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Biologically effective radiation of solar ultraviolet radiation and the depletion of stratospheric ozone

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Abstract — Based on the biological action spectra and total UV-B radiation in the atmosphere, the effective UV-dose for DNA, erythema, and plant at different seasons in the last decade, and their future change in Beijing area were calculated. Computation results indicate that the maximum of biologically effective radiation dose at noontime is in July and the minimum is in January. From 1980 to 1989 biologically effective radiation dose have increased with the average rates of about 0.6, 0.7 and 1.1 mW/m^2 per year for January, April and October, while in July the trend of radiation dose is not in evidence. For 1% reduction of ozone concentration radiation amplification factor for DNA, erythema and plant are 2.3, 2.3 and 1.4 and for 30% reduction of ozone concentration the RAF for DNA, erythema and plant are 4.2, 4.0 and 2.1, respectively.

Keywords: UV-B; ozone depletion; biological effects; solar radiation.

1 Introduction

The climatic and eco-environmental change due to the increase of trace gases in the atmosphere are being much concerned by scientists and governments all over the world. Stratospheric ozone is an effective protection layer for the life on the earth. CFCs and nitrous oxide have been proved responsible for the depletion of ozone layer. Reduction in the ozone concentration will result in not only the increase of solar ultraviolet radiation reaching the ground which may damage the earth ecosystems but also the enhancement of greenhouse effect caused by carbon dioxide, methane and other radiatively active trace gases.

Ultraviolet radiation has deleterious effects on life on the earth. It can kill microorganisms, destroy the cells of animals and plants and cause mutation of proteins and nucleic acids, making them lose their biological functions. Moreover, ultraviolet radiation has directly adverse effects on human health such as erythema, eye diseases, immune system change, and skin melanoma (skin cancer). A recent report concluded that the global ozone concentration has already decreased by an average of around 2%—3% over the past twenty years (WMO, 1990). Therefore, study on ozone reduction and increase of ultraviolet radiation is very important in protecting human health and earth environment. The content of this project is centered on the computation of biologically effective radiation due to observed ozone reduction in Beijing area.

Ultraviolet spectrum is commonly divided into three regions: UV-A (320—400 nm), UV-B (280—320 nm) and UV-C (200—280 nm). In general term, ozone absorbs radiation strongly in the UV-C band and little in the UV-A range. In the UV-B band, absorption by ozone is a sensitive function of wavelength, increasing as wavelength decreases. Any decrease in ozone concentration will increase the amount of UV-B radiation and have important influence on life on the earth.

2 Methods and materials

The efficiency of the UV-B radiation for a given biological response is usually assessed by the biological UV-dose which is strongly dependent on wavelength according to the action spectrum (Rundel, 1983; Caldwell, 1986). Biologically effective UV-B dose is defined as the integrated product of the action spectrum and the source spectrum. The dose rate and the total dose are given by expression (1) and (2), respectively.

$$\mathrm{d}D/\mathrm{d}t=\int_{280}^{340} A(\lambda)E(\lambda)\mathrm{d}\lambda, \qquad (1)$$

$$D=\int \mathrm{time} \int_{280}^{340} A(\lambda)E(\lambda)\mathrm{d}\lambda\mathrm{d}t. \qquad (2)$$

Where $A(\lambda)$ is the action spectrum of the particular biological effect studied. $E(\lambda)$ is the solar spectral irradiance at sea level.

2.1 Calculation of solar spectral irradiance

It is difficult to calculate the solar spectral irradiance precisely because it varies with several factors such as the ozone layer, atmospheric molecules, aerosol and solar zenith angle and so on. Frederick (Frederick, 1988; 1988a; 1988b) and Dahlback (Dahlback, 1989) implemented a two-stream model and a discrete ordinates method for radiative transfer equations, respectively. Green (Green, 1974; 1980; 1982; 1983) presented a parameterization model which is simple and effective in solar spectral irradiance calculation. We used it in this text.

Solar spectral irradiance includes direct UV sunlight and skylight which are presented as follows (Green, 1982; 1983).

$$E(\theta, \lambda)=B_d(\theta, \lambda)+B_s(\theta, \lambda), \tag{3}$$

$$B_d(\theta, \lambda)=\cos\theta H(\lambda)e^{-\sum_{i=1}^{4}\tau_i/\mu_i}, \tag{4}$$

$$B_s(\theta, \lambda)=A(\theta, \lambda)H(\lambda)e^{-\sum_{i=1}^{4}\tau_i}. \tag{5}$$

Where B_d (θ, λ) is direct sunlight and $B_s(\theta, \lambda)$ is skylight. θ is solar zenith angle and $H(\lambda)$ is the solar sources strength. The symbols τ_1, τ_2, τ_3, τ_4 denote the Rayleigh scattering, aerosol scattering, ozone absorption and aerosol absorption optical depths at sea level. The symbols μ_1, μ_2, μ_3 and $\mu_4=\mu_2$ denote generalized cosine functions of the form.

$$\mu_i(\theta)=[(\mu^2+t_i)/(1+t_i)]^{1/2}. \tag{6}$$

Where $\mu=\cos(\theta)$ and the small values t_i allow approximately for the roundness of the earth. $A(\theta, \lambda)$ represents term of two ratios which detailed formulae can be found elsewhere (Green, 1982; 1983).

2.2 Action spectrum

Action spectrum is used as weighting functions to (1) evaluate the relative increase of solar UV radiation, (2) evaluate the existing natural gradients of solar UV irradiance on the earth. The calculation adopted the action spectrum for damage to DNA (Green, 1974), erythema (Green, 1974), and the generalized plant (Caldwell, 1968) (Fig. 1). The DNA action spectrum is a standard model to describe the wavelength dependent on production of skin cancer in humans while erythema is a standard for human sunburn. The plant spectrum represents the relative photo effectiveness of UV-B irradiation to induce biological response when protein or nucleic acid chromophores are involved.

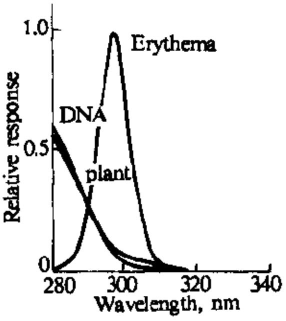

Fig. 1 Biological action spectrum

2.3 Determination of parameters

Input data in the Green' s model are air pressure, relative humility, ozone concentration, and aerosol level. Air pressure, relative humility and ozone concentrations were monthly average values measured in Beijing Observation Station (116°28'E, 39°56'N) and Xianghe Ozone Station (107°00'E, 39°N). Aerosol levels were chosen arbitrarily in Green and Björn (Björn, 1985) computation, but here they were determined by optical depths which were measured by several researchers (Mao, 1983; Qiu, 1988; Li 1989; Wang, 1989).

$$Wa = \tau a / Ka, \tag{7}$$

Wa, τa and Ka are aerosol level, optical depth and extinction coefficient, respectively. Ka' s form is presented in Green' s model formulae (Green, 1982; 1983). Average aerosol levels in January, April, July and October are obtained as 2.0, 3.5, 2.7, 2.0km, respectively.

3 Results and discussion

3.1 Comparison between measured and model computed values of UV-B irradiance

UV irradiance measurement was conducted in Shenyang in 89.6 — 90.5 (Tai, 1990) and the results were used for model verification (Fig. 2). Fig. 2 shows that UV irradiance of measurement and model computation are in good agreement, which means that Green's model is valid in UV irradiance prediction. With linear aggression between the measured and computed data the following relation was obtained.

$$Y\text{ (calculated)} = 0.156 + 0.928X\text{(measured)},\ R = 0.994$$

Measured values were monthly averages while calculated values were those of fifteenth day of each month. Air pressure and relative humility were monthly average measured in Shenyang Observation Station (123°26'E, 41°46'N). Because there were no acrosol optical depths in Shenyang available, we determined the aerosol content by surface visibility. Aerosol level has some relationship with visibility (Bjorn, 1985). Observed visibilities in Shenyang were near to that in Beijing in the past decade, so we chose aerosol level at each month in Shenyang as same as that in Be jing. Ozone concentrations were estimated with Björn formulae based on the satellite data of Gebhart (Gebhart, 1970) and Hilsenrath (Hilsenrath, 1981). For 0 — 44° north latitude (LA) ozone concentration is:

$$\text{ozone (atm cm)} = \text{(ozone annual average)} + 0.07[(\text{LA}+10)/90]$$

$$(\cos\{[(\text{DN}-90-(44-\text{LO})\times 3.1]2\pi/365\}. \tag{8}$$

For 44 — 77° north latitude ozone concentration is:

$$\text{ozone (atm cm)} = [\text{ozone annual average}] + 0.07\,[(\mathrm{LA}+10)/90]\,\cos[(\mathrm{DN}-90)2\pi/365], \tag{9}$$

where LO is longitude and DN is the day number from January 1.

3.2 Biologically effective radiation and wavelength

We regarded January, April, July and October as different seasons of winter, spring, summer and autumn, Fig. 3 shows biologically effective radiation dose versus wavelength in noontime. The maximum dose of plant is at 310 nm, while DNA and erythema are both at 305 nm. These values are different from those of their action spectrum which are at 280 nm (plant), 280nm (DNA), and 297 nm (erythema), respectively. Therefore, the sensitive range of biological effect is between 300 — 310nm. Fig. 4 presents the plot of biologically effective radiation dose versus wavelength in different seasons. The data demonstrate that effective UV-dose is highest in July and lowest in January with dose in October greater than that in April.

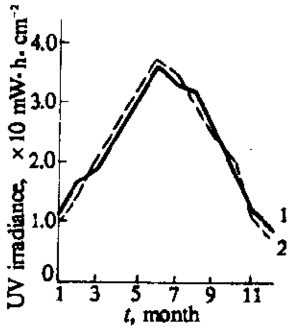

Fig. 2 Comparison between measured and computed UV irradiance in Shenyang
1. measurement; 2. calculation

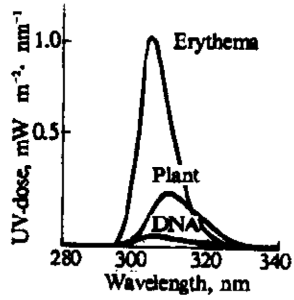

Fig. 3 UV-dose at noontime in Beijing
a. DNA b. crythema c. plant

3.3 Biologically effective UV-dose and depletion of ozone layer

Ozone layer over Beijing has decreased by different degrees with seasons in the past decade (Fig. 5). From 1980 to 1989, shifts of biologically effective UV-dose are shown in Fig. 6. In January, April and October the UV-dose increased opposite to ozone reduction, while in July the tendency of both were not in evidence. The annual UV-dose in three months were used as the dependent variable in regression analysis to obtain an estimate of the average annual trend (Table 1). The annual trend coefficient varied from 0.06 in January for DNA to 2.6 in October for erythema. Average biological UV-dose rates for January, April and October were 0.6, 0.7 and 1.1, respectively.

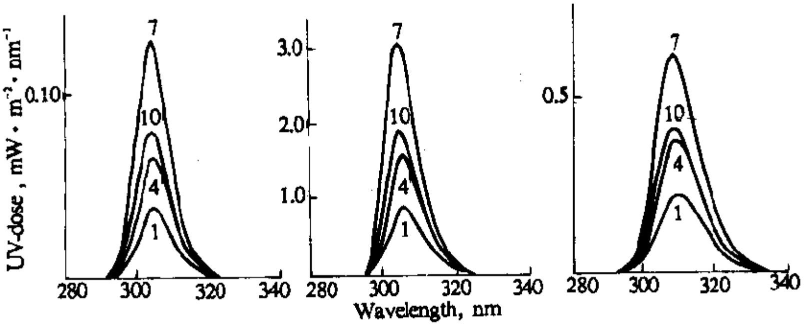

Fig. 4 Biologically effective UV-dose at different seasons in Beijing
a. DNA b. erythema c. plant

Table 1 Annual change coefficients of UV-dose in Beijing from 1980 to 1989 (mW/m²)

Biological effect	Month		
	1	4	10
DNA	0.06	0.07	0.12
Erythema	1.4	1.7	2.6
Plant	0.3	0.4	0.6
Average	0.6	0.7	1.1

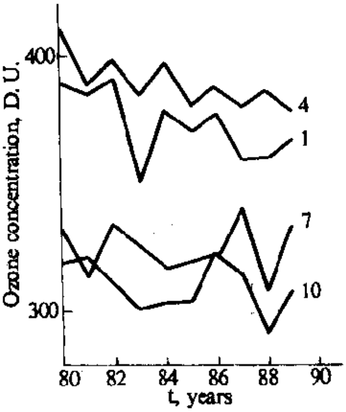

Fig. 5 Annual change trend of ozone layer in Beijing from 1980 to 1989

3.4 Radiation amplification factor and ozone reduction

The biological effectiveness of UV-B can be quantified by a radiation amplification factor (RAF). The RAF is defined as the ratio of percentage increase in UV-dose to the corresponding percentage decrease in total ozone (Gerstle, 1981). Setlow (Setlow, 1974) calculated the RAF for erythema and DNA with one-dimension model getting $RAF_{DNA} = 2.2$ and $RAF_{erythema} = 1.8$. Gerstle (Gerstle, 1981) concluded that RAF as a function of latitude and season is between 1.9 and 2.2 for erythema and

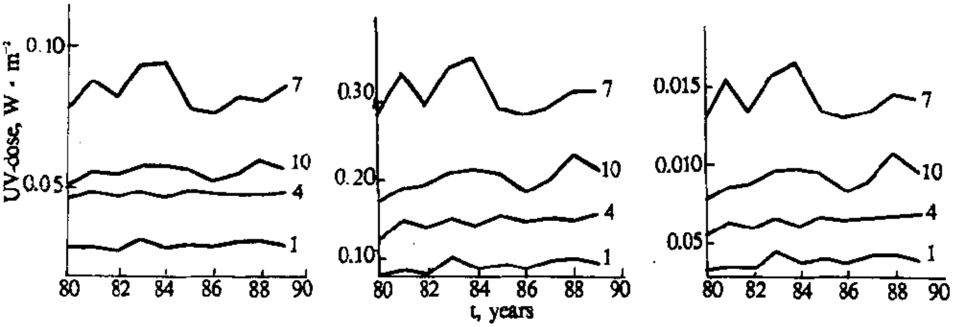

Fig. 6 Biologically effective UV-dose at different season in Beijing from 1980—1989
a. DNA b. erythema c. plant

between 2.5 and 2.8 for DNA. Fig. 7 shows that average RAF of four seasons for DNA, erythema and plant changed with percentage decrease in total ozone in Beijing. RAF for DNA, erythema and plant show nonlinear increase with percentage decrease in total ozone. For 1% reduction of ozone concentration radiation amplification factor for DNA, erythema and plant are 2.3, 2.3 and 1.4, and for 30% reduction of ozone concentration the RAF for DNA, erythema, and plant are 4.2, 4.0 and 2.1, respectively.

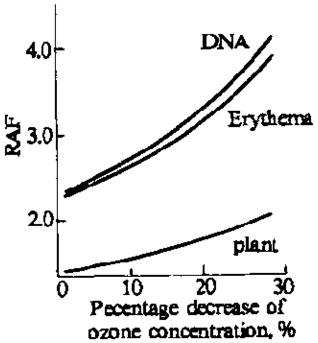

Fig. 7 RAF and percentage decrease of ozone layer in Beijing

3.5 Uncertainties in the prediction of surface UV radiation changes

The theoretical prediction of surface UV radiation in all kinds of model shows that ozone depletion will lead to increase in UV-B irradiance. However, Scotto (Scotto, 1988) reported a small negative trend in the measured UVB-dose (the wavelength region 290—330 nm) for 8 stations in the United States in the period 1974 to 1985. These conflicting data suggest that some factors in the troposphere are involved. Ozone concentration in the troposphere has been increasing due to air pollution with average annual rate of 1%—2%, which may compensate for 20%—30% reduction in total ozone (Logan, 1985). Bruehl (Bruehl, 1989) believed that the effective photo pathlength through absorbing ozone layer are different for the stratosphere and the troposphere which contributes to the uncertainty in the prediction of surface UV.

Environmental factors such as cloud cover, ground albedo and aerosol level remain constant in the model calculation and the assumption is valid in computing the long-term UV change. Calculation indicates that UV-dose is insensitive to the choice of specific environmental factors (WMO, 1990). Large errors in the surface UV prediction will result if cloud cover patterns change systematically in the future due to change in weather patterns associated with the so-call greenhouse effect. Relatively small changes in the average cloud cover may produce large changes in the average surface UV radiation (Frederick, 1988b). Changes in the average ground albedo may also be important.

4 Conclusion

Solar ultraviolet radiation has an important influence on life on the earth ecosystem. Any change of ozone layer will have an adverse effect on earth system. In Beijing biologically effective radiation dose varied with seasons and the annual average variation of UV-dose were 0.6, 0.7 and 1.1 mW/m^2 for January, April and October in the past decade. RAF for DNA, erythema and plant increase nonlinearly with percentage of ozone depletion. Several environmental factors contribute to the uncertainties in surface UV irradiance computation and are needed to study further.

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