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Aerosol optical density of atmosphere and possibility of its definitions by means of integrated radiation of the sun

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Abstract

It is considered the possibility of determination of atmosphere optical density to the integral solar radiation. The respective integral equation kernel together with the spectral solar constant consist the functions of penetration of the molecular dissipation of the water vapor and ozone. These penetration functions are obtained and from the integral equation was found the aerosol optical density of atmosphere. Obtained solution was used for study of the aerosol optical density distribution above the territory of Georgia.

1. Decay of the energy of sun's monochromatic radiation during its passing through the earth atmosphere may be described by following simple differential equation:

$$dI_\lambda = -k\rho I_\lambda ds\,, \tag{1}$$

where I_λ is the intensity of the monochromatic radiation in length of wave λ; ρ is optical density of environment, i.e. a case in point of atmosphere, and k is the proportionality factor, characterizing to easing individual radiant energy, at individual optical density of atmosphere, on individual length of a way.

If we admit that not at very low solar altitude h, atmosphere is flat and horizontally homogeneous medium, and the center of coordinate system is located at earth's surface, then the solution of the equation (1) may be presented in a following form:

$$I_\lambda = I_{\lambda 0}\exp(-m\int_0^\infty k\rho dz)\,, \tag{2}$$

where $I_{\lambda 0}$ is value of I_λ outside of the atmosphere, and $m = sec(90 - h)$.

Integrating expression (2) in a range from λ_1 to λ_2, i.e. in the range of lengths of waves in which sun radiation the right part we will receive the integrated radiant stream weakened after passage of all atmosphere i.e. is located:

$$I = \int_{\lambda_1}^{\lambda_2} I_{\lambda 0}\exp(-m\int_0^\infty k\rho dz)d\lambda\,. \tag{3}$$

Expression $\int_0^\infty k\rho dz$ characterizes an optical condition of atmosphere and is known as the optical thickness or optical density of atmosphere [1] and designate through τ . Thus,

$$I = \int_{\lambda_1}^{\lambda_2} I_{\lambda 0} \exp(-m\tau) d\lambda \,. \qquad (4)$$

Attenuation of radiant energy of the sun by atmospheric components occurs either dispersion, or absorption of this energy. The basic disseminating substances of sun rays are so-called ideally clear atmosphere (molecular dispersion) and atmospheric aerosol particles absorbing the ozone and water steam. As the optical density of atmosphere is exponential, the vertical distribution of mentioned components of atmosphere may represent as the sum of optical density of the mentioned components:

$$\tau = \tau_z + \tau_u + \tau_w + \tau_a ,$$

here $\tau_z, \tau_u, \tau_w, \tau_a$ are the optical density of the ideally clear atmosphere, ozone, water steam, and aerosol particles of atmosphere, respectively.

2. Modern reference books contain a great deal of measured sizes of an integrated stream of a straight line of radiation of the sun. The purpose of our work is to study possibility of the approached definition of aerosol optical density of atmosphere from the equations (4) with use of the formula (5). Otherwise, an unknown value τ_a to define from the integral equation

$$I = \int_{\lambda_1}^{\lambda_2} K(\lambda, m) \exp(-m\tau_a) d\lambda \qquad (5)$$

the kernel of which is

$$K(\lambda, m) = I_{\lambda 0} \exp[-m(\tau_z + \tau_u + \tau_w)] \,. \qquad (6)$$

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At a sea level for isothermal atmosphere, as is known [2], approximately it is possible to define the vertical optical density of molecular dispersion by the following formula:

$$\tau_z = 0.00879 \lambda^{-4.09} , \qquad (7)$$

where λ is expressed in microns. In the conditions of linearly decreasing temperature stratification of atmosphere with a gradient $6^0 C / km$ 6°, since height z from a sea level and higher, reduction of optical density of molecular dispersion with height can be considered a multiplier $\exp(-z/8)A(z)$, i.e.:

$$\tau_z = 0.00879 \lambda^{-4.09} \, exp(z/8)A(z) , \qquad (8)$$

where z is expressed in km, and $A(z)$ considers non-isothermal atmospheres. Its numerical values with height are calculated in work [3]. Thus, penetration function of molecular dispersion, in a direction of sun rays, may be presented as

$$P_z = \exp(-\tau_z m) = \exp(-0.00879 \lambda^{-4.09} \exp(-z/8) A(z) m \,. \qquad (9)$$

2.1. As is known, strong selective strips of absorption of ozone are located in ultraviolet area of a solar spectrum in a range of 0.2-0.37 microns. Besides, ozone has a weak wide strip to absorption from 0.45 to a micron. Using results of works [4, 5], function of ozone penetration (function of penetration $P_u = \exp(-\tau_u)$) has been calculated

$$P_u = \begin{cases} 0.713(um)^{0.1} & at \quad \lambda \le 0.37 mkm \\ 1 & at \quad 0.37 \prec \lambda \le 0.45 nkn \\ 1-0.06um & at \quad 0.45 \prec \pi \le 0.74 mkm \\ 1 & at \quad \lambda \succ 0.74 mkm \end{cases} \tag{10}$$

where u is a thickness of an ozone layer in vertical directions, normalized to standard pressure.

2.2. Beginning from 0.7 microns and above, water steam in a solar spectrum has eight strips of absorption. Using coefficients of absorption in the strips, dependences of penetration function, of one or another strip, from the quantity of water steam have been calculated. For first six strips, in a range of spectrum 0.7-2.10 microns, they were taken from work [6], and for two strips in the field of a spectrum 2.27-3.57 microns – from work [7].

Thus, dependence of integral penetrating functions of water steam from its general maintenance in atmosphere was assumed by the following expressions:

$$P_w = \begin{cases} exp[32(wm)^{0.792} & at \quad 0.70 \prec \lambda \le 0.74 mkm \\ 1 & at \quad 0.74 \prec \lambda \le 0.76 mkm \\ exp[38(wm)^{0.725}] & at \quad 0.76 \prec \lambda \le 0.84 mkm \\ 1 & at \quad 0.84 \prec \lambda \le 0.86 mkm \\ exp[132(wm)^{o.578}] & at \quad 0.86 \prec \lambda \le 0.99 mkm \\ 1 & at \quad 0.99 \prec \lambda \le 1.03 mkm \\ exp[158(wm)^{0.503}] & at \quad 1.03 \prec \lambda \le 1.23 mkm \\ exp[606(wm)^{0.265}] & at \quad 1.23 \prec \lambda \le 1.53 mkm \\ exp[388(wm)^{0.167}] & at \quad 1.53 \prec \lambda \le 2.10 mkm \\ 1 & at \quad 2.10 \prec \lambda \le 2.27 mkm \\ exp[1331(wm)^{0.306}] & at \quad 2.27 \prec \lambda \le 3.0 mkm \\ exp[824(wm)^{0.989}] & at \quad 3.0 \prec \lambda \le 3.57 mkm \end{cases} \tag{11}$$

where w is a quantity of the matter in the vertical air cylinder with unit horizontal section ($g \cdot cm^{-2}$).

2.3. Based on the function penetration of ozone and water steam (formulas (10) and (11)), an integral range in the formula (6) has been divided into 18 components. In each integral waves of function not depending not so from length of ozone penetration and water steam could be taken out from under a sign integral. Thus the integral equation (6) has become:

$$I = \sum_{i=1}^{18} P_{ui} P_{wi} \int_{(\lambda_{ii})} I_{\lambda 0} P_z \exp(-m\tau_a) d\lambda \ . \tag{12}$$

For determination of $I_{\lambda 0}$ it was used Planck's formula:

$$I_{\lambda 0}(T) = \frac{2\pi c^2}{\lambda^5} \frac{h}{\exp(hc/k\lambda T) - 1} , \quad (13)$$

where c is the velocity of light in vacuum, h is Planck's constant, k is Stefan-Boltzmann's constant. Absolute temperature of a surface of the sun (T) as a rule accept equal $T = 5996^0 K$ [2]. Using the specified value of temperature and integrating expression (13) on all lengths of waves, we receive a so-called solar constant which exceeds accepted to its value $I_0 = 1370\ W \cdot m^{-2}$ at an average of distances between the earth and the sun [8]. To receive mentioned value I0 at integration (13) on λ, it is necessary (13) to accept in the formula $T = 5700^0 K$. Using the specified value of temperature and considering actual distance between the earth and the sun expression $(R / R_0)^2$ where R and R_0 accordingly actual and average distance between the earth and the sun, the formula (13) has become:

$$I_{\lambda 0} = \frac{2\pi c^2}{\lambda^5} \frac{h}{exp(hc/5700k\lambda) - 1} (R/R_0)^2 . \quad (14)$$

2.4. The second expression in integral in the equation (12) $exp(-m\tau_a)$, contains required size τ_a. Influence of aerosol particles on distribution of a radiant stream to atmosphere is expressed by dispersion of a radiant stream on these particles. Intensity of dispersion basically depends on two parameters atmospheric an aerosol, from the general concentration and from distribution of particles in the sizes. For τ_a the known empirical formula of Ángström [9] is used

$$\tau_a = \beta \lambda^{-n} , \quad (15)$$

where empirical factors β and n characterize accordingly the general concentration of aerosol particles in atmosphere and distributed particles in the sizes. Taking into account (15), the function of atmospheric aerosol particles penetration may present in a following form:

$$P_a(\beta n) = \exp(-\tau_a) = \exp(-\beta \lambda^{-n}) . \quad (16)$$

The formula (16) characterizes penetration radiant energy, in a vertical direction, from the top limit of atmosphere to a sea level. The account of different heights from a sea level it is possible entering multiplier $exp(-z/h_a)$, where h_a is the aerosol scale of height [10]. Entering mentioned multiplier into the formula (16) we have:

$$P_a = \exp(-\beta \lambda^{-n} \exp(-z/h_a)) . \quad (17)$$

As the weight integral in the equations (12) is divided into 18 composing parts, a range of changes λ of each integral is narrow enough. On the other hand, variability of $I_{\lambda 0}$ and P_z from λ is monotonous without sharp changing. Therefore, their average values can be taken out from the integral. Then the equation (12) will become:

$$I = \sum_{i=1}^{18} P_{ui} P_{wi} \overline{I_{\lambda 0 i}} \, \overline{P_{zi}} \int_{(\lambda_i)} P_a dz . \quad (18)$$

3. Thus, the equations (18) contain two unknown values - β and n. It is known that the aerosol optical density within day changes a little. This is often used at graduation actinometric instruments [11]. Special days, with invariable during of midday both aerosols, and as a whole, an optical condition of atmosphere, are selected. Hence, if to pick up similar day and to spend corresponding measurements, it will turn out some equation with two unknown values. It is necessary to notice that basically it is enough to spend two experiments in currents of midday and from two equations to define two unknown values. But, for increasing of accuracy it is necessary to increase number of experiments, i.e. quantity of the equation. As a result, 18 equations are used, for definition of two unknown persons β and n.

3.1. Let's enter designations:

$$K_{ij} = P_{uij} P_{wij} \overline{I_{\lambda 0i}} \, \overline{P_{zij}} \int_{(\lambda)} d\lambda \,,$$

$$X_i = \exp(-\beta \lambda^{-n} \exp(-z / h_a) m \,, \quad (i, j = 1,2,...,18). \qquad (19)$$

We will also admit that in each integral β and n are weakly changing values. Then the equation (18) can present in the form of the system of algebraic equation, i.e.:

$$\begin{aligned} K_{11} X_1 + K_{12} X_2 + ... + K_{1,18} X_{18} &= I_1 \\ K_{21} X_1 + K_{22} X_2 + ... + K_{2,18} X_{18} &= I_2 \\ \dots\dots\dots\dots\dots\dots\dots\dots \\ K_{18,1} X_1 + K_{18,2} X_2 + ... + K_{18,18} X_{18} &= I_{18} \end{aligned} \qquad (20)$$

4. Above stated method we have applied to the conditions of Georgian territory. In particular, the data of six actinometric points of observation located in different climatic zones (Tbilisi, Telavi, Tsalka, Anaseuli, Sukhumi, Senaki) were used. Data about intensity of direct radiation of the sun at the clear sky, in midday and 3 hours prior to midday were taken from [11]. The intermediate data (all for day of 36 cases) has been defined with the help of interpolation.

4.1. The solution of system (20) has been executed by a following way. In the beginning for 100 pairs β and n, values in a range of change β from 0 to 1 with step 0.1, and for n from 0 to 4 with step 0.4, had been calculated average square-law deviations between calculated and actual I, i.e. σ_1. Then for the pairs, with minimum value of σ_1, then with 10 times reduced step the values of σ_1 were again calculated. It proceeds before decreasing of σ_1 less than 1 % from average I. Received pair β and n was accepted by the solution of the equations.

It was impossible to compare obtained results with actual or with data received by other methods. It is only possible to judge, how much the calculated sizes close to real once.

4.2. As it has been above noted the data for 6 points, on 7 months from March to September, separately in the forenoon and in the afternoon, only 84 examples have been calculated.

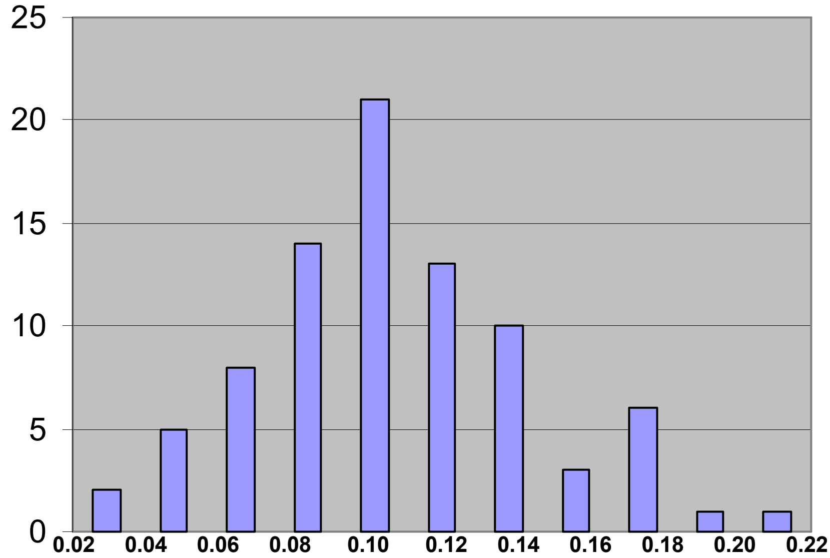

Fig. 1a. Distribution of numerical values of factor n from the formula (15).

In Fig. 1a distribution of numerical values of factor n on territory of Georgia on the average during 1954-1964 is given. As it is seen, β changes between 0.03 and 0.22 with a maximum nearby 0.1 which is close to the real picture.

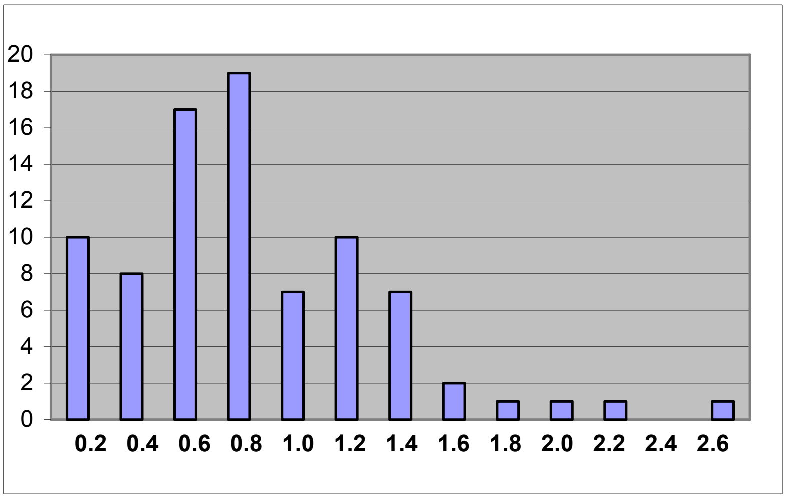

Fig. 1b. Distribution of numerical values of factor n from the formula (15).

As to factor n, the range of its changes on territories of Georgia makes 0.2-2.6, a maximum nearby 0.8 that is also correspond to the real values.

For each point of supervision, Figs. 2a and 2b represent change of these factors from March to September.

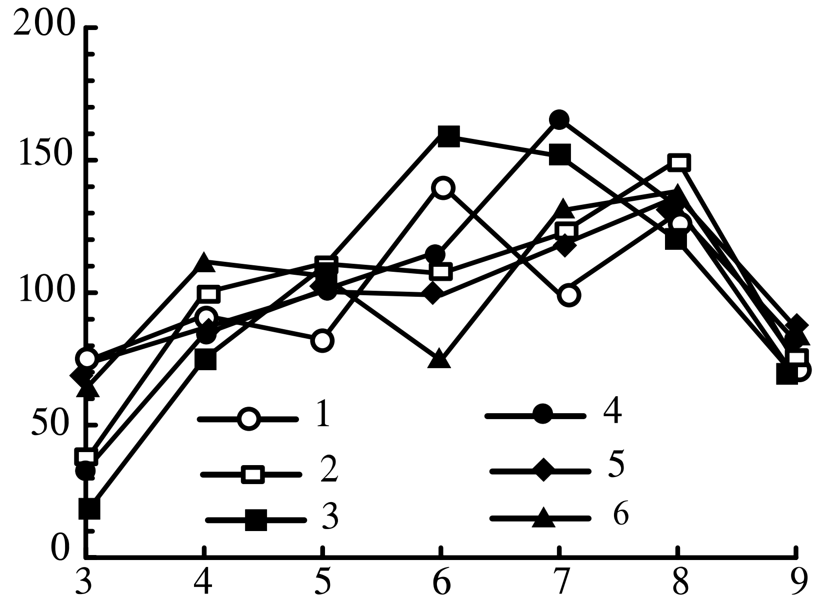

Fig. 2a. Change of normalized β-factor on months (1-Tbilisi; 2-Telavi; 3-Tsalka; 4-Anaseuli; 5-Sukhumi; 6-Senaki)

Fig. 2a shows relationship between the normalized values of β-factors (on a vertical) and the months (on a horizontal). Where the value of β-factor averaged over the seven months was taken as a normalizing parameter at that.

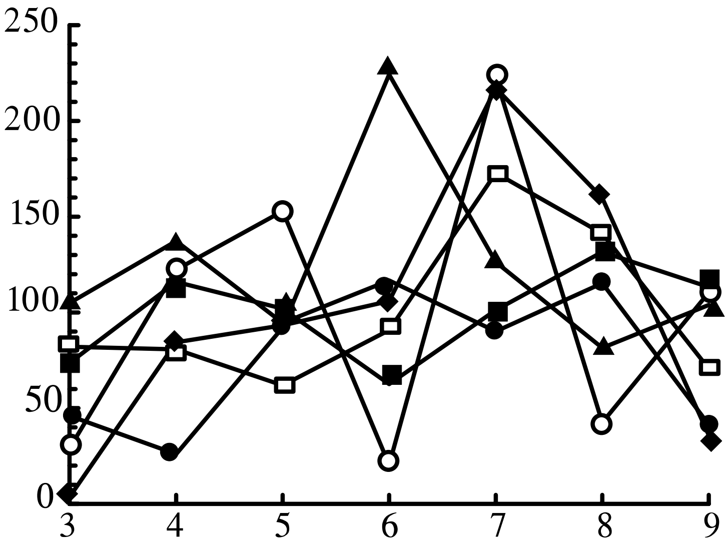

Fig. 2b. Change of normalized factor n on months
(Designations see on Fig. 2a)

If intraannual change of β-factor over whole territory of Georgia is in accordance with well expressed annual course, changing of n-factor has a casual character and changes in wider range.

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Аэрозольная оптическая плотность атмосферы и возможность ее определения по интегральному излучению солнца

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Резюме

Рассмотрена возможность определения аэрозольной оптической плотности по интегральному излучению солнца. Как известно, ядро интегрального уравнения переноса лучистой энергии солнца наряду со спектральной солнечной постоянной содержит функции пропускания молекулярного рассеивания водяного пара и озона. Определены эти функции пропускания и из интегрального уравнения получена аэрозольная оптическая плотность атмосферы. Полученное решение было использовано для изучения распределения аэрозольной оптической плотности по территории Грузии.

ატმოსფერული აეროზოლების ოპტიკური სიმკვრივე და მისი განსაზღვრის შესაძლებლობა მზის ინტეგრალური გამოსხივებით

კუკური ა. თავართქილაძე

რეზიუმე

განხილულია მზის ინტეგრალური გამოსხივებით ატმოსფერული აეროზოლების ოპ-ტიკური სიმკვრივის განსაზღვრის შესაძლებლობა. ატმოსფეროში მზის სხივური ენერგიის გადატანის ინტეგრალური განტოლების გული მზის სპექტრულ მუდმივასთან ერთად შეი-ცავს მოლეკულარული გაბნევის, წყლის ორთქლის და ოზონის გაშვების ფუნქციებს. გან-საზღვრულია აღნიშნული ფუნქციები და ინტეგრალური განტოლებიდან ამოხსნილია ატ-მოსფერული აეროზოლების ოპტიკური სიმკვრივე. მიღებული ამოხსნა გამოყენებულია საქართველოს ტერიტორიაზე ატმოსფერული აეროზოლების ოპტიკური სიმკვრივის გა-ნაწილების შესასწავლად.