The Ultraviolet Index in the Contiguous United States and its Verification in Los Angeles

Gong Yu Li and Tim Boyle
California State University, Northridge

Introduction
For the purpose of studying biological effects, ultraviolet radiation can be classified into three bands based on wavelength ranges: UV-C spans the 100 nm to 280 nm range, UV-B lies between 280 nm and 320 nm, and UV-A extends from 320 nm to 400 nm (EPAs 1994; UMD 1990). Unlike UV-A and UV-B radiations, the UV-C radiation is completely absorbed by the atmosphere before reaching the ground surface. Therefore, UVA and UV-B radiation is of major concern to human health. Human exposure to ultraviolet radiation provides some beneficial results such as skin tanning, vitamin D synthesis, and diagnostic and therapeutic applications in medicine. In contrast, overexposure to UV radiation may cause skin cancer, eye disorders, suppression of the immune system, and erythema (tanning or skin reddening).

Since June 28, 1994, the National Weather Service (NWS) has issued the daily Ultraviolet Index (UVI) to warn the public against potential sunburn risk for 58 cities in the United States (Figure 1). The UVI was developed by the National Centers for Environmental Prediction (NCEP), formerly National Meteorological Center of NWS, in collaboration with the Environmental Protection Agency (EPA) and the Center for Disease Control And Prevention (CDC). It is used as a tool to enhance public awareness of the health risks of excessive exposure to ultraviolet radiation. Other countries, such as Australia, Canada, Germany, New Zealand, and Britain also issue an ultraviolet index, although their criteria may be different from those of the US UVI (CUNIRP 1995).

This article intends to introduce geographers to the concept of UVI by discussing the spatial and temporal variations of the UVI and minute-to-minute time in the contiguous United States. Since the ultraviolet index is a real-time forecast of the likely exposure to ultraviolet radiation weighted by the erythemal action spectrum for a particular location at noon (EPA 1994), an attempt is made to verify the UVI forecast for Los Angeles by the measured UVI from the Yanklowicz environmental UV-B pyranometer located at Northridge.
**Literature Review**

The method of predicting the next day UVI is rather complicated. The EPA (1994a) provided a brief discussion of the method of computing UVI in the United States. Long et al (1996) presented the procedures of UVI forecasting in detail. Factors causing variation in amounts of ultraviolet radiation reaching the ground surface include the total column ozone, cloud cover, altitude, surface albedo, optical depth, and solar zenith angle or time of day. Clouds strongly absorb UV-B radiation but it is a poor absorber of UV-A radiation. Therefore, fluctuations in the incidence of UV-B radiation are particularly sensitive to variations in the total column ozone. Using the total column ozone observed from polar orbit satellites, a radiative transfer model, regression equations, and model output statistics (MOS), the spectrum irradiance at each wavelength between 290 nm and 400 nm are calculated and then weighted (multiplied) by the CIE (Commission Internationale d'Eclairage) action spectrum and integrated over the wavelength range to produce an erythemal dose rate in watts per square meter (W/m²). During the UVI experimental period, June 1994 through April 1995, the UVI was expressed as one hour’s erythemal dosage based on the integration of the predicted erythemal dose rate for the noon hour 11:30 am to 12:30 pm local time. The integration of the erythemal dose rate (W/m²) over one hour is converted into hesiopads per square meter (H/m²) or dose rate times 56. The scaled dosage in units of H/m², rounded to the nearest whole number, is the UVI issued to the public (EPA 1994a). The UVI derived from this method lies on a scale from 0 to 15. Since April 1995, the United States has adopted the international standard that expresses the UVI as the dose rate times 10. Most countries use a CIE weighted irradiance scale such that one unit of UVI is equal to 0.025 W/m² (UVMO 1994). The reciprocal of this value is 40, meaning that one W/m² erythemal radiation equals 40 UVI. The present UVI value is hence about 1.44 (10/40) times larger than the experimental UVI value (Long 1994a).

In order to provide a warning system for high levels of ultraviolet radiation, the EPA (1994a, 1995) set five exposure categories: Minimal (0-1 and 2), Low (3 and 4), Moderate (5 and 6), High (7, 8, and 9), and Very High (10 and higher), based on UVI values which affect fair skinned persons. The public is advised to minimize outdoor activities between the peak hours of 10 am and 4 pm when UVI lies in the category of High or Very High.

The UVI is a measurement of erythemally weighted ultraviolet radiation that requires some background knowledge of the erythemal action spectrum. An action spectrum describes the relative effectiveness of each...
wavelength of radiation in causing the same degree of a biological response, such as erythema, skin tumors, or DNA damage (Cole et al., 1966). It is defined as the reciprocal of the dose required to cause a threshold biological response. This effective radiant dose is normalized to 1 at the most effective wavelength. The effective radiant exposure of the other wavelengths, which are smaller than 1, are computed from statistically-derived normalized equations (McKinlay and Diffey, 1987).

The UVI employs the erythemal action spectrum as a weighting function because erythema is an immediately noticeable biological reaction when human skin is exposed to UV-B radiation. UV-A radiation may cause erythema but requires a threshold dose of 300 to 500 times that of UV-B radiation (Urth 1986). UV-A erythema is characterized by dark red color in contrast to bright red color of UV-B erythema. Furthermore, UV-A radiation may cause skin pigmentation without prior occurrence of erythema (Murthy and Cesarone, 1987).

The study of erythemal action spectra began in the 1920s by Hausner and Yohle (Urbach, 1986; 1987). Most recent studies of the action spectra of human skin were performed by Pariishi et al. (1962), Gange et al. (1963), Urbach (1969), Diffey (1980), and Anders et al. (1982). In 1994, the World Meteorological Organization (WMO) recommended the adoption of the CIE action spectrum normalized to 1.0 at a wavelength of 297 nm. The CIE action spectrum is based on a statistical analysis of the results of the minimum erythemal dose (MED) studies from various publications prior to 1982 (McKinlay and Diffey, 1987). The spectral erythema effectiveness is the reciprocal of the MED, which is defined as the smallest amount of UV dose necessary to induce a barely perceptible reddish of previously unexposed skin within 24 hours of exposure (Diffey, 1984).

The UVI is determined almost entirely by the amount of exposure to UV-B radiation. The relative erythema effectiveness of UV-A radiation is insignificant compared to that of UV-B radiation.

In order to provide information for the public to better understand the health risk of overexposure to ultraviolet radiation, the NWS issues daily UVI warnings accompanied by minutes-to-burn (sunburn) time for the noon hour. The time required to sunburn is calculated by dividing 60 minutes by the number of MEDs (minimum erythemal dose) in one hour. The EPA (1994a and b) has provided the values of a MED for four skin photos-type: never tans/always burns, sometimes tans/sometimes burns, usually tans/usually burns, and always tans/sometimes burns. The minimum energy required to produce skin reddening (MED) varies from 10 ml/cm² (milli-erythema) per square centimeter) for the most sensitive people (always tans/always burns) to 80 ml/cm² for the least sensitive people (never tans/never burns).

The most sensitive skin color in an unexposed area is pale, milky white, or alabaster. The time required to sunburn for the least sensitive person is about 5 times as long as that required for the most sensitive person. The skin color for the least sensitive person is brown, dark brown, or black.

The UVI value is first converted to ml/cm² and then divided by 10 ml/cm² to obtain the number of MEDs in one hour for the most sensitive person. The conversion of UVI to units of 0.02 W/m² to hourly UV-B energy dosage in units of ml/cm² is achieved by the following equation:

\[ UVI \times 0.025 \times 3600 \times 10 = UVI \text{ ml/cm}^2 \times 0.025 \text{ W/m}^2 = 9 \text{ UVI ML/m}^2 \times \text{9 UVI ML/m}^2 \times 9 \text{ UVI ML/m}^2 \]

Since the energy of minimal erythema for the most susceptible skin type (milky white) is 10 ml/cm² as recommended by the EPA, the most MEDs in one hour is 0.9 UVI (UVI/10). The minutes-to-burn time is computed by dividing 60 minutes by the MEDs in one hour or 60/90 UVI.

**Methodology**

The daily noon-hour UVI data for the period 1995-1997 in 55 cities in the contiguous United States (excluding Anchorage, Honolulu, and San Diego) are obtained from the NCEP archive (Long, 1997). The method of deriving UVI and minutes-to-burn time in the United States are already discussed in the section of literature review. Satellite software is employed to obtain basic statistics of the UVI for the 55 cities in the United States. Adobe Illustrator and DeltaGraph software are used to construct monthly distributions of mean daily noon-hour UVI maps and graphs.

In 1995, California State University at Northridge (CSU) installed a Yankee Environmental UV-B pyranometer at its weather station operated by the Department of Geography. The CSU weather station consists of a Campbell Scientific datalogger and typical meteorological sensors including an anemometer, wind vane, temperature, relative humidity, tipping bucket rain gauge, barometric pressure, total solar parameters and UV-B pyranometer (Figure 2). It is located at 34° 14' 17" north and 118° 31' 45" west. The UV-B pyranometer is about 10 meters above the ground. The measured UVI at Northridge weather station is obtained by the following equation:

\[ UVI = \frac{0.005 \times 3 \times 0.14 \times 0.14 \times 100 \times \text{voltage output}}{0.015 \times \text{voltage output}} \]

Where the factor 0.005 converts millivolts to volts, the number 2 trans-
Figure 2. Northridge weather station (UV Pyranometer - inset picture).

...f these voltage readings from the UVB-1 sensor to the Campbell Scientific CR10 datalogger which outputs the UVB energy in units of millivolts; the value 0.141 effective W/m²/volt converts UVB-1 instrument output voltage into the CIE-defined erythema irradiance (UVA action spectrum) in effective W/m². The CR10 outputs the erythema irradiance into UVI (long 1996). UVI measurements are taken every 5 seconds. Hourly values of average, maximum, and minimum of UVI and other weather variables are stored in a module of a Campbell Scientific datalogger and can be displayed on Excel spreadsheets on an IBM computer screen via a modem.

The NCEP prepares the UVI for Los Angeles using forecast ozone field within a 5×5 latitude/longitude grid, as well as location, altitude, and predicted cloud amounts at Los Angeles International Airport (LAX). The UVI issued for Los Angeles is valid within a 45-km (28-mi) radius of LAX (NOAA 1996). The observed UVI data for the period 1996–1997 at Northridge, approximately 46 km (28 mi) away from LAX and is hence within the forecast area, provide a good example of testing the validity of UVI forecast for Los Angeles by comparing the mean monthly distributions of observed and forecast UVI values. It is of interest to find the effect of altitude and cloud amounts on the accuracy of the UVI forecast.

Discussion

The spatial distribution of the mean monthly UVI at noon-hour in the contiguous United States illustrates the difference between regions with higher and lower levels of solar activity. The UV index is highest at noon-hour, when the sun is at its highest point in the sky. The highest UVI values are observed in the southern United States, particularly in the states of California, Nevada, and Arizona, where the UV index can reach up to 10 or even higher. In contrast, the lowest UVI values are observed in the northern United States, particularly in the states of Maine, New Hampshire, and Vermont, where the UV index can be as low as 2 or even lower.

In general, the UV index is highest in the summer months and lowest in the winter months. The UV index is also influenced by the amount of cloud cover, with clear skies leading to higher UV indices and cloudy skies leading to lower UV indices. The UV index is also influenced by the amount of pollution in the air, with higher levels of pollution leading to lower UV indices.

The UV index is a useful tool for understanding the potential for skin damage from sun exposure. It is important to note that the UV index is a measure of the erythema (redness) dose, which is the amount of UV radiation that causes redness of the skin. The UV index is not a measure of the total amount of UV radiation that reaches the Earth's surface, which is measured by the UVB index.

The UV index is also used to calculate the risk of skin cancer and other health effects associated with UV exposure. The UV index is a useful tool for understanding the potential for skin damage from sun exposure. It is important to note that the UV index is a measure of the erythema (redness) dose, which is the amount of UV radiation that causes redness of the skin. The UV index is not a measure of the total amount of UV radiation that reaches the Earth's surface, which is measured by the UVB index.
Figure 4 shows the area of maximum UVI in winter occurred persistently in Florida, shifting to southwestern desert states in summer. Figure 4 shows monthly variations of mean daily noon-hour UVI values in Los Angeles, Miami, and Seattle. The UVI values in Miami are higher than those in Los Angeles except in summer months, June through August. The decrease in UVI values in Miami from May to June can be attributed to the increased cloudiness and precipitation associated with increased thunderstorm activities in early summer. Rhizophylla Pinnata and frequently alternate the clear sky conditions by more than 50% (McKenzie et al., 1994). As expected, the UVI values in Seattle are lowest because of its location at a higher latitude and abundant clouds and precipitation associated with frequent cyclonic activity, particularly in winter. In June, a UVI minimum appears to extend from eastern Texas toward the upper Mississippi River Valley and the Great Lakes areas, corresponding to the June precipitation maximum in the same areas (Brewer et al., 1981). From June through August, the area covering the southern two-thirds of the nation has a High UVI category. In June, the maximum UVI occurs over Arizona, New Mexico, and southern California, with the UVI values approaching or reaching a Very High category (Mull, 1994). Figure 5 shows that in August, the UVI values decline slightly compared to those of July for all cities and nowhere in the contiguous United States is the mean monthly UVI of Very High category attained. Southern California experiences the highest UVI in the contiguous United States, with a value slightly exceeding 9. In September, only the Gulf coast area and the southwestern states attain the High UVI category. In October, the southeastern states experience the Moderate UVI category. Although the mean UVI values in the northern states along the U.S.-Canadian border fall in the Moderate UVI category from May through August, the maximum daily noon-hour UVI values reach the High category. Figure 6 shows that Seattle, where the mean UVI value is the lowest in the contiguous United States, attains a maximum daily noon-hour UVI value 9 in June. The figure also shows that the maximum daily noon-hour UVI reaches 13 in Miami in July, the highest value in the contiguous United States in the period 1995-1997.

Figure 6 shows the monthly variations of forecast (LAX) and observed (Northridge) mean daily noon-hour UVI values for the period 1995-1997. Visually, there is a good fit between the forecast and observed UVI values with a difference less than one UVI unit in each month. The forecast values are slightly lower than the observed values except for the summer months, June through September. Figure 7 also shows a good agreement between forecast and observed UVI values. Approximately 50% of the forecast and observed UVI values are equal. For about 87% of the days, the UVI forecast is within one index unit of the
observed value. The percentage increases to about 98% for the forecast values that are within two index units of the observed values. These accuracies are higher than those of the overall UVI forecasts for other cities in the nation having a comparable accuracy of 72%, 76%, and 92% (Long et al. 1995a, 1994a). The forecast UVI levels are lower than the observed UVI as reflected by more negative values (93%) than the positive values (93%) in figure 7. LAX is located at a lower altitude and more cloudy than Northridge (Keifer 1980), resulting in lower UVI values. An examination of daily UVI data indicates that the large differences of higher or lower positive or negative values between forecast and observed UVI are attributed to the occurrence of rain and/or cloudy days. The occurrence of a few cloudy days that resulted in a very low UVI values at Northridge accounted for the slightly lower mean daily noon-hour UVI values in the summer months of 1996-1997. Although cloud observations are not available at Northridge, the extreme low UVI values occurred on the days characterized by a significant decline in air temperature and increase in relative humidity from the previous days, indicating the presence of clouds or fog.

Since the UVI issued by the National Weather Service is accompanied by minute-to-hour time, it is of a geographical interest to study the spatial and temporal variations of minute-to-hour time in the contiguous United States and to warn the public about the potential risk of sunburn. Figure 8 shows the spatial pattern of minutes-to-hour time for the most sensitive person in January and July. In January, it varies from about 20 to 30 minutes in the south to more than one hour in the north of the contiguous United States. The northwest and northeast regions require the longest time to cause sunburn. Previous studies have concluded that a person exposed to sunlight for a long period of time may be at a health risk despite the fact that the UVI is in the Low or Minimum category. A UVI value of two may cause sunburn in about 30 minutes for the most sensitive people and 150 minutes for the least sensitive people. The low UVI value in winter by no means implies that it is safe to expose the skin to sunlight for many hours. In July, the time required to sunburn the most sensitive people at noon is about 12 minutes or less everywhere in the United States (Figure 8). In the southwest desert area, it requires less than 7 minutes to cause sunburn at noon, the shortest time required to cause sunburn in the contiguous United States.

Figure 6. Monthly variations of forecast (Los Angeles) and observed (Northridge) mean daily noon-hour UVI values.

Figure 7. Frequency of the differences between forecast and observed UVI values at Northridge (Los Angeles).
Summary

The spatial pattern of the UV in the contiguous United States is mostly latitude and altitude dependent and is inversely related to that of precipitation and cloud cover. The northwest and northeastern regions, where cloud cover and precipitation are greatest, are characterized by the minimum UV throughout the year in the midsummer. Maximum UV occurs in the southeastern United States. Except for the summer months, Florida is characterized as having the highest UV in the contiguous United States. Mean daily noon-hour UV values vary from near 0 in the northwest in winter to about 12 in the southeastern in summer.

The forecast UV index is verified with observed UV values in Los Angeles. It is found that the forecast UV index is within one index of the observed values for 80% of the days tested. The accuracy of the UV index forecast in Los Angeles is much higher than that of the overall UV forecast for other cities in the nation. In Los Angeles, the forecast UV values are consistently lower than the observed ones during winter months. The difference between the forecast and observed values may be attributed to the difference between the locations where forecast and observed UV values are taken. Observed values are measured at Northridge, located on an inland valley northwest of LAX, from which the forecast values are derived. The UV values are expected to be lower at LAX than at Northridge because of its lower elevation and more cloudy days. However, for cloudy days associated with extreme low UV values, Northridge resulted in lower observed means daily noon-hour UV values than forecast ones in the summers of 1996-1997. The 1996 and 1997 summers should be viewed as abnormal summers. This result can be verified further as more summer UV data become available.

In summary, it takes about 12 minutes or shorter time to get sunburn for most sensitive people anywhere in the United States. This information will enhance the public awareness to take proper protection when conducting outdoor activities.

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