± 1.8%	3426 ± 115 ± 3.4%	3388 ± 117 ± 3.5%

data for that month is shown by the number in parentheses and varies from 4 to 8. The standard deviation from the mean is shown next to the average daily dose. Figure 4 graphically presents the average daily dose per month for 5 of the 14 stations.

Table 3 lists the sunburn units per year for each station. This is obtained by adding the average daily doses for each of the 12 months and multiplying by 30. The average of the annual doses, the standard deviation of the annual doses from the mean annual dose, and the standard deviation as a percent are also listed.

Table 4 lists the percent variation of each station-year from the means of Table 3. In the right hand column the average of percent variations of all stations for each year are averaged, and the standard deviation of all percentages from the annual average percentage is shown.

DISCUSSION

The entries in Table 2 are listed in the order of increasing absolute station latitude. Since sunburning UVR decreases with increasing latitude the table should reflect this. In general this is true; however, local conditions can cause offsetting effects. Comparing El Paso and Tallahassee, it can be seen that the former station, although 1.4° farther north, exceeds the latter in every month of the year. This reversal is attributable to the cloudier weather in Tallahassee as well as the higher elevation of El Paso.

Melbourne and Oakland are 0.3° different in latitude. Melbourne is in the southern hemisphere, however, and Oakland in the northern. The earth–sun distance is 3.4% less for the southern hemisphere summer as compared to the northern hemisphere summer. This alone should increase the total SUV radiation in the southern compared to the northern hemisphere by over 6% for part of its summer. On the other hand, the earth–sun distance is 3.4% less for the northern winter than for the southern hemisphere winter. This should decrease the SUV in the southern hemisphere for part of its winter by over 6% compared to the same northern hemisphere latitude. Melbourne has less SUV than Oakland for its winter, and more SUV for its summer. The direction of the

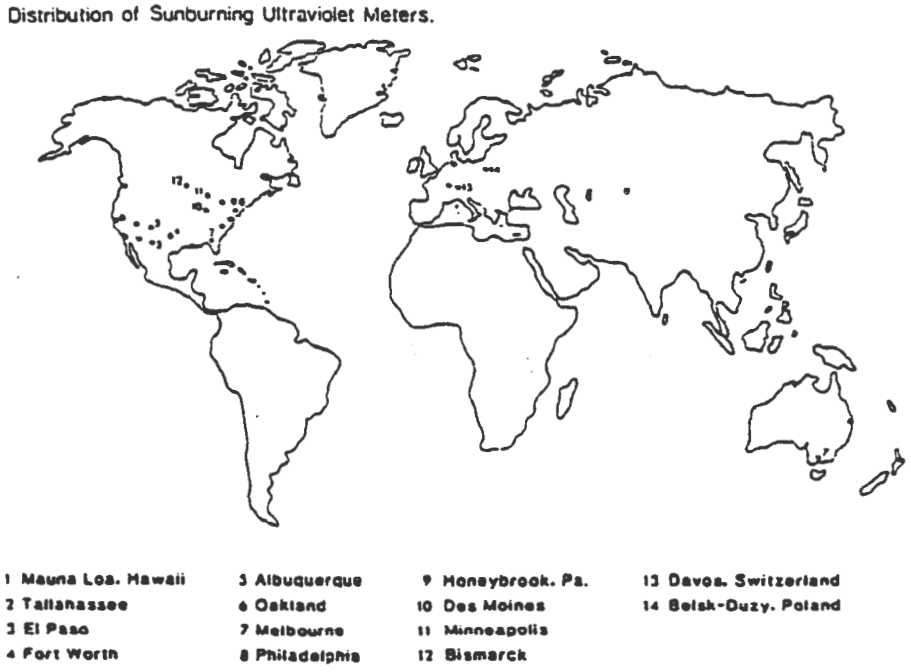

Figure 3. The distribution of the 14 stations where the SUV data was gathered. Unnumbered dots are stations with too few years to be reported here.

Table 3 *continued*

PHL SU/yr	HNY SU/yr	DSM SU/yr	MNP SU/yr	BIS SU/yr	DAV SU/yr	BSK SU/yr
2453		2731	2344	2551		
2381	2523	2754	2401	2408	2616	
2563	2600	2852	2672	2727	2427	1641
2543	2555	2715	2351	2593	2178	1463
2441	2723	2745	2506	2698	2453	1418
2247	2427		2141	2675	2504	1563
2459						
2441 ± 106 ± 4.3%	2566 ± 108 ± 4.2%	2759 ± 54 ± 2.0%	2403 ± 178 ± 7.4%	2609 ± 119 ± 4.6%	2436 ± 161 ± 6.6%	1521 ± 100 ± 6.6%

change is as predicted but the magnitude is greater than expected: ozone, weather differences and air pollution might be the additional factors.

The variability of the annual SUV dose appears to be less than for some other meteorological variables. For example, annual sunlight hours in El Paso, Philadelphia, Bismarck and Tallahassee vary more, as do heating or cooling degree days, or annual precipitation. Annual average temperature is a little less variable than annual SUV dose (NOAA Climatological Data).

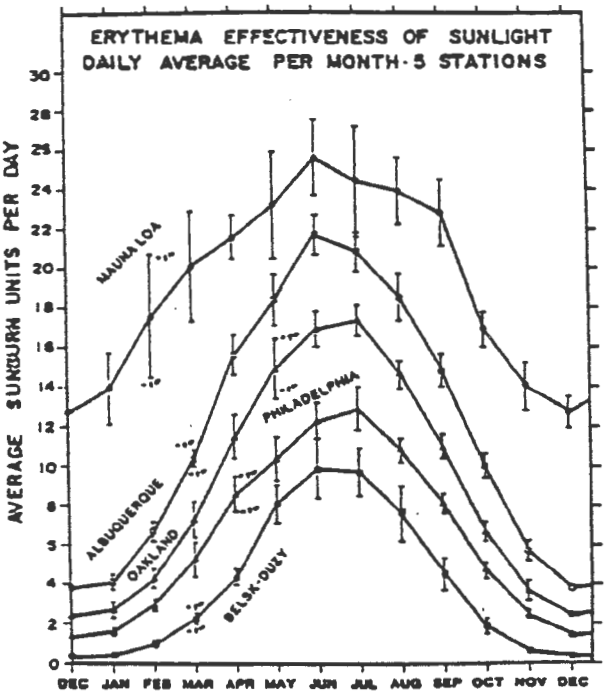

Figure 4. Daily average dose per month for 5 stations including the extremes of high insolation at Mauna Loa, Hawaii (19.5°N, 3.38 km above sea level) to the low insolation at Belsk-Duzy, Poland (51.8°N), the most northerly site reported here.

The variability of the total annual SUV dose from year to year is a minimum of ±1.8% at El Paso and Albuquerque and increases to ±7.4% at Minneapolis.

The change in annual dose per degree of latitude varies from 3.2% (Belsk-Duzy to Fort Worth) to 4.8% (Philadelphia to Tallahassee) to 5.1% (Des Moines to Oakland). These latitudinal changes are within the calculated latitudinal variations for 311.4 nm, a wavelength close to that which the SUV meter responds to most effectively (Sudararaman *et al.*, 1975).

The change in annual dose with altitude is affected by solar angle and albedo. This change is calculated to be 2–6% per km when albedo is between 0.2 and 0.6 (Sundararaman *et al.*, 1974). Comparing Davos to Bismarck could indicate the effect of altitude. Both stations are 46.8°N but Davos is 1 km higher than Bismarck. From May through September SUV readings at Davos, however, are lower than at Bismarck. These lower readings are probably the result of greater cloudiness at Davos than at Bismarck.

It is interesting to compare the urban Philadelphia SUV data to that of rural Honey Brook. These stations are 40 miles apart with the Honey Brook site being west and about 7 miles north of the Philadelphia site. In every year Honey Brook has had a higher annual SUV insolation than Philadelphia. The average difference is +5.1% with a ±4.1% standard deviation. The 0.1° more northerly location would tend to

Table 4. Percent variation of sunburn units per year from mean

	MLO %	TLH %	ELP %	FTW %	ABQ %	OKD %	MLB %	PHL %	HNY %	DSM %	MNP %	BIS %	DAV %	BSK %	Avg var. %
1974	−6.4	0.9	2.1	0.4	−0.7	−0.9	—	0.5	—	−1.0	−2.5	−2.2	—	—	−1.0 ± 2.4
1975	6.9	0.7	−0.1	X	−1.5	−1.0	0.4	−2.5	−1.7	−0.2	−0.1	−8.3	7.4	—	0.0 ± 4.1
1976	−2.8	2.4	−0.1	−2.3	3.5	3.8	2.0	5.0	1.3	3.4	11.2	4.5	−0.4	7.9	2.8 ± 3.8
1977	0.6	3.6	−1.2	5.9	−1.1	0.9	2.7	4.2	−0.4	−1.6	−2.2	−0.6	−11.8	−4.0	−0.4 ± 4.3
1978	−1.1	−1.6	2.0	−0.1	0.6	2.8	−6.3	0.0	6.5	−0.5	4.3	3.4	0.7	−7.3	0.2 ± 3.7
1979	3.5	−6.5	−2.6	−4.2	−0.9	−5.9	0.8	−8.6	−5.7	X	−12.2	2.5	2.8	2.8	−2.6 ± 5.0

— Station not in operation.
X Malfunction voids annual total.

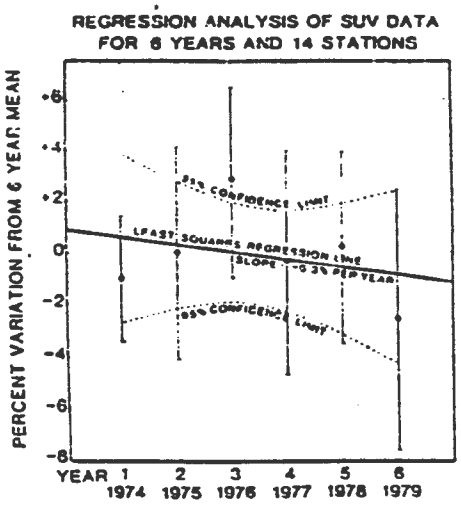

Figure 5. Regression analysis of SUV data for 6 years and 14 stations. Note a −0.3% annual slope of mean SUV.

reduce the Honey Brook insolation by about 0.3%. The 0.2 km greater altitude of the Honey Brook meter should result in about a 1% increase. The combined latitude and altitude corrections should therefore make Honey Brook about 0.7% higher than Philadelphia, an insignificant difference. The rural agricultural setting in Honey Brook as compared to the urban setting for the Philadelphia meter must produce the factors which result in the +5% average increase observed. Less pollution in Honey Brook and/or a different albedo probably account for the difference. Urban pollution results in increases in aerosols which absorb and scatter radiation. The net loss due to aerosols can be as much as 7% depending on concentration, particle size, absorption, refractive index and spatial distribution (Sundararaman *et al.*, 1975), but smaller reductions of 1–3% would be expected.

On the other hand, albedo differences can cause significant changes in UV flux. Increasing albedo from 0.05 to 0.15 increases flux by 5%, for example (Sundararaman *et al.*, 1975). These low albedo figures are not unusual for UVR. Actual measurements of UVR albedo at Philadelphia and Honey Brook would be needed to support the hypothesis that albedo is a significant factor for the UVR differences noted.

A comparison similar to that of Philadelphia to Honey Brook has been made for Warsaw, in relation to Belsk-Duzy, Poland (Slomka, 1974). Belsk-Duzy is also to the west and therefore upwind of urban pollution. Belsk-Duzy is 0.45 farther south than the Warsaw meter. This should cause no more than a 2% increase in annual SUV. Belsk-Duzy had +7% more SUV in the one year measured than Warsaw. The +5% increase not accounted for by latitude could again be attributed to urban pollution and decreased urban albedo.

Any trend in the annual dose of SUV would be of major importance. A least squares regression line fitted to the annual means has a −0.3% annual slope. The 95% confidence envelope decrease shows that changes in SUV of less than 6.5% in a 6 year period would not be detectable (Fig. 5).

The present data do not show any evidence for a recognizable change in SUV dose from 1974 to 1979.

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