

# A Pilot Study to Identify Factors Affecting UV-B Radiation Exposure in Selected Microenvironments

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## Abstract

A pilot study was conducted to test a protocol for collecting data useful for identifying local factors affecting exposure to ultraviolet-B radiation (UV-B). A trained technician followed a prepared script through a series of microenvironments representing varying conditions of overhead shielding and ground cover while collecting UV-B irradiance and related data on days selected to represent varying conditions of solar radiation, cloud cover, ground-level ozone concentration, and fine particulate matter (PM<sub>2.5</sub>) concentration. The resulting data were combined with air pollution, UV-B, and meteorological data obtained from local fixed-site monitoring stations and analyzed to identify the principal factors affecting (1) UVI (UV Index) measured by the Safe Sun monitor and (2) fixed-site UV-B. Results of these analyses indicated that the best predictors of UVI were degree of shielding, solar angle, fixed-site UV-B, cloud cover, wind speed, time of day, and season. Although cloud cover was an important predictor of UVI, the clearest days did not correspond to the highest UVI values. Variations in cloud parameters can cause intraday UVI variations not reflected in a daily forecast. Residential outdoor microenvironments tended to have lower mean UVI values than outdoor recreation microenvironments (e.g., athletic field, pool), which may have implications for estimating total personal exposure to UV-B.

**Keywords:** Ultraviolet-B radiation; UV-B; microenvironment; Personal exposure; Prediction; Meteorological data; Personal monitoring; Cloud cover; Fine particulates; Ozone

## Introduction

Since the discovery of the ozone hole over Antarctica in 1985 [1]; increased emphasis has been placed on observing the stratospheric ozone concentrations throughout the world. Today it is generally accepted that stratospheric ozone has decreased in the Northern Hemisphere over the last 30 years [2]; a likely result of anthropogenic emissions of halogen-containing compounds. Since the Montreal Protocol was signed in 1990; it was hoped that these declines would come to an end near the year 2000 with a slow increase expected to return ozone to its previous values by 2050.

If other factors that influence ultraviolet (UV) transmission (e.g. clouds; aerosols; and tropospheric ozone) remain constant; an increase in the surface UV irradiance would be expected to follow any substantial decrease in ozone layer thickness [3]. However, none of these factors has remained constant over the last 30 years; as anthropogenic aerosol emissions and tropospheric ozone concentrations have decreased [4]. While there have been numerous studies [5,6] exploring the supposed increase in surface UV radiation resulting from stratospheric ozone decline [7]; none has consistently observed any increasing long-term trend [8]. Experimental observations have indicated that variability in the attenuating properties of the troposphere will obscure the effect of stratospheric ozone trends [9].

Studies have explored the various factors influencing surface UV variability; such as clouds [10-12] and aerosols in urban [13,14] and rural locations [15,16]. Potential increases in surface UV radiation due to stratospheric ozone depletion may have effects in the areas of human health; infectious diseases; vaccination efficacy; and cataract and melanoma incidences [17]. Likewise in the aquatic and terrestrial ecosystems; the affected areas include food production and biodiversity [18]. Human exposure to UV radiation is strongly influenced by time spent outdoors and the types of activities undertaken; and a recent study has categorized general activity patterns for use in epidemiologic

studies of UV exposure [19]. The influence of tropospheric air quality; overhead shielding; and groundcover characteristics on UV irradiance have not been adequately characterized for highly time-resolved outdoor activities.

The UV radiation spectrum has been divided into three sections. UV-C (220-290nm) is the shortest and contains the highest energy photons of the UV spectrum; but is shielded from the Earth's surface by the stratospheric ozone layer. UV-B and UV-A (290-400nm) are the wavelengths important in producing erythema or reddening of the skin (sunburn). UV-A (320-400 nm) is thought to produce changes in the human immune system [17]. Increases in surface levels of UV-B irradiance have been shown to adversely affect biological organisms [18]. Additionally; UV radiation is the principal energy source influencing tropospheric photochemistry; and thus; ozone production [20]. Since many biological organisms are affected by UV radiation; the study of its surface trends has become a significant topic in recent years. It is important to analyze surface UV variations with simultaneous measurements of surface pollutants such as ozone; fine particulate matter (PM<sub>2.5</sub>); and aerosols (including black carbon) to determine the effects these have on UV levels at the earth's surface.

The primary goal of the research described in this article was to test a protocol that would be useful in local (city-specific) studies of UV-B exposure. Of special interest was the ability of such a study to provide data that could be analyzed to develop area-specific mathematical

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relationships for predicting UV-B irradiance during activities likely to result in UV exposure. These data include local indices of daily-maximum and hourly UV-B; ground-level ozone and PM<sub>2.5</sub> concentrations; measures of haze and visibility; microenvironment; overhead shielding and groundcover; and other factors found to be statistically-significant predictors of UV-B levels measured by a personal UV-B monitor. This approach could then be applied to other study areas with the long-term goal of combining the results to identify general relationships for predicting UV-B exposure from time-activity information and other data.

## Materials and Methods

The study was conducted by TRJ Environmental; Inc. (TRJ) in Raleigh; North Carolina. A trained technician collected UV-B and related data from 9 am to 5 pm on sixteen days during the summer of 2003. The days were selected to represent varying conditions of solar radiation; cloud cover; ground-level ozone concentration; and PM<sub>2.5</sub> concentration. During each 8-hour monitoring period; the technician recorded or data-logged measurements from a handheld UV-B monitor (SafeSun "Classic"); a Micro Tops II handheld; multiband sunphotometer; a Garmin GPS III global positioning system; and a Kestrel 3000 handheld weather meter. He also filled out a real-time diary as he traveled through a series of scripted microenvironments. These data were combined with ozone; PM<sub>2.5</sub>; black carbon; particle scattering (nephelometer); and meteorological data from local fixed-site monitoring stations to create a comprehensive database. The data were analyzed by stepwise linear regression and other statistical techniques with the goal of identifying the principal factors affecting (1) UVI measured by the SafeSun monitor and (2) UV-B measured by the local fixed-site monitor. The following subsections provide details concerning the procedures used in the field portion of the study.

### Location

The Raleigh metropolitan area has several characteristics which made it an ideal location for this study:

1. This location has relatively high levels of solar radiation; ozone; and particulate matter.
2. A permanent UV-B monitoring station is operated as part of the U.S. Department of Agriculture UV-B Monitoring and Research Program. The station is located at the North Carolina State University (NCSU) Air Quality Educational Unit near Lake Wheeler Road (southwest of downtown Raleigh) at latitude 35.720 and longitude 78.680 with a monitor altitude of 124 m above sea level.
3. An air pollution monitoring site is also located at the NCSU Air Quality Educational Unit facility on Lake Wheeler Road. The site has been operated continuously since late May 2003. Measured pollutants have included continuous surface ozone; black carbon; particle scattering (nephelometer); oxides of nitrogen; sulfur dioxide; and carbon monoxide.
4. A permanent fixed-site air quality monitoring station on Millbrook Road in Raleigh (AQS site identification no. 37-183-0014) collects hourly-average concentration data for PM<sub>2.5</sub> and ozone in addition to continuous data for solar radiation and various meteorological parameters. Supplemental meteorological data are collected at the nearby Raleigh-Durham International Airport.

5. The area has diverse topography; vegetation; and land-use patterns.

### Time of year

UV-B exposure is affected by solar radiation intensity (which tends to increase exposure) and may be affected by ambient concentrations of ground-level ozone and PM<sub>2.5</sub>. The temporal solar pattern; or seasonal variations in the UV-B can be accounted for with two other parameters. These are the sine and cosine of the angle  $\Theta$ ; where  $\Theta$  is defined as  $[(2\pi)(\text{Julian day}/365)]$ . To determine temporal and spatial patterns of ozone and PM<sub>2.5</sub>; analysts reviewed data for the year 2000 obtained from 17 fixed-site monitoring sites located in and around the RTP area. Overall; these data indicated that June through September would coincide with high solar radiation conditions and moderate to high concentrations of ozone and PM<sub>2.5</sub>.

### Sampling matrix

Researchers attempted to schedule 16 sampling days such that each of the 16 sets of conditions listed in Table 1 was represented by one day between June 1 and September 30; 2003. The sampling matrix in Table 1 accounted for all possible combinations of the following factors: moderate vs. high solar radiation; moderate vs. high ozone; moderate vs. high PM<sub>2.5</sub> concentration; and clear vs. scattered clouds. The definitions of these categories (listed in Table 1) were developed through a review of historical data and consultation with staff from the NC Department of Environment and Natural Resources; Division of Air Quality (DAQ).

TRJ personnel monitored local forecasts throughout summer 2003 to identify days in which each of the 16 specified sets of conditions was likely to occur during a predefined midday period. Predictions of target-day UV Index were obtained from the Climate Prediction Center (CPC) of the U.S. National Weather Service. Predictions of target-day ozone were obtained from DAQ. As similar predictions were not available for target-day PM<sub>2.5</sub> concentrations; researchers developed the following "in-house" predictive equation based on stepwise linear regression analyses of 153 days of data collected between May 1 and September 30; 2002.

$$PM_{2.5} = -24.9 \mu\text{g}/\text{m}^3 + (360)(\text{OZONEMA8}) + (0.199)(\text{LPM25M18}) + (0.144)(\text{RHUM1}) + (0.105)(\text{RHUM17}). \quad (1)$$

in which PM<sub>2.5</sub>: forecast of target-day 24-h average PM<sub>2.5</sub> concentration

OZONEMA8: forecast by DAQ of the target-day value for daily maximum 8-h ozone concentration (ppm)

LPM25M18: maximum 1-h PM<sub>2.5</sub> concentration reported for first 18 hours of day preceding target day

RHUM1: forecast of 1-h relative humidity value (percent) expected to occur during the hour beginning 100 EST on target day

RHUM17: forecast of 1-h relative humidity value (percent) expected to occur during hour beginning 1700 EST on target day.

This regression equation had an R<sup>2</sup> value of 0.6486. The ozone term (OZONEMA8) was the best single predictor (accounting for an incremental R<sup>2</sup> value of 0.4694). Due to the tendency for PM<sub>2.5</sub> and ozone concentrations to covary; different PM<sub>2.5</sub> ranges were used on high and moderate ozone days (Table 1). Adding the PM<sub>2.5</sub> term (LPM25M18) to the regression equation increased the R<sup>2</sup> value from 0.4694 to 0.5805.

Specified conditions for test day				Date Completed
Ozone <sup>†</sup>	PM <sub>2.5</sub>	Cloud cover	Solar radiation <sup>‡</sup>	
High range (≥ 0.06 ppm)	High range <sup>‡</sup> (≥ 20 µg/m <sup>3</sup> )	Clear	High range	6/26/03
			Mod. range	6/24/03
		Scattered clouds	High range	6/11/03
			Mod. range	6/6/03
	Moderate range <sup>‡</sup> (< 20 µg/m <sup>3</sup> )	Clear	High range	9/11/03
			Mod. range	6/22/03
		Scattered clouds	High range	7/18/03
			Mod. range	7/25/03
Moderate range (< 0.06 ppm)	High range <sup>§</sup> (≥ 10 µg/m <sup>3</sup> )	Clear	High range	9/26/03
			Mod. range	9/24/03
		Scattered clouds	High range	7/9/03
			Mod. range	7/21/03
	Moderate range <sup>§</sup> (< 10 µg/m <sup>3</sup> )	Clear	High range	9/30/03
			Mod. range	9/25/03
		Scattered clouds	High range	8/20/03
			Mod. range	7/11/03

<sup>†</sup>High range: 8-hr maximum = 0.06 ppm or greater; Moderate range: 8-hr maximum < 0.06 ppm

<sup>‡</sup>For High-range ozone - High range PM<sub>2.5</sub>: 24-hr average = 20 µg/m<sup>3</sup> or greater; Moderate range PM<sub>2.5</sub>: 24-hr average < 20 µg/m<sup>3</sup>

<sup>§</sup>For Moderate-range ozone – High range PM<sub>2.5</sub>: 24-hr average = 10 µg/m<sup>3</sup> or greater; Moderate range PM<sub>2.5</sub>: 24-hr average < 10 µg/m<sup>3</sup>

<sup>||</sup>High range: forecast noon UV Index = 9 or greater; Moderate range: forecast UV Index 6-8

Table 1: Sampling Matrix for Pilot Field Study.

### Daily script

During each 8-hour (9 am - 5 pm EDT) monitoring period; the technician followed a prepared script listing (1) a defined geographic area and (2) a set of target microenvironments (ME's) to be visited during each one-hour script "slot." The technician attempted to make at least six UV-B measurements in six different locations representing different overhead shielding and groundcover conditions during each one-hour period for a total of 48 or more measurements per 8-hour monitoring period. The 16 monitoring days were conducted between June 6 and September 30; 2003. The study yielded 788 UV-B measurements; an average of 49 measurements per 8-hour monitoring period.

The majority of ME's were outdoor locations with full or partial UV-B exposure that were representative of places frequently visited by the general public. These outdoor ME's included residential yards; decks; porches; and driveways; sidewalks; parking lots; roadways; school campuses; playgrounds; stadiums; golf courses; and parks. Monitoring locations were selected to represent a variety of land uses; ground surfaces (e.g.; concrete; asphalt; wood; grass; sand; dirt; forest floor litter); and overhead shielding (e.g.; none; vegetation; translucent plastic). The scripts also included representative indoor and vehicle ME's in which UV-B exposure could occur; such as screened-in porches and cars with open windows or sunroofs. Since initial testing indicated that window and windshield safety glass is an effective barrier to UV-B (unpublished data); we included relatively few ME's that were completely shielded by glass.

Researchers considered a variety of factors when apportioning target ME's among the one-hour script periods; including the likelihood of visitation by the general public (determined through a review of time/activity data); potential exposure level; time of day; and the characteristics of the geographic area specified for the period. The goal was a set of scripts that represented a realistic mix of conditions affecting UV-B exposure.

Table 2 presents a typical script. The script is in the form of a loop that can be cycled through different time periods (Versions A; B; and

C) depending on the event selected to initiate the script for a particular day.

### Field data sheet

The technician completed a field data sheet for each UV-B measurement made by the SafeSun monitor. Figure 1 presents a blank field data form. The data entry form includes items pertaining to date; time; latitude/longitude/altitude (determined by the GPS); address; and microenvironment. It also provides information concerning proximity to roads; the horizontal surface type below the monitor; shielding above the monitor; and the degree of direct light falling on the monitor sensor.

The form provided places for entering the UV Index readings for the SafeSun monitor when pointed directly at the sun; pointed in a vertical direction; and pointed horizontally at the sun (i.e.; parallel to the ground) to capture diffuse radiation. If circumstances required a reading in another direction; the technician entered the zenith and azimuth angles in the spaces provided.

The form provided spaces for eight MicroTops II readings: scan ID; scan time; ozone column (Dobson Units); solar zenith angle (degrees); irradiance on a normal surface (W/m<sup>2</sup>) at 300; 305; and 312 nm; and "other" readings as appropriate. The MicroTops II unit provides instantaneous total column ozone readings at a specific location as opposed to a once-a-day reading from the Total Ozone Mapping Spectrometer (TOMS) satellite. Since the total column ozone is the largest factor; other than clouds; in reducing the UV-B levels at the surface; accurate and highly time-resolved readings here play a major role in developing an effective model for predicting UV-B exposure. A recent study has shown that day-to-day variations in TOMS ozone values result in an uncertainty in erythemally-effective UV irradiance of 0.5 UVI at a latitude similar to that of Raleigh [21].

Sky conditions were characterized by percent cloud coverage (tenths); cloud type; sun obscuration; cloud backlighting; haziness; rain; and "other" readings. These entries provided actual sky conditions affecting UV-B at the time of the measurement. Similar data reported

by local weather stations would lack this specificity. Detailed characterization of cloud conditions are an important feature of our study; since knowledge of the presence of cloud cover alone does not appear to provide sufficient information to determine the impact of partial cloud cover on personal exposure to UVB [11].

One of the entries in Figure 1 under sky conditions is “bright backlit cloud  $\leq 35^\circ$  from the sun.” This condition was included because UV-B levels may be increased as much as 20 percent by cloud reflections within 35 degrees of the sun when clouds are not actually blocking the sun [22].

Starting time Version A	Starting time Version B	Starting time Version C	Locations	Microenvironment	Positions <sup>†‡§</sup>
9 am	Noon	3 pm	Millbrook Middle School	School grounds; Athletic field; Parking lot	Shade/Grass; Sun/Grass; Sun/Asphalt; Shade/Asphalt
10 am	1 pm	4 pm	A) Spring Forest Park B) Sidewalk/Roadway	A) Park B) Sidewalk; Roadway	Shade/Grass; Sun/Grass; Sun/Concrete; Shade/Concrete; Sun/Asphalt
11 am	2 pm	9 am	Spring Forest Shopping Center	Market; Parking lot	Sun/Asphalt; Shade/Asphalt; Sun/Concrete; Shade/Concrete
Noon	3 pm	10 am	Service Station	Service Station	Sun/Asphalt; Shade/Asphalt; Sun/Concrete; Shade/Concrete
1 pm	4 pm	11 am	St. Matthews Church	Cemetery; Church grounds	Sun/Grass; Shade/Grass; Sun/Leaves; Shade/Leaves
2 pm	9 am	Noon	Sidewalk/Roadway	Sidewalk; Roadway	Sun/Concrete; Shade/Concrete; Sun/Asphalt; Shade/Asphalt
3 pm	10 am	1 pm	Millbrook Apts	Residential yard; Porch; Driveway	Sun/Grass; Shade/Grass; Sun/Asphalt; Shade/Asphalt
4 pm	11 am	2 pm	A) Hampton Inn B) Vehicle <sup>  </sup>	A) Yard; Parking lot; B) Vehicle	Sun/Grass; Shade/Grass; Sun/Asphalt; Shade/Asphalt; Glass/Vehicle; Sun/Vehicle

<sup>†</sup>Make measurements at 2-3 positions in each microenvironment

<sup>‡</sup>Choose a suitable indoor position near a window for one measurement during the sampling day

<sup>||</sup>Move Vehicle slots to starting or ending Location as required

Table 2: Script No. 1 showing starting times for Versions A; B; and C<sup>†</sup>Near-road: within 10 meters of the road edge.

<p>Date _____ Time _____ am/pm Script No. _____</p> <p>Lat. _____ Long. _____ Altitude _____ feet</p> <p>Location name _____ Address _____ City or county _____</p> <p><b>Microenvironment</b> 01 Outdoors — residential yard 02 Outdoors — residential deck/porch 03 Outdoors — residential driveway 04 Outdoors — sidewalk 05 Outdoors — parking lot 06 Outdoors — roadway 07 Outdoors — market 08 Outdoors — service station 09 Outdoors — beach/lakeside 10 Outdoors — park 11 Outdoors — golf course 12 Outdoors — stadium 13 Outdoors — athletic field 14 Outdoors — school grounds 15 Outdoors — playground 16 Outdoors — church grounds 17 Outdoors — cemetery 18 Outdoors — business park 19 Outdoors — manufacturing site 20 Outdoors — other: _____ 21 Vehicle — type: _____ 22 Indoors: _____</p> <p>Near road (within 10 m)? <input type="checkbox"/> yes <input type="checkbox"/> no</p>	<p><b>Surface below monitor</b> 30 Grass 31 Leaves (forest litter) 32 Concrete 33 Asphalt 34 Gravel 35 Sand 36 Dirt 37 Wood boards 38 Wood chips 39 Vehicle interior 40 Other: _____</p> <p><b>Shielding above monitor</b> 41 None 42 Opaque material: _____ 43 Translucent material: _____ 44 Vegetation: _____ 45 Glass: Tinted? <input type="checkbox"/> yes <input type="checkbox"/> no 46 Other: _____</p> <p><b>Direct sunlight falling on monitor</b> 50 Unobstructed (including glass) 51 Partially obstructed (e.g., dappled by leaf filtering) 52 Completely obstructed (e.g., under roof)</p> <p><b>SafeSun monitor readings</b> At sun: UV Index _____ Vertical: UV Index _____ Horiz. toward sun: UV Index _____ Other: UV Index _____ _____ altitude angle _____ azimuth angle</p>	<p><b>MicroTops readings</b> Scan ID _____ Scan Time _____ O3 (corr) _____ DU SZA _____ degrees 300 _____ W/m<sup>2</sup> 305 _____ W/m<sup>2</sup> 312 _____ W/m<sup>2</sup> Other: _____</p> <p><b>Sky conditions</b> Cloud amount: _____ tenths Cloud type: _____ Sun obscured by clouds or haze? <input type="checkbox"/> yes <input type="checkbox"/> partially <input type="checkbox"/> no Obscuration type: _____ Bright backlit cloud <math>\leq 35^\circ</math> from the sun? <input type="checkbox"/> whole cloud <input type="checkbox"/> edge only <input type="checkbox"/> no Haze? <input type="checkbox"/> high <input type="checkbox"/> moderate <input type="checkbox"/> none Rain? <input type="checkbox"/> yes <input type="checkbox"/> no Other: _____</p> <p><b>Kestrel weather readings</b> Wind speed _____ mph Wind direction _____ azimuth Temperature _____ deg. F Relative Humidity _____ % Other: _____</p> <p><b>Special conditions</b> _____ _____ _____ _____</p>
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Figure 1: Field data entry form.

The data form provided spaces for four measurements made by the Kestrel monitor (wind speed; wind direction; temperature; and relative humidity). The form also included a section for describing special conditions.

### Personal UV-B monitor

The SafeSun "Classic" UV monitor (Figure 2) was used to monitor personal UV-B exposure throughout the pilot study. The unit reports UV Index (UVI) on an integer scale. The unit is the size of a small cell phone and can run continuously for 900 hours on two lithium batteries. The manufacturer specifies an accuracy of 10 percent from 3 to 15 UVI and 20 percent from 0 to 3 UVI. Additional information concerning the unit can be found at [http://www.cgmdirect.com.au/CGM\\_Main/Archive/SafeSun.htm](http://www.cgmdirect.com.au/CGM_Main/Archive/SafeSun.htm).

The U.S. Environmental Protection Agency (EPA) has compared simultaneous readings by co-located SafeSun monitors and found that unit-to-unit variability is relatively low. The coefficient of variation was between 7.8 and 12.2 % for UVI values in the range of 5-7. Since these are reported by the instrument as integer values; some additional variability is likely introduced by internal rounding. Cumulative dose measurements integrated over the course of a day; making them less susceptible to rounding error; had a coefficient of variation of 3-6% during the EPA comparability study (J. Shreffler; unpublished data).

### Supplemental personal monitoring equipment

In addition to the SafeSun UV-B monitor; the technician carried a Microtops II sunphotometer; a Garmin GPS III Plus global positioning system; and a Kestrel 3000 weather meter.

The Microtops II is a hand-held; multi-band instrument capable of measuring the total ozone column; the water vapor column (i.e. precipitable water); and aerosol optical thickness at 1020 nm. The instrument is equipped with five accurately aligned optical collimators with a full view of 2.5 degrees. Each channel is fitted with a narrow-band interference filter and a photodiode suitable for the particular wavelength. A sun target and pointing assembly is permanently attached to the optical block and laser-aligned to ensure accurate alignment with the optical channels. When the image of the sun is centered in the bull's-eye of the sun target; all optical channels are oriented directly at the solar disk. Additional information about the instrument can be found in a user's guide prepared by the Solar Light Company [23].

The Garmin GPS unit was used to determine the latitude; longitude; and altitude for each location where there was an unobstructed view of

the sky. Topographic maps of the area were used to determine these coordinates for other locations. The Kestrel weather meter was used to measure temperature; relative humidity; wind speed; and wind direction.

### Local Source of UV-B data

The U.S. Department of Agriculture (USDA) UV-B Monitoring and Research program funds the operation of approximately 30 fixed-site UV monitoring stations in the U.S. Researchers used data from the USDA monitor in Raleigh to determine ambient UV levels for each field measurement made during the pilot study. Data obtained from the USDA monitor included UV-B broadband erythema-weighted irradiance values and corresponding solar zenith angle values.

### Local sources of data on ozone; PM<sub>2.5</sub>; and black carbon concentrations

The Millbrook Road site in Raleigh; NC; (AQS ID No. 37-183-0014) was designated the principal site for characterizing conditions on the 16 sampling days; and the majority of scripted activities were performed within three miles of this site. As noted above; this site provided hourly-average values for ground-level ozone and PM<sub>2.5</sub> together with continuous data for solar radiation and various meteorological parameters.

In addition the site at the NCSU Air Quality Educational Unit operated a full complement of ground-based pollution monitors during the study; including ozone; sulfur dioxide (SO<sub>2</sub>); carbon monoxide (CO); and nitrogen oxides (NO<sub>x</sub>). Anaethalometer measuring black carbon concentrations and two nephelometers measuring aerosol light scattering at 530 nm were also in operation during the study.

### Results and Discussion

Analysts constructed a database listing data for 788 SafeSun sampling events. The entries for each sampling event included

- UV Index values (integers) measured by the SafeSun monitor in three orientations (sun-oriented; vertical; and horizontal);
- solar zenith angle and total column ozone data from the Micro Tops II;
- meteorological data from the Kestrel 3000 weather meter;
- GPS (location and altitude) data from the Garmin GPS III Plus;
- data on date; time; microenvironment occupied; surface below monitor; shielding above monitor; obstructions; proximity to roads; and sky conditions as reported on the field data sheets;
- TOMS total column ozone measured by the National Aeronautics and Space Administration (NASA);
- UV-B (280-320 nm) irradiance and solar zenith angle measured by the USDA station;
- ozone; nephelometer; and black carbon data measured by fixed-site monitors at the NCSU Air Quality Educational Unit;
- forecasts of the noon UV Index and total column ozone made by CPC;
- ozone concentration; PM<sub>2.5</sub> concentration; and solar radiation measured by fixed-site monitors at the Millbrook Road station operated by DAQ; and
- supplemental meteorological data from local weather stations.



Figure 2: SafeSun "Classic" UV index monitor.

Analysts entered information from the field data sheets into the database and checked the data for internal consistency (e.g.; when location = roadway; then ground surface = concrete; asphalt; or gravel). Fixed-site monitoring data available as one-hour measurements or averages were assigned to the sampling event that occurred during the clock hour. Researchers also screened the entire database for anomalous values prior to statistical analyses.

### Descriptive statistics for UV Index measured by the SafeSun monitor

Table 3 presents descriptive statistics for SafeSun UV Index (UVI) by monitor orientation (sun-oriented: pointed towards the sun; vertical: perpendicular to the ground; and horizontal: parallel to the ground and pointed towards the sun). Note that the statistics for “sun-oriented” and “vertical” are very similar; each having an arithmetic mean around 3.6 and a maximum value of 10. The statistics for “horizontal” indicate substantially lower; but measurable; UVI levels; with an arithmetic mean of 0.81 and a maximum of 3. Horizontal UVI values are 10-50% of corresponding percentile vertical UVI; with increasing fractional contribution at lower UVI levels.

Table 4 presents arithmetic means for SafeSun UVI by hour and date for each monitor orientation. As expected; UVI values tend to peak at midday and during July. The mean horizontal UVI is higher in July through September (0.82-0.94) than in June (0.54-0.75). Table 5 lists arithmetic means by ME. ME’s with sun-oriented means greater than 4.5 include the following outdoor locations: stadium; manufacturing site; pool; and construction site. ME’s with sun-oriented means between 4.0 and 4.49 include: parking lot; beach; lakeside; or dock; athletic field; church grounds; business park; and basketball or tennis court. Such specific information on UVI levels in microenvironments typically visited during outdoor activities may be useful in estimating total UV exposure; as discussed in Kwok et al. [19]. Kwok and colleagues identified seven groups of outdoor activities (driving; gardening; home; walking/light exercise; recreation; water; and leisure); but did not have UV data associated with these activities. Our study indicates that driving; although responsible for a significant portion of time spent outdoors in the Kwok et al. study; may not be responsible for substantial UV exposure; since the mean sun-oriented UVI in the “vehicle – passenger car” ME was 1.38. However; brief exposure in the parking lot ME is likely to be high. The recreation and water activity groups may result in high UV exposure; as they involve several ME’s with UVI values greater than 4.0. Residential and neighborhood activities; as represented by the groups gardening; home; and walking/light exercise; appear to be associated with moderate UV exposure; as evidenced by UVI values of 3.3-4.0 for the first four ME’s in Table 5.

Statistic	Descriptive statistics for UV Index values (n = 788) measured by SafeSun according to monitor orientation		
	Sun-oriented	Vertical	Horizontal
Arithmetic mean	3.61	3.60	0.81
Arithmetic SD	2.27	2.31	0.43
Minimum	0	0	0
25 <sup>th</sup> percentile	2	2	1
50 <sup>th</sup> percentile	3	3	1
75 <sup>th</sup> percentile	5	5	1
90 <sup>th</sup> percentile	7	7	1
95 <sup>th</sup> percentile	8	8	1
99 <sup>th</sup> percentile	9	9	2
Maximum	10	10	3

**Table 3:** Descriptive statistics for 788 UV Index values measured by SafeSun according to monitor orientation.

Variable	Category	n	Arithmetic mean of UV Index values according to monitor orientation		
			Sun-oriented	Vertical	Horizontal
Hour	9	100	1.55	1.52	0.61
	10	100	3.01	2.98	0.85
	11	95	3.88	3.88	0.79
	12	97	5.42	5.40	0.90
	13	101	5.05	5.11	0.83
	14	98	4.27	4.24	0.83
	15	96	3.67	3.65	0.91
Date	6/6/03	48	3.38	3.40	0.54
	6/11/03	48	3.38	3.35	0.65
	6/22/03	48	3.27	3.27	0.65
	6/24/03	48	3.69	3.67	0.67
	6/26/03	48	3.15	3.17	0.75
	7/9/03	48	4.54	4.58	0.85
	7/11/03	49	4.82	4.96	0.94
	7/18/03	50	3.96	3.98	0.92
	7/21/03	49	4.39	4.39	0.88
	7/25/03	51	3.63	3.65	0.83
	8/20/03	48	3.58	3.58	0.90
	9/11/03	50	3.94	3.92	0.92
	9/24/03	50	3.16	3.14	0.94
	9/25/03	51	2.88	2.84	0.82
	9/26/03	50	2.82	2.72	0.84
	9/30/03	52	3.23	3.04	0.87

**Table 4:** Arithmetic means for UV Index values measured by SafeSun by hour of day and date.

Activities in the leisure activity group may have highly variable UV values (e.g.; 2.9 for outdoors – restaurant; 4.8 for outdoors – stadium). This type of information may also be useful in designing questionnaires to evaluate UV exposure retroactively.

Table 6 provides descriptive statistics for surface and proximity to road. Surfaces associated with mean sun-oriented UVI values greater than 4.0 include asphalt; gravel; dirt; wood chips; water; and aluminum bleachers. Water had the highest mean UVI value (5.05); consistent with its high reflectance. UVI was slightly higher on average when the technician was located within 10 m of a roadway. Although mobile-source-related pollutants including combustion aerosols; suspended road dust; or gaseous pollutants such as NO<sub>2</sub> could reduce UVI in the vicinity of a roadway; the mix of overhead shielding conditions in this study may have obscured this effect.

Table 7 lists arithmetic means for UVI according to the characteristics of the light falling on the monitor. As expected; UVI tended to be lowest when the monitor was shielded or behind glass. Mean UVI was slightly lower under coniferous trees than broadleaf trees.

Tables 8 and 9 provide UVI statistics for categories relating to various meteorological conditions; total column ozone; and solar zenith angle. The statistics at the top of Table 9 are consistent with previous findings [22] suggesting that average UVI may increase when clouds near the sun are backlit and the sun itself is not obscured by clouds. Cloudless days have lower UVI than days with some cloud cover; consistent with previous estimates for tree-shielded UV exposure [11]. No trend is observed between fractional cloud cover and UVI. Cumulus clouds are associated with higher UVI levels; with the highest UVI observed for a combination of cirrus with some cumulus clouds. As expected; mean

Index	Name	n	Arithmetic mean of UV Index values according to monitor orientation		
			Sun-oriented	Vertical	Horizontal
1	Outdoors - residential yard	60	3.32	3.28	0.73
2	Outdoors - residential deck; porch; or terrace	16	3.31	3.31	0.44
3	Outdoors - residential driveway	18	3.89	4.00	0.89
4	Outdoors - sidewalk	53	3.55	3.57	0.83
5	Outdoors - parking lot	69	4.20	4.19	0.87
6	Outdoors - roadway	46	3.59	3.57	0.78
7	Outdoors - market or shopping center	46	2.93	2.87	0.87
8	Outdoors - service station	82	3.94	3.94	0.88
9	Outdoors - beach; lakeside; or dock	20	4.30	4.30	0.85
10	Outdoors - park	47	2.72	2.70	0.68
11	Outdoors - golf course	17	3.82	4.00	0.76
12	Outdoors - stadium	5	4.80	4.80	1
13	Outdoors - athletic field	34	4.26	4.26	0.94
14	Outdoors - school grounds	45	3.56	3.53	0.80
15	Outdoors - playground	33	3.88	3.85	0.91
16	Outdoors - church grounds	52	4.27	4.29	0.90
17	Outdoors - cemetery	30	3.17	3.13	0.73
18	Outdoors - business park	7	4.29	4.14	0.86
19	Outdoors - manufacturing site	10	4.80	4.80	1.10
21	Vehicle - passenger car	39	1.38	1.31	0.44
22	Indoors - conference room	1	0	0	0
23	Outdoors - pool	25	4.80	4.84	1.00
24	Outdoors - basketball or tennis court	14	4.00	4.00	0.93
25	Outdoors - baseball diamond	1	8	8	1
26	Outdoors - restaurant	13	2.92	2.85	0.77
27	Outdoors - construction site	3	4.67	4.67	1
109	Indoors - market	2	0	0	0

**Table 5:** Arithmetic means for UV Index values measured by SafeSun by microenvironment.

Variable	Category	n	Arithmetic mean of UV Index values according to monitor orientation		
			Sun-oriented	Vertical	Horizontal
Surface	30: grass	202	3.90	3.91	0.85
	31: leaves (forest litter)	62	2.42	2.39	0.60
	32: concrete	173	3.51	3.50	0.86
	33: asphalt	141	4.01	4.02	0.87
	34: gravel	22	4.41	4.41	0.82
	35: sand	27	3.78	3.74	0.96
	36: dirt	23	4.09	4.09	0.96
	37: wood boards	16	3.50	3.50	0.50
	38: wood chips	18	4.33	4.22	0.89
	39: vehicle interior	39	1.38	1.31	0.44
	40: carpet	4	0.25	0.25	0.25
	101: water	20	5.05	5.05	1.00
	102: brick pavers	31	3.39	3.29	0.74
	104: aluminum	5	4.80	4.80	1.00
106: safety rubber	4	3.75	3.75	0.75	
108: rip-rap rock	1	7	7	2	
Near road (within 10 m)	Yes	190	3.68	3.72	0.81
	No	598	3.59	3.56	0.81

**Table 6:** Arithmetic means for UV Index values measured by SafeSun by surface and proximity to road.

UVI increases significantly as solar zenith angle is reduced (i.e.; as the sun appears higher in the sky); while the ratio of horizontal UVI to vertical UVI decreases with decreasing solar zenith angle. The statistics in Table 10 suggest that mean UVI increases as wind speed increases; as temperature increases; and as relative humidity decreases. These conditions are frequently associated with incoming fronts that tend to clear pollution and water vapor from the atmosphere. Such frontal movement may have caused the observed increase in UVI. UVI was

highest when wind direction was from the southeast compared to the other three azimuth quadrants. In North Carolina; southeasterly winds representing marine air masses exhibit decreased black carbon concentrations [23,24]; which would result in decreased absorption of solar radiation. Wind direction effects have also been observed for a UV study conducted in the Baltimore area [16]. The effect of relative humidity on horizontal UVI was less pronounced; possibly due to increased scattering in the atmosphere.

Characteristics of light falling on monitor	Shielding above monitor	n	Arithmetic mean of UV Index values according to monitor orientation		
			Sun-oriented	Vertical	Horizontal
50: unobstructed; including glass	41: none	514	4.67	4.66	0.98
	45: glass - untinted	17	0	0	0
	47: glass - tinted	3	0	0	0
	all	534	4.49	4.48	0.94
51: partially obstructed (e.g.; dappled)	44: vegetation - deciduous tree leaves	161	1.93	1.94	0.55
	48: vegetation - pine tree needles	50	1.60	1.64	0.44
	all	211	1.85	1.87	0.52
52: completely obstructed (e.g.; under roof)	42: opaque material - metal roof	21	1.48	1.29	0.71
	49: opaque material - shingle roof	3	1.33	1.00	0.33
	105: opaque material - deck umbrella	5	1.40	1.40	0.60
	107: opaque material - tar/stone roof	14	0.93	0.71	0.50
	all	43	1.28	1.09	0.60

Table 7: Arithmetic means for UV Index values measured by SafeSun according to characteristics of light falling on monitor.

Variable	Category	n	Arithmetic mean of UV Index values according to monitor orientation		
			Sun-oriented	Vertical	Horizontal
Cloud cover; tenths	0	241	3.02	2.96	0.77
	1	73	4.08	4.07	0.93
	2	32	4.25	4.22	0.72
	3	26	4.31	4.34	0.69
	4	35	3.00	3.00	0.91
	5	32	4.22	4.25	0.88
	6	62	4.08	4.11	0.89
	7	95	4.27	4.27	0.88
	8	85	4.06	4.08	0.84
	9	74	3.39	3.42	0.80
	10	33	2.24	2.27	0.48
Cloud type	0: None	241	3.02	2.96	0.77
	1: Cirrus	53	3.26	3.28	0.62
	2: Cumulus	380	3.94	3.94	0.86
	12: Cirrus with some cumulus	19	4.21	4.26	0.68
	21: Cumulus with some cirrus	95	3.83	3.87	0.84
Haze	0: none	161	3.36	3.29	0.90
	1: high	352	3.79	3.80	0.80
	2: moderate	275	3.52	3.52	0.78
Sun obscured by clouds or haze?	0: no	496	3.76	3.74	0.84
	1: yes - completely	145	2.74	2.74	0.68
	2: yes - partially	147	3.97	3.98	0.83
Obscuring category	0: none	496	3.76	3.74	0.84
	1: cirrus	63	3.71	3.75	0.62
	2: cumulus	149	3.32	3.32	0.80
	4: haze	49	3.49	3.51	0.78
	5: cumulus - sun not visible through center	31	2.58	2.58	0.81

Table 8: Arithmetic means for UV Index values measured by SafeSun according to cloud cover; cloud type; and obscuring conditions as determined by technician.

Table 11 presents UVI statistics for categories relating to air quality measurements made by an ozone monitor; a nephelometer; and a black carbon analyzer located at the NCSU/USDA station. Sun-oriented and vertical UVI appear to be higher when the ground-level ozone concentration exceeds 30 ppb with the highest average values occurring when the ozone concentration falls between 50 ppb and 69 ppb. Sun-oriented and vertical UVI also appear to be higher when the black carbon concentration is below 2000 ng m<sup>-3</sup>. There is no discernable pattern in the nephelometer data except at the highest readings; for which UVI is reduced.

Table 12 provides UVI statistics categorized by data reported by the Millbrook monitoring station. Sun-oriented and vertical UVI

appear to increase as ozone concentration increases from 30 to 59 ppb. Above that level; the data do not display an obvious pattern. The means for all UVI parameters decrease with increasing PM<sub>2.5</sub> concentration. Sun-oriented and vertical UVI are higher when the solar radiation (400 - 1100 nm) equals or exceeds 300 watts m<sup>-2</sup>. However; UVI does not appear to increase uniformly with increasing solar radiation above 300 watts m<sup>-2</sup>.

Table 13 lists UVI means by category for the UV index forecasts (clear-sky and cloud-corrected) and for the total column ozone forecast made by CPC. These forecasts are made for the noon hour on each day. As expected; sun-oriented and vertical UVI tend to increase as either of the UV forecast metrics increase. However; the highest



Variable	Category	n	Arithmetic mean of UV Index values according to monitor orientation		
			Sun-oriented	Vertical	Horizontal
Bright backlit cloud ≤ 35 degrees from sun?	0: no	317	3.32	3.27	0.79
	1: whole cloud	141	3.70	3.70	0.75
	2: edge only backlit	129	3.60	3.64	0.81
	12: whole cloud and edge of cloud	201	4.01	4.02	0.89
Rain	0: no	787	3.61	3.60	0.81
	1: yes	1	4	4	1
Other sky condition	None	767	3.62	3.61	0.81
	"quilt" sky - patchy small cumulus	12	3	3	0.83
	contrail less than 35 degrees from sun	6	4.00	4.17	0.67
	sky clear; but hazy glow around sun	1	4	4	1
Total column ozone; Dobson units† (MicroTops reading)	sky has milky appearance	2	2.5	2.5	1
	0 - 199	4	1.5	1.5	0.75
	200 - 299	71	3.06	2.94	0.77
	300 - 399	545	4.35	4.36	0.92
	400 - 599	24	1.67	1.75	0.58
	600+	9	1.89	2.00	0.44
Solar zenith angle; degrees (MicroTops reading)	all	653	4.06	4.06	0.89
	10 - 19	127	5.35	5.39	0.80
	20 - 29	133	4.45	4.48	0.80
	30 - 39	192	4.00	4.01	0.90
	40 - 49	190	2.94	2.89	0.82
	50 - 59	122	1.82	1.75	0.71
	60 - 69	23	0.87	0.78	0.70
	70 - 79	1	4	4	1

†See <http://jwocky.gsfc.nasa.gov/teacher/basics/dobson.html> for a definition of Dobson unit.

**Table 9:** Arithmetic means for UV Index values measured by SafeSun according to backlight; rain; and other sky conditions; total column ozone; and solar zenith angle as determined by technician.

Variable	Category	n	Arithmetic mean of UV Index values according to monitor orientation		
			Sun-oriented	Vertical	Horizontal
Wind speed; mph	0 - 0.9	138	2.66	2.62	0.61
	1.0 - 1.9	220	3.34	3.32	0.85
	2.0 - 2.9	195	3.73	3.73	0.83
	3.0 - 3.9	102	3.88	3.87	0.81
	4.0 - 4.9	65	4.51	4.49	0.92
	5.0 - 5.9	43	4.58	4.58	1.00
	6.0 - 6.9	16	4.94	4.94	0.75
	7.0 - 7.9	6	5.33	5.67	1.00
	8.0 - 8.9	2	4.50	5	1
Wind direction; degrees	9.0 - 9.9	1	9	9	1
	Calm wind	115	2.50	2.43	0.58
	0 - 89	177	3.47	3.42	0.87
	90 - 179	118	4.22	4.21	0.92
	180 - 269	221	3.79	3.81	0.81
Temperature; degrees F	270 - 359	157	3.89	3.90	0.83
	60 - 69	45	2.80	2.71	0.82
	70 - 79	167	2.98	2.92	0.75
	80 - 89	406	3.64	3.64	0.82
	90 - 99	169	4.34	4.38	0.86
Relative humidity; percent	100+	1	8	8	1
	50 - 59	55	4.24	4.11	0.82
	60 - 69	179	3.79	3.75	0.82
	70 - 79	242	3.72	3.75	0.83
	80 - 89	196	3.73	3.74	0.82
	90 - 99	74	2.76	2.73	0.81
	100	42	2.33	2.31	0.62

**Table 10:** Arithmetic means for UV Index values measured by SafeSun according to wind speed; wind direction; temperature; and relative humidity as determined by technician.

Variable	Category	n	Arithmetic mean of UV Index values according to monitor orientation		
			Sun-oriented	Vertical	Horizontal
ozone concentration; ppb	10 - 19	13	1.38	1.31	0.62
	20 - 29	28	1.43	1.36	0.75
	30 - 39	67	2.81	2.75	0.82
	40 - 49	131	3.15	3.12	0.79
	50 - 59	157	4.39	4.43	0.86
	60 - 69	166	4.23	4.23	0.89
	70 - 79	130	3.28	3.25	0.80
	80 - 89	43	3.98	4.02	0.60
nephelometer; 10 <sup>-4</sup> m <sup>-1</sup>	0 - 0.49	207	3.66	3.64	0.88
	0.50 - 0.99	268	3.39	3.38	0.76
	1.00 - 1.49	117	4.14	4.14	0.87
	1.50 - 1.99	83	3.70	3.71	0.83
	2.00 - 2.49	89	3.64	3.62	0.74
	2.50 - 2.99	24	2.63	2.67	0.67
black carbon concentration; ng m <sup>-3</sup>	0 - 499	219	4.31	4.32	0.86
	500 - 999	379	3.44	3.42	0.84
	1000 - 1499	152	3.35	3.34	0.70
	1500 - 1999	13	3.69	3.69	0.85
	2000 - 2499	12	1.92	1.83	0.50
	2500 - 2999	13	1.31	1.31	0.54

**Table 11:** Arithmetic means for UV Index values measured by SafeSun according to ozone concentration; nephelometer reading; and black carbon concentration as measured by NCSU/USDA station.

Variable	Category	n	Arithmetic mean of UV Index values according to monitor orientation		
			Sun-oriented	Vertical	Horizontal
ozone concentration; ppb	30 - 39	13	2.08	1.92	0.85
	40 - 49	116	2.71	2.63	0.86
	50 - 59	227	3.99	4.02	0.84
	60 - 69	185	3.75	3.73	0.85
	70 - 79	157	3.43	3.42	0.75
	80 - 89	67	4.46	4.48	0.70
	90 - 99	17	2.76	2.76	0.65
	100 - 109	6	3.33	3.33	1.0
PM <sub>2.5</sub> concentration; µg m <sup>-3</sup>	0 - 9	68	4.21	4.18	0.97
	10 - 19	258	3.68	3.69	0.83
	20 - 29	192	3.66	3.65	0.79
	30 - 39	121	3.79	3.78	0.77
	50 - 59	25	3.36	3.40	0.76
solar radiation (400 - 1100 nm); watts m <sup>-2</sup>	0 - 99	25	1.52	1.44	0.84
	100 - 199	26	2.81	2.81	0.92
	200 - 299	57	2.32	2.25	0.75
	300 - 399	49	3.65	3.63	0.84
	400 - 499	60	4.62	4.62	0.95
	500 - 599	89	3.97	3.98	0.76
	600 - 699	107	3.78	3.75	0.75
	700 - 799	151	3.41	3.38	0.82
	800 - 899	135	3.95	3.98	0.76
900 - 999	41	4.10	4.12	0.88	

**Table 12:** Arithmetic means for UV Index values measured by SafeSun according to ozone concentration; PM<sub>2.5</sub> concentration; and solar radiation as measured at Millbrook station.

UVI levels were not observed on the highest forecast day; when more individuals are likely to take precautions against UV exposure. No pattern can be identified in the total column forecast ozone statistics. Under clear sky conditions with no shielding; sun-oriented and vertical UVI readings would be expected to correlate well with total column ozone; although UV attenuation by stratospheric ozone may weaken this trend somewhat at high total column ozone levels. However; the

statistics listed in Table 13 for total column ozone pertain to a variety of radiation conditions; including cloudy skies and shielding by vegetation.

Table 14 reports UVI statistics for categories defined by total column ozone as measured by TOMS; UV-B irradiance and solar zenith angle reported by the USDA station; and visibility as reported by the Raleigh-Durham (RDU) International Airport. As expected; sun-

Variable	Category	n	Arithmetic mean of UV Index values according to monitor orientation		
			Sun-oriented	Vertical	Horizontal
Clear sky UV Index forecast	5.0 - 5.9	50	2.82	2.72	0.84
	6.0 - 6.9	153	3.09	3.01	0.88
	7.0 - 7.9	50	3.94	3.92	0.92
	8.0 - 8.9	144	3.51	3.51	0.74
	9.0 - 9.9	294	3.65	3.66	0.76
	10.0 - 10.9	97	4.68	4.77	0.90
Cloud-corrected UV Index forecast	4.0 - 4.9	102	3.03	2.88	0.85
	5.0 - 5.9	151	3.32	3.30	0.89
	6.0 - 6.9	96	3.48	3.49	0.72
	7.0 - 7.9	295	3.91	3.94	0.81
	8.0 - 8.9	144	3.79	3.81	0.76
Total column ozone forecast; Dobson units	280 - 289	52	3.23	3.03	0.87
	290 - 299	346	3.67	3.67	0.89
	300 - 309	48	3.38	3.35	0.65
	310 - 319	198	3.78	3.80	0.84
	320 - 329	48	3.38	3.40	0.54
	330 - 339	96	3.48	3.47	0.66

**Table 13:** Arithmetic means for UV Index values measured by SafeSun according to UV Index and Total Column Ozone forecasts made by the Climate Prediction Center of the National Weather Service.

Variable	Category	n	Arithmetic mean of UV Index values according to monitor orientation		
			Sun-oriented	Vertical	Horizontal
TOMS <sup>†</sup> total column ozone for RTP; Dobson Units	270 - 279	52	3.23	3.04	0.87
	290 - 299	197	3.82	3.85	0.84
	300 - 309	149	3.40	3.36	0.84
	310 - 319	294	3.68	3.69	0.82
	320 - 329	48	3.69	3.67	0.67
	330 - 339	48	3.27	3.27	0.65
UV-B irradiance; watts m <sup>-2</sup> (USDA station)	0.000 - 0.099	232	2.11	2.06	0.72
	0.100 - 0.199	381	4.08	4.07	0.85
	0.200 - 0.299	87	5.51	5.59	0.78
solar zenith angle; degrees (USDA station)	10 - 19	123	5.33	5.36	0.79
	20 - 29	108	4.48	4.52	0.78
	30 - 39	174	3.90	3.90	0.87
	40 - 49	164	2.96	2.93	0.82
	50 - 59	113	1.78	1.72	0.70
	60 - 69	18	1.00	0.83	0.67
visibility; miles (RDU International Airport)	1.5	18	3.50	3.50	0.83
	3	3	5.67	5.33	1.00
	4	12	1.58	1.42	0.58
	5	36	1.92	1.94	0.67
	6	86	4.47	4.48	0.84
	7	82	2.91	2.90	0.73
	8	25	4.16	4.16	0.88
	9	44	3.00	3.02	0.80
10	482	3.77	3.76	0.83	

<sup>†</sup>Total Ozone Mapping Spectrometer

**Table 14:** Arithmetic means for UV Index values measured by SafeSun according to local measurements of TOMS total column ozone; UV-B radiation; solar zenith angle; and visibility.

oriented and vertical UVI increases with increasing UV-B irradiance and decreases with increasing solar zenith angle. No obvious patterns can be discerned in the UVI means classified by TOMS and visibility. Here again; as in Table 12; the UVI statistics categorized by TOMS pertain to a variety of radiation conditions (including cloudy skies and shielding by vegetation) that tend to weaken the expected correlation between UVI and total column ozone. The results for UVI classified by visibility were also expected. Visibility (normally expressed as light scattering and absorption coefficients) accounts for only a small portion

(generally less than 10 percent) of the unobstructed UV radiation component. Consequently; the correlation between visibility and UVI tends to be very weak.

### Stepwise linear regression analyses to identify predictors of the UV Index measured by the SafeSun monitor

An apparent correlation between UVI measured by the SafeSun monitor and one of the variables listed in Tables 3 through 14 does not necessarily imply a “cause-and-effect” relationship. There is always

the possibility that a “strong” predictor variable is actually correlated with another quantity that is the true cause of the noted effect. With this caveat in mind; we defined 39 continuous variables and 30 binary variables as candidate (potential) predictors of UVI. These variables included measures of location and altitude; meteorological conditions (temperature; relative humidity; cloud cover; wind speed; visibility; etc.); ground-level pollution concentrations; irradiance measured by the MicroTops; sun angle; erythema-weighted UV-B (as measured by the USDA monitor); microenvironment; time; shielding; and surface. Using selected sets of these variables as candidate predictor (independent) variables; we performed a series of stepwise linear regression (SLR) analyses to (a) identify the most significant predictors and (b) develop regression-based models appropriate for predicting personal UV-B exposure in future population exposure models. Three dependent variables were evaluated in these analyses: sun-oriented UVI (UVI\_SUN); vertical UVI (UVI\_VERT); and horizontal UVI (UVI\_HORZ).

In reviewing the results of each SLR analysis; researchers checked various appropriate diagnostics provided in the SLR outputs (e.g.; the variance inflation factor) to determine whether the pool of candidate variables exhibited significant co linearity. Variance inflation factors never exceeded 3.5; in agreement with guidelines that such values not exceed 5.0 [25]. In performing the SLR analyses; analysts specified p-to-enter and p-to-exit values of 0.05 for adding and removing variables; consistent with recommendations by Draper and Smith [26]. Results for specific SLR analyses are not presented here due to space limitations. (A tabulation of all results can be obtained from the corresponding author.)

Overall; the results of the SLR analyses suggest that the best predictors of UVI\_SUN and UVI\_VERT are degree of shielding; UV-B levels measured at local fixed-site monitors; cosine of the solar zenith angle; obscuring of the sun by clouds; wind speed; time of day; and season. As UVI\_SUN and UVI\_VERT are highly correlated; it is not surprising that they share many of the same “best” predictors. Variables associated with ozone;  $PM_{2.5}$ ; and black carbon did not tend to be important predictors of UVI\_SUN and UVI\_VERT when tested in combination with other strong predictors.

Degree of shielding was also a good predictor of UVI\_HORZ; a UVI measure that never exceeded 3. In addition; black carbon and cloud cover were found to be relatively important predictors of UVI\_HORZ. These results are consistent with research on the effect of cloud cover on diffuse radiation received in shaded microenvironments [11].

UV exposures received in open (unshielded) locations under near-vertical solar conditions are of special concern to risk assessors. To identify key predictors of UV exposure under these conditions; researchers conducted supplemental SLR analyses on the relatively small subset ( $n = 131$ ) of the UVI\_SUN values that met the following two criteria: (1) the cosine of the solar zenith angle equaled or exceeded 0.9 and (2) the SafeSun monitor was not shielded. Significant predictor variables included sun obscured by clouds; total column ozone reported at RTP; wind speed; back-lighting of clouds; cloud cover; location in one of 11 “high UVI” microenvironments; solar radiation measured at Millbrook monitor; and date between 7/9/03 and 9/11/03; together these variables produced a cumulative  $R^2$  value of 0.6506. Although none of the candidate ground-level pollution variables was selected into the regression equation; the inclusion of a wind speed variable in the regression equation may reflect the effects of incoming fronts that tend to reduce atmospheric pollution and water vapor.

### Stepwise linear regression analyses to identify predictors of hourly-average UV Index measured by the USDA monitor

A series of supplemental SLR analyses (also available from the corresponding author) were conducted to identify important predictors of the UV-B measurements made at the USDA monitor during daylight hours over the nominal period of the study. Note that these measurements were; by definition; unaffected by many of the factors affecting the SafeSun measurements (microenvironment; shielding; surface; etc.). Table 15 presents descriptive statistics for hourly average values of UV-B irradiance reported for hours beginning 0800 to 1800 for June 1 through September 30; 2003. The UV-B data were 92 percent complete with values ranging from 0.0 to 0.255 Watts  $m^{-2}$ . The arithmetic mean was 0.088 watts  $m^{-2}$  with a median value of 0.075 Watts  $m^{-2}$ . Analysts compiled hourly-average values reported for various air quality and meteorological variables for the same time period. Researchers conducted SLR analyses of UV-B using two sets of candidate predictor variables (A and B). Set A included four variables associated with hourly average values of black carbon; ozone; and  $PM_{2.5}$ . Set B included all of the Set A variables plus variables taken from Table 15 relating to solar zenith angle; UV Index; time of day; hour; month; and various meteorological indicators. The dependent variable was either (1) UV-B reported for all hours beginning 0800 to 1800 or (2) UV-B reported only for the midday hours (hours beginning 1200; 1300; or 1400).

When the candidate predictor variables were limited to concentrations of ozone; black carbon; and particulate matter measured by local fixed-site monitors (Set A); the best predictors of increasing UV-B during the hours 0800 to 1800 were found to be an increase in ozone concentration measured by the Millbrook station; a decrease in black carbon measured by the NCSU/USDA station; and a decrease in  $PM_{2.5}$  concentration measured by the Millbrook station (listed in order of importance). The associated regression equation had an  $R^2$  value of 0.4265 with the ozone variable yielding an  $R^2$  of 0.3048 when considered by itself. When the pool of candidate variables was expanded to include various non-pollutant variables (set B); the best predictors were found to include variables relating to solar angle; relative humidity; forecast total ozone column; and temperature. Although none of the measured air pollutant variables was included in the regression equation; the resulting  $R^2$  value was substantially higher (0.8483). The site of the solar zenith angle was the best single predictor of those tested; producing an  $R^2$  value of 0.6975 when used as the sole independent variable in the regression equation.

Overall; the results of these SLR analyses suggest that hourly-average values of summertime UV-B (hours 800 - 1800) in the Raleigh area can be relatively well predicted ( $R^2 = 0.8483$ ) using data relating to solar zenith angle; relative humidity; forecast total ozone column; and temperature. The addition of data concerning local; ground-level concentrations of ozone;  $PM_{2.5}$ ; and black carbon does not significantly increase the accuracy of the prediction. The fact that the sine of the solar zenith angle was the best single predictor of those tested is consistent with the earth-sun relationship and the time of the year. High solar zenith angle combined with total column ozone are the two most dominating factors for UV-B prediction on a clear day.

When the candidate predictor variables in Set A were evaluated for the midday hours (1200 - 1400); the best predictors of increasing UV-B were found to be an increase in ozone concentration measured by the Millbrook station; a decrease in black carbon measured by the NCSU/USDA station; and an increase in ozone concentration measured at

Definition	Number of values <sup>†</sup>	Arithmetic mean	Arithmetic std. dev.	Min	Median	Max
hourly average of erythral UV-B measured by fixed-site USDA monitor; watts m <sup>-2</sup>	1241	0.088	0.064	0.000	0.075	0.255
black carbon (NCSU/USDA); ng m <sup>-3</sup>	1240	619	413	0.25	523	3441
nephelometer (NCSU/USDA); m <sup>-1</sup>	907	0.0178	0.383	4.80E-6	1.11E-4	9.52
ozone concentration (NCSU/USDA); ppb	1336	43.1	21.6	1.0	41.5	105.0
ozone concentration (Millbrook); ppm	1270	0.0449	0.0185	0.001	0.044	0.122
total column ozone (TOMS); Dobson units	1342	308	15.9	268	306	367
total column ozone forecast (CPC); Dobson units	1320	304	17.0	278	301	374
PM <sub>2.5</sub> concentration (Millbrook); µg m <sup>-3</sup>	1221	18.4	10.5	0.0	16.5	58.5
relative humidity (Millbrook); percent	1267	63.9	14.3	31	63	93
solar radiation (Millbrook); watts m <sup>-2</sup>	1267	407	295	0	422	998
sine of solar zenith angle (USDA)	1241	0.660	0.218	0.218	0.683	0.995
temperature at 10 m (Millbrook); deg C	1267	26.3	3.74	14.8	26.4	34.3
temperature at 2 m (Millbrook); deg C	1267	26.6	3.84	14.0	26.8	35.0
10 m temperature - 2 m temperature (Millbrook); deg C	1267	-0.327	0.321	-2.3	-0.4	1.3
clear sky UV Index (CPC)	1320	8.75	1.16	5.68	9.05	10.9
cloud-corrected UV Index (CPC)	1320	6.27	1.36	3.00	6.46	8.78
visibility (RDU Airport); miles	1342	7.98	2.52	0.25	9	10
wind speed at 10 m (Millbrook); m sec <sup>-1</sup>	1267	2.46	1.01	0.1	2.3	10.5
wind speed at 2 m (Millbrook); m sec <sup>-1</sup>	1267	1.73	0.73	0.0	1.6	6.4

<sup>†</sup>Possible values = 1342

**Table 15:** Descriptive statistics for hourly average values of selected variables relating to UV-B; air quality; and meteorological conditions for June 1 through September 30; 2003 (clock hours beginning 800 - 1800).

the NCSU/USDA station (listed in order of importance) with a slightly higher R<sup>2</sup> value (0.3403). The best predictors of midday UV-B based on Set B were related to relative humidity; clear sky UV Index; black carbon measured by the NCSU/USDA station; and temperature. In this case; the relative humidity variable was the best single predictor of those tested; yielding an R<sup>2</sup> of 0.4070 when used as the sole independent variable in the regression equation. Adding the other variables increased the R<sup>2</sup> to 0.6256. Note that the sine of the solar zenith angle was not expected to be an important predictor; as the analyzed data were limited to hours when the sun was nominally overhead.

These results suggest that summertime UV-B at midday (hours 1200 - 1400) can be reasonably well predicted (R<sup>2</sup> = 0.6256) using data relating to relative humidity; clear sky UV Index; black carbon; and temperature. The coefficients for measured (ground-level) ozone concentration in the SLR results were always positive; suggesting that UV-B increases with increasing ozone. This result is consistent with the fact that surface ozone formation rates and clear-sky UV-B both increase with increasing solar radiation. When the pool of candidate variables included factors related to measured ozone and solar radiation; measured ozone was no longer found to be a significant predictor variable. When measured black carbon or PM<sub>2.5</sub> was found to be a statistically significant predictor of UV-B measured by the USDA monitor; the regression coefficient was always negative; indicating that UV-B tends to decrease as measured black carbon or PM<sub>2.5</sub> increases. This finding is consistent with research by Barnard et al. [27] which found black carbon; day of year; total column ozone; and PM<sub>10</sub> to be major factors in determining the surface levels of UV-B radiation. Statistical analysis of data collected in Riverside; CA in the summer of 1997 yielded the following regression equation:

$$DUV = (608.9)[\text{Sin}(\Theta)] - (2049.0)[\text{Cos}(\Theta)] - (16.9)(\text{TOMS}) - (7.1)(\text{PM}_{10}) - (148.4)(\text{black carbon}) + 8484.0. (2)$$

where DUV is the Diffey-weighted UV exposure as measured throughout the day by a Brewer spectroradiometer;  $\Theta = (2\pi)$  (Julian date/365); TOMS values are in Dobson units; and PM<sub>10</sub> and black

carbon are in micrograms per cubic meter. This equation was tested using data recorded at Mt. Gibbs in the mountains of western NC. Actual UV-B readings taken at this NCSU site were plotted against estimates obtained from Equation 2 using appropriate TOMS; PM-10; and measured black carbon concentrations. A correlation coefficient (R<sup>2</sup>) of 0.92 was obtained. The findings are also consistent with research by Vuilleumier et al. [28] who evaluated solar UV irradiance measurements made at two Southern California sites experiencing differing levels of air pollution. The researchers concluded that optical depth variability at the two sites was attributed mainly to concentration changes in aerosols and only marginally to changes in the ozone column. Overall; the results suggest that particulate matter concentration - as represented by the black carbon and PM<sub>2.5</sub> measurements - has a more significant effect on UV-B than does measured ground-level ozone.

## Conclusions

The pilot study demonstrates a protocol for collecting micro-environmental exposure data under varying conditions of cloud cover; overhead shielding; and ground cover and then combining this information with local fixed-site monitoring data to quantify the principal factors affecting personal exposure to UV-B during typical activities. This protocol was used in Raleigh; NC to produce a detailed database for 788 SafeSun sampling events with minimal data loss. Results of SLR analyses performed on the complete database indicated that the best predictors of sun-oriented UVI (UVI\_SUN) and vertical UVI (UVI\_VERT) were degree of shielding; solar angle; UV-B measured at a local fixed-site monitor; cloud cover; wind speed; time of day; and season. Although cloud cover was an important predictor of UVI; cloudless days had lower UVI values than days with some cloud cover. In addition; hourly variations in fractional cloud cover; cloud type; and cloud location can cause intraday UVI variations not reflected in a daily maximum UVI forecast. Residential outdoor microenvironments tended to have lower mean UVI values than outdoor recreation microenvironments (e.g.; athletic field; pool); which may have implications for estimating total personal exposure

to UV-B. In-vehicle UVI values were lower than values in residential or recreation microenvironments. Variables associated with ozone; PM<sub>2.5</sub>; and black carbon were less important predictors of UVI\_SUN and UVI\_VERT when nested together with other strong predictors. Degree of shielding; wind speed; and season were also good predictors of horizontal UVI (UVI\_HORZ); a UVI measure that never exceeded 3. Black carbon and cloud cover were found to be relatively important predictors of UVI\_HORZ.

To identify key predictors of UV exposure in open sunlight under near-vertical solar conditions; researchers conducted supplemental SLR analyses using only the sun-oriented (UVI\_SUN) values that met the following two criteria: (1) the cosine of the solar zenith angle equaled or exceeded 0.9 and (2) the SafeSun monitor was not shielded. The best predictors included wind speed; cloud cover; season; solar angle; and fixed-site measurements of solar radiation and UV-B. Variables related to microenvironment; cloud backlighting; and total column ozone were identified as weaker; but still statistically significant; predictors. None of the tested variables associated with ozone; PM<sub>2.5</sub>; and black carbon was found to be an important predictor of UVI\_SUN under these specified special conditions.

Researchers also conducted a series of SLR analyses to identify important predictors of the UV-B measurements made at the USDA monitor during daylight hours over the period of the study. When pollutant variables were considered separately from solar radiation and meteorological variables; the best predictors of increased fixed-site UV-B were increasing ozone concentration; decreasing black carbon concentration; and decreasing PM<sub>2.5</sub> concentration. Combinations of these variables measured at the two monitoring sites explained 34% of the variation in midday UV-B irradiance and 43% of the variation in full-day UV-B. When other variables; such as relative humidity; temperature; and forecast total ozone column; were included in the analysis; pollutant variables were no longer selected into the regression; except for black carbon in the midday UV-B regression. R<sup>2</sup> values for regressions including the full set of variables were substantially higher; at 0.84 for daytime UV-B and 0.63 for midday UV-B; indicating that pollutant-related variables are less important predictors of fixed-site UV-B than solar radiation or meteorological variables.

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