Modelling and observations of biologically active solar UV radiation: towards balancing between health risks and benefits

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Abstract – Studies of the UV-radiation are the most actual ecological problems that are called by ozone depletion increasing the level of biologically active solar UV-B radiation in the biosphere. The air pollution and atmospheric aerosols prevent penetrating appropriate dose UV radiation, which is beneficial for people, specifically due to production of vitamin D_3 in skin from its precursor 7-dehydrocholesterol. Both factors define necessity of the control of the UV-radiation terrestrial level. Many physiologic genetic and biochemical cell parameters change under the UV radiation impact. Thus the UV-radiation is the active bio-regulator. Here we elucidate the synergic biologic interaction with biologic objects, for natural conditions of the solar UV irradiance, various atmospheric state and with different lightning geometry. In addition, we present here reliable algorithm for direct calculation of the vitamin D synthetic capacity of sunlight using the photoreaction model of vitamin D synthesis with solar UV-spectra at the input.

Keywords: solar UV radiation, aerosols, optical model, biologic impact, health

1. INTRODUCTION

Ozone depletion leads to an increase in the ultraviolet-B (UV-B) component (280–315 nm) of solar ultraviolet radiation (UVR) reaching the surface of the Earth with important consequences for human health. Solar UVR has many harmful and some beneficial effects on individuals and, widely discussed (de Gruijl et al., 2003, Terenetskaya, I., 2003, Orlova and Terenetskaya 2008). Solar ultraviolet (UV) radiation (280-400 nm) is essential for vital functions in biosphere, therefore permanent UV monitoring is conducted at the meteorological stations over the globe along with satellite measurements. Latitudinal, seasonal and diurnal variability of terrestrial solar UV-B (280-315 nm) radiation is intensified by the changes in cloudiness, total ozone (both in the stratosphere and in troposphere), aerosols and air pollutions (Kondratyev and Varotsos 1996). Prediction of biologic effects of solar radiation on human health, in particular, involving terrestrial level of solar UV radiation, requires development of adequate methodological strategy for remote sensing. To date, it is well understood that in appropriate dose UV radiation is beneficial for people, specifically due to production of vitamin D_3 in skin from its precursor 7-dehydrocholesterol. But as far as excessive UV exposures cause acute and chronic health effects, in most cases biological activity of solar UV radiation is calculated by weighting solar UV spectra with CIE erythemal action spectrum. Yet, the beneficial vitamin D synthetic capacity of sunlight cannot be correctly estimated by this way in view of significant difference between the erythemic and the vitamin D synthesis action spectra.

The atmospheric ozone is the major medium attenuating the UV radiation and is characterized by an inhomogeneous distribution in the atmosphere with a maximum height level of 20–25 km. However, the flux of the UV radiation is also significantly reduced by molecular scattering, atmospheric aerosols and clouds. UV radiation is calculated using the Eddington method on the base of the simplest model of a homogeneous atmosphere.

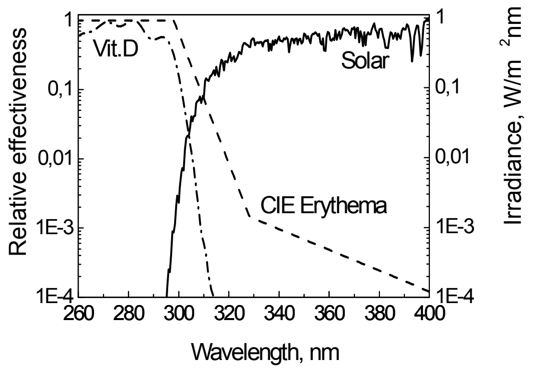

Figure 1. The Vitamin D synthesis and the CIE erythema action spectra in relation to solar UV spectrum.

2. ATMOSPHERIC OPTICAL MODEL

The model of a homogeneous atmosphere is used, considering the six wavelengths 280, 300, 320, 340, 360, 400 nm at two atmospheric pressure levels, 1000 and 500 mb (corresponding on average to altitudes of 0 and 5 km, respectively, above the mean sea level), and two atmospheric ozone levels, normal for summer mid-latitudes plus those decreased by 50%. The surface albedo is assumed to be 0 and 0.8 (corresponding to water and snow cover).

The optical thickness of the clear atmosphere is $\tau_0 = \tau_{as} + \tau_{aa} + \tau_{Rel} + \tau_{oz}$, where τ_{as} and τ_{aa}, are the optical thickness' of aerosol scattering and absorption; τ_{Rel} and τ_{oz}, optical thicknesses of molecular (Rayleigh) scattering and ozone absorption, respectively; the single scattering albedo (probability of photon survival) is $\omega = (\tau_{as} + \tau_{Rel})/\tau_0$. The atmospheric model includes the following parameters whose values were chosen according to Kondratyev (1969, Kazantidis et al. 2005, Meleti et al. 2009):

τ_{Rel} 1000mb is the optical thickness of molecular scattering at the sea level; and 5-km altitude; τ_{scatt} is the optical thickness of scattering by molecules and aerosols; τ_{oz} is the optical thickness of absorption for normal ozone content (Model I); $0.5\tau_{oz}$: the optical thickness of absorption for normal ozone content decreased by 50% (Model II); $\tau_{,i,1000}$ and $\tau_{,i,500}$: the total optical thicknesses for *i*-th model of the ozone content at the sea level and 5-km altitude, respectively; $\omega_{i,1000}$ and $\omega_{i,500}$: the single scattering albedos for *i*-th model of the atmosphere at the sea level and 5-km altitude, respectively; F_λ: the spectral solar incident flux at the top of the atmosphere according to. The spectral values of the optical parameters are presented in Table A.

Table A. Optical model of the atmosphere in the UV spectral region

Model	λ, nm	280	300	320	340	360	400
	τ_{Rel} 1000mb	1.51600	1.15240	0.88850	0.69740	0.55470	0.36400
	τ_{Rel} 500mb	0.75800	0.57620	0.44430	0.34870	0.27740	0.18200
	τ_{as}	0.38700	0.37110	0.35500	0.33900	0.33900	0.27600
	τ_{aa}	0.04000	0.04000	0.04000	0.04000	0.04000	0.04000
	τ_{diff} 1000mb	1.90300	1.52350	1.24350	1.03640	0.89370	0.64000
	500mb	1.14500	0.94730	0.79930	0.68770	0.61640	0.45800
I	τ_{oz}	36.14000	3.44500	0.30610	0.02200	0.61×10^{-3}	0.00000
II	$0.5\,\tau_{oz}$	18.07000	1.72330	0.15300	0.01100	0.30×10^{-3}	
I	$\tau_{I,1000}$	38.08000	5.00850	1.58960	1.09840	0.94400	0.68000
II	$\tau_{III,1000}$	20.01300	3.00680	1.43650	1.08740	0.94300	
I	$\omega_{0\ I,1000}$	0.04044	0.30418	0.78227	0.94355	0.95657	0.94118
II	$\omega_{0\ III,1000}$	0.10566	0.50669	0.86564	0.95310	0.95758	
I	$\tau_{I,500}$	37.32500	4.46700	1.14540	0.74970	0.66710	0.49800
II	$\tau_{III,500}$	19.25500	2.74510	0.99230	0.73870	0.66400	
I	$\omega_{0\ I,500}$	0.03067	0.18914	0.69784	0.91730	0.93089	0.91967
II	$\omega_{0\ III,500}$	0.05946	0.31505	0.80550	0.93096	0.93524	
	F_λ (W m^{-2} nm^{-1})	87.96150	305.72000	793.82300	1195.79000	1294.81100	1850.01000

3. CALCULATION METHODOLOGY

The UV irradiances in units of incident flux at the top of the atmosphere (Fl_0) and in energy units on the horizontal and vertical surfaces, as well as the proportion of the scattered light on the ground and the ratio of reflected irradiance to that transmitted by the atmosphere are calculated with using the Eddington method, because they demonstrate the biological impact of the UV radiation. Given below are the expressions for the above mentioned characteristics that were obtained for hemispherical fluxes with A=0 following to Harshvardhan and King (1993)

$$F^{\uparrow}(0,\mu_0) = m_6\left[(1-\kappa\mu_0)(a_2+\kappa\gamma_3)e^{\kappa\tau_0} - (1+\kappa\mu_0)(a_2-\kappa\gamma_3)e^{-\kappa\tau_0} - 2\kappa(\gamma_3 - a_2\mu_0)e^{-\tau_0/\mu_0}\right]$$
$$F^{\downarrow}(\tau_0,\mu_0) = \left[1 - m_6(m_1 - m_2 - m_3)\right]e^{-\tau_0/\mu_0} \qquad \textbf{(1)}$$

The surface reflectivity is accounted for by the known relationships (Minin, 1988):

$$\overline{F}^{\uparrow}(0,\mu_0) = F^{\uparrow}(0,\mu_0) + A_s V(\tau')\overline{F}^{\downarrow}(\tau_0,\mu_0)$$
$$\overline{F}^{\downarrow}(\tau_0,\mu_0) = \frac{F^{\downarrow}(\tau_0,\mu_0)}{1 - A_s A(\tau_0)} \qquad (2)$$

$A(0)$ and $V(\tau_0)$ are the spherical albedo and transmission of the atmosphere. The expressions for $A(0)$ and $V(\tau_0)$ was derived in Harshvardhan and King (1993). For diffuse radiation only the following holds:

$$A(0) = \frac{\gamma_2\left(1 - e^{-2\kappa\tau_0}\right)}{\kappa + \gamma_1 + (\kappa - \gamma_1)e^{-2\kappa\tau_0}} \qquad (3)$$

$$V(\tau_0) = \frac{2\kappa e^{-\kappa\tau_0}}{\kappa + \gamma_1 + (\kappa - \gamma_1)e^{-2\kappa\tau_0}} \qquad (4)$$

The irradiance to vertical surface (the flux to the skin of a vertically standing person) is helpful in assessing the potential hazard for human health, associated with external UV exposures. According to Kondratyev (1977), the irradiances are calculated by the following expression for the direct radiation flux incoming to the vertical surface oriented toward the Sun:

$$\overline{F}^{\downarrow}_{vert}(\tau_0,\mu_0)direct = \sqrt{1-\mu_0^{\,2}}\,\exp\left(-\tau_0/\mu_0\right) \qquad (5)$$

And for the overall radiation flux incoming to the vertical surface oriented toward the Sun :

$$\overline{F}^{\downarrow}_{vert}(\tau_0,\mu_0)_{Sum} = \sqrt{1-\mu_0^{\,2}}\,\exp\left(-\frac{\tau_0}{\mu_0}\right) + 0.5\left[\overline{F}^{\downarrow}(\tau_0,\mu_0) - \exp\left(-\frac{\tau_0}{\mu_0}\right)\right] \qquad (6)$$

Then, the total radiation flux oriented opposite to the Sun is expressed by the formula:

$$\overline{F}^{\downarrow}_{vert}(\tau_0,\mu_0)_{Sum} = 0.5\left[\overline{F}^{\downarrow}(\tau_0,\mu_0) - \exp\left(-\tau_0/\mu_0\right)\right] \qquad (7)$$

4. RESULTS OF CALCULATION

Figure 1 presents the spectral dependence of the ratio of reflected irradiance at the top of the atmosphere to that transmitted at the ground level. The information obtained from figure 1 is how much the reflected UV-irradiance exceeds the transmitted irradiance in the 280 – 400 nm range. It is clearly seen that the influence of the atmospheric model by the ozone content and atmospheric pressure is negligible at wavelengths longer than 300 nm. At the same time, the ozone content primarily governs the considered ratio at $\lambda < 300$ nm. A significant increase in the transmitted irradiance (because of 50% ozone depletion) causes a strong decrease in the ratio at short wavelengths.

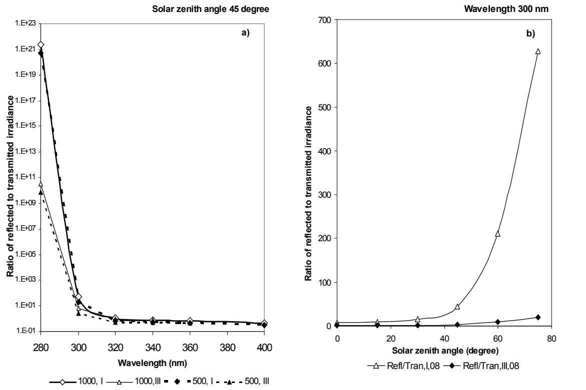

Figure 2. Spectral (a) and angular (b) dependences of the ratio of the reflected to transmitted irradiance for two models of the atmospheric ozone content: I (triangles) and II (rhombs) and for two values of the atmospheric pressure: 500 mb (dashed line) and 1000 mb (solid line), the case (a) for solar zenith angle of 45 degrees and surface albedo of 0; the case (b) at wavelength 300 nm and surface albedo of 0.8

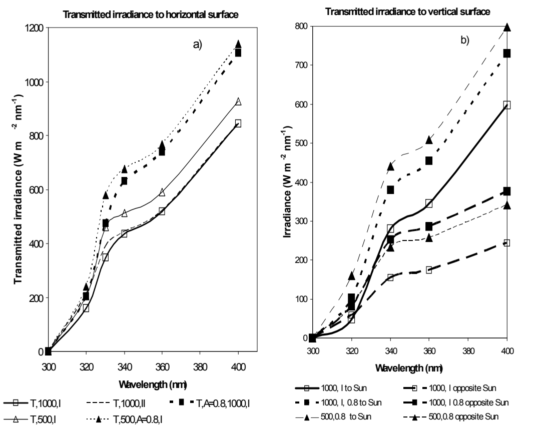

Figure 3. Spectral dependence of transmitted irradiance in the energy units to the horizontal (a) and vertical (b) surfaces, for two models of the atmospheric ozone content: I (solid and dashed lines) and II (dotted line), for two values of the atmospheric pressure: 500 mb (triangles) and 1000 mb (squares), for two values of the surface albedo: A=0 (open symbols in curves) and A=0.8 (solid symbols).

The Figure 2a presents the spectral transmitted flux in the energy units incoming to horizontal surface, which shows the strong influence of ground albedo, atmospheric pressure, and geometry of illumination (the surface is oriented toward or opposite to the Sun). The spectral flux incoming to the vertical surface is shown in Figure 2b. This flux fairly adequately simulates the illumination of a standing human body; it reaches a maximum at the solar incident angle of 45°. Two cases are considered: the surface orientations toward and opposite to the Sun. It is important that an increase in albedo exerts even more significant impact on the UV flux than does a decrease in the atmospheric pressure.

5. BIOLOGICAL EFFECT OF THE UV-RADIATION

To weigh the risks and benefits of sun exposure it is necessary to determine moderate exposures that provide adequate vitamin D nutrition for people but prevent skin cancer. Recently various approaches were suggested to solve this problem (Webb and Engelson 2006, Fioletov et al. 2009, McKenzi et al. 2009).

Taking into account the widespread of natural photosynthesis of vitamin D in biosphere the new algorithm for direct calculation of the vitamin D effective solar irradiance has been introduced (Orlova and Terenetskaya 2008) which is based on the First Law of Photochemistry: "Light must be absorbed for photochemistry to occur" and enables calculation of the photoreaction kinetics for any UV radiation source with known spectral irradiance. As is known, the complex network of Vitamin D synthesis consists of the two stages of monomolecular isomerization (Havinga, 1973). At the first stage, UV irradiation of provitamin D yields previtamin D, which further is thermally converted into vitamin D (Scheme 1), and just amount of previtamin D accumulated during an UV exposure is a measure of biologically active UV dose.

The kinetics of provitamin D photoisomerization can be described by the system of rate equations (Galkin and Terenetskaya 1999), and for estimation of the vitamin D synthetic capacity of sunlight at any latitude a solar spectrum is used at the model input. To validate the proposed algorithm, an *in vitro* model of vitamin D synthesis was used in Kiev in 2004 for direct measurement of the accumulated previtamin D concentration during April – September, and the amount of accumulated previtamin D was calculated using solar UV spectra simulated with FASTRT Program (Engelsen and Kylling 2005).

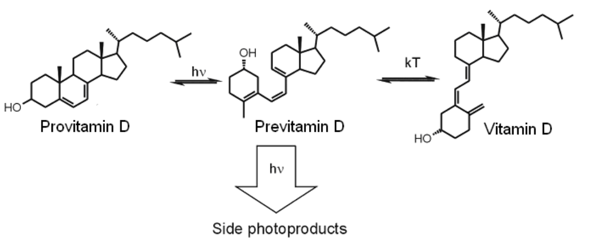

Figure 4. Schematic representation of vitamin D_3 synthesis under UV irradiation.

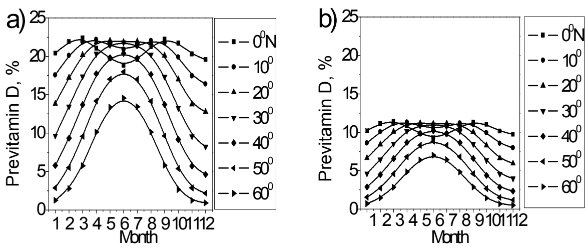

Figure 5. Calculated effect of seasonal changes of previtamin D production *in vitro* as a percentage of the starting solution of 7-DHC exposed to sunlight for one hour exposure around noontime at the ozone thickness 200 DU (a) and 300 DU (b) on different geographic latitudes.

The experimental results are presented in figure 4 together with calculated seasonal dynamics of accumulated previtamin D, i.e., of the vitamin D synthetic capacity of solar UV radiation. At, on the whole, satisfactory consent of experimental data with calculated curve one can see that clear majority of the experimentally measured concentrations is considerably below than the curve (dotted line) calculated for cloud and aerosol free conditions and ozone layer 300 DU.

As to the ozone layer thickness effect, specificity of ozone effect on the vitamin-D-synthetic capacity was shown earlier (Terenetskaya, 2003). It appeared that not only the rate of previtamin D accumulation is markedly dependent on the position of the short-wave edge of solar spectra, but its maximum achievable concentration is strongly increased with ozone layer decrease.

Just to illustrate immense effect of total ozone on the vitamin D synthetic capacity of sunlight we calculated seasonal changes of terrestrial UV solar spectra at the North Hemisphere for two different ozone layer thicknesses (200 DU and 300 DU) at several geographic latitudes using FASTRT program. Then the previtamin D concentration dependences under normal solar rays incidence during 1 hour exposure were obtained (see figure 6) by solving the system of rate equations (2) with calculated solar spectra as $I_0(\lambda)$. Significant effect of total ozone on previtamin D synthesis is evident by comparison the graphs in figures 5a) and 5b). Besides, from the figure 4 one can see that effect of season on previtamin D photosynthesis is much more pronounced at latitude 60^0, but becomes less evident at latitude 30^0 and almost disappears near equator.

6. CONCLUSION

The major component of the atmosphere, attenuating the UV radiation, is atmospheric ozone. However, an important attenuating factor is molecular scattering, as suggested by comparison of the results obtained for the atmospheric pressures of 1000 and 500 mb. The illumination geometry and the surface albedo also contribute greatly. Thus, under selected combinations of these factors, the UV flux for the normal ozone content even exceeds that for 50% ozone depletion. These results should be taken into account when considering the biological hazard associated with ozone depletion.

Although there are both beneficial and detrimental UV effects, it is an increase in the detrimental effects, associated with ozone depletion and/or climate change, attracts most attention. However, UV index introduced by WMO in 1994 to raise public awareness, is not attributable to the vitamin D synthetic capacity of sunlight in view of the remarkable difference between the CIE erythema and the 'Vitamin D' action spectra. Hence, estimating the risk of getting sunburn, the erythemal action spectrum is unable to estimate correctly the benefit for vitamin D synthesis (Terenetskaya 2003).

This study gives practical guidance on direct calculation of the vitamin D synthetic capacity of sunlight using solar spectra together with the photoreaction model. Critical dependence of previtamin D_3 accumulation on stratospheric ozone, season, and illumination conditions, is demonstrated.

We think that global UV mapping as well as annual and daily forecasts should consider both erythemal and ‘antirachitic’ solar indices. In our opinion presented algorithm is useful for direct estimation of the vitamin D synthetic capacity of sunlight and provides a means for introduction of new UV ‘D-index’.

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