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*Full Length Research Paper*

# Estimation of different biologically effective irradiances at Visakhapatnam (17.7°N, 83.3°E) from standard action spectra

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**Measurements of solar ultraviolet radiation in the biological band (280 - 320 nm) using a ground based UV-B Photometer at VISAKHAPATNAM have been used to estimate the biological effects of the incoming radiation on various species like human, animals, plants etc. with the help of standard action spectra. A comparison is made with TOMS ozone data to find the dependence on column ozone at a subtropical Indian station Visakhapatnam (17.7°N, 83.3°E). It is found that there is no significant change in the incoming biological effective radiation in the latitude (10 - 20° North) which corresponds to very less change in the columnar ozone content for this latitude. A bilinear regression model developed for this station was used to find the RAF (Radiation Amplification Factor) which indicates the change in the biological effect with respect to the corresponding change in ozone. The values of RAF for different biological effects were evaluated and are presented in this paper.**

**Key words:** UV-B irradiance, TOMS ozone, RAF, regression model, solar zenith angle, action spectrum.

## INTRODUCTION

Depletion of stratospheric ozone and increase in the ground reaching solar UV-B flux in the biological band (280 - 320 nm) during the last couple of decades has gained large significance due to its adverse affects on the human, animal and plant species. Long back it is reported that a 1% decrease in stratospheric ozone could cause about 2% increase in UV-B radiation (Cutchis, 1974). However it may vary with respect to wavelength, season and zenith angle of the sun and the location of observation (Bias et al., 1994; Everett et al., 1966). The consequences of increased exposure of the human body to UV-B radiation include erythema, sunburn, aging of the skin, harm eyes and can cause skin cancer which is due to 0.5% of the surface solar irradiance. Madronich et.al (1998) reported an approximate annual erythemal dose of 2.35 MJ/m$^2$ with a an increase in erythemal induction by 4 ± 1.5%, DNA damage by 6.3 ± 2.4% and skin cancer by 4.7 ± 1.7 % for a subtropical latitude. It is also reported that high latitude population receive more UV exposure when compared to low latitude population (Merila et al., 2000). It is estimated that the number of excess skin cancers (1980 - 2100) due to this radiation increase from 100 - 500 millions per year (Longstreth et al., 1998).

In addition to these effects of UV-B radiation on human species, it also shows significant influence on animals, agriculture, forest, plants and crops (Caldwell et al., 1998). Middleton et al. (2001) reported that amphibian declines occur due to the increase in UV-B exposure. It is reported that the physiological and developmental processes of plants are affected by UV-B radiation. Since the first reports of stratospheric ozone reduction 35 years ago (Johnston, 1971), effects of UV-B radiation on higher plants have been the subject of considerable research. Enhanced UV-B radiation can have many direct and indirect effects on plants. UV-B radiation can alter both the time of flowering as well as the number of flowers in certain species (Caldwell et al., 1998). In addition to these effects, UV-B radiation has its influence on air quality (Tang et al., 1998), materials (Andrady et al., 1998) and also on biogeochemical cycles (Zepp et al.,

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1998). to assess the changes in the incoming biological ultraviolet radiation with ozone depletion, the values of RAF (Radiation Amplification Factor) are calculated for various effects like Erythema, DNA (Plants and Human), Skin Cancer etc. It is a known fact that the increase in UV-B radiation strongly depends on wavelength( in additiion to its dependence on solar zenith angle, ozone etc) and to assess a particular biological effect, an action spectrum that gives the sensitivity of wavelength dependent UV-B change is to be considered (Madronich et al., 2003). Once an action spectrum was developed based on the wavelength the biologically effective irradiance can be calculated using the formula from Parisi et al. (2003) given by

$$E_{eff} = \sum_{200}^{400} S_\lambda E_\lambda \Delta\lambda$$

Where; Eλ represent the incoming UV flux at wavelength λ and $S_\lambda$ represent the spectral response to a particular effect at wavelength λ. The integration range depends on the corresponding band of wavelengths considered (Wong and Parisi, 1999). By using this formula, for different biological effects, the values of $S_\lambda$ are calculated and the corresponding effective irradiances $E_{eff}$ were estimated and their analysis with respect to zenith angle, season etc. can be made. The variation of biologically effective irradiance with respect to ozone is given by RAF which is defined as the percentage increase in the incoming biological UV irradiance for a given species that would result from a 1% decrease in the amount of total columnar ozone (Madronich et al., 1998). RAF values indicate the sensitivity of a particular biological effect to the corresponding change in ozone. It is reported that for action spectra that decrease approximately exponentially with increasing wavelength between 300 - 330 nm, the biologically active irradiances scale with ozone changes according to the power law given by $UV_{bio} \sim [Ozone]^{-RAF}$ (Madronich et al., 1998). Madronich et al. (1998) also reported the values of RAF's for different biological effects with the help of different action spectra. They also studied the trends in biologically active radiation (Erythema) by using the action spectrum suggested by Mc Kinlay and Diffey, (1987) and TOMS ozone data for various latitudes and reported that latitudes lying between 10 - 20° North have zero percent change per decade and latitudes lying between 20 - 30° North are having 1% change per decade.

Regular measurements of the ground reaching solar UV-B radiation were started in India during the Indian Middle Atmosphere Programme (IMAP) at different locations. Comparison between the data obtained from various stations and the temporal variation of incoming UV-B irradiance with respect to wavelength, season, solar zenith angle etc., have been done. However the biological effects due to incoming UV-B irradiance have not been reported earlier. Keeping this view an attempt is made to explore some of the biological effects due to increasing UV-B irradiance by developing a statistical model is made. This paper reports some of the biological effects at a tropical coastal station Visakhapatnam on the east coast of India since 1983. The columnar ozone values from TOMS aboard Nimbus 7 for this station are obtained from the NASA website and were used to calculate the RAF values of biologically effective irradiances at this station.

## 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 Optical Unit, Data Logger and Power Supply Unit to measure the surface UV irradiance (direct + diffuse). The UV-B Photometer system is designed in such a way that it can be operated in the wavelength range between 280 - 310 nm. The whole system is made to work automatically and it can be left unattended throughout the day. The system takes about 5 min 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 min. The photometer output (mV) for each of the interference filters is converted into absolute irradiance ($Wm^{-2}$ $nm^{-1}$) by determining the calibration factor K ($W\ m^{-2}\ nm^{-1}$ per mv) of the filter. The calibration is done around local noon on a day with clear sky to avoid variations in solar intensity, air mass etc (Kirshna Prasad and Niranjan, 2005).

### REGRESSION MODEL

It is a known fact that the incoming solar UV-B irradiance is a function of total columnar ozone (T) and the solar zenith angle (χ). This implies that the incoming Biological Effective Irradiance (I) is also a function of solar zenith angle and ozone. The functional relationship between the three is given by;

$$ln\ I = a + RAF\ ln(T) + C(\chi) + u \quad \text{.....(1)}$$

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 (Kirshna et al., 2005).

RAF is known as Radiation Amplification Factor which expresses the dependence of UV-B flux on total ozone and is given by:

$$RAF = -\frac{d[\ln I]}{d[\ln T]} \quad (2)$$

Which gives the relative change in effective irradiance corresponding to the relative change in ozone. By using the known values of *ln* I, *ln* T and χ, the estimated model would be;

$$\left(\hat{\ln I}\right) = \hat{a} + \left(\hat{RAF}\right)\ln T + \hat{c}\chi \quad (3)$$

Where; a and c are regression coefficients.

## RESULTS AND DISCUSSION

### Action spectra

Action spectra for different biological effects have been

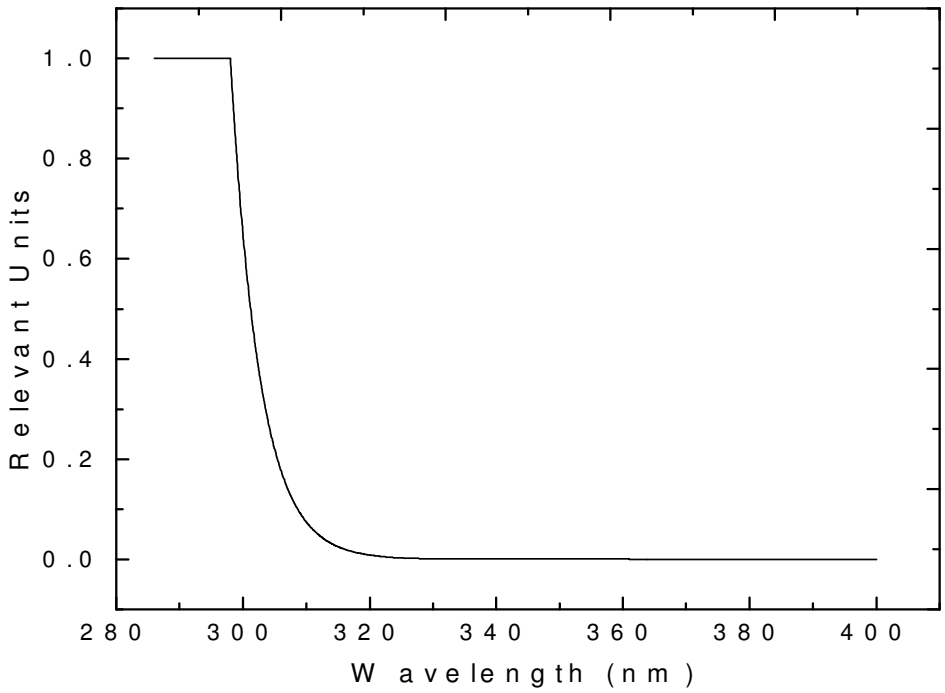


**Figure 1.** Action spectrum for erythemal irradiance.

drawn by taking their relative effectiveness values as function of wavelength which was considered as reference to calculate the biologically effective irradiances at this station.

**Action spectrum for erythema:** The effective values of erythema induced in human skin suggested by McKinlay and Diffey (1987) were considered to draw the action spectrum. According to them values of effective action are parameterized as follows:

$A(\lambda) = 1$ for $250 <= \lambda <= 298$ nm
$A(\lambda) = 10^{0.094(298-\lambda)}$ for $298 < \lambda < 328$ nm
$A(\lambda) = 10^{0.015(139-\lambda)}$ for $328 < \lambda < 400$ nm
Integration range: 286 - 400 nm

The action spectrum describes the effect per energy unit where one unit = 1 microwatt / $cm^2$.

For wavelength range 286 - 400 nm the energy decreases from 1 - 0.0001216

By using the above values the action spectrum for Erythma was drawn and is shown in Figure 1

**Action spectrum for DNA damage:** This effective value of DNA damage suggested by Setlow (1974) was considered in drawing the action spectrum. The values are parameterized as follows:

$A(\lambda) = 10^{(13.04579 + (\lambda * - 0.047012))}$ for $286 <= \lambda < 290$ nm
$A(\lambda) = 10^{(20.75595 + (\lambda * - 0.073595))}$ for $290 <= \lambda < 295$ nm
$A(\lambda) = 10^{(30.12706 + (\lambda * - 0.105362))}$ for $295 <= \lambda < 300$ nm
$A(\lambda) = 10^{(42.94028 + (\lambda * - 0.148073))}$ for $300 <= \lambda < 305$ nm
$A(\lambda) = 10^{(45.24538 + \lambda * - 0.15563))}$ for $305 <= \lambda < 340$ nm
Integration range: 286 - 340 nm

For the parameterization given above and the values below it was assumed that the action spectrum describes the effect per energy unit where one unit = one microwatt per sq cm.

For wavelength range 286 - 340 nm it decreases from 0.039935 - 0.000000021438340. The action spectrum was shown in Figure 2.

**Generalized plant action spectrum:** The effective values of Plant Action given by Caldwell (1971) were used to draw the action spectrum. The values are parameterized according to the equation given below;

$A(\lambda) = 2.618*(1-(\lambda / 313.3)^2)* \exp((300-\lambda)/31.08)$ where $\lambda$ is wavelength in nm.
Integration range: 286 nm - 313 nm

For wavelength range 286 - 313 nm it decreases from 0.684674136 - 0.003298358. The Action Spectrum was shown in Figure 3.

**Action spectrum for growth response of plants:** The effective values of Growth Response of Plants by Flint and Caldwell (2003) were used to draw the action

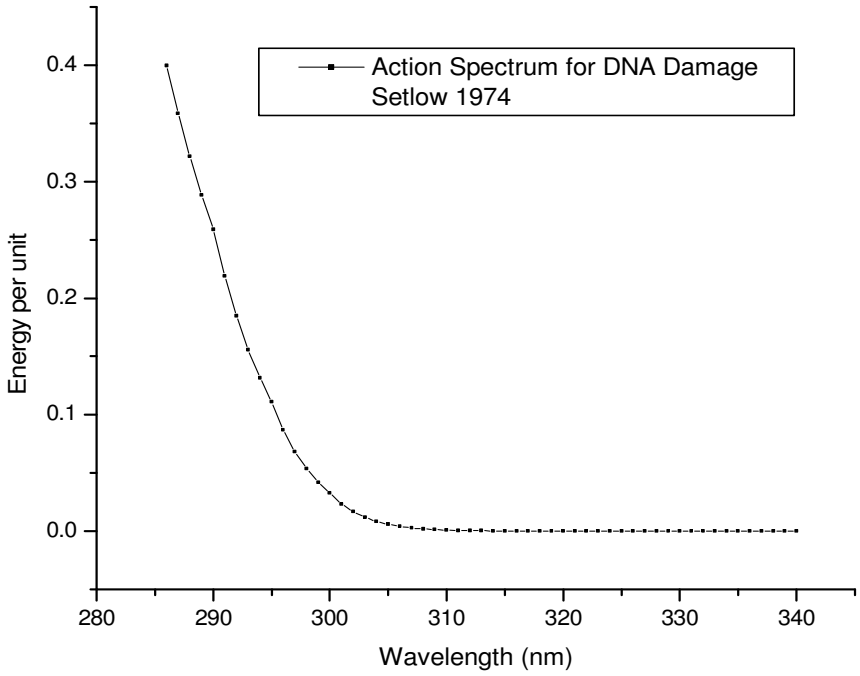


**Figure 2.** Action spectrum for DNA damage.

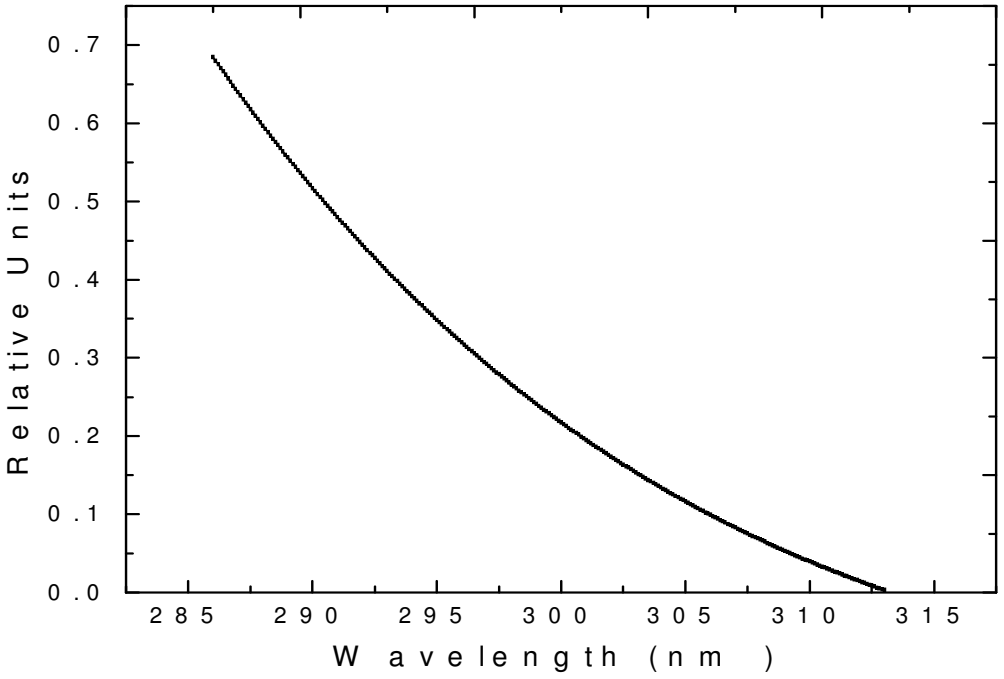


**Figure 3.** Action spectrum for generalized plant damage.

spectrum. Spectrum was parameterized with the equation given below:

$A(\lambda) = \exp(4.688272 * \exp(-\exp(0.1703411*(\lambda-307.867)/1.15))+((390-\lambda)/121.7557-4.183832))$

Where; λ = wavelength in nm
Integration range: 286 - 390 nm
For wavelength range 286 nm to 390 nm it decreases from 3.249075906 - 0.015239996.

The action spectrum is shown in Figure 4.

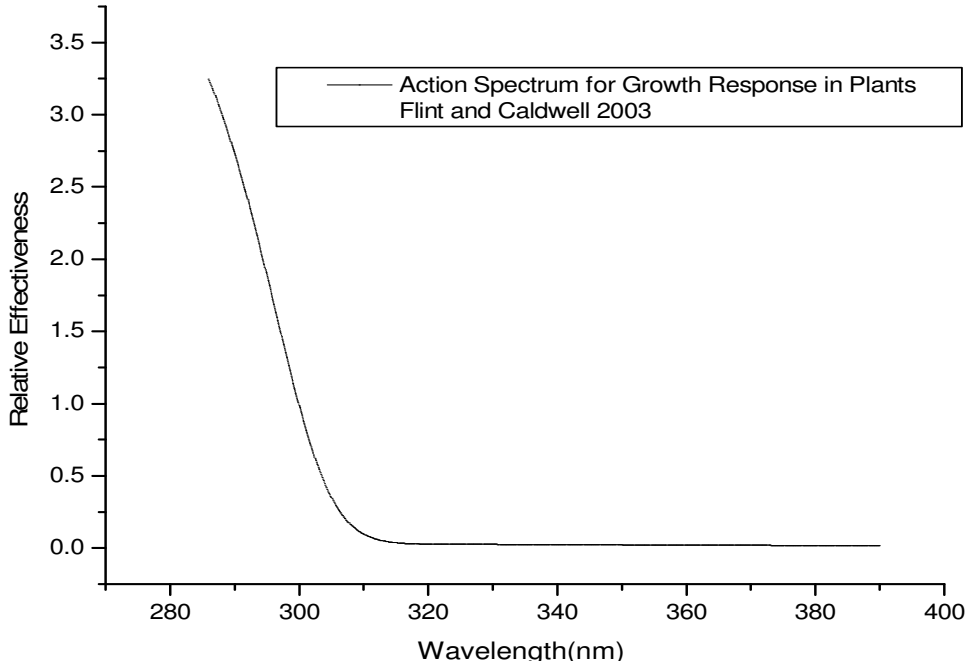


**Figure 4.** Action spectrum for growth response of plants.

**Variation of biological effective irradiance with solar zenith angle**

Figures 5 and 6 represent the variation of the biological doses for Erythema and Generalized Plant damage with respect to solar zenith angle for this station. The biological erythemal dose is plotted by taking a set of 216 points as a function of solar zenith angle calculated from the numerical formula using equation of time, date and declination angle as parameters. It exhibits strong anti-correlation with correlation coefficients of R = -0.87. Similar attempt was made to study the variation of Generalized Plant Damage as a function of solar zenith angle and it also exhibits an anti-correlation of R = -0.88. In these two cases the incoming irradiance at wavelengths 290 and 310 nm are recorded through out the day and the corresponding flux values are multiplied with the standard coefficients (weighting functions) of action spectrum which give the effect of particular biological effect and integrated for the whole range of wavelength between 290 - 310 nm. In general a weighting function at the effects level is the composite of more than one spectrum at molecular level, and is modified by absorbing molecules filtering the radiation before it reaches its target. Therefore the weighting functions and data derived from them depend on various independent factors that should be taken into consideration. Traditionally, action spectra have been developed for very different purposes than evaluating biological effects corresponding to ozone reductions. Action spectra allow a photobiologist to draw some conclusions regarding the biological pigment or molecule that absorbs the radiation and mediates the effect within an organism. The criteria often used to develop action spectra are directed to this traditional use in photobiology and these, along with many technical constraints, limit the usefulness of action spectra as weighting functions (Stratospheric Ozone and Human Health Project, Environmental Effects of Ozone Depletion: 1994 Assessment). Here the effect of ozone is not taken into consideration since it is a known fact that the biological effect is strongly wavelength dependant and the impact of ozone absorption varies strongly with wavelength (Figure 1 of Madronich et al., 1998). Hence the variation of ozone should be taken into consideration which is necessary to estimate the amount of sensitivity of a particular effect at a particular solar zenith angle.

**Variation of biological effective irradiance with ozone**

The variation of effective irradiance with solar zenith angle does not give the effect of a particular biological effect and its sensitivity on a particular living or nonliving organism. To know its relative affect it has to be calculated with respect to the corresponding change in ozone given by RAF. The relationship between UV-B irradiance and total ozone is generally expressed in terms of Radiation Amplification Factor (RAF) where RAF is defined as the percent change of UV-B irradiance divided by the percent change in total ozone (Bodhaine et al., 1997; Dubrovsky, 2000). By using the regression model developed for this station (Krishna Prasad and Niranjan,

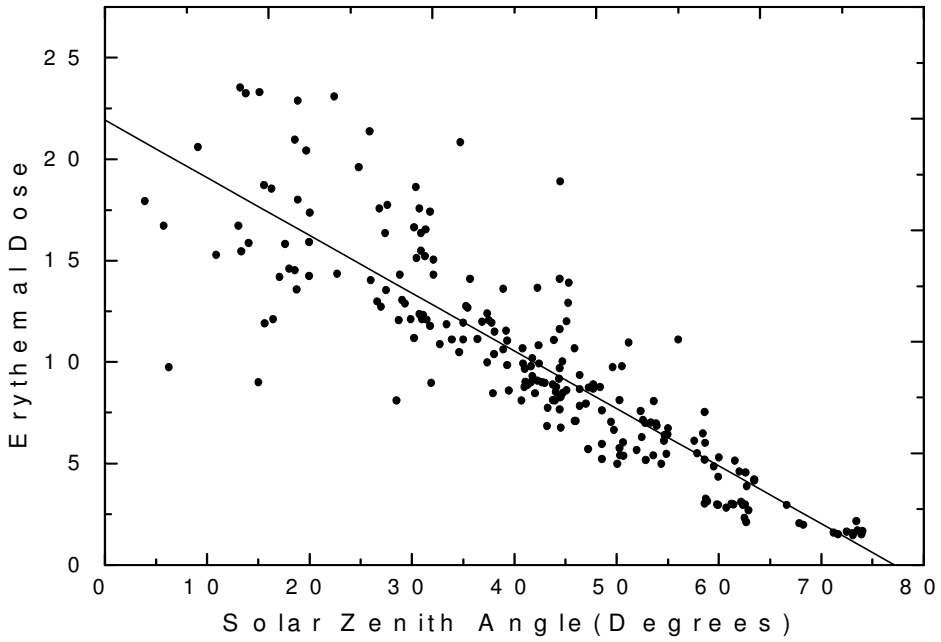


**Figure 5.** Mass plot showing erythemal dose as a function of solar zenith angle.

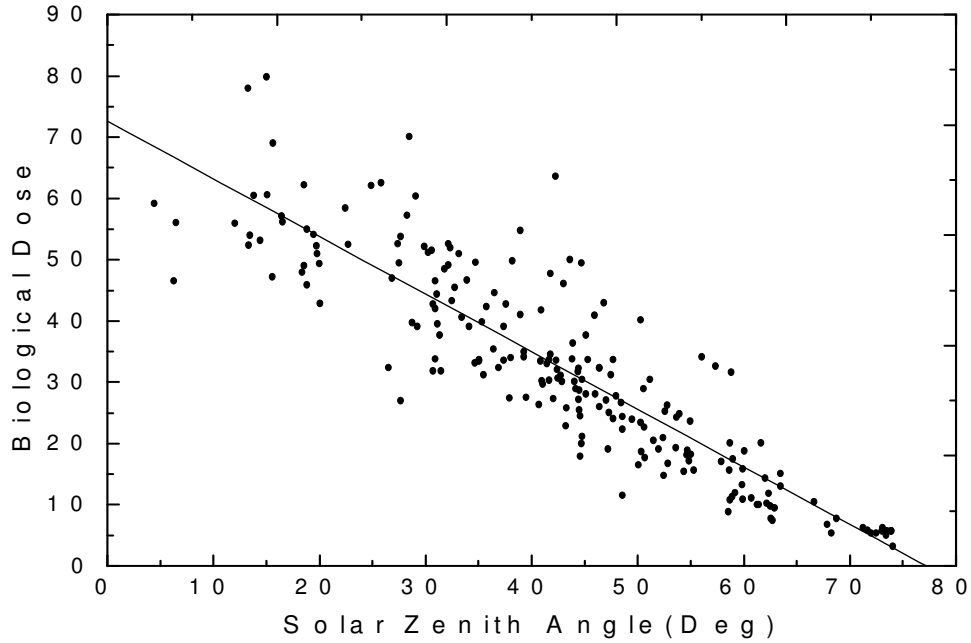


**Figure 6.** Mass plot showing biological dose of generalized plant damage as a function of solar zenith angle.

2005) RAF was calculated for Erythemal Irradiance. It is a known fact that incoming irradiance depends on solar zenith angle in addition to ozone and to assess the impact of solar zenith angle on RAF, the data was sorted into bins of solar zenith angle intervals between 10 - 15°, 16 - 20°, 21 - 34°, 35 - 40° and 41 - 54° solar zenith angles and RAF values were calculated from the above model and are presented in Table 1.

From the above table it is observed that the RAF corresponding to erythmal irradiance decreases with

**Table 1.** Values of RAF for Erythemal Irradiance as a function of solar zenith angle.

| $\ln I = a - RAF \ln.T + c\chi$ | | | | | |
|---|---|---|---|---|---|
| **Solar zenith angle** | **a** | **c** | **RAF** | **$R^2$** | **Adjusted $R^2$** |
| 10 - 15° | 44.32 | -0.09 | 7.20 | 0.86 | 0.83 |
| 16 - 20° | 36.20 | -0.02 | 5.94 | 0.94 | 0.93 |
| 21 - 34° | 18.63 | -0.03 | 2.78 | 0.60 | 0.56 |
| 35 - 40° | 16.87 | -0.02 | 2.56 | 0.68 | 0.64 |
| 41 - 54° | 18.97 | -0.01 | 2.98 | 0.71 | 0.67 |

**Table 2.** Estimated values of RAF for various biological effects at Visakhapatnam.

| **Biological effect** | **Action spectrum values** | **RAF** | **Reference** |
|---|---|---|---|
| Erythema | $S_{290} = 1.000$, $S_{310} = 0.070$ | -2.524 | McKinlay and Diffey , 1987 |
| DNA Damage Plants and Human | $S_{290} = 0.330$, $S_{310} = 0.035$ | -2.476 | Setlow, 1974 |
| Generalized Plant Damage | $S_{290} = 0.510$, $S_{310} = 0.040$ | -2.530 | Caldwell et al., 1986 |
| Growth Response (Plants) | $S_{290} = 2.730$, $S_{310} = 0.096$ | -2.605 | Caldwell et al., 1971 |
| Erythema | $S_{290} = 0.340$, $S_{310} = 0.053$ | -2.465 | Komhyr and Machta, 1973 |
| Damage to eggs | $S_{290} = 0.250$, $S_{310} = 0.003$ | -2.586 | Hunter et al., 1979 |
| Skin Cancer in 1994 Albino Hairless Mice (corrected to human skin) | $S_{290} = 0.420$, $S_{310} = 0.200$ | -2.528 | deGruijl and van der Leun, 1994 |
| Skin Cancer in Albino Hairless Mice | $S_{290} = 1.460$, $S_{310} = 0.118$ | -2.533 | deGruijl et al., 1993 |

Niranjan, higher sensitivity of incoming solar UV-B irradiance during low solar zenith angles which correspond to summer months. A 1% change in column ozone causes 5 - 7% 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 solar zenith angles at this tropical station. The biological effective doses calculated for various effects with their RAF values at this station are listed in Table 2.

The values of RAF for various biological effects calculated indicate almost 2.5% decrease for corresponding increase of 1% in ozone. Madronich et al. (1998) reported the RAF value as 1.7 for biological erythemal UV radiation calculated from the action spectra of McKinlay and Diffey (1987) at 30° North latitude where as the value of RAF obtained for this latitude 17.7° North with same action spectrum is found to be 2.524 which is greater than that at mid latitudes. It is due to the general tendency that lower latitudes receive more UV-B irradiance when compared to higher latitudes. However the other biological effects like DNA Damage (plants and human) , skin cancer in albino hairless mice corrected to human skin have RAF values 2.476 and 2.528 corresponding to 2.0 and 1.2 reported by Madronich et al. (1998) at 30° North. Here only the wavelengths 290 - 310 nm are only taken into consideration since the ground reaching flux available for this station is for these four wavelengths only.

## Conclusions

The present paper estimates some of the biological effects that arise due to incoming solar UV-B irradiance at a low latitude coastal station Visakhapatnam (17.7°N, 83.3°E). Erythema is one of the biological effects that affect human skin and hence the analysis was mainly focused on erythema. It is found that the erythemal RAF increases with decrease in solar zenith angle. RAF values for other biological effects like DNA Damage and Growth Response in Plants etc were estimated using the regression model developed for this station. The effectiveness of these biological effects corresponding to wavelength was taken from various references listed in Table 2. The RAF values for various biological effects are found to range between 2.4 - 2.6.

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