An Increase in the Global Solar Ultraviolet-B Irradiance at 35°N in Japan since 1990

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The global solar ultraviolet-B (UV-B: 290–320 nm) irradiance has been measured by a newly designed band-spectral solar UV-B radiometer at Tokai University, Hiratsuka (35°N, 139°E), Japan from October 1990 to April 1994. The global solar total (Total: 300–3300 nm) irradiance has also been measured by a pyranometer. When the seasonal variation is removed by taking 12-month moving averages, an increase at an average rate of 3.4% per year is found in the monthly averages of daily integrated global solar UV-B irradiance. In contrast, the monthly averages of daily integrated global solar Total irradiance remained nearly constant throughout the same period. The existence of a linear trend over the above time period is confirmed by a statistical method different from the analysis of the moving averages, using the global solar UV-B irradiance normalized by dividing it by the global solar Total irradiance. Corresponding to the increase in the global solar UV-B irradiance, a decrease is found in the total ozone amount measured at Tateno (35°N, 140°E), offering supportive evidence for a direct link between these two parameters.

1. Introduction

The depletion of stratospheric ozone has been discussed extensively in the literature (e.g., Chubachi, 1984; Farman *et al.*, 1985; Solomon *et al.*, 1986; Schoeberl *et al.*, 1989; Stolarski *et al.*, 1991; Herman *et al.*, 1991). As a consequence of the ozone depletion an increase is expected in the biologically active solar UV-B radiation at the earth's surface. Madronich (1992) has recently assessed by calculation the biological dose rate in the wavelength range 280–400 nm, using the ozone column amount data from the Total Ozone Mapping Spectrometer of the Nimbus 7 satellite for the period January 1979 through December 1989 and the spectral response functions for the biological process of interest. The results showed that the calculated increase in biologically active solar UV radiation reaching the earth's surface in this time period was on the average substantially larger than earlier estimates, particularly at mid and high latitudes of both hemispheres. However, direct measurements of the trend in solar UV-B radiation are scarce (Scotto *et al.*, 1988; Bittar and McKenzie, 1990; Blumthaler and Ambach, 1990). An example of measurement showing an increasing trend has recently been provided by Kerr and McElroy (1993) using a Brewer ozone spectrometer.

A band-spectral solar UV-B radiometer has been developed by us and preliminary results of observations by this instrument have been reported by Sasaki *et al.* (1993). Measurements of global solar UV-B (290–320 nm) irradiance by this radiometer and of global solar Total (300–3300 nm) irradiance by a conventional pyranometer (EKO MS-801) have been conducted at Tokai University at Hiratsuka (35°2' N, 139°2' E) for a 43-month period, October 1990 to April 1994. From these observations, trends in the global solar UV-B irradiance and in the global solar Total irradiance are determined and are compared with the trend in the total ozone amount observed at Tateno (also referred to as Tsukuba), Ibaraki (35°3' N, 140°8' E) by the Japan Meteorological Agency (JMA).

2. Data Sampling and Analysis

The global solar UV-B irradiance is being measured continuously with high time-resolution by the newly developed band-spectral solar UV-B radiometer at Tokai University in Hiratsuka, Japan, as has been described previously by Sasaki *et al.* (1993). Monthly averages of daily integrated global solar UV-B irradiances were analyzed for the 43-month (3 years and 7 months) period from October 1990 to April 1994. The data collection is interrupted for two weeks in the middle of November in each year for recalibrations of the instrumental constant and the spectral and angular responses of the radiometer in the manner described by Sasaki *et al.* (1993). Within the accuracies of the measurements no changes have been found in the instrumental constant and in the spectral and angular responses of the radiometer during the period of observation.

The purpose of the present analysis is to examine if there is any linear trend in the observed quantity. However, the global solar UV-B irradiance undergoes a large seasonal variation (see, for instance, Figs. 4 and 5 in Sasaki *et al.* (1993); also, Table 1 of this paper), which tends to mask a relatively small trend. To reduce the seasonal variation we take 12-month moving averages of any quantity x :

$$\bar{x}_n = \left(\sum_{i=-6}^6 w_i x_{n+i} \right) / 12$$

where the weights w_i are defined by

$$w_{-6} = w_6 = 1/2,$$

$$w_j = 1, \quad j = -5, -4, \dots, 0, \dots, 5.$$

This procedure is equivalent to applying a numerical low-pass filter; its transfer function is shown in Appendix. The moving averages are taken for the global solar UV-B irradiance, the global solar Total irradiance, the ratio of these quantities, and the total ozone amount.

The total ozone amount provided by the nearest JMA station at Tateno, Ibaraki (35°3' N, 140°8' E), is taken to be the daily representative value of the vertical total columnar ozone to be used in the present analysis.

3. Results and Discussion

3.1 Increase in the monthly averages of daily integrated global solar UV-B irradiance

In the lower panel of Fig. 1, the monthly averages of the daily integrated global solar UV-B irradiance are shown. The standard deviation is given by a vertical bar for each monthly data point. From inspection of this plot a trend over the 43-month period is not obvious. In the upper panel of Fig. 1 we show the 12-month moving averages, as defined in the preceding section, of the data plotted in the lower panel and the linear trend as determined by the least squares method. A linear trend is evident in the moving averages. The linear change is represented by

$$f_1(t) = 0.0488t + 16.9$$

where f_1 is the global solar UV-B irradiance in units of kJ/m² and where t is time in months measured from October 1990. The average rate of increase in the global solar UV-B irradiance is 3.4% per year over the period of observation. This average rate of increase is larger than those given in the literature (e.g., Madronich, 1992).

Fig. 1. Monthly averages of daily integrated global solar UV-B irradiance during October 1990 to April 1994 at Hiratsuka (lower panel) and 12-month moving averages of the same data showing an increasing trend (upper panel).

For comparison, the monthly averages of daily integrated global solar Total irradiance and their 12-month moving averages are shown in Fig. 2 in the same format as in Fig. 1. For the moving averages of the monthly average daily integrated global solar Total irradiance the linear change can be expressed as

$$f_2(t) = -3.35 \times 10^{-4}t + 12.2$$

where f_2 is the global Total irradiance in units of MJ/m² and where t is measured in months from October 1990. Thus the trend is virtually zero (of the order of $-3 \times 10^{-2}\%$ per year) for the global Total irradiance.

The solar UV-B irradiance is influenced by effects from weather conditions, for instance, through scattering and reflection by clouds. In an attempt to normalize the solar UV-B irradiance with regard to cloud effects, we take the ratio of the monthly average daily integrated global solar UV-B irradiance to the monthly average daily integrated global Total irradiance. The ratios and their 12-month moving averages are plotted in the lower and upper panels of Fig. 3, respectively. An increasing trend in the ratio is apparent in the moving averages over the period of observation.

3.2 Decrease in the monthly averages of daily representative value of total ozone amount

We now attempt to compare the increasing trend in the global solar UV-B irradiance with the ozone trend. However, the total ozone amount is not being measured at Hiratsuka. Therefore we use observations of the total ozone amounts made by JMA at their station at Tateno, which is nearly at the same latitude as Hiratsuka.

Monthly averages of the daily representative total ozone amount for the 43-month interval at Tateno are shown in the lower panel of Fig. 4, and the 12-month moving averages of these data are plotted in the upper panel of the same figure. The decreasing trend in this parameter is evident. The linear change can be expressed as

Fig. 2. Monthly averages of daily integrated global solar Total irradiance during October 1990 to April 1994 at Hiratsuka (lower panel) and 12-month moving averages of the same data (upper panel).

Fig. 3. Ratios of the global UV-B irradiance to the global solar Total irradiance during October 1990 to April 1994 at Hiratsuka (lower panel) and 12-month moving averages of the same data showing an increasing trend (upper panel).

Fig. 4. Monthly averages of total ozone amount during October 1990 to April 1994 at Tateno (lower panel) and 12-month moving averages of the same data showing a decreasing trend (upper panel).

$$f_3(t) = -0.332t + 315$$

where f_3 is the total ozone amount in Dobson units (DU) and where t is time in months measured from October 1990. The average rate of decrease in the total ozone amount over the period of observation is 1.3% per year at Tateno.

The latitudes of Tateno and Hiratsuka are almost the same, that is, 35°N, and their longitudes differ only by 1.1°. Therefore we consider the total ozone amounts at Tateno to be representative of those at Hiratsuka, and compare the UV-B data taken at Hiratsuka with the ozone data obtained at Tateno.

We see that corresponding to the increase in the global solar UV-B irradiance at an average rate of 3.4% per year at Hiratsuka (in the upper panel in Fig. 1), there is a decrease in the total ozone amount at an average rate of 1.3% per year (in the upper panel in Fig. 4) during the 43-month period of October 1990 to April 1994.

The stratospheric ozone amounts are known to undergo natural oscillations such as the eleven-year solar cycle and quasi-biennial oscillation (Stolarski *et al.*, 1991). However, these effects are relatively small according to the results of analysis by these authors. Madronich (1992) states that the ozone trend derived by Stolarski *et al.* after subtraction of these oscillations is not significantly different from the trend derived from the original data used. Therefore, in the present analysis the effects of these oscillations are assumed to be small and are not taken into account.

3.3 Linear change derived by a different method

The seasonal variation in the global solar UV-B irradiance is quite large as evidenced in the plot in Fig. 1. Although the 12-month moving average procedure we adopted removes most of the seasonal variation, we use in this section a different method to confirm the existence of an increasing trend in the global solar UV-B irradiance.

We perform the same analysis with the monthly average daily integrated solar Total irradiance. The results are plotted in Fig. 5(b). The linear trend determined by the least squares method and the standard deviation are also shown. The standard deviation is 0.983 MJ/m^2 , which is substantially larger than the magnitude of the total linear change of 0.268 MJ/m^2 . Thus there is no statistically significant linear trend in the Total irradiance; that is, the global Total irradiance remained nearly constant.

Next, we normalize the observed monthly average daily integrated global solar UV-B irradiance by dividing it by the monthly average daily integrated solar Total irradiance. Taking the time series of these ratios to be Δx_i , we perform the same analysis as above. The deviations Δx_i for the ratios are plotted in Fig. 5(c). The standard deviation and the total linear change are 0.963×10^{-2} and 1.487×10^{-2} , respectively. Thus the linear trend in the normalized monthly average daily integrated global solar UV-B irradiance is considered to be statistically significant. From inspection of the solar UV-B irradiance data it is evident to us that cloud cover has an appreciable influence on the daily integrated UV-B irradiance. However, in the absence of any established technique to allow for the cloud cover effects we have attempted to normalize the observed daily integrated global UV-B irradiance by dividing it by the global Total irradiance. The above results may be construed as an indication that this normalization is to some extent effective. This point is now being studied in more detail, but further investigation into this question is outside the scope of the present paper.

4. Conclusions

The global solar UV-B (290–320 nm) irradiance has been measured by a newly designed band-spectral solar UV-B radiometer at Hiratsuka (35°N, 139°E), Japan from October 1990 to April 1994. The global solar Total (300–3300 nm) irradiance has also been measured by a pyranometer. An estimated increase at an average rate of 3.4% per year is found in the global solar UV-B irradiance for the 43-month period, using 12-month moving averages of the quantity. The existence of an increasing trend is further confirmed by a different statistical method, using values of the monthly average daily integrated global solar UV-B irradiance normalized by dividing it by the monthly average daily integrated solar Total irradiance. However, the above value of the estimated rate of increase should be regarded as being preliminary. The reason for the relatively large rate of increase is now being investigated. Corresponding to the increasing trend in the global solar UV-B irradiance, there is a decrease in the total ozone amount at Tateno (35°N, 140°E) at an average rate of 1.3% per year. These results provide supportive evidence that the linear decrease in the monthly average daily integrated global solar UV-B irradiance over the 43-month period is related to the observed decrease in the total ozone amount over the same period.

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APPENDIX

The response function, $Y(r)$ for the 12-month moving average procedure adopted is shown in Fig. A1 as a function of r , which is the frequency normalized by the sampling frequency; thus $r = 0.5$ corresponds to the Nyquist frequency.

The time series obtained from the 12-month moving averages still contains quasi-periodic variations as is seen in the upper panels of Figs. 1–4, which are only partially filtered. Because of the limited length of the observations available it is not possible to design a numerical filter to eliminate all these low frequency variations. These variations can have a significant effect on the determination of the linear trend. It is for this reason that the statistical method described in Subsection 3.3 was additionally used.

Fig. A1. Response function for the 12-month moving averages as a function of frequency normalized by the sampling frequency.

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