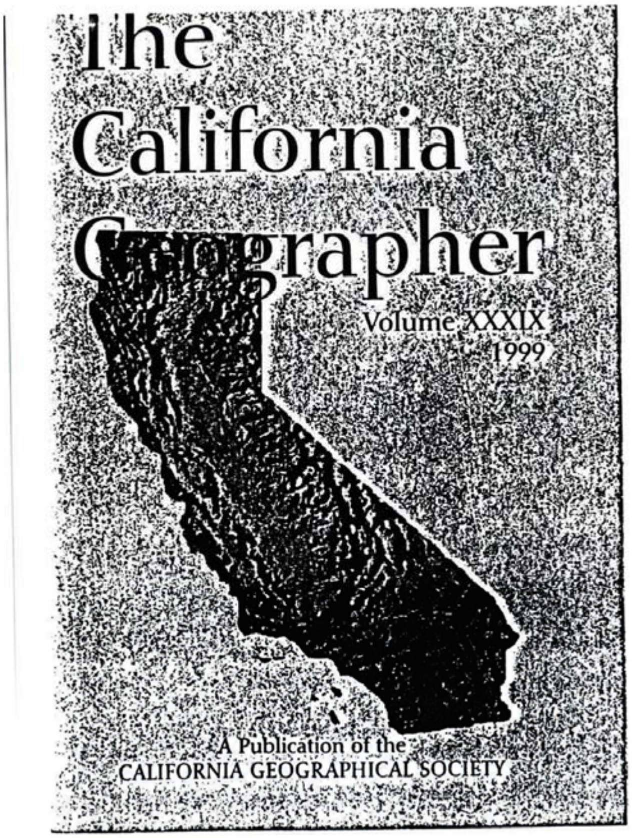

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Volume XXXVIII included the article "California's Northeast Border: Political Pragmatism Turned Territorial Imperative" by Gregory A. Reed. Mr Reed is at Southwest Texas State University.

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

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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 (EPA 1994a ; Urbach 1986). Unlike UV-A and UV-B radiations, the UV-C radiation is completely absorbed by the atmosphere before reaching the ground surface. Therefore, UV-A 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 (sunburn 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 (ICNIRP 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-burn time in the contiguous United States. Since the ultraviolet index is a next-day forecast of the likely exposure to ultraviolet radiation weighted by the erythemal action spectrum for a particular location at noon (EPA 1994a), an attempt is made to verify the UVI forecast for Los Angeles by the measured UVI from the Yangkee's environmental UVB-1 pyranometer located at Northridge.

Figure 1. The locations of UVI stations.

Literature Review

The method of predicting the next day UVI is rather complicated. The EPA (1994b) provided a brief discussion of the method of computing UVI in the United States. Long et al. (1996a) presented the procedures of UVI forecasts 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. Ozone strongly absorbs 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 irradiances at each wavelength between 290 nm and 400 nm are calculated and then weighted (multiplied) by the CIE (International Commission on Illumination or Commission Internationale d'Eclairage) action spectrum and integrated over the wavelength range to produce an erythemal dose rate in watts per square meter (W/m^2). 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/m^2) over one hour is converted into hectojoules per square meter (hJ/m^2) or dose rate times 36. The scaled dosage in units of hJ/m^2, rounded to the nearest whole number, is the UVI issued to the public (EPA 1994b). 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 40. Most countries use a CIE weighted irradiance scale such that one unit of UVI is equal to 0.025 W/m^2 (WMO 1994). The reciprocal of this value is 40, meaning that one W/m^2 erythemal radiation equals 40 UVI. The present UVI value is hence about 1.11 (40/36) times larger than the experimental UVI value (Long 1996b).

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. 1986). 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 exposures 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 dosage 500 to 5000 times that of UV-B radiation (Urbach 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 (Mutzhas and Cesarini 1987).

The study of erythemal action spectra began in the 1920s by Hausser and Vahle (Urbach 1986; 1987). Most recent studies of the action spectra of human skin were presented by Parrish et al. (1982), Gange et al. (1986), Urbach (1989), Diffey (1994), and Anders et al. (1995). In 1994, the World Meteorological Organization (WMO 1994) 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 erythema 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 redness of previously unexposed skin within 24 hours of exposure (Diffey 1994). The UVI is determined almost entirely by the amount of exposure to UV-B radiation. The relative erythemal 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 erythema dose) in one hour. The EPA (1994a and b) has provided the values of a MED for four skin phototypes: never tans/always burns, sometimes tans/usually burns, usually tans/sometimes burns, and always tans/rarely burns. The minimum energy required to produce skin reddening (MED) varies from 10 mJ/cm^2 (millijoules per square centimeter) for the most sensitive people (never tans/always burns) to 50 mJ/cm^2 for the least sensitive people (always 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 people is about 5 times as long as that required for the most sensitive people. The skin color for the least sensitive people is brown, dark brown, or black.

The UVI value is first converted to mJ/cm^2 and then divided by 10 mJ/cm^2 to obtain the number of MEDs in one hour for the most sensitive people. The conversion of UVI in units of 0.025 W/m^2 to hourly UV-B energy dosage in units of mJ/cm^2 is achieved by the following equation:

$$UVI \times 0.025\ Js^{-1}m^{-2} \times 3600\ s = 90\ UVI\ Jm^{-2} = 0.9\ UVI\ hJm^{-2} = 9\ UVI\ mJcm^{-2}.$$

Since the energy of minimal erythema for the most susceptible skin type (milky white) is 10 mJ/cm^2 as recommended by the EPA, the number of MEDs in one hour is therefore 0.9 UVI (9 UVI/10). Minutes-to-burn time is computed by dividing 60 minutes by the MEDs in one hour or 60/(0.9 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 Juan) are derived 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. Statview 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 (CSUN) installed a Yankee Environmental UVB-1 pyranometer at its weather station operated by the Department of Geography. The CSUN 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 pyranometer and UVB-1 pyranometer (Figure 2). It is located at 34"14'17" north and 118"31'48" west. The UVB-1 pyranometer is about 10 meters above the ground. The measured UVI at Northridge weather station is obtained by the following equation:

$$UVI = 0.001 \times 2 \times 0.141 \times 40 \times (\text{CR10 voltage output}) = 0.0113 \times (\text{CR10 voltage output}).$$

Where the factor 0.001 converts millivolts to volts; the number 2 transfers 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 $(W/m^2)/volt$ converts UVB-1 instrument output voltage into the CIE defined erythemal irradiance (Diffy action spectrum) in effective W/m^2 (YES 1997); and the multiplier 40 converts the erythemal irradiance into UVI (Long 1996a). UVI measurements are taken every 3 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.

Figure 2. Northridge weather station (UV Pyranometer - inset picture).

The NCEP prepares the UVI for Los Angeles using forecast ozone field within 1° x 1° latitude/longitude grid, as well as location, altitude, predicted cloud amounts at Los Angeles International Airport (LAX). The UVI issued for Los Angeles is valid within a 48 km (30 miles) radius of LAX (NOAA 1995). The observed UVI data for the period 1996-1997 at Northridge, approximately 32 km (20 miles) 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 altitudes 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 a strong latitudinal dependence with a gradient showing the decrease of UVI from south to north (Figures 3). During the months of November, December, and January, the mean monthly UVI is in the Low and Minimal categories (4 or lower) everywhere in the contiguous United States. There is a distinct UVI maximum over the Rocky Mountains and a UVI minimum over the Mississippi River Valley areas. Obviously, elevation and the dry atmosphere over the Rocky Mountains account for such a spatial distribution of the monthly mean UVI. In February, Miami, Florida experiences a Moderate category of UVI while the other cities are still in Low and Minimal categories. In March, Miami leads other stations in the contiguous United States with a mean monthly UVI of higher than 7. Beginning in April, a High category of UVI values (7 and 8) appears in Arizona, New Mexico, and southern California. Florida still experiences the highest mean monthly UVI of 8 in the contiguous United States. In May, the southern states of the country experience UVI greater than 7. A striking feature is found over Miami, Florida where the mean monthly UVI exceeds 9, approaching a Very High category. Florida is consistently characterized by the highest mean monthly UVI in the contiguous United States except during summer months of June, July, and August (Figures 3 and 4).

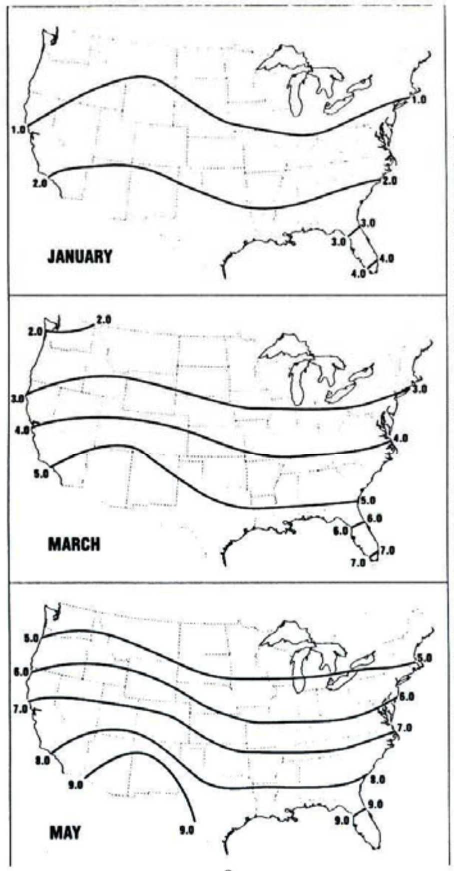
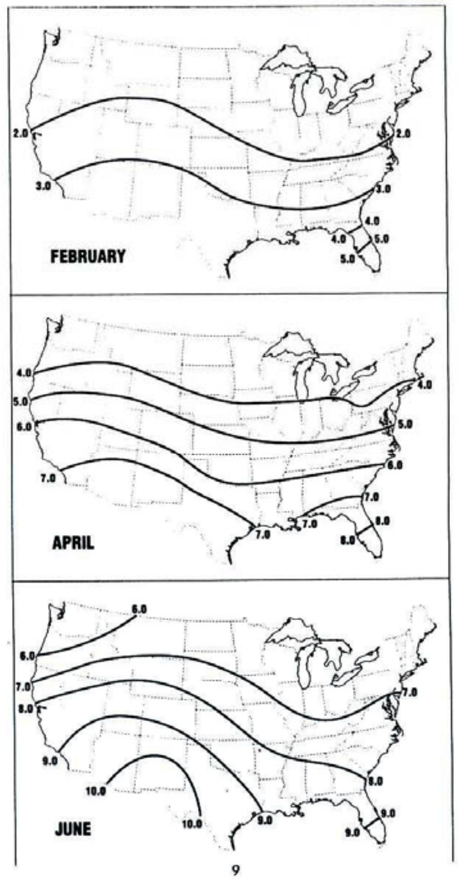
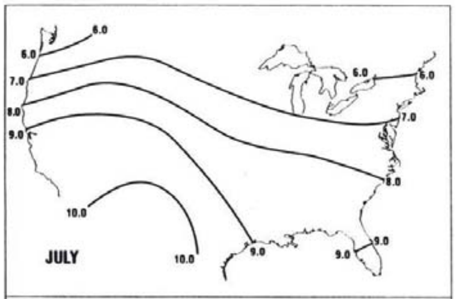


Figure 3. Monthly spatial distributions of mean daily noon-hour UVI, 1995-1997 (pages 8-11).





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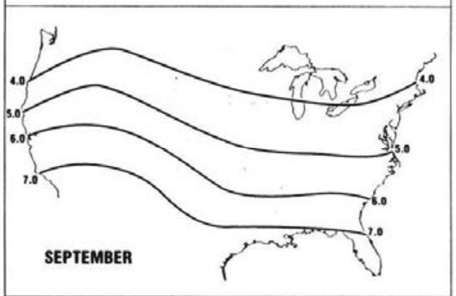

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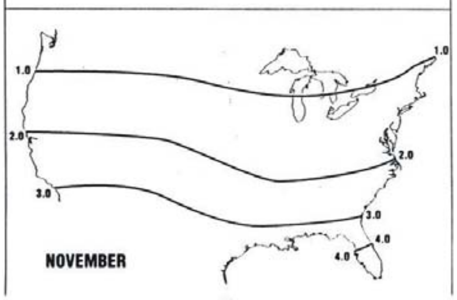

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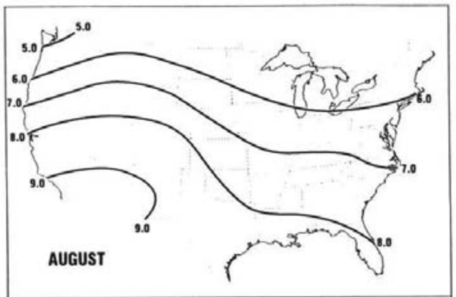

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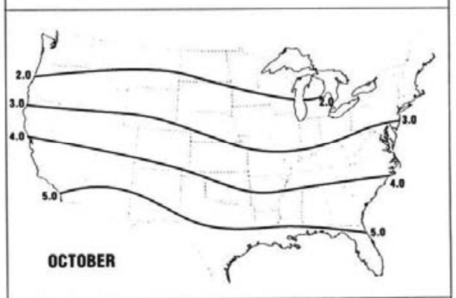

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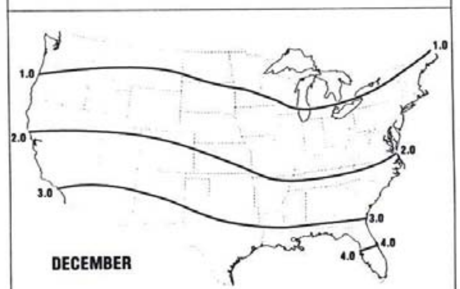

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Figure 3 shows the area of maximum UVI in winter occurred persistently in Florida, shifting to southwestern desert states in summer. Figure 4 shows monthly variations of mean daily noon-hour UVI values in Los Angeles, Miami, and Seattle. The UVI values 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 (Lydolph 1985). Clouds frequently attenuate the clear sky irradiances by more than 50% (McKenzie et al. 1991). 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 (Trewartha 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 (10+) (Figure 3). 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 southernmost states experience the Moderate UVI category. Although the mean UVI values in the northern states along the US-Canadian border fall in the Moderate UVI category from May through August, the maximum daily noon-hour UVI values reach the High category. Figure 5 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 1996–1997. 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 39% 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

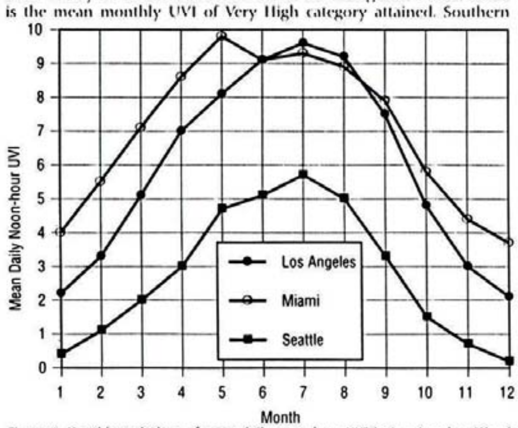

Figure 4. Monthly variations of mean daily noon-hour UVI in Los Angeles, Miami and Seattle.

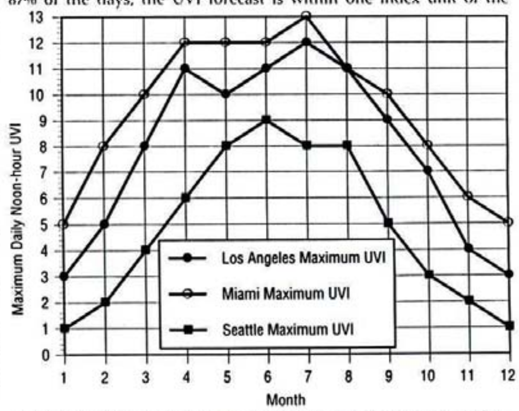

Figure 5. Monthly variations of maximum daily noon-hour UVI in Los Angeles, Miami, and Seattle.

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 52%, 76%, and 92% (Long et al. 1996a; 1996c). The forecast UVI tends to be lower than the observed UVI as reflected by more negative values (39%) than the positive values (21%) in figure 7. LAX is located at a lower altitude and more cloudy than Northridge (Keith 1980), resulting in lower UVI values. An examination of daily UVI data indicates that the large differences, 3 or higher either positive or negative values, between forecast and observed UVI are attributed to the occurrences of rainy 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 (Figure 6). 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 fogs.

Since the UVI issued by the National Weather Service is accompanied by minute-to burn time, it is of a geographical interest to study the spatial and temporal variations of minute-to-burn 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-burn time for the most sensitive people 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.

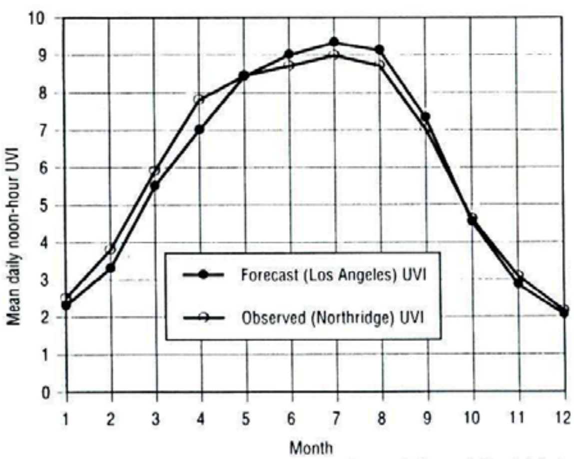

Figure 6. Montly variations of forecast (Los Angeles) and observed (Northridge) mean daily noon-hour UVI values.

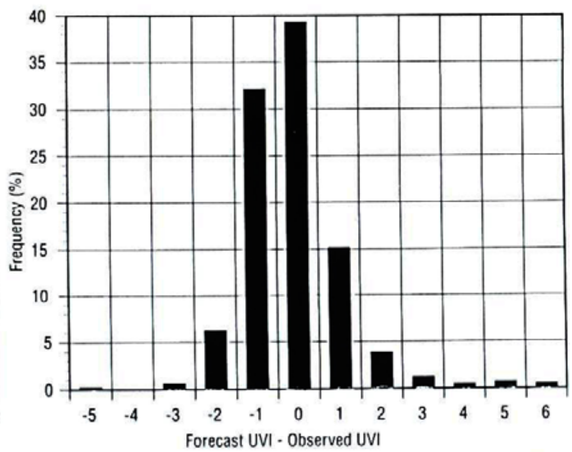

Figure 7. Frequency of the differences between forecast and observed UVI values at Northridge (Los Angeles).

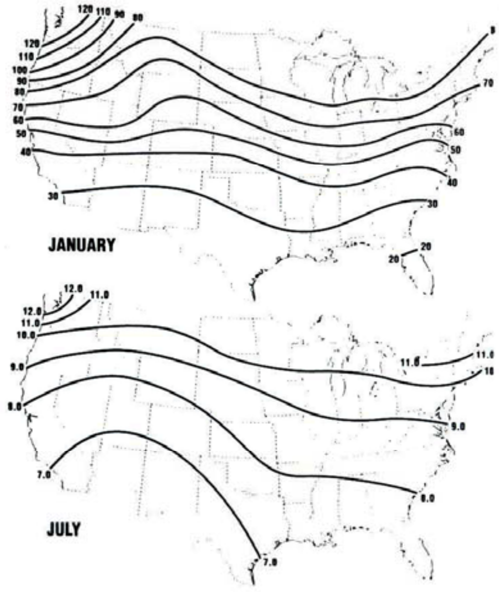

Figure 8. Mean noon-hour minute-to-burn time in January and July, 1995-1997.

Summary

The spatial pattern of the UVI 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 northeast regions, where cloud cover and precipitation are greatest, are characterized by the minimum UVI throughout the year. In midsummer, maximum UVI occurs in the southwest United States. Except for the summer months, Florida is characterized as having the highest UVI values in the contiguous United States. Mean daily noon-hour UVI values vary from near 0 in the northwest in winter to about 12 in the southwest in summer.

The forecast UVI values are verified by observed UVI values in Los Angeles. It is found that the forecast UVI values are within one index unit of the observed values for 87% of the days tested. The accuracy of the UVI forecast in Los Angeles is much higher than that of the overall UVI forecast for other cities in the nation. In Los Angeles, the forecast UVI values are consistently lower than the observed ones during winter months. The discrepancy between the forecast and observed values may be attributed to the difference between the locations where forecast and observed UVI values are taken. Observed values are measured at Northridge, located in an inland valley northwest of LAX, from which the forecast values are derived. The UVI values are expected to be lower at LAX than at Northridge because of its lower elevation and more cloudy days. However, a few cloudy days associated with extreme low UVI values at Northridge resulted in lower observed mean daily noon-hour UVI values than forecast ones in the summer of 1996–1997. The 1996 and 1997 summers should be viewed as abnormal summers. This result can be verified further as more summer UVI data become available.

In summer, 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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