Photochemistry and Photobiology, 2004, 80: 422–428

Solar Ultraviolet-B Radiation in Urban Environments: The Case of Baltimore, Maryland¶†

Gordon M. Heisler*[1], Richard H. Grant[2], Wei Gao[3] and James R. Slusser[3]

[1]USDA Forest Service, Syracuse, NY
[2]Purdue University, West Lafayette, IN
[3]USDA UVB Monitoring and Research Program, Fort Collins, CO

Received 14 May 2004; accepted 23 August 2004

ABSTRACT

Ultraviolet-B radiation (UV-B, 280–320 nm) has important effects in urban areas, including those on human health. Broadband UV-B radiation is monitored in Baltimore, MD, as part of the Baltimore Ecosystem Study, a long-term ecological research program. We compare broadband UV-B irradiance in Baltimore with UV-B at two nearby locations: a more rural station 64 km southeast and a suburban station 42 km southwest. The monitoring station in Baltimore is on the roof of a 33-m-tall building; there are no significant obstructions to sky view. The U.S. Department of Agriculture UV-B Monitoring and Research Program provided all sensors, which were calibrated at the National Oceanic and Atmospheric Administration Central UV Calibration Facility. UV-B irradiances at the three sites generally were similar. Over all conditions, Baltimore and the suburban site measured 3.4% less irradiance than the rural site. This difference is within the anticipated ±3% calibration uncertainty of the pyranometers. On 59 days with cloud-free conditions at all three sites, average differences in measured UV-B among the three sites were even smaller; Baltimore measured 1.2% less irradiance than the rural site. High aerosol optical thickness strongly reduced daily UV-B dose, whereas [SO_2] had no influence. Surface O_3 increased with increasing UV-B dose when [NO_2] exceeded 10 ppb.

¶Posted on the website on 30 August 2004.
*To whom correspondence should be addressed: USDA Forest Service, 5 Moon Library SUNY-ESF, Syracuse, NY 13210, USA. Fax: 315-448-3216; e-mail: gheisler@fs.fed.us
†A portion of this study was presented at the symposium, "Ultraviolet Ground- and Space-based Measurements, Models, and Effects II" sponsored by The International Society for Optical Engineering (SPIE), held in Hangzhou, China, in October 2002.

Abbreviations: AOD, aerosol optical density; AOT, aerosol optical thickness; BARC, Beltsville Agricultural Research Center; BES, Baltimore Ecosystem Study; CUCF, Central UV Calibration Facility; EPA, U.S. Environmental Protection Agency; EPTOMS, Earth Probe Total Ozone Mapping Spectrometer; LTER, Long Term Ecological Research; MED, minimal erythemal dose of UV-B radiation; MFRSR, multifilter rotating shadowband radiometer; NASA, National Aeronautics and Space Administration; PAR, photosynthetically active radiation; SRMS, Solar Radiation Monitoring Station; TO_3, total ozone column thickness; USDA, U.S. Department of Agriculture; UV-B, ultraviolet radiation of wavelengths 280–320 nm.

INTRODUCTION

Ultraviolet radiation from the sun, especially the UV-B (280–320 nm), has important effects in urban areas, including those on human health (1,2). Though many city residents visit beaches and other rural locations where they receive large doses of UV-B radiation, the routine exposure to UV-B radiation during daily activities may also be important for health. However, few UV-B monitoring stations are located near the centers of cities where the effects of urban atmospheres on UV-B radiation can be measured. For example, the U.S. Department of Agriculture (USDA) UV-B Monitoring and Research Program, which operates the most extensive UV-B monitoring system in the United States with 33 stations, purposely located nearly all its stations well outside of urban areas to serve the agricultural research community, though it was realized that the data would serve other purposes including studies on human health (3). The U.S. Environmental Protection Agency (EPA) maintains a network of 22 spectrometers that measure UV radiation, and eight of these are designated as urban monitors. However, some of these urban monitors are in fact located not within cities but in adjacent rural areas, and data from the network have not been analyzed for urban to rural differences in UV-B (1).

Though UV-B radiation is generally considered a hazard to human health because of its relation to eye cataracts and its role as a causative factor in skin cancers including melanoma that is often fatal, there is a substantial school of epidemiological thought that suggests that too little exposure to UV-B radiation may lead to other cancers because people have too little vitamin D (4–7). UV-B radiation regulates vitamin D (8), and some research suggests that vitamin D prevents many cancers (5). These assertions continue in the literature despite the fact that vitamin D synthesis occurs at low UV-B doses, far below 1 minimal erythemal dose, or MED (8). Though vitamin D is acquired from dietary sources, it is reported that for most populations the main source of vitamin D is exposure of the skin to UV light (4). This is especially true for elderly people who have a dislike for or intolerance to milk and who do not regularly take multivitamins (9). Most of the elderly residents living on their own who took part in a study in a suburb of Boston, MA, had normal levels of vitamin D from their diet and routine sun exposure, whereas a normal diet was not sufficient to maintain normal vitamin D in residents confined to a nursing home (9). Vitamin D has long been known to prevent rickets (8), and low levels of UV radiation because of severe air pollution have been linked to high incidences of rickets in Mexico City (10).

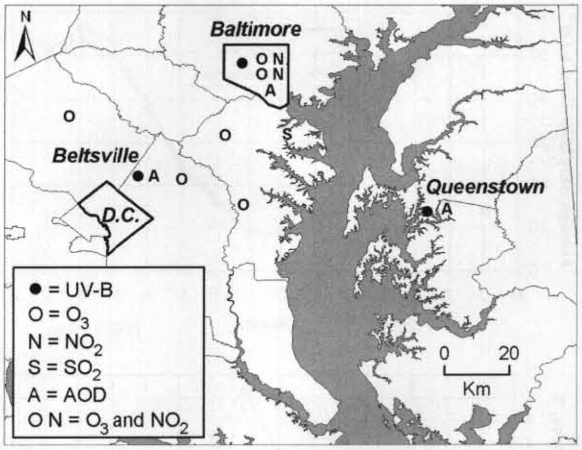

Figure 1. Locations of UV-B (filled circles) and some of the surface air-quality sites where O_3, SO_2 and NO_2 are measured in the Washington–Baltimore area. Sites marked "**A**" measure AOT (AOT at the Maryland Science Center Aeronet site or AOD at USDA UVB Program sites).

Clearly, it is important to understand the spatial variation in UV-B irradiance for epidemiological studies and for health education. Many studies have inferred the influence of UV-B on populations by examining the relationship between disease incidence and estimates of average UV-B irradiance (11–16). In these studies, average irradiance has been based on measurements at sparse ground-based sites or on predictive models applied to satellite reflectance measurements, which are not able to accurately include the effects of aerosols in the atmospheric boundary layer (17). Thus, possible differences in UV-B exposures between urban and rural locations were usually not accounted for in existing epidemiological studies.

In urban areas, incoming UV-B irradiance may differ significantly from that in rural areas, where it is more commonly measured (17,18). We found relatively few reports of urban atmosphere influences on UV-B radiation in the United States. In Athens, Greece, Repapis *et al.* (19) noted reductions of 25% to 35% in erythemal effective radiation during high- *versus* low-pollution days in Athens. In Italy, Meloni *et al.* (20) reported that higher aerosol optical depths in cities reduced UV (295–325 nm) irradiance. With cloud-free skies, Vuilleumier *et al.* (21) found larger variability of optical depths for UV wavelengths in a Southern California urban site than in a high-elevation rural site. They also found that in the urban site, factors other than aerosols were insignificant in determining optical depths, whereas in the rural site, total column ozone was significant in optical depth variability.

It is difficult to determine the quantitative influence of the aerosols and gaseous pollutants in urban atmospheres on UV irradiance (22). A given quantity of ozone (O_3) in the troposphere is thought to be relatively more effective than the same quantity in the stratosphere (23). Thus, although the volume of O_3 in the urban boundary layer may be small relative to stratospheric O_3, the urban boundary layer [O_3] (brackets indicate concentration) may have a significant influence on ground-level UV-B. Some study results declare that elevated levels of [SO_2] may also affect UV-B (24,25), though Meloni *et al.* (20) carried out sensitivity tests that showed the influence of [SO_2] and [NO_2] on modeled UV (295–325 nm) irradiance in Italy to be negligible.

In part to determine how the solar radiation environment of the City of Baltimore (MD) differs from that of adjacent more rural locations, we installed the Baltimore Ecosystem Study (BES) Solar Radiation Monitoring Station (SRMS) in May 2001. The BES is a National Science Foundation Long Term Ecological Research (LTER) site. One planned application of the monitoring site is to provide data for use in local educational programs. The LTER program encourages applications of research results to education, including K-12 schools and to local environmental issues in or near the LTER sites. Another application is to serve as an above-canopy reference for measurements below canopy to evaluate tree and building influences on UV-B irradiance at pedestrian level.

The SRMS includes a broadband UV-B sensor supplied by the USDA UVB Radiation Monitoring Program (http://uvb.nrel.colostate.edu/UVB/), a total solar pyranometer and a photosynthetically active radiation (PAR) pyranometer. In the initial analysis reported in this study, variations in the UV-B radiation were related to weather conditions, surface ozone levels, total ozone column thickness (TO_3) and aerosol optical thickness (AOT) to evaluate differences in the urban and rural UV-B radiation environments.

MATERIALS AND METHODS

We evaluated the UV-B radiation environment in the Baltimore–Washington metropolitan area using measurements at three Maryland locations: Baltimore (39.32°N, 76.66°W), Beltsville (39.01°N, 76.95°W), and Queenstown (38.91°N, 76.14°W) (Fig. 1). The greater Baltimore metropolitan area has a population of about 2.5 million, and it grades into the Washington, DC, metropolitan area, about 65 km to the southwest. The Washington, DC, metropolitan area has a population of about 4.7 million. The Baltimore SRMS is about 5 km northwest of Baltimore's central business district, which lies just to the north of the city's Inner Harbor. The monitoring station in Baltimore is at an elevation of 146 m on the roof of a 33-m-tall building. Except for distant communication towers that have no significant influence on solar irradiance, the sky view is free of obstructions over a full 90° from the zenith except to the northwest where distant hills rise less than 1° above the horizontal.

The Beltsville UV-B Radiation Monitoring site is located on the grounds of the Beltsville Agricultural Research Center (BARC), just north of the University of Maryland at College Park. Whereas the BARC is an area of 2800 ha on which are located farms, forests and institutional buildings, the UV-B monitoring site is on a part of the research center that is just inside the interstate highway beltway around Washington, DC. Land uses in the immediate vicinity are agricultural and forest, though the wider area is suburban. Elevation is 34 m above sea level at the Beltsville monitoring station. It is about 42 km from the BES SRMS.

The Queenstown UV-B monitoring site is on the east side of the Chesapeake Bay at the Wye Research and Education Center of the University of Maryland. This area generally is rural and is only about 5 km from the main portion of the Bay and only 1–1.5 km from large inlets from the Bay. The Queenstown site is 7 m above sea level and about 64 km from the BES SRMS.

Hourly averages of measurements at 5 s intervals of UV-B irradiance as well as PAR and total solar shortwave radiation were recorded at the Baltimore SRMS. At the USDA UVB monitoring sites, including those at Beltsville and Queenstown, UV-B irradiance is measured at 3 min intervals. The USDA sites also measure global and diffuse irradiance at 415, 500, 610, 665, 862 and 940 nm with a multifilter rotating shadowband radiometer (MFRSR) and global and diffuse irradiance at 300, 305, 311, 317, 325, 332 and 368 nm with a UV MFRSR. The multifilter instruments produce the data for calculation of aerosol optical density (AOD), sometimes termed aerosol optical thickness (3). The UV-B broadband sensors (model UVB-1) and the multifilter instruments are from Yankee Environmental Systems (YES, Turners Falls, MA)[‡].

Comparison among the measurements of broadband UV-B at the three sites was possible because the sensors were identical in manufacture and calibration. The sensors were calibrated at the National Oceanic and Atmospheric Administration Central UV Calibration Facility (CUCF) in Colorado. The sensors and calibration procedures are described by Lantz *et al.* (26) and by Frederick *et al.* (27), who considered possible shifts

‡Names of manufacturers are for the convenience of the reader and do not imply endorsement by the U.S. Department of Agriculture or the Forest Service.

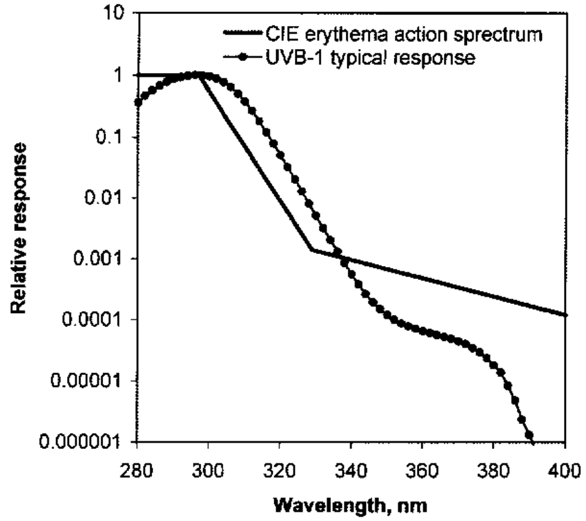

Figure 2. Typical response of UVB-1 pyranometers (K. Lantz, personal communication) and the CIE erythemal action spectrum (30).

in radiometric sensitivity, cosine angle of incidence errors and changes in spectral response functions, to assign an uncertainty to the difference between two UVB-1 sensors of ±3%. The UVB-1 sensors have a response that extends beyond 320 nm into the UV-A waveband (Fig. 2), although the response drops rapidly from a peak response at about 296 nm to a factor of 10^6 less at 390 nm. We compared sites on the basis of total UV-B irradiance as defined by the manufacturer's calibration factor (1.97 W m^{-2} V^{-1}) and the average scale factors for the particular instruments determined by CUCF. No correction for solar zenith angle was applied. The significance of the UVB-1 response for estimation of biological effects of UV radiation has been discussed in detail elsewhere (26–28).

For the 14 month period from June 2001 through July 2002, we compared the average total daily UV-B dose (in kJ m^{-2}) for each month at all three sites for all days on which the sites had valid data throughout the day. For days without evident effects of cloud in the irradiance signals, we compared the total daily UV-B doses. We examined the effect of total column ozone by using Earth Probe Total Ozone Mapping Spectrometer (EPTOMS) total column ozone data reported by National Aeronautics and Space Administration (NASA) for Washington, DC; these data are available on Internet from the NASA.

For the summer period from June through September 2001, we examined the effect of average wind direction on differences between Baltimore and Queenstown daily UV-B doses. We also related the UV-B doses to (1) measurements of SO_2 concentrations at the Rivera Beach monitoring site, 23 km southeast of the BES SRMS; (2) surface [O_3] from sites in Baltimore; (3) AOT measured at the Beltsville and Queenstown UV-B monitoring sites; and (4) [NO_2] measurements in Baltimore. The [SO_2], [NO_2], and surface ozone data came from sites in the state air-quality monitoring program in cooperation with EPA (see Fig. 1).

RESULTS AND DISCUSSION

Data

The Baltimore UVB-1 operated continuously throughout the 14 month study period. During this time, there were occasional periods of a few seconds to several minutes duration that the sensors were partially obscured during maintenance and checking for level; we considered these periods to be inconsequential to the hourly averaged values. The UVB-1 sensor at Queenstown was changed twice during the study period—once for the planned annual sensor rotation for calibration and once in July 2001 because of a failure of the temperature control system that led to 11 days in July with missing data. On 41 of the 424 days that comprised the study period, some or all the UVB-1 data were unavailable because of instrument

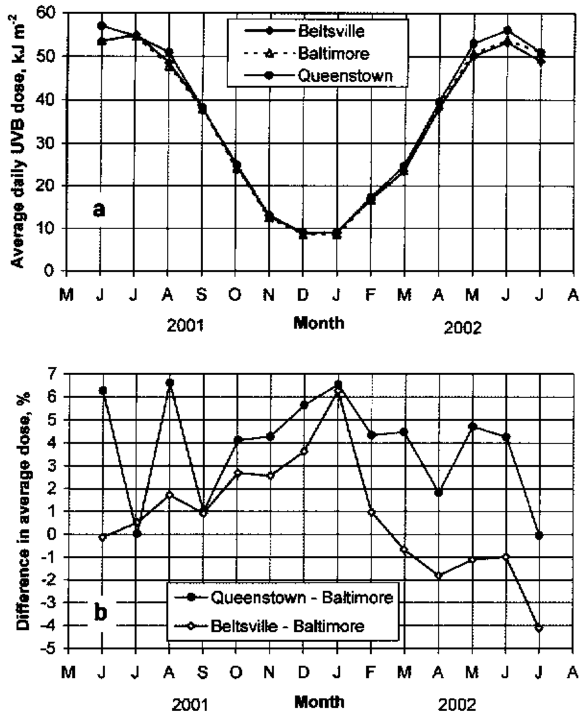

Figure 3. a: Average daily UV-B dose at the three Maryland sites by month. b: Percent difference of Beltsville and Queenstown doses from that of Baltimore.

problems at either Queenstown or Beltsville. Most of the data loss seemed to be due to loss of AC power to the installations. The Beltsville sensor was changed once during the period (January 2002).

Average UV-B dose differences

Monthly averages of daily totals of UV-B doses at the three Maryland sites differed by less than 7% (Fig. 3). Queenstown usually had the highest monthly averaged daily UV-B radiation dose. The three doses were within 1% in July 2001, but this month had only 20 days of valid data. Baltimore was consistently lower than Queenstown except in July of both years. Although the differences in daily dose are larger in absolute terms in summer months, the dose differences in percentages are similar over the year, ranging up to about 6% (Fig. 3b). Frederick *et al.* (27) found that at seven of eight USDA monitoring stations in the United States, including Queenstown, MD, the monthly integral of UVB-1 solar irradiance averaged over a 4 year period in the 1990s peaked in July rather than in June, the month with the highest solar elevation angles. The decreasing trend in the annual stratospheric O_3 cycle during summer months at least partly accounts for the frequent observation of greater UV-B in July. In the data reported here, the only July peaks in dose were for Baltimore and Beltsville in 2001.

During the entire 14 month period, the Beltsville and Baltimore sites had identical average exposure that was only 3.4% less than at rural Queenstown (Table 1). We did not attempt an analysis to determine whether the mean differences are statistically significant because the difference is within the ±6% uncertainty that would result by the combined ±3% calibration uncertainties of two sensors (27). The average differences with clear skies were even smaller; the Beltsville average clear-sky UV-B dose was 0.3% less than the Queenstown dose, and the Baltimore dose was 1.2% less

Table 1. Daily UV-B dose (kJ m^{-2}) from June 2001 to July 2002 at the three Maryland locations and difference between the Beltsville and Baltimore sites and Queenstown

		All skies		Clear skies	
Location	Condition	Daily UV-B dose	% difference	Daily UV-B dose	% difference
Queenstown	Rural	35.6		33.74	
Beltsville	Suburban	34.4	−3.4	33.65	−0.3
Baltimore	Urban	34.4	−3.4	33.35	−1.2

than Queenstown. These comparisons do not consider differences in latitude and elevation among the sites. Although latitude and elevation effects would tend to cancel each other, their net effect may be significant relative to the small measured differences between the sites.

We could have used conversion factors to arrive at estimates of irradiance for various action spectra (29). For example, the conversion to the Diffey erythema action spectra (30) would have yielded irradiance values of between 5% and 8% of the total irradiance values we measured, depending on solar zenith angle. However, the comparison between sites in terms of percentage differences would have remained essentially the same. With broadband sensors, conversion factors for converting total response to a particular action spectrum response differ with solar zenith angle. However, our zenith angles at the three sites would have been the same within about 0.4° (Baltimore–Queenstown latitude), and relative estimated irradiances at our three sites would not have differed significantly with different assumed action spectra. This does point out the importance of spectral measurements.

Influence of total column ozone

Although there were only small differences in monthly or 14 month average doses between the sites, it is of interest to examine the influence of factors that alter day-to-day dose differences at the three sites. In Fig. 4, the daily-integrated UV-B doses for the 59 clear days during the study period were fit to a sine function by nonlinear regression to establish the average seasonal variation through the 14 month period. Total column ozone on these days

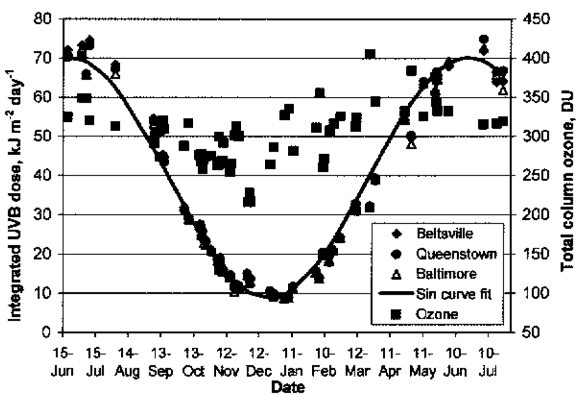

Figure 4. Total UV-B dose on clear days at the three sites and EPTOMS ozone for Washington, DC. The curve is a least squares fit sine function with minimum at the winter solstice and maxima at dates of summer solstice. Spacing of tick marks on the x-axis is 30 days.

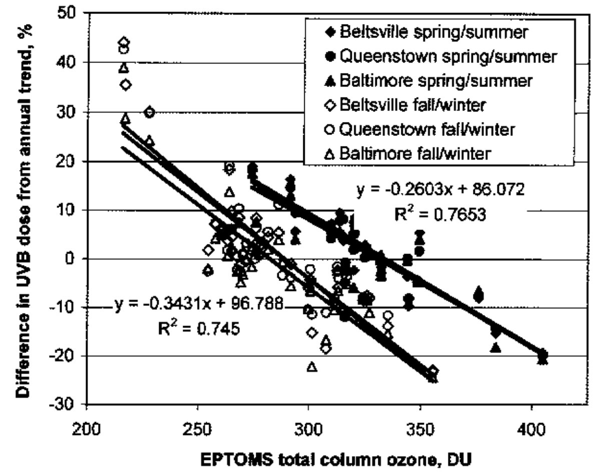

Figure 5. Daily total dose deviation from fitted average curve for days with clear skies. The regression equations shown are for the Baltimore site.

also is shown, and the effect of TO_3 on the daily UV-B dose is apparent. On most days, there is little difference among the three sites. On days with higher-than-average TO_3, UV-B doses lie below the seasonal variation curve, and on days with lower-than-average TO_3, doses usually are above the curve.

The influence of TO_3 on daily dose is seen more clearly in simple linear regressions of the deviations as a percent from the seasonal variation on TO_3 (Fig. 5). The relationship between deviation and TO_3 was similar for the three sites, with a larger slope in winter than in summer. Such relationships will be useful for educational purposes.

Boundary layer influences

Differences in daily UV-B exposure between Baltimore and Queenstown tended to be smaller when the winds were from the west or northwest, that is, the direction to advect continental air over Baltimore and urban-influenced air toward Queenstown (Fig. 6). Differences tended to be larger with winds from other directions

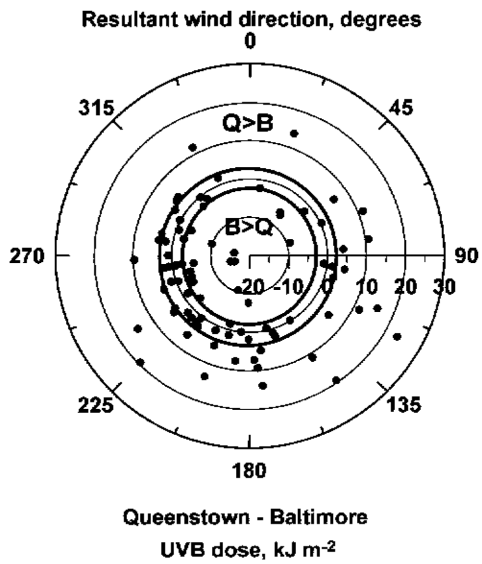

Figure 6. Difference between Queenstown and Baltimore UV-B doses in the summer of 2001 *versus* wind direction as measured at the Baltimore–Washington airport.

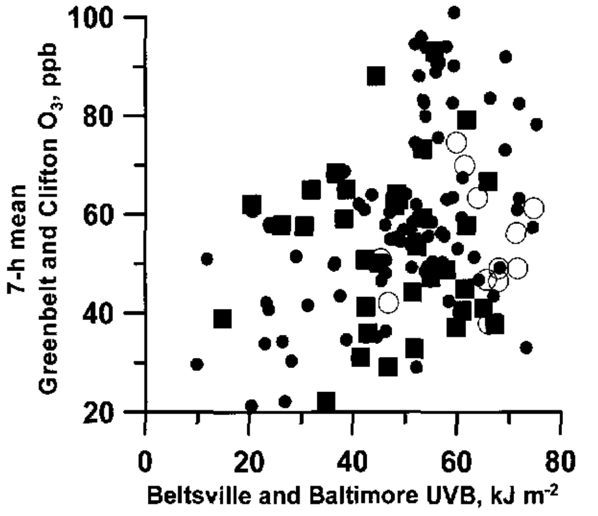

Figure 7. Relationship between the daily UV-B dose at Beltsville, MD, with nearby Greenbelt surface ozone (filled circles) and UV dose at Baltimore with nearby Clifton surface ozone (filled squares) for the period June through September 2001. The open circles represent days that had NO_2 concentrations less than 10 ppb in Baltimore.

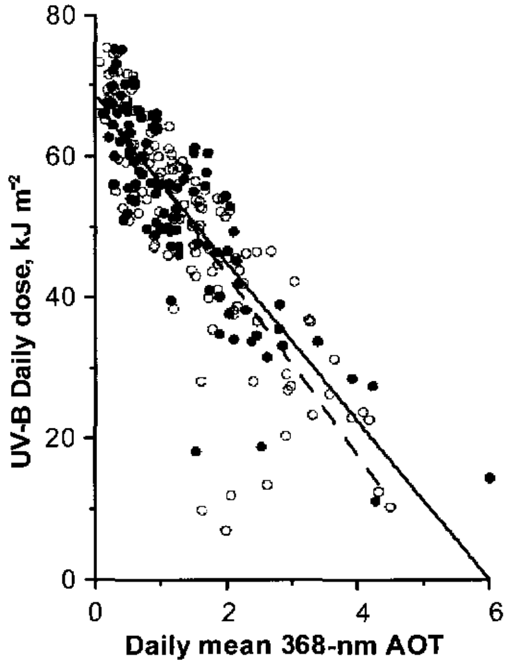

Figure 8. Daily UV-B dose at the Beltsville (open circles and dashed line) and Queenstown (filled circles and solid regression line) USDA monitoring stations *versus* AOD at 368 nm for the period from 1 May to 31 August 2001. Clear days have AOD less than about 0.4.

or when the air was nearly stagnant over the region, indicating conditions with advection of similar rural air or dominant local influence on the irradiative environment. HYSPLIT4 trajectory analyses (31) for the days of significantly greater UV-B irradiance at Queenstown than Baltimore indicated that on these days the air arriving over Queenstown generally did not pass over the Baltimore–Washington or other metropolis, and thus may have had less urban-produced pollutants brought in by advection from distant sources.

It would be desirable to compare the Baltimore irradiances with rural sites that are farther from upwind urban areas, such as locations to the west that have essentially the same latitude and elevation and similar cloud cover as Baltimore. However, the nearest such sites at similar latitude with currently available data collected by the same type of instruments with identical calibration procedures are the USDA UVB Monitoring Program sites at West Lafayette, IN (40.47°N, 86.99°W), and Bondville, IL (40.04°N, 88.36°W), where differences in types of cloud cover and TO_3 would complicate the comparison (32).

There generally are greater traffic intensities and consequently higher levels of traffic emissions (including NO) in urban than in rural areas. Previous studies indicated that surface $[O_3]$ should be positively correlated with UV-B irradiance when sufficient $[NO_2]$ is available as an ozone precursor. Conversely, UV-B and $[O_3]$ are negatively correlated if low levels (1–2 ppb) of NO_2 are present (33). Surface $[O_3]$ in the metropolitan area (both urban and suburban) was correlated with the UV-B irradiance at Beltsville and Baltimore (Fig. 7). The 7 h mean $[NO_2]$ for both Baltimore city air-quality monitoring locations (Fig. 1) was 12.5 ppb during the summer of 2001, *i.e.* there usually was sufficient NO_2 in the urban metropolis for UV-B irradiance to contribute to surface $[O_3]$. During 12 days with NO_2 concentrations less than 10 ppb, surface $[O_3]$ did not reach the highest concentrations, even with high UV-B dose. The highest $[O_3]$ events occurred in the presence of low to calm winds and with fronts or troughs nearby producing significant fog and cloud cover, somewhat limiting the UV-B irradiance at the surface.

Surface $[O_3]$ was inversely correlated (weakly) with TO_3. This was expected because high TO_3 reduces UV-B. Although TO_3 clearly influenced UV-B dose on clear days, the daily UV-B dose at Queenstown and Beltsville was more strongly dependent on the AOT than on TO_3 (Fig. 8). For AOT less than 1.5 as measured for 368 nm at the Beltsville and Queenstown USDA sites, daily UV-B doses were highly negatively correlated with AOT.

High $[SO_2]$ apparently did not cause reductions in UV-B daily dose (Fig. 9); in fact, the reverse was observed during the summer of 2001. High $[SO_2]$ concentrations were associated with high UV-B

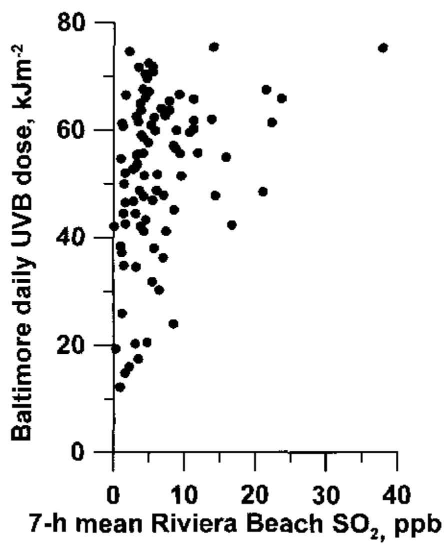

Figure 9. Baltimore daily UV-B dose *versus* SO_2 concentrations at the Maryland SO_2 monitoring site, located about 22.5 km south-southeast of the BES SRMS, for the period June through September 2001.

doses. One possible explanation is that high [SO_2] concentrations are associated with high electrical power production on warm sunny days. UV-B irradiance was also little affected by [SO_2] in Cordoba, Argentina (34). Using a radiative transfer model, Ma and Guicherit (25) found a 2.5% reduction in UV-B (280–315) irradiance and actinic flux with an [SO_2] of 95 ppb, more than twice the concentration for the measurements near Baltimore in our study. The SO_2 absorption cross section in the UV-B wavelengths consists of narrow bands of high absorption alternating with bands of low absorption (35), so that average absorption as seen by a broadband sensor is small.

On clear days, maximum total UV-B irradiance in Baltimore ranged from about 3 W m^{-2} in June to about 0.6 W m^{-2} in December; these values correspond to approximately 0.23 and 0.045 W m^{-2} when weighted for the Diffey erythema spectrum (29). The mean hourly irradiance corresponding to 1 MED (201 J/m^2) is 0.056 W m^{-2}. Thus, the UV-B dose on horizontal surfaces in Baltimore was about 0.8 MED/h in midwinter and about 4 MED/h in June. The December irradiance probably would limit vitamin D production for most people, who spend little time outdoors and are well bundled against the cold in December. This is especially true because wavelengths less than 300 nm, which are most responsible for vitamin D production, are relatively more diminished by the large atmospheric optical depths in December (8). In summer, a few minutes of exposure to full sun should be ample for vitamin D production and much exposure more than that on light skin would cause sunburn.

CONCLUSIONS

Over a 14 month period, average urban Baltimore broadband UV-B irradiance was similar to irradiance at a suburban measurement site at Beltsville, MD, and 3.4% less than irradiance at a rural site near Queenstown, MD. Monthly averages of Baltimore irradiance were smaller than averages of irradiance at the rural site by as much as 6.6%. On cloud-free days, the daily integral of UV-B irradiance was influenced strongly by total column ozone so that at all three sites TO_3 caused differences from the average seasonal cycle of UV-B irradiance that sometimes exceeded 20%. Variations in TO_3 explained about 75% of the differences in UV-B daily irradiance from the annual cycle when clear-day data were divided into two groups—spring–summer and fall–winter. The spring–summer and fall–winter grouping also showed the effect of the higher TO_3 in spring–summer and the larger zenith angles in fall–winter.

Differences in daily-integrated UV-B dose among sites were related to boundary layer winds and pollution. Wind trajectory with flow over urban areas tended to reduce UV-B irradiance, apparently because the urban areas were a source of higher concentrations of aerosols. The correlation between UV-B and surface 7 h mean [O_3] was positive for both urban and suburban locations; this relationship was less evident when concentrations of [NO_2] were less than 10 ppb. UV-B dose was closely correlated—negatively—with AOT, but higher [SO_2] concentrations did not reduce UV-B dose. Supplementary air-quality measurements greatly enhance the value of the UV-B monitoring in urban areas.

Analysis of future measurements is necessary to evaluate UV-B regimens in the city under extreme pollution events. Future analysis will incorporate aerosol data for Baltimore from the NASA Aeronet site (http://aeronet.gsfc.nasa.gov) at the Maryland Science Center in southern Baltimore.

Acknowledgements—Gwen Scott provided data from the USDA UVB Monitoring and Research Program, which also provided instrumentation for the study. Mr. Edwin Gluth, Maryland Department of the Environment, provided data on air quality. Comments on an earlier version of the manuscript by Dr. Cheryl Bawhey, Purdue University, and Dr. Kathy Lantz, U.S. Central UV Calibration Facility, significantly improved it. We thank Emil Feldsher, Edward Huff and Ralph Cullison of the City of Baltimore for permission to use city facilities and for their assistance with instrument installation and security. Ken Belt assisted with logistics in Baltimore. Corinne Ehrlich collected the Baltimore data. Financial support for technical assistance was provided by the National Science Foundation to the Baltimore Ecosystem Study through the Institute of Ecosystem Studies, Millbrook, NY.

REFERENCES

1. Heisler, G. M. and R. H. Grant (2000) Ultraviolet radiation in urban ecosystems with consideration of effects on human health. *Urban Ecosyst.* **4**, 193–229.
2. Heisler, G. M., R. H. Grant and W. Gao (2002) Urban tree influences on ultraviolet irradiance. In *Ultraviolet Ground- and Space-based Measurements, Models, and Effects* (Edited by J. R. Slusser, J. R. Herman and W. Gao), pp. 277–290. SPIE, The International Society of Optical Engineering, Bellingham, WA.
3. Bigelow, D. S., J. R. Slusser, A. F. Beaubien and J. H. Gibson (1998) The USDA ultraviolet radiation monitoring program. *Bull. Am. Meteorol. Soc.* **79**, 601–615.
4. Garland, C. F., F. C. Garland, E. D. Gorham, M. Lipkin, H. Newmark, J. V. Raffa and M. F. Holick (2002) Ultraviolet B, vitamin D and their mechanisms in cancer prevention. In *Ultraviolet Ground- and Space-based Measurements, Models, and Effects* (Edited by J. R. Slusser, J. R. Herman and W. Gao), pp. 313–323. SPIE, The International Society for Optical Engineering, Bellingham, WA.
5. Grant, W. B. (2002) Health benefits of solar UV-B radiation: cancer risk reduction. In *UV Ground- and Space-Based Measurements, Models, and Effects* (Edited by J. R. Slusser, J. R. Herman and W. Gao), pp. 324–334. SPIE, The International Society for Optical Engineering, Bellingham, WA.
6. Gorham, E. D., C. F. Garland and F. C. Garland (1989) Acid haze air pollution and breast and colon cancer mortality in 20 Canadian cities. *Can. J. Public Health* **80**, 96–100.
7. Lefkowitz, E. S. and C. F. Garland (1994) Sunlight, vitamin D, and ovarian cancer mortality rates in US women. *Int. J. Epidemiol.* **23**, 1133–1136.
8. Webb, A. R. (1993) Vitamin D synthesis under changing UV spectra. In *Environmental UV Photobiology* (Edited by A. R. Young, L. O. Bjorn, J. Moan and W. Nultsch), pp. 185–202. Plenum Press, New York.
9. Webb, A. R., C. Pilbeam, N. Hanafin and M. F. Holick (1990) An evaluation of the relative contributions of exposure to sunlight and of diet to the circulating concentrations of 25-hydroxyvitamin D in an elderly nursing home population in Boston. *Am. J. Clin. Nutr.* **51**, 1075–1081.
10. Galindo, I., S. Frenk and H. Bravo (1995) Ultraviolet irradiance over Mexico City. *Air Waste Manag. Assoc.* **45**, 886–892.
11. Dubin, N., M. Moseson and B. S. Pasternack (1986) Epidemiology of malignant melanoma: pigmentary traits, ultraviolet radiation, and the identification of high-risk populations. *Cancer Res.* **102**, 56–75.
12. Scotto, J. and T. R. Fears (1987) The association of solar ultraviolet and skin melanoma incidence among Caucasians in the United States. *Cancer Investig.* **5**, 275–283.
13. Weinstock, M. A. (1993) Ultraviolet radiation and skin cancer: epidemiological data from the United States and Canada. In *Environmental UV Photobiology* (Edited by A. R. Young, L. O. Bjorn, J. Moan and W. Nultsch), pp. 295–343. Plenum Press, New York.
14. Scotto, J., T. R. Fears and G. B. Gori (1975) *Measurements of Ultraviolet Radiation in the United States and Comparisons with Skin Cancer Data.* National Institutes of Health DHEW (NIH) 76-1029. U.S. Department of Health, Education, and Welfare, Washington, DC.
15. Leffell, D. J. and D. E. Brash (1996) Sunlight and skin cancer. *Sci. Am.* **275**, 52–59.
16. Garland, F. C., C. F. Garland, E. D. Gorham and J. F. Young (1990) Geographic variation in breast cancer mortality in the United States: a hypothesis involving exposure to solar radiation. *Prev. Med.* **19**, 614–622.

17. Madronich, S., R. L. McKenzie, L. O. Bjorn and M. M. Caldwell (1998) Changes in biologically active ultraviolet radiation reaching the Earth's surface. *J. Photochem. Photobiol. B: Biol.* **46**, 5–19.
18. Grant, R. H., G. M. Heisler and J. R. Slusser (2000) Urban UV measurements: rationale for the establishment of long-term monitoring in the Baltimore Ecosystem Study. In *Third Urban Environment Symposium*, pp. 195–196. American Meteorological Society, Boston, MA.
19. Repapis, C. C., H. T. Mantis, A. G. Paliatsos, C. M. Philandras, A. F. Bais and C. Meleti (1998) Case study of UV-B modification during episodes of urban air pollution. *Atmos. Environ.* **32**, 2203–2208.
20. Meloni, D., G. R. Casale, A. M. Siani, S. Palmieri and F. Cappellani (2000) Solar UV dose patterns in Italy. *Photochem. Photobiol.* **71**, 681–690.
21. Vuilleumier, L., R. A. Harley, N. J. Brown, J. R. Slusser, D. Kolinski and D. S. Bigelow (2001) Variability in ultraviolet total optical depth during the Southern California Ozone Study (SCOS97). *Atmos. Environ.* **35**, 1111–1122.
22. Papayannis, A., D. Balis, A. Bais, H. v. d. Bergh, B. Calpini, E. Durieux, L. Fiorani, L. Jaquet, I. Ziomax and C. S. Zerefos (1998) Role of urban and suburban aerosols on solar UV radiation over Athens, Greece. *Atmos. Environ.* **32**, 2193–2201.
23. Bruhl, C. and P. J. Crutzen (1989) On the disproportionate role of tropospheric ozone as a filter against solar UV-B radiation. *Geophys. Res. Lett.* **16**, 703–706.
24. Zerofos, C. S., C. Meleti, A. F. Bais and A. Lambros (1995) The recent variability of total ozone over southeastern Europe. *J. Photochem. Photopathol. B: Biol.* **31**, 15–19.
25. Ma, J. and R. Guicherit (1997) Effects of stratospheric ozone depletion and tropospheric pollution on UVB radiation in the troposphere. *Photochem. Photobiol.* **66**, 346–355.
26. Lantz, K. O., P. Disterhoft, J. J. DeLuisi, E. Early, A. Thompson, D. Bigelow and J. Slusser (1999) Methodology for deriving clear-sky erythemal calibration factors for UV broadband radiometers of the U.S. Central UV Calibration Facility. *J. Atmos. Oceanic Technol.* **16**, 114–130.
27. Frederick, J. E., J. R. Slusser and D. S. Bigelow (2000) Annual and interannual behavior of solar ultraviolet irradiance revealed by broadband measurements. *Photochem. Photobiol.* **71**, 488–496.
28. Dichter, B. K., A. F. Beaubien and D. J. Beaubien (1993) Development and characterization of a new solar ultraviolet-B irradiance detector. *J. Atmos. Oceanic Technol.* **10**, 337–344.
29. Yankee Environmental Systems, Inc. (1991) *Instruction Manual Model UVB-1 Ultraviolet Pyranometer.* Yankee Environmental Systems, Inc., Turners Falls, MA.
30. McKinlay, A. F. and B. L. Diffey (1987) A reference action spectrum for ultraviolet erythema in human skin. *Int. Illumination Comm. [CIE] J.* **6**, 17–22.
31. National Oceanic and Atmospheric Administration. (1997) *HYSPLIT4 (Hybrid Single-Particle Lagrangian Integrated Trajectory) Model.* Air Resources Laboratory, Silver Spring, MD. Web page: http://www.arl.noaa.gov/ready/hysplit4.html.
32. Grant, R. H. and J. R. Slusser (2003) Spatial variability in UV radiation during the growing season across the continental USA. *Theor. Appl. Climatol.* **74**, 167–177.
33. Bronnimann, S., W. Eugster and H. Wanner (2001) Photo-oxidant chemistry in the polluted boundary layer under changing UV-B radiation. *Atmos. Environ.* **35**, 3789–3797.
34. Palancar, G. G. and B. M. Toselli (2002) Erythemal ultraviolet irradiance in Cordoba, Argentina. *Atmos. Environ.* **36**, 287–292.
35. Vandaele, A. C., P. C. Simon, J. M. Guilmot, M. Carleer and R. Colin (1994) SO_2 absorption cross section measurement in the UV using a Fourier transform spectrometer. *J. Geophys. Res.* **99**, 25599–25605.