<Back to Index>

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Solar UV-B Irradiance at a Tropical Indian Station,Visakhapatnam (17.70°North, 83.30°East) - a Relation with TOMS Ozone

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ABSTRACT

Hourly mean values of incoming UV-B irradiance measured by UV-B Photometer at Visakhapatnam (17.70°N, 83.30°E) were analyzed and the variability of incoming UV-B irradiance with solar zenith angle and total column ozone is investigated in terms of RAF (Radiation Amplification Factor) for three wavelengths 310, 290 and 280 nm. A regression model for estimating UV-B irradiance from TOMS ozone, air-mass, sun-earth distance correction and solar zenith angle was developed for this station. With the developed model long-term variation of incoming UV-B irradiance for the period 1978 - 1993 was evaluated using TOMS ozone. A study was carried out on the possible effect of UV-B irradiance on human beings (erythema) in terms of RAF and solar zenith angle which indicated higher erythemal sensitivity at lower solar zenith angles.

(Key words : UV-B irradiance, TOMS Ozone, RAF, Regression Model, Solar Zenith Angle)

1. INTRODUCTION

Measurement of solar ultraviolet radiation and its analysis worldwide indicates a decrease in the total ozone content in the atmosphere (Bojkov et al. 1995; Chandra et al. 1996). Decrease in ozone causes an increase in incoming harmful UV-B radiation (280 - 315 nm) which emphasizes the need to quantify the relation between ground reaching UV-B irradiance and atmospheric ozone. The significant depletion of the stratospheric ozone layer, which shields the earth from much of the biologically effective solar ultra-violet radiation, is mainly due to anthropogenic activity on the earth. This has become a major scientific concern (Bener 1972;

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Dave and Halpern 1976; Halpern et al. 1974). Solar radiation is unevenly distributed throughout the world showing wide variability with latitude, altitude and season in addition to its dependence on ozone and other factors like solar zenith angle, air pollution, humidity, clouds etc. Since solar ultraviolet radiation is the prime energy source, its variability is expected to cause changes in the atmospheric temperature (Brasseur and Simon 1981). It is reported that a 1% decrease in stratospheric ozone could cause about 2% increase in UV-B radiation (Cutchis 1974). This increase may vary depending on specific wavelength, season and solar zenith angle (Bais et al. 1994). Studies on stratospheric ozone depletion at many locations on the globe are being made using instruments like the Dobson spectrophotometer, Brewer spectrophotometer etc. In addition to these ground based ozone measurements, which have limited spatial coverage, measurements done by Total Ozone Mapping Spectrometer (TOMS) aboard Nimbus-7 Satellite provide a good database for the long-term monitoring of column ozone with extensive spatial coverage. TOMS ozone data and UV-B radiation data at Athens (38°N, 24°E) indicate that a total ozone reduction of 2.5% during summer and 7% during winter per decade cause an increase in UV-B irradiance by 5% and 14% respectively (Varotsos 1994). Echer and Kirchoff (2000) found strong anti-correlation between ozone and UV-B radiations at two South American stations Cuiaba (15°S, 56°W) and Punta Arenas (53.2°S, 70.90°W). Eck et al. (1995) from measurement of total ozone and UV reflectivity reported that local noon overpass time of the satellite is best suited for monitoring the peak daily UV irradiances.

Regular measurements of the ground reaching solar UV-B radiation were started in India during the Indian Middle Atmosphere Program (IMAP) at different locations and this paper reports such measurements made by a UV-B Photometer operated during 1988 - 1989 at a tropical coastal station Visakhapatnam (17.7°N, 83.3°E) located 30 meters above sea level on the east coast of India. The data used here comprises of 5-minute values of the incoming UV-B irradiance for the year 1988 - 1989 from which mean hourly values of incoming UV-B irradiance at wavelengths 280 nm, 290 nm and 310 nm were estimated. TOMS (Total Ozone Mapping Spectrophotometer) ozone data for this latitude was obtained from the Internet website www.jwocky.gsfc.nasa.com for the respective observation of UV-B irradiance and the hourly values of incoming UV-B irradiance are used to calculate the erythemal irradiance corresponding to each observation.

2. EXPERIMENTAL TECHNIQUE

The UV-B Photometer used in the present study was developed at National Physical Laboratory, New Delhi, India basing on the principle of filter wheel radiometers (Shaw et al. 1973). The system basically consists of three units namely, the Optical Unit, Data Logger and Power Supply Unit. The UV-B Photometer system is designed in such a way that it can be operated in the wavelength range between 280 nm to 310 nm. The whole system is made to work automatically and it can be left unattended throughout the day. The system takes about 5 minutes to complete one cycle of observation at four different wavelengths (280, 290, 300 and 310 nm) and the dark count, hence has got a time resolution of 5 minutes. The optical unit consists of three parts namely, an integrating sphere, filter wheel and photomultiplier tube.

They are enclosed in a metal housing. The integrating sphere is an optical glass component that directs the incident sunlight onto the filter wheel. The inner surface of the integrating sphere is coated with a solution of barium sulphate in distilled water with binder. The diameter of the integrating sphere is 15 cm. It consists of a hemispherical dome with an opening of 25 mm diameter at the top of the sphere. Right angle to this opening there is an aperture of 10 mm diameter to enable the radiation to reach the photo multiplier tube through the filter. The filter wheel is a circular disc holding four filters used for wavelength selection, along with one opaque slot that is sealed to measure the dark current. The filter wheel is mounted on the shaft of a synchronous motor which rotates a coupling device in such a manner that each filter comes into the field of view for nearly 45 seconds and then moves away. The filter wheel consists of four interference filters 280 nm, 290 nm, 300 nm and 310 nm with 10 nm full width at half maximum (Barr Associates Make) and a covered blank position to record the dark current of the photo-multiplier tube. A cycle of 5 minutes is required for complete rotation of the filter wheel to sequence through all filters. After passing through the filters the radiant energy is detected by a suitable photo-multiplier tube which detects the radiation energy after wavelength selection through filters and is recorded by the data logger.

2.1. Calibration of UV-B Photometer

The photometer output (mV) for each of the interference filters is converted into absolute irradiance ($W\ m^{-2}\ nm^{-1}$) by determining the calibration factor K ($W\ m^{-2}\ nm^{-1}$ per mv) of the filter. The calibration method depends on the generation of the spectral irradiance G($W\ m^{-2}\ nm^{-1}$) from a standard instrument (OL-742 double mono-chromator with quartz diffuser) which is exposed to solar radiation and kept near the global UV-B photometer which is under calibration. Both the double mono-chromator and global UV-B photometer receive the same solar radiation simultaneously at the same location. Thus the double mono-chromator gives the spectral irradiance over the wavelength region of interest for the same atmospheric conditions (like intensity of solar radiation, ozone, aerosol etc.) for which the global UV-B photometer gives an electrical output (mV). The calibration is done around local noon on a day with clear sky to avoid variations in solar intensity, air mass etc. The OL-742 double mono-chromator instrument is periodically calibrated at the Standards Calibration Laboratory of NPL (National Physical Laboratory) with a standard radio active source and any corrections to the calibration of this instrument are duly incorporated in the UV-B irradiance calibration for the global UV-B photometer.

3. MEAN DIURNAL VARIATION OF UV-B IRRADIANCE

The mean diurnal variation of the global UV-B irradiance at 310 nm wavelength for the three seasons namely summer (March, April, May & June), monsoon (July, August, September & October) and winter (November, December, January & February) are shown in Fig.1 along with their standard deviation. The seasonal classification is done based on local weather conditions and monsoon patterns. The effective wavelength for erythemal irradiance is about

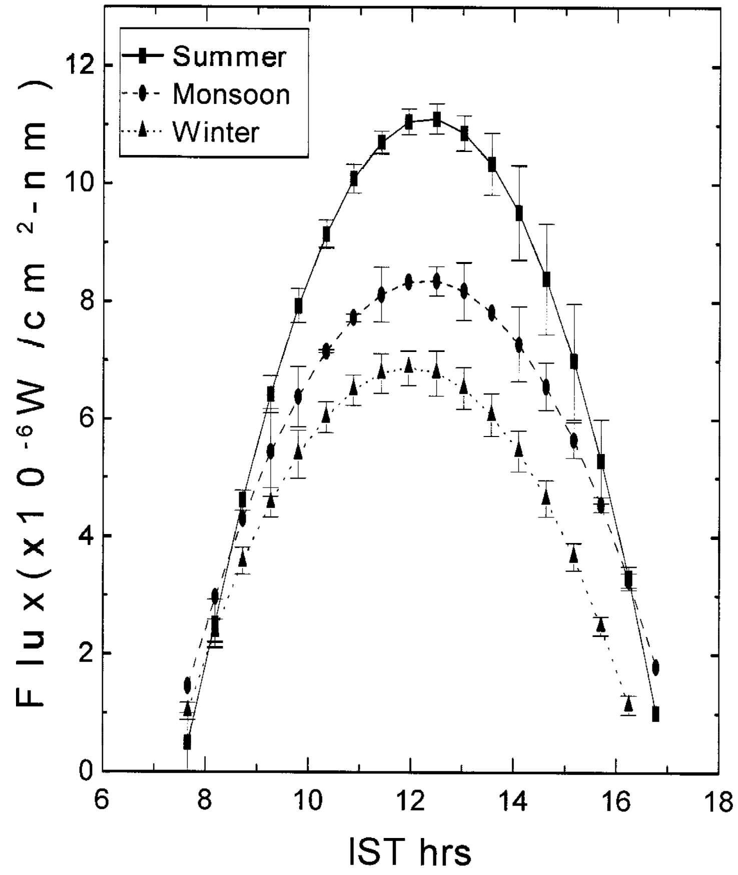

Fig. 1. Mean diurnal variation of measured solar UV-B Irradiance at 310 nm wavelength over Visakhapatnam during 3 different seasons.

308 nm as the erythemally weighted UV-B irradiance generally peaks near this wavelength (Bodhaine et al. 1997) and hence 310 nm, which is the closest to the UV-B effective wavelength is chosen for this study. It is observed that the UV-B irradiance is at a maximum during the noon hours of summer months followed by monsoon and winter. The mean UV-B irradiance at summer noon is approximately 50 - 60% higher than that during the winter, when annual low UV-B irradiances are observed at this location. Lam et al. (2002) also reported similar seasonal variation in the global UV flux at Cape D'Aguilar (22°N, 114°E) in Hong Kong with maximum UV index being 13 - 14 W cm^{-2} nm^{-1} in summer solstice when noon solar zenith angles are near zero and minimum UV index being 5 - 6 W cm^{-2} nm^{-1} in winter solstice when the noon solar zenith angles are around 45°. Eck et al. (1995) reported that due to strong absorption by ozone and strong Rayleigh scattering, the diurnal distribution of UV flux is strongly dependent on the solar zenith angle.

4. VARIATION OF UV-B IRRADIANCE AS A FUNCTION OF SOLAR ZENITH ANGLE AND COLUMN OZONE

In Fig. 2 are shown the mean diurnal variations of the ground reaching UV-B irradiance at 310 nm and the respective solar zenith angle at the given time for the months of May, October and December representing three seasons namely summer, monsoon and winter. Here it is seen that the incoming UV-B irradiance is minimum in December that corresponds to winter season. During winter seasonal atmospheric turbidity is minimum and hence the incoming UV-B irradiance should be maximum. But the incoming irradiance is less which may be due to

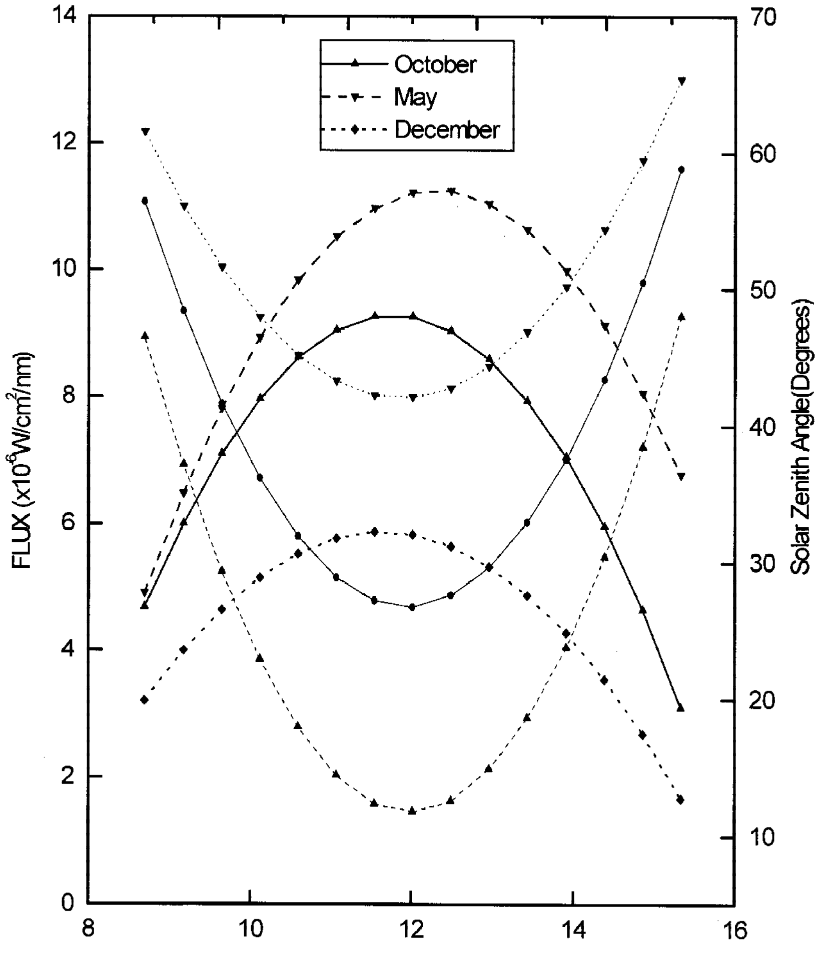

Fig. 2. Mean diurnal variation of UV-B Irradiance during 3 typical months October, May and December along with the variation of solar zenith angle.

abundance of ozone during winter season. Kundu (1983) reported that total ozone at Indian stations show higher values in winter when compared to monsoon season. Srivastava et al. (1984) reported a decrease of incoming UV-B irradiance with an increase in ozone content but not in a definite proportion to the abundance of ozone. It may be seen that the solar UV-B irradiance shows an inverse variation as a function of solar zenith angle for all the three months and hence it is important to screen the UV-B irradiance data with solar zenith angle before any attempt is made to compare the observed flux with column ozone. In order to assess the impact of ozone variations on the ground reaching UV-B irradiance, it is important to quantify the relationship between UV-B irradiance at the ground and the atmospheric ozone content, which is possible only with a simultaneous measurement of both the parameters. Echer and Kirchoff (2000) reported that a simple correlation study using daily average ozone and UV-B daily maximum values show very low, if not complete absence of any correlation for both low and high latitude data. However, better correlations are seen when the variables are obtained at fixed solar zenith angles.

Figure 3 shows the variation of the measured UV-B irradiance during a 60-day period at 40° (top panel) and 50° (bottom panel) solar zenith angles. Also shown are the column ozone values from TOMS which show an inverse variation with UV-B irradiance.

Table 1 shows the correlation coefficients along with their errors for different solar zenith angles during three different seasons. The seasonal variation of the observed UV-B irradiance may partly be influenced by atmospheric turbidity in addition to atmospheric ozone. Atmospheric turbidity is a measure of the vertically integrated particulates in the atmosphere. The Angstroms formula for the aerosol extinction coefficient can be written as $\tau_a = \beta\lambda^{-\alpha}$ where β is the turbidity coefficient which indicates particulate concentration and α indicates particle size distribution. Monsoon month's correlation coefficients show a large variability. It may be mentioned that the data base in monsoon is less and due to prevalence of cloudy skies. Secondly, whenever data is available, the skies are very clear after post rain cleansing and removal of the atmospheric aerosols and hence the variations in the ground reaching UV-B irradiances are directly related to the changes in atmospheric column ozone, at times leading to large correlation coefficients to the level of even -0.9.

It has been reported at Visakhapatnam that the Angstroms parameter α, evaluated using the monthly mean aerosol extinction derived from multi wavelength measurements, show large seasonal variations. The turbidity increases during summer and decreases in monsoon and winter seasons. Niranjan et al. (1997) reported that β is maximum in May and minimum in September for this station. This may account for the large variations in correlation coefficients during monsoon for this station. Lam et.al. (2002) reported an anti-correlation of -0.632 with UV-B irradiance at 305 nm on the average and the present results also indicate such an average correlation.

5. DEPENDENCE OF UV-B IRRADIANCE ON TOTAL OZONE AND SOLAR ZENITH ANGLE

Ground level UV-B irradiance is mainly affected by solar zenith angle in addition to its

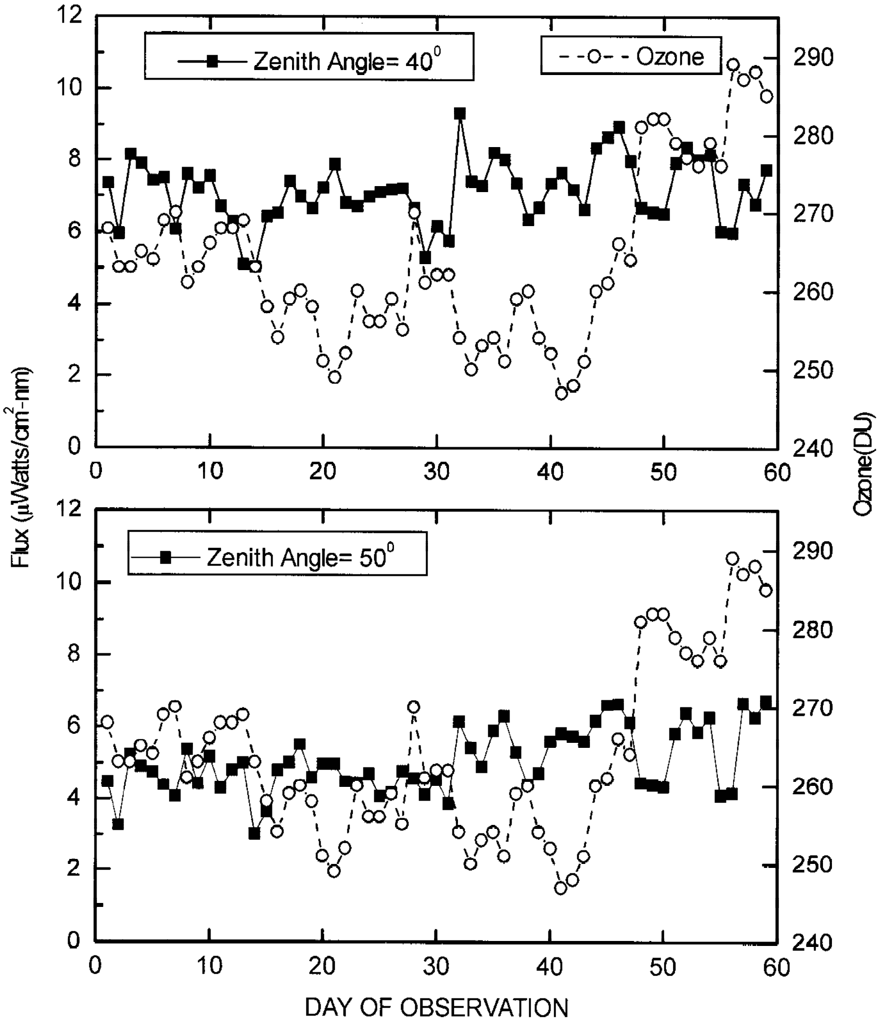

Fig. 3. Day to day variability of UV-B Irradiance at 40° (top panel) and 50° (bottom panel) along with TOMS ozone (broken line).

dependence on cloudiness and other factors. For clear sky conditions and for a given solar zenith angle the UV-B irradiance is mainly affected by the concentration of total ozone. The effect of ozone concentration on incoming UV-B irradiance is expressed in terms of the following equation:

$$I/I_0 = [T/T_0]^{-RAF}, \qquad (1) \text{ (Dubrovsky 2000)}$$

Table 1.

Solar Zenith Angle in degrees	**Winter**		**Summer**		**Monsoon**	
	Corr. Coef.	**Error**	**Corr. Coef.**	**Error**	**Corr. Coef.**	**Error**
30	-	-	-0.64	0.007	-0.12	0.07
40	-0.71	0.001	-0.71	0.001	-0.68	0.003
50	-0.55	0.014	-0.77	0.003	-0.9	0.007
60	-0.33	0.007	-0.63	0.002	-0.3	0.004
70	-0.48	0.002	-	-	-	-

where
$$\mathrm{RAF} = \frac{\mathrm{d}[\ln \mathrm{I}]}{\mathrm{d}[\ln \mathrm{T}]}. \qquad (2)$$

The Radiation Amplification Factor "RAF" indicates the relative change in effective irradiance corresponding to the relative change in ozone. Two approaches were used in this paper to derive RAF value from the measured data for this station. In the first approach, RAF was determined by assuming solar zenith angle and logarithm of total ozone as independent variables and logarithm of UV-B irradiance as dependent variable. The relationship between the incoming UV-B irradiance (I), Total Ozone (T) and the Solar Zenith Angle (χ) is assumed to be in the form:

$$\ln \mathrm{I} = \mathrm{a} - \mathrm{RAF} \ln \mathrm{T} + \mathrm{c}\chi + \mathrm{u}, \qquad (3)$$

where a is the regression constant. RAF and c are the regression coefficients and u is the disturbance term, which has $N(O,\sigma^2)$ distribution.

Eq. (3) can be written as $\mathrm{Y} = \beta_1 + \beta_2 \mathrm{X}_2 + \beta_3 \mathrm{X}_3 + \mathrm{u}$, (4) where β_1, β_2, β_3, Y, X_2 and X_3 corresponds to a, RAF, c, ln I, ln T and χ. In deviation form (4) can be expressed as

$$y = \beta_2 x_2 + \beta_3 x_3 + (u - \bar{u}), \tag{5}$$

where $\bar{u}$ is the mean disturbance term.

Using ordinary least squares, we can obtain the estimated parameters as:

$$\begin{bmatrix} \hat{\beta}_2 \\ \hat{\beta}_3 \end{bmatrix} = \begin{bmatrix} \sum x_2^2 & \sum x_2 x_3 \\ \sum x_2 x_3 & \sum x_3^2 \end{bmatrix}^{-1} \begin{bmatrix} \sum y x_2 \\ \sum y x_3 \end{bmatrix}, \tag{6}$$

where $x_{i2} = X_{i2} - \overline{X}_2$ etc.

Further $\hat{\beta}_1 = \overline{Y} - \hat{\beta}_2 \overline{X}_2 - \hat{\beta}_3 \overline{X}_3$.

By using the known values of ln I, ln T, and χ the estimated model would be:

$$\left(\hat{\ln}\ I\right) = \hat{a} + \left(R\hat{A}F\right) \ln T + \hat{c}\chi, \tag{7}$$

and the estimated values of RAF are found to range between 2.83 to 4.13 for wavelengths ranging between 280 - 310 nm with rms (root mean square) errors ranging between 2.4 to 8.6%. The adjusted values of R^2 are found to lie between 0.64 to 0.74. Here it is observed that the RAF value decrease with decrease in wavelength.

The second approach differs from the first one by using the measured UV-B irradiance normalized for sun-earth distance and mean total ozone for this station. By using equation (1) we define I^* the UV-B irradiance normalized for mean earth-sun distance and the mean total ozone T_0 = 275.17 Dobson Units (the annual mean of total ozone at Visakhapatnam made during 1988-1989) given by:

$$I^* = I\ [T/T_0]^{RAF}\ C_{d^{-1}}. \tag{8}$$

To develop the statistical model for estimating UV-B irradiance from the solar zenith angle and total ozone the regression function relating I^* and the solar zenith angle χ is expressed as:

$$\ln\ I^* = a \ln \cos\chi + b + c\ m + d\ m^2, \tag{9}$$

where b is the regression constant, a, c and d are the regression coefficients and u is the disturbance term, which has normal distribution, $m = 1/\cos\chi$ is the air mass. The above relation separates the effects of total ozone and solar zenith angle on UV-B irradiance (Dubrovsky 2000).

From equations (8) and (9) the complete statistical model for estimating the incoming UV-B irradiance is given by:

$$\ln I = a \ln \cos\chi + b + c\, m + d\, m^2 - \mathrm{RAF} \ln [T/T_0]. \qquad (10)$$

Using regression technique (Johnston 1985) the parameters are estimated and the values of RAF are found to lie in the range 2.56 - 3.77 for wavelengths ranging between 280 - 310 nm with rms errors lying in the range 2.1 - 7.6%. Inter-comparison of values obtained from the above two approaches indicate almost same values for RAF. The adjusted R^2 values obtained in the second approach lie in the range of 0.72 to 0.84 and are found to be more significant than the first. Hence this approach is retained for further analysis.

6. VARIATION OF MODELED UV-B IRRADIANCE AS A FUNCTION OF MEASURED UV-B IRRADIANCE

The regression model explained above was analyzed for known values of TOMS ozone, the respective solar zenith angles and the incoming solar UV-B irradiance was estimated for about 40 days that were not used in evaluating the model. This exercise was done with a view to validate the model formulation with experimental observations. Figure 4 shows a mass plot of measured flux versus modeled flux, which shows a very good correlation with a correlation coefficient of 0.88. Here the 40 days data of measured values not fitted in the developed model were used and hence is a data set independent from that used in the model. It is observed that the developed model could re estimate the observed fluxes with an rms error of 9.7 % between solar zenith angle 30 - 40° and with an rms error of 7.7% in the interval of 40 - 50°. Dubrovsky (2000) reported an rms error of 8% at 30° solar zenith angle and 14% at 70° from his statistical model developed from multi regression analysis.

7. DEPENDENCE OF ERYTHEMAL RAF ON SOLAR ZENITH ANGLE

Erythema is one of the important biological effects causing harmful effects on human skin and hence it is important to study the incoming UV-B irradiance in terms of erythemal RAF which is defined as the ratio of change in erythemal irradiance to the corresponding change in ozone. McKenzie et al. (1991) reported that the RAF values of erythemal irradiance for clear sky observations at fixed zenith angle lie in the range of 0.15 to 1.25 and tend towards higher values at higher solar zenith angles and also suggested that the ozone dependence of RAF can be ignored (Dubrovsky 2000). Ambach et al. (1997) reported the values of RAF for erythemal irradiance too lie between 0.095 and 1.22. Dubrovsky (2000) reported the RAF values for two stations in Czech Republic to lie between 0.9 and 1.2. and they increase with

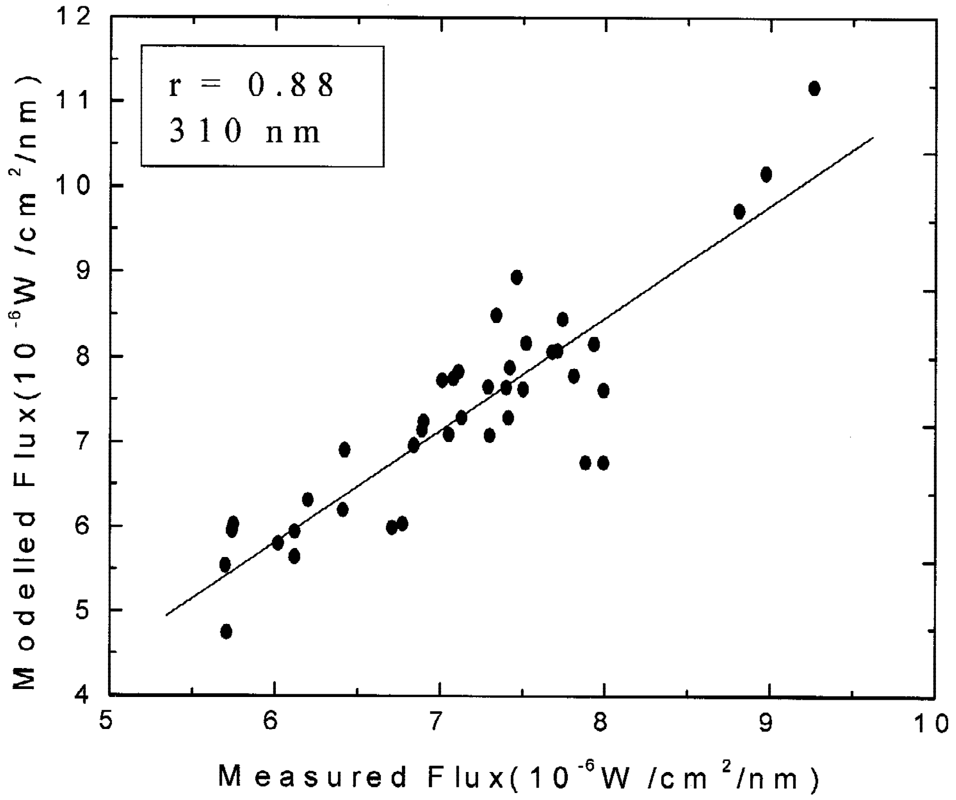

Fig. 4. Mass plot showing measured flux against modeled for 310 nm wavelength flux at Visakhapatnam.

increase in solar zenith angle. The erythemal irradiance in the above study was evaluated from standard erythemal spectrum given by McKinlay and Diffey (1987). The erythemal irradiance for this station was calculated using the formula:

$$BED = \int_{\lambda} UV(\lambda)A(\lambda)d\lambda ,$$

where BED corresponds to the effective dose corresponding to a particular biological effect UV(λ) corresponding to the UV-B irradiance at wavelength λ. A(λ) corresponds to the action or sensitivity of a particular biological effect at that wavelength.

The incoming UV-B irradiances measured through out the day are multiplied with the standard coefficients (weighting functions) of action spectrum which give the particular biological effect (erythema) and are integrated for the whole range of wavelength in between 290 - 310 nm. By substituting the erythemal irradiance values into the developed model the corresponding RAF values were found.

To check the dependence of erythemal RAF on solar zenith angle, the available data is sorted into bins of solar zenith angle ranges 10 - 15°, 15.01 - 20°, 20.01 - 35° and 35.01 - 50° and the erythemal RAF value is evaluated for those data sets and the results are presented in Fig. 5 along with their standard errors. The results indicate higher sensitivity of incoming solar UV irradiance to ozone at lower zenith angles which mostly correspond to summer months. A 1% change in column ozone causes 5 - 6% change in incoming solar UV-B irradiance during low solar zenith angles while a similar change in ozone will cause only 1 - 3% change in incoming solar UV-B irradiance at higher zenith angles at this tropical station. Echer and Kirchoff (2000) reported that a 25% depletion of Ozone implies 200% increase in UV-B irradiance at a solar zenith angle of 60° and 160% increase at 50° solar zenith angle.

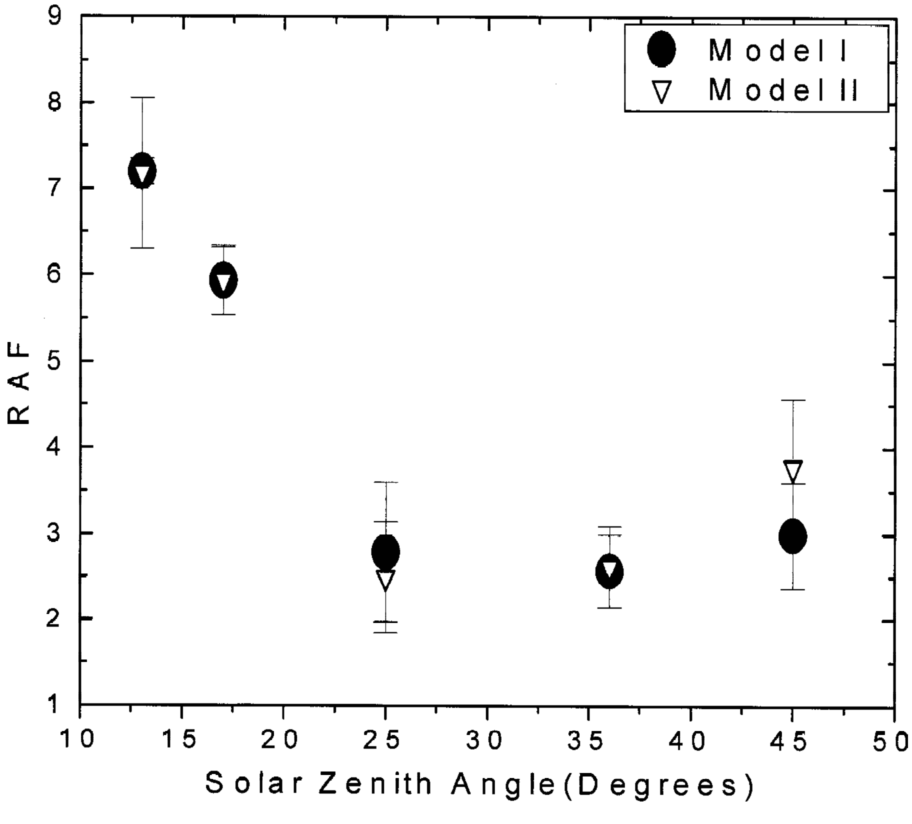

Fig. 5. Plot showing variation of RAF calculated for Erythemal Irradiance with effect of air-mass (Model II) and without effect of air-mass (Model I) as a function of Solar Zenith Angle.

8. LONG-TERM VARIATION OF INCOMING UV-B IRRADIANCE

With a view to monitor the long term variation in the incoming solar UV-B irradiance, the TOMS ozone values for the period 1978 to 1993 are incorporated in the developed model to estimate the monthly mean surface UV-B irradiance. Figure 6 shows a 13-point running mean of the estimated global flux for the co-ordinates of Visakhapatnam (dotted line) along with the TOMS ozone (solid line) with standard deviations. The 13-point running mean is taken to remove the seasonal trends in the data. The mean value of total ozone is found to be approximately 270 Dobson Units for the whole period and the plot does not indicate any significant increase or decrease in the ground reaching UV-B irradiance at this tropical latitude in India. This insignificant change in the ozone may lead to analytical relations between incoming UV-B irradiance, zenith angle and other atmospheric parameters whose values may reflect less variation than expected. In fact they show a marginal decrease in UV irradiance from 1978 to 1984.

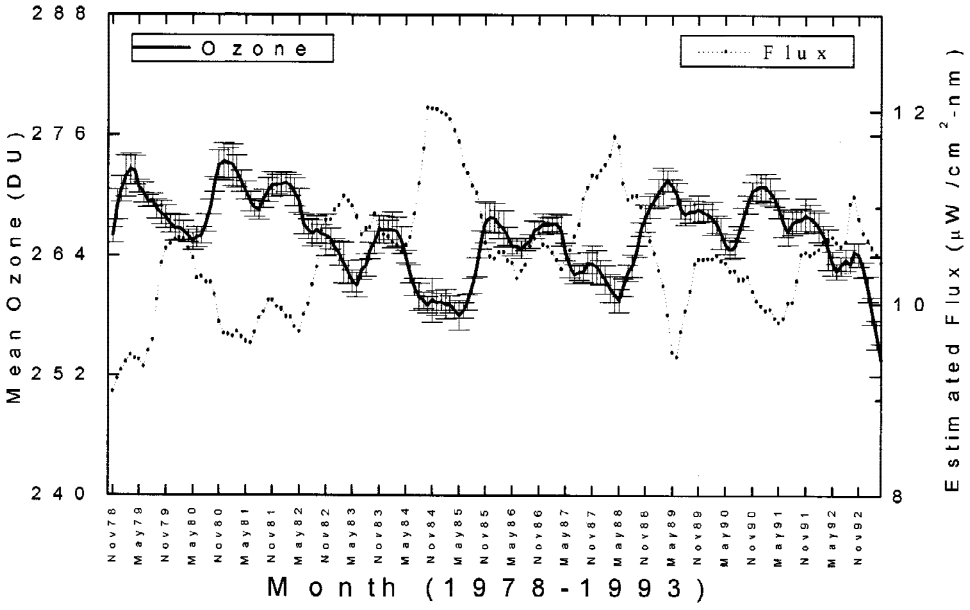

Fig. 6. Long-term variation of TOMS ozone and the UV-B irradiance derived from the statistical model during 1978 - 1993.

9. CONCLUSIONS

The present paper analyzes the UV-B radiation measured by UV-B Photometer that works on the principle of narrow band filter mechanism at a low latitude coastal station Visakhapatnam (17.7°N, 83.3°E) located on the east coast of India. The analysis was mainly focused on (1) study of diurnal variation in the incoming UV-B radiation seasonally and its dependence on solar zenith angle, (2) study of incoming UV-B irradiance measured by ground based UV-B photometer and its variability with satellite measured TOMS ozone, (3) parameterization of regression function relating incoming UV-B irradiance with total ozone and solar zenith angle, (4) determination of radiation amplification factor and its variation with wavelength from the developed model (5) to study the variation of erythemal RAF in terms of solar zenith angle and (6) to study the variation of long term UV-B irradiance from the developed model.

The incoming UV-B irradiance was found to be strongly anti-correlated with solar zenith angle. However, during monsoon, the variation in the correlation coefficient is very high (0.1 to 0.9) which was explained in terms of turbidity coefficient for Indian atmosphere.

RAF values determined for the incoming UV-B irradiance are found to decrease with wavelength. RAF value determined for erythemal irradiance is found to increase with decrease in solar zenith angle. From the regression model developed it is found this affect of air mass is not significant for this station. However the error obtained for RAF estimated with air-mass effect is found to be less than that of the RAF estimated without air-mass effect.

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