Journal of Photoscience (2002), Vol. 9(2), pp. 154–157

Characteristics of Environmental Solar Ultraviolet Irradiance

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Direct, continuous, and accurate measurements of solar ultraviolet irradiance (290-400 nm: UVR) have been carried out since 1990, by using both band-spectral ultraviolet-B (290-320 nm: UV-B) and ultraviolet-A (320-400 nm: UV-A) radiometers at Tokai University in Hiratsuka, Japan (35°N, 139°E). From our observations, the following findings are provided: 1) an increasing trend in solar UV-B from Oct. 1990 to Sept. 2000; 2) a regional comparison of solar UVR in Japan; 3) the distinct characteristics of UV-B and UV-A irradiance, such as diffuse property, daily and seasonal variation; and 4) human body protection against solar UVR. An increasing 10-year trend in global solar UV-B in Hiratsuka corresponded to a decrease in the total ozone amount measured at Tsukuba (36°N, 140°E), giving supportive evidence for a direct link between these two parameters. Furthermore, a strong correlation was found between solar UV-B and total ozone amount from results of UVR measurements at four Tokai University monitoring stations dispersed throughout Japan. Additional results revealed different diffuse properties in global solar UV and in global solar total (300-3000 nm: Total) irradiances. For example, in the global UVR, the diffuse component was dominant: about 80 % independent of weather, with more than 60 % of global UV-B, and more than 50 % of global UV-A with even a cloudless clear sky. On the other hand, the portion of the diffuse in the global total irradiance was very low, less than 10 % on a cloudless clear day. Daily and seasonal variations of UV-B and UV-A irradiances were found to be quite different, because of the marked dependence of UV-B irradiance on the atmospheric ozone amount. Moreover, UV-B irradiance showed large daily and seasonal variations: the ratio between maximum and minimum irradiances was more than 5. In contrast, the variation in UV-A was small: the ratio between maximum and minimum was less than 2. Three important facts are proposed concerning solar UVR protection of the human body: 1) the personal minimal erythema dose (MED); 2) gender based difference in MED values; and 3) proper colors for UVR protective clothing.

Key words: diffuse irradiance, global irradiance, increasing trend, minimal erythema dose, MED, total ozone amount, protection of solar UVR, solar ultraviolet irradiance, UVR, ultraviolet-B, UV-B, ultraviolet-A, UV-A

INTRODUCTION

Solar ultraviolet irradiance (290-400 nm: UVR) is a small portion of the total solar irradiance, especially biologically active solar ultraviolet-B (290-320 nm: UV-B) irradiance which is less than 0. 2 %. Solar ultraviolet-C (< 290 nm: UV-C) and a portion of UV-B irradiances have been absorbed by the stratospheric ozone layer for billions of years. Recently, however, a decreasing trend in stratospheric ozone amount has been found over Antarctica [1-3], during the past decade, and a similar decrease has been found in the both hemispheres. As a consequence of the ozone depletion, an increase in biologically active solar UV-B irradiance is expected at the earth's surface. Scientists have suggested that a 1 % decrease in the ozone layer will lead to an increase of 2 % in solar UV-B radiation at the earth's surface, and an increase of 3 to 6 % in the incidence of human skin cancer and immune system suppression [4].

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A narrow band-spectral solar UV-B radiometer was developed [5, 6] and the preliminary results were reported previously [5, 7-9]. Global solar UV-B irradiance by this radiometer, global solar ultraviolet-A (UV-A: 320-400 nm) and global solar total (300 – 3000 nm: Total) irradiances by conventional radiometers have been measured and analyzed at Tokai University in Hiratsuka, Japan (35° 21' N, 139° 16' E) since 1990.

In the present paper, the topics based on our observations are covered, including: 1) an increasing trend of solar UV-B irradiance in Hiratsuka for the 10-year period from October 1990 to September 2000 (120 months); 2) the regional comparison of solar UV-B irradiance at four monitoring stations at Tokai University in Japan including Wakkanai: 45°N, Hiratsuka: 35°N, Kumamoto: 32°N, and Iriomote 24°N; 3) the distinct characteristics of solar UV-B and UV-A irradiances such as diffuse property, and daily and seasonal variation; and 4) human body protection against solar UVR.

EXPERIMENTAL

Data sampling at the primary station in Hiratsuka, Japan (35° 21' N, 139° 16' E): Global and diffuse solar irradiances have been measured using UV-B radiometers [5, 6], UV-A radiometers, and pyranometers since 1990. All the instruments are placed horizontally. The UV-B, UV-A and total solar irradiances are measured every 20 seconds, 24 hours a day. The recording system is designed to give instantaneous readings and average values every 5 minutes, including instantaneous temperature and humidity. To obtain a reliable long-term trend in the solar UV-B irradiance, the radiometer response was periodically calibrated by measuring spectral and angular responses, and sensitivity. The UV-B irradiance obtained was then corrected using the expected sensitivity change of the UV-B radiometer as described by Sasaki et al. [10]. From these calibrated data the trends were estimated.

Data sampling of four stations of the Tokai Solar Radiation Monitoring Network: Monitoring stations are located in Wakkanai in Hokkaido (45° 21'N : 141 °48'E), Hiratsuka in the central Japan, Kumamoto in Kyusyu (32° 50'N : 130°52'E), and Iriomote in Okinawa (24°19'N: 123° 41'E). In all stations except Hiratsuka, global solar UV-B, UV-A and total irradiances have been measured.

Total ozone amount data: *To* compare UV-B data with the total ozone amount, we used ozone data observed by the closest stations to the Tokai University monitoring stations mentioned above. The four closest Japan Meteorological Agency (JMA) stations are located at Sapporo (43° 03' N, 141° 20' E), Tsukuba (36° 03' N, 140° 08' E), Kagoshima (31° 38' N, 130° 36' E), and Naha (26° 12' N, 127° 41' E).

RESULTS AND DISCUSSION

Increasing trend in global solar UV-B irradiance: Seasonal variations of the daily accumulated monthly mean values of UV-B irradiance are shown in Fig. 1. The seasonal variation is marked, so a regression analysis was carried out. To remove the seasonal variation effect, the 12-month moving averages were calculated as shown in the Fig. 2. A linear increasing trend in the UV-B irradiance is evident for the 10-year monitoring period since 1990. The linear change was approximated by the following first order regression: $UV_B(t) = 0.0178\,t + 13.6$ (1)

where UV_B is the global solar UV-B irradiance [kJ/m^2] and t is time [month] from October 1990 to September 2000. This regression was statistically significant in F-estimation analysis and the correlation coefficient was 0.60. In the yearly base calculation, the initial irradiance can be estimated from the y-intercept of the regression line (13.6 kJ/m^2). Using the equation (1), the normalized increase rate was 1.57 %/year. The UV-B irradiance is influenced by weather conditions. To solely extract the ozone effect for the UV-B irradiance from other factors such as solar zenith angle, cloud effects, and aerosols, we took the ratios of the

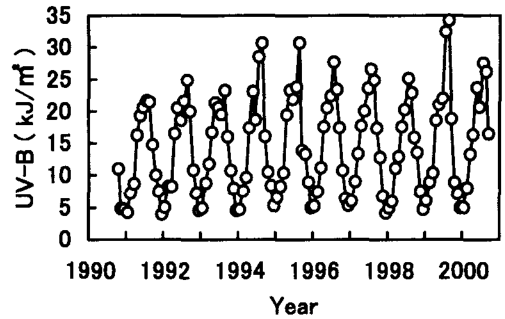

Fig. 1 Seasonal variation of the monthly mean values of global solar UV-B irradiance daily accumulated from October 1990 to September 2000 (at Hiratsuka).

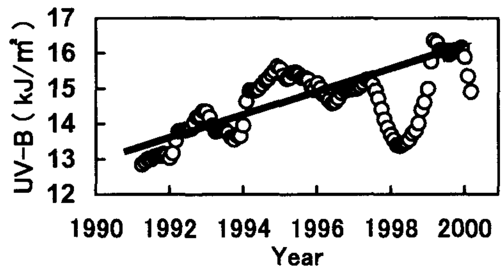

Fig. 2 Trend of 12-month moving averages of monthly mean values of global solar UV-B irradiance daily accumulated from October 1990 to September 2000 (at Hiratsuka).

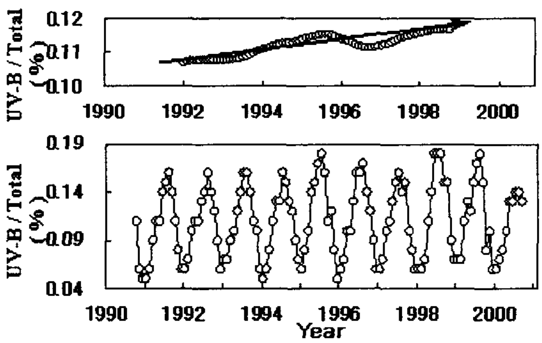

Fig. 3 The ratios of global solar UV-B irradiance to global total solar irradiance from October 1990 to September 2000 (lower chart) and the 12-month and 26-month moving averages of the same data showed an increasing trend (upper chart).

global solar UV-B irradiance to the global solar Total irradiance. The ratios are plotted in the Fig. 3. The change can be expressed as a linear function as follows: $R(t) = 1.09 \times 10^{-4} t + 0.108$ (2)
where R is in units of % and t is the month number. The first order regression was statistically significant and the correlation was fairly high (r = 0.86). In the yearly base calculation, the initial R is calculated from the y-intercept of the regression line (0.108 %). Using the equation (2), the normalized increasing average rate was 1.22 %/year. The analysis clearly demonstrated an increase in solar UV-B in mid-latitude Japan since 1990.

Regional comparison of global solar UV-B irradiance: The result clearly indicates that the UV-B irradiance occurred at higher intensity in a lower latitude and at lower intensity in a higher latitude depending on the ozone amount (Figure 4). The distance between Wakkanai and Iriomote is about 3,000 km, and difference in latitude between the two locations is about 20 degrees. It is suggested that Japan is one of the suitable monitoring places to detect solar UV-B trends in the northern populated zone.

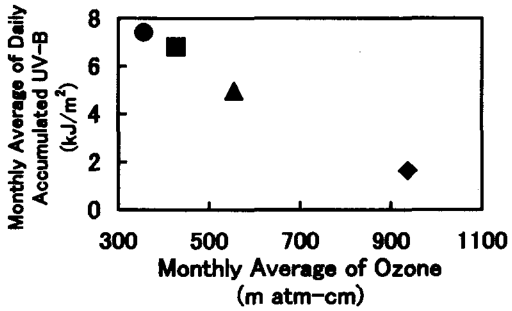

Fig. 4 Inverse correlation between UV-B irradiance (Wakkanai ●, Hiratsuka ■, Kumamoto ▲, Iriomote ◆) and total ozone amount (Sapporo, Tateno, Kagoshima, Naha).

Characteristics of solar UV-B and UV-A irradiances:

Diffuse property: The UV irradiance is easily scattered by air molecules, aerosols and especially clouds. This scattered irradiance is called "diffuse irradiance". Diffuse properties of UV and that of Total irradiances on a cloudless clear day were compared as shown in Fig. 5. The result demonstrates that, even on a cloudless clear day, more than 60 % of global UV-B and more than 50 % of global UV-A were diffused irradiance. As annually averaged global UV-B and UV-A, about 80 % of global solar UV-B and UV-A was diffused irradiance. In contrast, for Total irradiance, the portion of the diffuse to the global was found to be less than 20 %.

Daily variation of UV-B and UV-A irradiances: The daily profile of global (direct + diffuse) solar UV-B and UV-A irradiances shows a maximum intensity at around noon every month though affected by clouds and pollutants [5]. The UV irradiance between 10:00 am and 2:00 pm accounts for about 50 % of total irradiance in a day. These findings indicate that

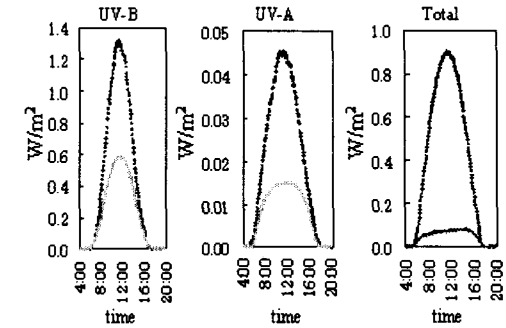

Fig. 5 Comparison between global (●) and diffuse (●) in UV-B, UV-A, and total solar irradiances.

solar irradiance at the earth's surface depends mainly on the solar zenith angle. The daily variation of UV-B irradiance is quite different from UV-A irradiance. UV-B increased one hour after sunrise and decreased one hour before sunset with a large change in amplitude during the day affected by ozone absorption. On the other hand, UV-A increased at the same time at sunrise and decreased at the same time at sunset with a moderate change in amplitude during the day without ozone effect.

Seasonal variation of UV-B and UV-A irradiances: Seasonal variations of the monthly mean value of the UV-B and UV-A irradiances accumulated daily are shown in Fig. 6. As shown in the figure, we divided the twelve months of the year into four seasonal groups: the *spring equinoctial group* (March, April); *fall equinoctial group* (September, October); *summer solstitial group* (May, Jun, July, August); and *winter solstitial*

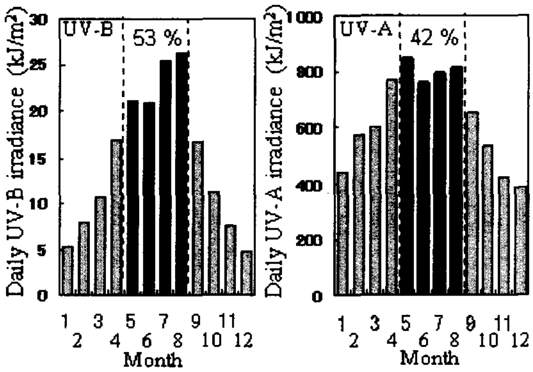

Fig. 6 Seasonal variation between UV-B and UV-A

group (November, December, January, February). Note the seasonal variation of UV-B and UV-A irradiances were distinct. The UV-B occurred at maximum intensity in August with a large seasonal variation. Also, the irradiance level in summer is about 5 times greater than that in winter. On the other hand, UV-A irradiance occurred at maximum intensity in May with moderate seasonal variation. Overall, the UV-A levels in summer were found to be about 2 times that in winter.

Protection of the human body against solar UV irradiance: Three important facts concerning UV protection: 1) required time for minimal erythema dose (MED), 2) gender based difference in MED values, and 3) proper color for UV protective clothing material were discussed.

1) MED is defined as the minimum UV exposure resulting in sunburn. MED varies according to an individual's age and skin type [11]. An example is presented here. It is well known that most Japanese could get a sunburn in 20 min at noontime in midsummer. It follows using our measured UV irradiance data, an average MED value for Japanese adults was estimated to be 1800 J/m^2. 2) the difference in MED according to gender is clearly reported in two papers [11, 12], though the quantitative values measured showed a big difference. The researchers found that the MED value for males was smaller than that for females. The reason was not discussed for these papers. However, gender differences in MED are valuable for UVR protection in an advanced age society like Japan and Western countries. 3) It was widely reported last summer in Japan that black clothing materials were more effective than white clothing materials in prevention of UVR exposure. We evaluated the claim and determined that it was overstated as shown in Fig. 7. The difference in protection effect between black and white clothing materials is, in fact, quite small. Moreover, black clothing absorbs more heat than white clothing and could be less comfortable in hot weather. The main point in protecting the body from UV is to wear proper clothing. An evaluation method of UVR protective clothing is under future study.

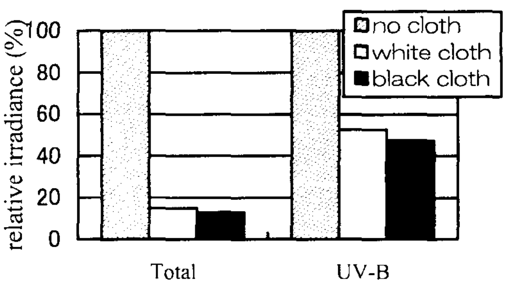

Fig. 7 UV protective ability between black and white clothing materials.

Conclusion: Stratospheric ozone depletion is predicted to continue at least until the year 2030. Moreover, we need to improve our awareness of rising solar UV-B levels and their effects on the human race and the earth's ecosystems.

ACKNOWLEDGMENTS

We sincerely thank the Japan Meteorological Agency for providing the ozone data used in the present analysis. We also gratefully acknowledge the Communications of Research Laboratory, Japan for their great help in recording the data at Wakkanai station.

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