Erythemal dose computations from UV-B irradiance model

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Modelling of the ground-reaching UV-B flux (280-320 nm) in the experimental studies of this biologically harmful radiation is important from the point of validating the experimental measurements and also to predict the temporal and geographic variations of the UV-B erythema due to stratospheric ozone depletion brought by anthropogenic causes. The erythemal dose is computed as the convolution of the global UV-B flux with a suitable action spectrum for human skin. More than one definition of erythemal dose unit (in terms of the absolute energy content) is currently used in UV-B studies and thus there is a need to standardize the erythemal dose unit. The global UV-B flux data from the UV-B photometer radiometer studies at Mysore (12.6° N, 76.6° E) and also computed from a UV-B irradiance model are used to estimate the seasonal variation of erythemal dose.

1 Introduction

Erythemally effective and biologically damaging middle ultraviolet solar radiation (UV-B) in the wavelength range 280-320 nm is strongly absorbed by the stratospheric ozone. The erythemal response of the human skin being maximum at 297 nm, the UV-B radiation affects DNA, RNA and protein synthesis and thus is the prime cause of sunburn of human skin and skin cancer. Considerable attention has been given in recent years to the measurements and model simulations of the ground-reaching ultraviolet radiation flux under various atmospheric conditions and to assess the biological impacts thereof. Several techniques and instrumentation have been employed for the measurement of direct, diffuse and global (sum of direct and diffuse) radiation starting from the pioneering work of Bener7. Robertson-Berger (R-B) meters have been deployed in a network of stations in USA, Europe and Australia8. These R-B meters are designed to measure the sunburn units directly.

A calibrated Eppley pyranometer carried on deck of a cruising ship3 has been used for measuring the UV-B flux reaching the sea surface at equatorial latitudes. Double monochromators are used specially by the research groups in Antarctica for studying the well-known ozone hole phenomenon4-6. A distinct and new type of instrument, UV-B photometer radiometer, based on filter photometry (designed and fabricated at the National Physical Laboratory, New Delhi) is deployed at several locations in India for the measurement of global UV-B flux at four wavelengths 280, 290, 300 and 310 nm as part of the Indian Middle Atmosphere Programme (IMAP)7. One of the radiometers is deployed at Mysore (12.6° N, 76.6° E) which is a continental station free from industrial pollution and large scale biomass burning. The global UV-B irradiance data (at four wavelengths), however, are inadequate to compute the erythemal dose which is the convolution of the human action spectrum with the UV-B irradiance spectrum (280-320 nm). Also regular UV-B flux data cannot be obtained at Mysore during the monsoon period lasting from May/June to September/October. The experimental data at Mysore are validated from the results of an UV-B irradiance model8. The model is then used to obtain the seasonally varying UV-B flux and hence the erythemal dose by using the known seasonal variation of atmospheric ozone and aerosol optical depth as inputs to the model. The results of our analysis and computations are presented in this paper.

2 UV-B erythemal dose and energy equivalence

A network of stations to measure the effectiveness of sunburning ultraviolet radiation and correlating the same with the incidence of skin cancer was initiated by Robertson9 in Australia. The instrument designed for this purpose was later adopted and suitably modified by Berger10 for measuring the sunburn effectiveness of UV-B radiation under the Climatic Impact Assessment Program (CIAP). The data from R-B
meter however are limited to a single broad-band (280-375 nm, with a peak at 300 nm) obtained by weighing the spectrum by a response function designed to approximate the erythemal response of the Caucasian skin.

The sunburn unit (SBU) has somewhat subjectively been defined by Robertson\(^8\) as the amount of radiation causing minimum perceptible reddening of normal fair skin. It is approximately equal to 12 min exposure on a cloudless day with the sun overhead and fairly normal ozone column of 3 mm at STP. The energy equivalent of this SBU can be computed from a UV-B irradiance model (see Sec. 4) and is found to be 115 \(\text{J/m}^2\). The UV-B erythemal effectiveness from the Australian network of R-B meters is expressed in erythemal dose (ED) units such that 180 of the ED units is equivalent to 1 SBU defined as above. The contour map of erythemal dose for the Australian continent is available in terms of ED units\(^11\).

In contrast to this, the R-B meter indication of the USA network is less ambiguous and straightforward. Here also one SBU or the minimum erythemal dose (MED) as given by Berger\(^10\) is equivalent to the UV-B energy received in 12 min by untanned average Caucasian skin at sea level for overhead sun in clear sky and stratospheric ozone of 2.6 mm thickness. This energy when computed from the model is found to be 145 \(\text{J/m}^2\). The difference in the energy equivalence of 1 SBU defined by Robertson (115 \(\text{J/m}^2\)) and Berger (145 \(\text{J/m}^2\)) arises due to difference in ozone amount used in the model calculations. Also, a few minor variations are seen in the energy equivalence of SBU (Refs 12 and 13).

Apart from the SBU/MED energy units (for the erythemal effectiveness) used by the R-B meter network of stations, another energy unit, minimum perceptible erythema (MPE), has been employed by Sharma et al.\(^14\) in calculating the erythemal dose for locations in the Indian subcontinent. One MPE is taken to be 2.5 \(\times 10^4\) ergs/cm\(^2\) (or 250 \(\text{J/m}^2\)) and this is larger than the energy equivalent of SBU/MED (115 \(\text{J/m}^2\) and 145 \(\text{J/m}^2\)) mentioned above. Since the SBU (or MED) unit is defined keeping in view the fair Caucasian skin, the larger energy for MPE in the context of the population in Indian subcontinent (non-Caucasian and less-fair coloured skin) could be in order.

3 Experimental results

The details of the UV-B photometer radiometer system used in Mysore, the calibration requirements, etc. have been discussed in earlier publications\(^7\)-\(^{15}\). The system has been designed to measure the global UV-B flux at the four wavelengths 280, 290, 300 and 310 nm. On calibration the central wavelengths of these interference filters were found to be at 283, 295, 303, and 311 nm. Global UV-B irradiance computations from the model (see Sec. 4) indicated that the filters deteriorated over a period of time and hence the UV-B data are not reliable after May 1989.

The UV-B irradiance data are recorded throughout the day for clear sky conditions and in the absence of any visible clouds. A good quality record (free from cloud effects) for the day shows a bell-shaped curve with the maximum at local noon and smooth increase and decrease for the morning (AM) and afternoon (PM) periods\(^7\). Cloud effects, if any, can thus be detected from an examination of the daily data and only good quality data are selected for the analysis. Although the UV-B radiometer observations at Mysore were started in April 1987, continuous data could not be obtained for the period October 1987 to December 1987 due to adverse weather conditions. Also, the monsoon period prevailing from May/June to September/October in any year is not conducive for the collection of UV-B data. Continuous and fairly good quality data are available for the period January to May 1988 and October 1988 to May 1989. The data for October 1988 to May 1989 covering one continuous period of observation are selected for modelling the global UV-B irradiance. This observation period includes post-monsoon, winter and summer (pre-monsoon) seasons.

Figure 1 shows the daily values of global UV-B irradiance at \(\lambda = 303\) nm for the AM and PM periods and at the solar zenith angle \(\theta = 40^\circ\). The broken lines represent the best fitting (polynomial) lines for the AM and PM data points. Day-to-day fluctuations in the recorded irradiance are seen, although the measurements refer to clear sky conditions. Such fluctuations could be due to changes in the vertical distribution of ozone as well as total ozone and aerosols. Similar fluctuations in the experimental data of Lubin et al.\(^6\) are attributed to changes in cloudiness and ozone abundance. In Fig. 1, a marked asymmetry between the AM and PM data can be seen and this asymmetry changes sign in February. These trends in the seasonal variation and the asymmetry in AM/PM irradiance are also seen in the data for other years and at other wavelengths. Thus the experimental data indicate a likely daytime variation in the atmospheric parameters (like ozone and/or aerosol extinction) which control the ground-reaching UV-B irradiance. This point is further examined in relation to the results of model computations discussed below.

4 UV-B irradiance model for global flux

The two components of solar UV-radiation incident on the surface of the earth are (i) direct solar radi-
The calculation of direct solar radiation is a relatively straightforward problem, but the calculation of the scattered radiation fluxes, i.e., the radiative transfer problem, is more complicated. Because of the complex and lengthy computer procedures necessary for the numerical solution of the radiative transfer equations, semi-empirical and analytic models have been developed for calculating the UV-B irradiance reaching the earth's surface. These models accommodate variations in wavelength, solar zenith angle, ozone thickness, aerosol thickness, and surface albedo.

Green and Schippnick have refined the ratio method model of Green et al. for computing the ground-reaching solar UV-B irradiance. We have used the model of Green and Schippnick (GS model) in our present study for computing the ground-reaching direct radiation (I), diffuse radiation (D), and global irradiance \( G = I \cos \theta + D \).

In computing the diffuse radiation the expression for ground albedo is taken from Paltridge and Barton. This value is 0.1 at \( \theta = 0^\circ \) and increases to 1.0 at \( \theta = 90^\circ \). The ground albedo is likely to vary with season since factors like moisture in the soil, vegetation cover, type of vegetation, etc., affect the ground albedo. However, we have not included any seasonal variation for the ground albedo in our model computation of seasonally varying global UV-B irradiance.

Ozone and aerosol optical depths \( \tau_O \) and \( \tau_a \) are required as inputs to the UV-B model. Ozone measurements are not available for Mysore. We have used the atmospheric ozone data (DU) from the Dobson spectrophotometer operated at Kodaikanal (10.2°N, 77.5°E) by India Meteorological Department (IMD).

The latitudinal variation of ozone between Kodaikanal and Mysore (differing in latitude by 2°) is assumed to be negligible. Also the Kodaikanal meteorology station is located in a hilly region with negligible industrial pollution similar to the conditions at Mysore.

The daily mean ozone data at Kodaikanal are derived from the Dobson data recorded six times corresponding (approximately) to solar zenith positions 34°, 58.5°, and 68° for AM and PM. An examination of these ozone data for the year 1988 does not indicate any daytime asymmetry. For computing the UV-B irradiance from the GS model we have used the monthly mean ozone data from Kundu based on the statistical analysis of 25 years of ozone data.

In our present study, we have used the seasonally varying aerosol optical depth derived from the corresponding turbidity coefficient \( \beta \) obtained from radiation data. These \( \beta \) values are used to compute \( \tau_a (= \beta \tau) \). The value of the exponent \( \alpha \), indicative of particle size, also shows a seasonal variation for Indian stations. However, in the absence of specific data on \( \alpha \) for Mysore, we have used \( \alpha = 1.3 \) (Ref. 23) in our computations. The values of \( \beta \) and the monthly mean ozone (DU) used in our model computations are shown in Fig. 2.

We have taken the aerosol absorption term to be 15% of the scattering term \( \tau_a \) which is approximately the value used by Green et al. and Dave and Halpern for the wavelength range 297.5 nm to 375.0 nm. The transmission characteristics of the UV-B interference filters are taken into account in computing the model UV-B irradiance.
5 Results and discussion

The computed UV-B irradiance values at $\lambda = 303$ nm, $\theta = 40^\circ$ from the UV-B model are shown in Fig. 1 as a superposed line on the experimental data. The general feature of the seasonal variation of the measured UV-B irradiance is also seen in the computed irradiance. However, the computed and experimental AM winter data differ considerably. For a good agreement between the model and experimental irradiances, the inputs to the model on ozone and/or $\tau_a$ are to be varied. The required daytime variations (asymmetry) in either ozone or aerosol optical depth to match the experimentally observed AM/PM asymmetry in UV-B data are rather unrealistic. In particular, the model input on ozone would require a daytime variation (more in PM than in AM) of more than 10 DU from the mean in winter months but a smaller variation in summer months. As mentioned earlier, the ozone data at Kodaikanal do not show any AM/PM asymmetry and the turbidity measurements for several Indian stations do not indicate any large daytime variations. Hence the observed AM/PM asymmetry can arise due to causes other than the daytime variations of atmospheric parameters.

A likely cause for this AM/PM asymmetry was thought to be the stray reflections from nearby buildings or structures, particularly the control room situated some 6 ft from the radiometer platform. However, the data recorded with the radiometer located at different distances from the control room and other nearby structures, but with the same orientation with reference to the meridian, did not show any variations in the observed data. Hence our data are not contaminated with stray reflections from nearby structures, and therefore the other possible causes were looked for. The integrating sphere (IS) used in our radiometer together with the north-south (NS) orientation of the radiometer was found to be responsible for the observed enhanced irradiance in the winter AM data and thus for the AM/PM asymmetry. Figure 3(a) shows the schematic diagram of the IS in our present radiometer and Fig. 3(b) the IS used with the spectroradiometer (double monochromator) model OL 752 manufactured and marketed by M/s Optronics Lab., USA (Ref. 26). The earlier Optronics spectroradiometer model OL 742 used quartz/teflon diffusers instead of IS. The IS in our radiometer does not incorporate an internal baffle seen in Fig. 3(b). In the absence of baffle inside the IS, the photomultiplier tube (PMT) in our radiometer would view a spot on the rear wall of the internal surface of the IS for a particular zenith position of the sun with the NS orientation of the radiometer. This results in an enhanced input irradiance to the PMT at this solar zenith position. However this large irradiance in the recorded data is restricted to small zenith angles around noon. At large zenith angles $\theta \geq 40^\circ$, the PMT in our radiometer does not view the spot and hence the recorded irradiance will not be in error (see Fig. 4 and the discussion). This defect can be avoided by using an internal baffle [Fig. 3(b)] of a suitable size and location which ensures that all entering light rays will have at least two points of incidence (scatter) before exiting the sphere and entering the detector slit. It would appear that our radiometer can give enhanced irradiance twice a day, once in AM and again in PM if the radiometer is oriented such that the sun's rays fall on the rear wall of the IS facing the entrance slit of the PMT. This aspect has been verified experimentally by changing the orientation of the radiometer.

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Fig. 2—Monthly mean ozone and turbidity coefficient $\beta$. 

Fig. 3—Schematic diagrams of the integrating sphere (IS) used with (a) radiometer of this study and (b) commercial spectroradiometer model OL 752 of Optronics Lab., USA (Ref. 26).
Seasonal variation of UV-B erythemal dose

In view of the fairly good agreement between our model computations and measured UV-B data for PM and since the UV-B measurements are not possible for nearly four months during monsoon period, we have computed the seasonally varying UV-B erythemal dose from the model. The computed UV-B irradiance at 1 nm interval (280-320 nm) is convolved with the action spectra recommended by the International Electrotechnical Commission (IEC) and the erythemal dose is derived by integration over one-hour period around each hour. The contours of constant MPE/h from model computations (using monthly mean data on ozone and aerosols, Fig. 2) are shown in Fig. 5. Also shown are the erythemal dose from our experimental data computed from the global UV-B radiometer.

From the beginning of our UV-B project (since April 1987), we have deployed the radiometer at Mysore along north-south (NS) direction with the IS at the north end. With this arrangement the above-mentioned effect of the PMT viewing a spot on the rear wall of the IS occurs during winter months, the effect being maximum around winter solstice when the sun's declination is large. This effect diminishes gradually with the decrease of solar declination, i.e. from December onwards and the effect is negligible during the months February-May. This aspect has been experimentally verified during the recent observation period starting from January 1993 after incorporating a new set of imported UV-B filters. By trial and error we have found that by deploying the radiometer along the southeast-northwest direction with the IS towards the southeast end, the above mentioned extra irradiance effect (i.e. AM/PM asymmetry) is suppressed. We refer to this position as the zero-error (ZE) position in our work. It is to be noted that with the use of a properly designed IS having an internal baffle [Fig. 3(b)], the global UV-B radiometer can be deployed in any direction for UV-B measurements as is done with the commercial spectroradiometers.

The radiometer output with NS and ZE orientations are shown in Figs 4(a) and 4(b) for two days in January (winter) and April (summer) 1993. These data are obtained by altering the radiometer orientation between NS and ZE positions once in 5 min. Figure 4(a) shows the large erroneous UV-B irradiance for winter around noon ($\theta < 40^\circ$) for the NS orientation. For the summer data in Fig. 4(b), where the solar declination is minimal, the extra irradiance is absent even with the NS orientation. The vertical lines marked in Figs 4(a) and 4(b) correspond to $\theta = 40^\circ$ for AM and PM. A comparison of the data for NS and ZE positions indicates that (1) AM/PM asymmetry exists only with the winter data for $\theta \leq 40^\circ$ in the NS orientation, (2) there is negligible AM/PM asymmetry with the summer data, and (3) even with the NS orientation, the winter PM data are nearly the same as those of ZE orientation for $\theta \geq 40^\circ$.

Further, in Figs 4(a) and 4(b) the peak values of radiometer output at local noon on 24 Jan. 1993 ($\theta_{\text{min}} = 32^\circ$) and 17 Apr. 1993 ($\theta_{\text{min}} = 2^\circ$) show the correctness of the ZE orientation compared to the NS orientation since the noon solar irradiance should be large for smaller noon zenith positions.

The previously discussed AM/PM asymmetry in our data is thus due to the effect of the IS, and the data obtained with the zero-error (ZE) position are to be considered for model analysis in future. However all the summer data and the winter PM data for $\theta \geq 40^\circ$, obtained in previous years, can be used for model analysis and hence the PM data in Fig. 1 are considered in the present study.

6 Seasonal variation of UV-B erythemal dose

In view of the fairly good agreement between our model computations and measured UV-B data for PM and since the UV-B measurements are not possible for nearly four months during monsoon period, we have computed the seasonally varying UV-B erythemal dose from the model. The computed UV-B irradiance at 1 nm interval (280-320 nm) is convolved with the action spectra recommended by the International Electrotechnical Commission (IEC) and the erythemal dose is derived by integration over one-hour period around each hour. The contours of constant MPE/h from model computations (using monthly mean data on ozone and aerosols, Fig. 2) are shown in Fig. 5. Also shown are the erythemal dose from our experimental data computed from the global UV-B radiometer.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{fig4}
\caption{Diurnal variation of the UV-B raw data (mV) for (a) a winter day (24-01-1993, $\theta_{\text{min}} = 32^\circ$) and (b) a summer day (17-04-1993, $\theta_{\text{min}} = 2^\circ$) with the radiometer along the NS (• • •) and ZE (⋆ ⋆ ⋆) orientations.}
\end{figure}
irradiance at 283, 295, 303 and 311 nm. The experimental erythemal doses indicate the times at which 1 MPE/h are found. These are for Wednesdays (World days) from the experimental data for 1988 (Ref. 28). Our experimental UV-B data show larger (2-3) MPE/h for the winter months, that too for the AM period only, but these are not shown in Fig. 5 as these large MPE/h values are due to enhanced UV-B irradiance arising from the radiometer orientation discussed above. It is to be noted that the noon solar zenith position (θ_{min}) being small in summer than in winter, the total daily UV-B will be more in summer days than in winter days and hence more MPE in summer. In contrast to this, the UV-B irradiance at θ = 40° is more in winter than in summer (Fig. 1) since the ozone and aerosols are less in winter than in summer (Fig. 2).

We have also computed the total erythemal dose for each month and hence the erythemal dose for the year (MJ/m²/year) and these are shown in Table 1. Our results of erythemal dose in Fig. 5, for which the energy units are in terms of MPE, would be more if expressed in terms of SBU or MED by a factor of about 1.7 to 2.2. Thus there is a need to standardize the erythemal dose unit. The biological/medical consequences of our MPE computations and their significance on human health will be discussed in a separate communication.

7 Conclusions
The seasonal variation in the ground-reaching UV-B is controlled by the seasonal variation in atmospheric ozone and aerosols. The atmospheric ozone data from Dobson spectrophotometer at a nearby station and the seasonal variation of aerosol optical depth derived from total solar radiation data are used to model the global UV-B irradiance for validating the experimental UV-B data at a low latitude station Mysore. The biologically harmful ultraviolet erythemal dose for any location can be computed from an UV-B irradiance model if the model input parameters on atmospheric ozone and aerosol optical depth are known. The AM/PM asymmetry in our measured UV-B irradiance at low solar zenith angles (θ ≤ 40°) and at large solar declinations (winter) is attributed to the improper design of the integrating sphere in the radiometer. Thus a disproportionately large global UV-B irradiance can result from an improperly designed radiometer set up.

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