Comparison of experimental and calculated data on intensity of scattered ultraviolet radiation on the Earth's surface for the cloudless atmosphere

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Received January 25, 2001

Scattered fluxes of ultraviolet radiation on the Earth's surface are modeled by the Monte Carlo method. Ultraviolet irradiance of the Earth surface was measured by a filter spectrophotometer in two spectral regions *A* and *B*. Calculated results and experimental data are compared in order to refine spectrophotometer characteristics and conditions of observations.

Introduction

Investigation of ultraviolet (UV) radiative fluxes on the Earth's surface is of great significance. Although the UV fraction in the net flux of solar energy reaching the ground is no more than 4–5%, it shows high biological and photochemical activity because of high quantum energy. The data on the principal characteristics of the UV radiation field and its variability depending on different parameters of the atmosphere are of interest as well. Unfortunately, UV fluxes are regularly measured at a small number of sites and often by different equipment.[1] Therefore, complex investigations (observations and calculations for different models of the atmosphere) of characteristics of the UV radiation field are especially significant. In this connection, the choice of the technique for calculating the UV fluxes in the atmosphere is especially important. The technique should take into account not only physical factors of the transfer process, but also all known characteristics of instrumentation, as well as give the capability of selecting the parameters of the optical model most closely corresponding to the conditions of observations.

Solution of the problems of UV radiation in the atmosphere is complicated by the fact that propagation of UV radiation in the atmosphere has some peculiarities.

1. In the spectral region $\lambda < 0.32$ μm, ozone plays an essential role, and the optical absorption thickness increases quickly as the wavelength decreases;
2. The optical thickness of molecular and aerosol scattering is large in the considered spectral region ($\lambda < 0.4$ μm);
3. The net flux of UV radiation, especially, in its short-wave region is principally determined by the scattered component, in which the fraction of multiple scattering is large;
4. The UV spectral region is characterized by a low surface albedo, especially, in summer.

Numerical results are very often obtained with simplified models (plane geometry, medium homogeneity, spherical or molecular scattering phase function, etc.). With such an approach, it is difficult to compare calculated data with experimental observations. Calculations by the Monte Carlo method are successfully applied to interpretation of observations in the UV spectral range.[2,3] Principal advantages of this method are caused by its capability of determining spatial and spectral distributions of characteristics of atmospheric radiative fields with a sufficient accuracy taking into account actual atmospheric geometry and arbitrary spatial distribution of scattering and absorbing components by probabilistic modeling of the transfer process. Due to the wide variety of models, the efficiency of the Monte Carlo method can be increased significantly, and a wide range of problems of atmospheric optics can be solved.[4]

In this paper, the Monte Carlo method is applied to modeling of the solar UV fluxes on the Earth's surface. Calculations are carried out for the cloudless model of the atmosphere. The UV fluxes on the Earth's surface were experimentally measured by a filter spectrophotometer[5] for the period of 1994–2000 in two wavelength regions *A* and *B*. Filters corresponding to these regions had the central wavelengths of 353 and 281 nm and bandwidths of 53 and 24 nm, respectively. Calculated results are compared with the results of observations.

Modeling of the field of scattered ultraviolet radiation

The scattered UV radiative fluxes on the Earth's surface were modeled using the method of adjoint trajectories.[2] This method was chosen because it is most efficient for estimation of fluxes at a point of the phase space in the illuminated area of the atmosphere.[3] The idea of the method lies in modeling of random trajectories from the point of observation with directions uniformly distributed in the solid angle of observations Ω. The following parameter was calculated at every point x_n of photon collision with an atmospheric particle:

$$\psi_n = \frac{e^{-\tau(r_n)}\, g(-\omega^{(S)}\, \omega_n)\, q(r_n)}{2\pi}\,\Omega ,$$

where n is the serial number of collision on the particle's trajectory; $\tau(r_n)$ is the optical length of the segment from the point r_n to the atmospheric boundary in the direction $-\omega^{(S)}$ (direction to the Sun), ω_n is the direction of particle motion before collision at the point r_n; $q(r) = \sigma_s(r)/\sigma(r)$, $\sigma(r)$ and $\sigma_s(r)$ are the total radiation extinction and scattering coefficients of the atmosphere; $g(\mu)$ is the normalized atmospheric scattering phase function; Ω is the solid angle of observation. Then the total intensity of multiply scattered solar radiation can be estimated as $I = M\xi$, $\xi = \sum\limits_{n=1}^{N} \psi_n$, where N is the number of particle collisions on the trajectory.

The 32-level models of the atmosphere[8] corresponding to the midlatitude conditions were used in calculations. The total column ozone in these models was equal to 332 D.u. in summer and 376 D.u. in winter. The contents of other gases absorbing UV radiation (NO_2 and SO_2) were equal to $5.11\cdot10^{15}$ and $3.4\cdot10^{15}$ mol/cm^2, respectively. Variations of the aerosol absorption and scattering optical thickness were taken into account via the meteorological range (MR) in the surface layer of the atmosphere. The values of 25 and 50 km were taken as boundary values of this parameter. The spectral behavior of the aerosol absorption and scattering coefficients, as well as molecular absorption and scattering coefficients in the atmospheric column (midlatitude summer model) is shown in Fig. 1. The surface albedo in winter was equal to 0.6, and the Lambert's reflection law was used, i.e., $G(\mu) = 2\mu$, $0 \le \mu \le 1$, where μ is the cosine of the angle between the normal to the surface and the reflection angle. Geometric and optical characteristics of instrumentation and observational conditions were taken into account as well.

The Monte Carlo algorithm was implemented based on a program developed at the Institute of Atmospheric Optics SB RAS.[6] The intensity of the scattered UV radiation was calculated for the spherical model of the atmosphere. The intensity of the UV radiative flux was calculated in the wavelength range from 290 to 395 nm with the step of 5 nm. The number of modeled trajectories was equal to 50000. The relative rms error of the obtained results did not exceed 10%.

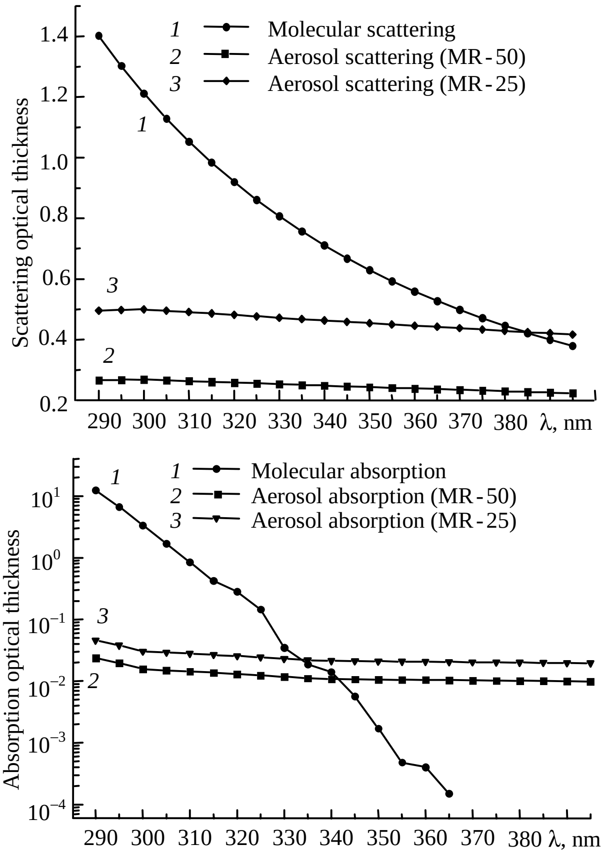

Fig. 1. Optical parameters of the atmospheric models used for calculations.

Experimental observation of UV radiative fluxes

A spectrophotometer for measurement of the total intensity of UV radiation in the wavelength regions A and B was developed at the Tomsk State University early in the 90's.[5] This device has been used since 1994 for regular observation of solar UV radiative fluxes on the surface in Tomsk.

The UV spectrophotometer is shown schematically in Fig. 2. It consists of receiving antenna *1*, filters *2*, photomultiplier tube (PMT) *3*, measuring system *4*, and PMT power supply *5*. The KU-2 quartz hemisphere placed the convex side up was used as a receiving antenna. This antenna collects radiation in the solid angle of 0.586π that corresponds to the plane angle at the top of a collection cone γ = 90°. Radiation was received by the FEU-170 photomultiplier with a Te-Rb photocathode. Characteristics of the used filters, as well as the PMT sensitivity are shown in Fig. 3.

The digital measuring system with a liquid-crystal display was used to measure an electric signal from the photomultiplier. The display showed the voltage drop, in millivolts, across the output resistor. This value is proportional to the photocurrent, which, in its turn, is proportional to the intensity of the light flux incident on the receiving antenna. Thus, the spectrophotometer outputs the intensity of the UV radiative flux in relative units. Simultaneous measurements of the solar radiation intensity by the UV spectrophotometer and the UBF biological photometer developed by the group headed by Lazarev[7] were used for obtaining the calibration curves.

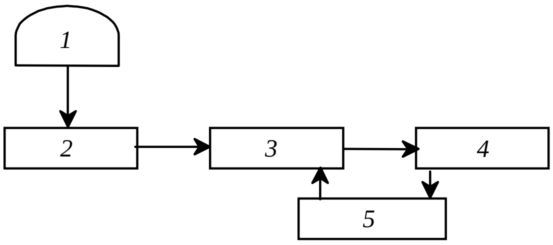

Fig. 2. Layout of the UV spectrophotometer: receiving antenna *1*, filters *2*, photomultiplier tube (PMT) *3*, measuring system *4*, and PMT power supply *5*.

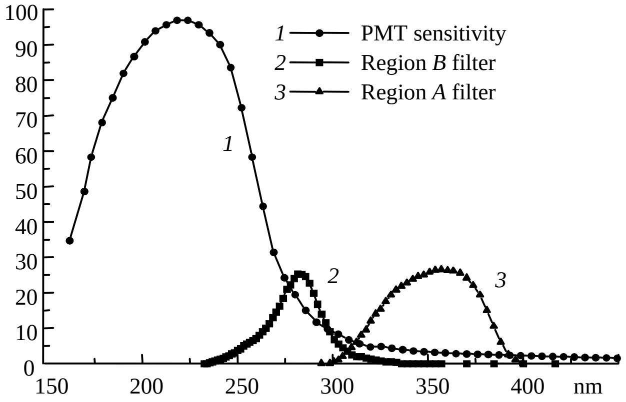

Fig. 3. Optical characteristics of the spectrophotometer.

Observations of the UV radiative fluxes were carried out as follows. The spectrophotometer was installed on a horizontal plane with the receiving antenna directed at zenith. Observations were carried out for the sun elevation angles multiply to five (5, 10, 15°, etc.) in the regions *A* and *B*. Series of five measurements with different PMT gain factors were performed for each spectral region. Each obtained value was recalculated to an absolute value (in W/m^2) with the use of the calibration curves. The mean value over a series of five measurements was taken as a result of observation.

The results of measurements obtained in summer (April till September) and winter (October till March) periods at almost cloudless atmosphere (total cloud fraction of 0 to 0.2, lower cloud fraction of 0) were selected for the study to avoid the effect of clouds and to smooth the annual behavior of the total column ozone. The selected observations were averaged for every sun elevation angle, and the confidence intervals were calculated for every mean value. The UV radiation intensities calculated by the Monte Carlo method for midlatitude summer were reduced to the experimental values (Fig. 4).

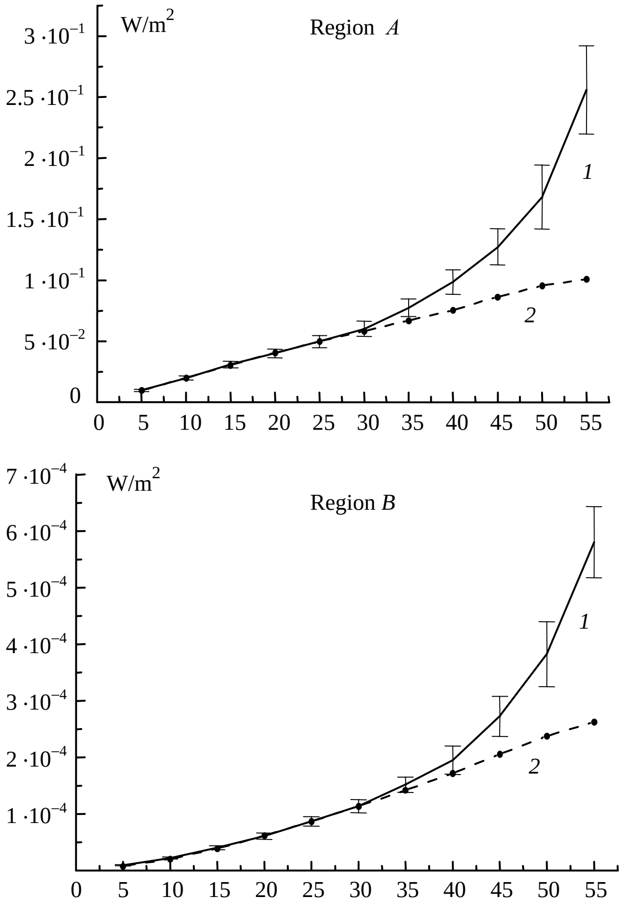

Fig. 4. Comparison of calculated and measured UV radiative fluxes in the regions *A* and *B*: observations (curve *1*) and calculation by the Monte Carlo method (*2*).

Significant discrepancies between the calculated and experimental data at angles larger than 30° are connected with the fact that the receiving antenna did not have the well-pronounced 90° reception cone and had a complex diagram of radiation collection. Most likely, the spectrophotometer begins to record the direct radiation already at the sun elevation angle of 35° (that corresponds to the radiation collection angle of 110°). The fraction of direct radiation in the net UV radiative flux recorded by the spectrophotometer increases, as the sun elevation angle increases, but has a complex and not fully understood behavior. Therefore, calculations were carried out only for the scattered component, and the direct UV radiation was neglected.

Theoretically, the fraction of the direct radiation in the net flux is the difference between the experimental and calculated values. Nevertheless, for the complex study of the UV radiation at the sun elevation angles ≥ 35°, it is necessary to experimentally obtain the function describing the dependence of the fraction of the direct radiation in the net UV flux recorded by the spectrophotometer. It will allow the spectrophotometer characteristics to be refined and considered more accurately in subsequent calculations and comparison with the results of measurements.

Thus, we can conclude that only the values obtained at the sun elevation angle less than 35° correspond to measurements of the scattered component of UV fluxes with this spectrophotometer.

To refine the spectrophotometer characteristics and conditions of observation at the sun elevation angle less than 35°, calculations were made at two values of the solid angle of the receiving antenna ($\gamma = 90$ and 110°) and different aerosol optical thickness (the MR parameter). The calculations were performed for summer and winter conditions, and the values obtained by the Monte Carlo method were reduced to the experimental ones (Table 1). The calculated and measured results for the summer conditions are shown in Fig. 5.

Table 1. Normalization coefficients for calculated data

Region	MR	Summer	Winter	Summer	Winter
		γ = 90°		γ = 110°	
A	50	0.877	0.912	1.254	1.459
	25	0.916	0.950	1.274	1.493
B	50	5.84	6.74	8.81	10.4
	25	5.88	6.75	8.68	10.3

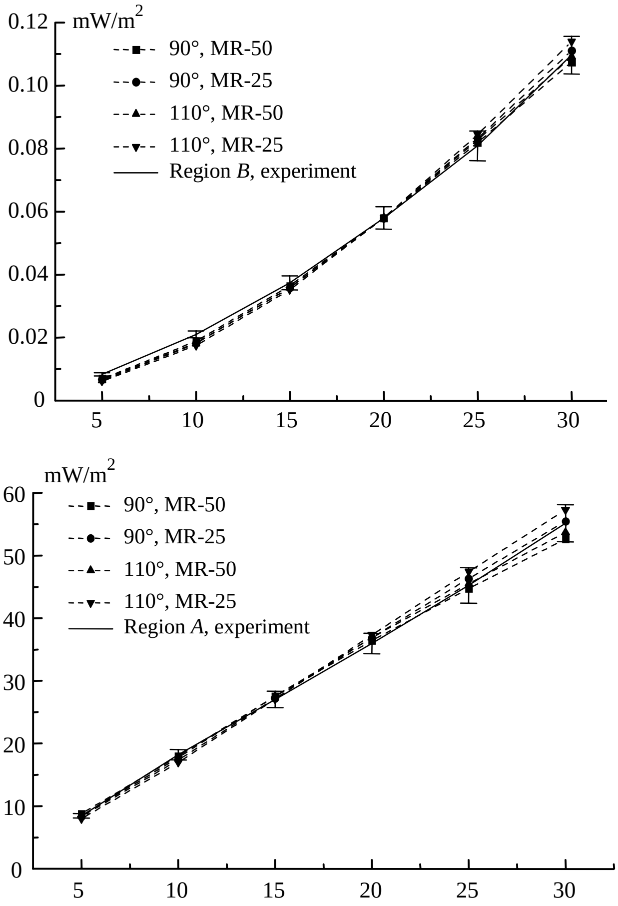

Fig. 5. Comparison of calculated and measured values of UV fluxes in the regions *A* and *B* as functions of the sun elevation angle.

The calculations have shown that the absolute values of the UV-A radiation intensity in summer are underestimated for the receiving antenna angle of 90° and overestimated for the angle of 110° (see Table 1). Herefrom we can conclude that this parameter should be taken close to 100° in calculations. The discrepancy between the calculation and the experiment in the regions *A* and *B* is larger in winter than in summer, and the normalization coefficient in the region *A* is large. This is indicative of the more complex behavior of optical parameters of the atmosphere and the surface in winter.

The calculated data for the summer period after normalization lie within the confidence intervals of measurements, thus evidencing that the parameters of the atmospheric optical model used for calculation in the region *A* are adequate to measurement conditions. The overestimated values of the calculated data in the region *B* indicate that some additional attenuating factors in the atmosphere or in the spectrophotometer's optical channel were ignored. One of such factors may be the atmospheric water vapor absorption band in the region from 250 to 320 nm.[9,10] This fact should be necessarily taken into account in the following modeling of UV fluxes and interpretation of measurement results.

The analysis of calculations has also shown that variation of the aerosol scattering and absorption optical thickness in the atmospheric surface layer changes only the absolute value of the intensity of the scattered UV radiation and insignificantly affects its behavior as a function of the sun elevation angle. Then, as the parameter MR decreases, the intensity of UV fluxes increases in the region *A* and possibly decreases in the region *B* (see Table 1). Such a behavior is connected with the fact that, as the aerosol optical thickness increases, the number of scattering events in the atmosphere increases (see Table 2). Absorption is low in the region *A*; therefore, practically pure scattering occurs. The region *B* is characterized by stronger absorption, so the increase of scattering at large optical thickness can lead to the decrease of the radiation intensity. Just this effect is observed in the region *B* at small sun elevation angles (5 to 20°).

Table 2. The fraction of single scattering, in %, for the sun elevation angles from 5 to 55° (as calculated by the Monte Carlo method)

Region	MR-25	MR-50
A	26–53	33–56
B	24–44	30–47

Thus, the comparison of the calculation and the experiment has allowed us to refine some characteristics of the spectrophotometer and to reveal the presence of additional factors attenuating the UV-B radiation. The use of the obtained results in following modeling of UV fluxes will help not only to interpret the results and conditions of observations, but also to refine the parameters of optical models used in calculations.

Acknowledgments

In conclusion, the author would like to thank I.I. Ippolitov and V.V. Belov for useful discussion and Z.S. Teodorovich for the kindly presented results of experimental observations.

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