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Direct Solar Radiation Distribution over the Territory of Georgia at Apparent Noon of Summer Solstice

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ABSTRACT. The paper provides development of the theoretical scheme for calculation of direct radiation spectral distribution for clear sky. Based on this the intensities of direct radiation on perpendicular surface at apparent noon, summer solstice for the clear sky and for cloud cover were calculated. Schematic maps of their distribution on the territory of Georgia were constructed. *© 2017 Bull. Georg. Natl. Acad. Sci.*

Key words: direct solar radiation, apparent noon, summer solstice

Sun is a single source of energy for the Earth ensuring existence of the biosphere. Before the radiant energy reaches the Earth surface it is subjected to complex transformations in the atmospheric strata. These transformations are mostly characterized with energy scattering and absorption. Propagation of the polychromatic ray through the multi-component medium is a complex process and currently it can be roughly described.

In the territory of Georgia, systematic observations over the solar radiation energy have taken place at several points for different periods (currently no observations are performed) though its distribution over the territory is not studied. Currently, only theoretical study of direct solar radiation distribution over the Georgian territory is possible. The purpose of this work is to provide theoretical calculation of direct solar radiation by 28 regions of Georgia with equal capacities and different in physical-geographical respect. Calculations are provided for a single moment – apparent noon on summer solstice. This is the period when, expectedly, the Earth surface receives maximal amount of energy from the sun. Though, we regard that here the main thing is well formulated calculation scheme that could be further used for any moment and any beam of the rays.

Transformation of monochromatic ray energy in the uniform medium is described by Bouguer-Beer formula [1]:

$$I = I_0 \exp(-\tau m), \qquad (1)$$

where I_0 and I are radiation energy intensities before entering the medium and after traveling through it with m optical mass; τ is the so-called extinction coefficient, i.e. optical density of the medium (frequently it is referred to as optical depth of the atmosphere [2]).

Formula (1) could be valid for the monochromatic rays, if the atmosphere consisted of single component. This formula describes transformation of the polychromatic ray in the multi-component atmosphere very roughly. Nevertheless, for the purpose of rough computations, this formula is frequently used and the error is improved by one or another correction [3].

Minimization of such error currently is possible, if the calculations are performed for the narrow wavelength range (Δλ) and calculate total energy through integration and express the atmosphere by individual strata of substances composing it. This is possible as with traveling through all the substances of the atmosphere the monochromatic ray transformation is exponential, i.e., this could be expressed through their superposition. Regarding that of atmosphere composition the propagating ray is impacted significantly only by the so-called ideally pure atmosphere, i.e., molecules of nitrogen and oxygen, water vapor, nitrogen, carbon dioxide and atmospheric aerosols (of them, carbon dioxide impact on direct solar radiation is negligible, it impacts significantly only the heat radiation of the atmosphere and land surface), the formula (1) could be written as:

$$I(\text{²ǀ꞊µǀ꞊~}, m) =$$
$$I_0(\lambda)\text{exp}\{-\text{²꞊}(\text{ª},\text{r})+\text{²꞊}(\text{ªǀµ})+\text{²꞊}(\text{ªǀ¬})+\text{²꞊}(\text{ªǀ~})]\text{m}\}\text{dª} \quad (2)$$

In expression (2) integration is provided by wavelength, boundaries of which are determined by the direct radiation spectrum. Actually, it is within the range from 0.22 to 5 μm. ²ǀ꞊¬ǀ꞊~ respectively, represent ideally pure atmosphere (nitrogen and oxygen), water vapor, ozone and atmospheric aerosols quantities in the vertical cylinder with unit cross-section of the atmosphere divided into the layers.

Thus, to determine the energy (direct solar radiation) that have reached the Earth surface directly from the sun, it is necessary to know the spectral composition of the radiant flux beyond the atmosphere boundaries and optical densities of ideal atmosphere, water vapor, ozone and aerosols. The mentioned parameters prevailing in Georgia can be found in the reference sources.

Spectral distribution of the solar radiant energy beyond the atmosphere boundaries is measured permanently and it is well known. Though, identification of the small parts of the initial and terminal sections of spectral range is possible only based on the theoretical considerations. This causes certain errors and may result at most, in one or two percent difference in the total energy. This paper uses the compared value of spectral distribution of solar radiation energy, obtained by K. Kondratyev [4]. Spectrum range (0.220-5.0 μm) is divided into 247 sections of 0.005 μm width, from 0.220 to 0.600 μm, 0.01 μm sections from 0.60 μm to 2.0 μm and 0.1 μm sections from 2.0 to 5.0 μm. For each of the sections average radiant energy is obtained. Their sum, i.e. solar constant is 1370 watt/m^2.

In the ideal atmosphere the energy attenuation is caused by scattering on nitrogen and oxygen molecules. In addition to the scattering substances, the scattering intensity depends on the shape of scattering elements, their linear dimensions and complex refraction index [5]. These parameters are well known and optical density of ideal atmosphere, from the sea level to upper limit of the atmosphere for vertically isothermal atmosphere could be quite accurately expressed by the following empiric formula:

$$\text{²꞊}(\text{ª},\text{r}) = 0.00879\text{exp}(-\text{ª}^{4.09}). \qquad (3)$$

Regarding that the sun ray fall on the underlying surface at the angle h and in the horizontally uniform isothermal atmosphere (i.e. h $\geq 15^{\text{O}}$) and has to travel through the optical mass m=sec (90$^{\text{O}}$-h) and the underlying surface is located at height z over the sea level and the atmosphere is not vertically isothermal, then formula (3) will be as follows:

$$\text{²꞊}(\text{ª},\text{r}) = 0.00879\text{exp}(-\text{ª}^{4.09})\text{exp}(z/8)A(z). \qquad (4)$$

where 8 is stated height of the atmosphere in km and $A(z)$ is the correction for atmosphere non-isothermal nature [5].

Irrespective of low content, water vapor and ozone significantly impact radiant energy propagation process in the atmosphere, being the key absorbers of solar energy. Their absorption spectrum is apparently very selective, with respect to wavelength and in the literature [6] they are presented in a form of Tables. After dividing the solar spectrum into 247 spectral sections, we have calculated average absorption factors of water vapor [7] and ozone [8] for each of them from the literature. As for distribution of total quantities of water vapor and ozone over the territory of Georgia, these data are known. Thus, Optical densities of water vapor and ozone in 247 sections of the individual strata are calculated by similar formulas:

$$^{2}\text{-}(^{a}|\mu) = k\,(^{a}|\mu)\mu. \tag{5}$$

For water vapor and ozone:

$$^{2}\text{-}(^{a}|\neg) = k\,(^{a}|\neg)\neg| \tag{6}$$

where $k\,(^{a}|\mu)$ and $k\,(^{a}|\neg)$ are average absorption factors of water vapor and ozone for each section, respectively.

Impact of atmospheric aerosols on the process of radiant energy transformation is the most complex problem of modern atmosphere physics. Such complexity is primarily caused by the necessity of knowing of the distribution spectra and complex refraction factor of the aerosols, as the radiant energy scattering substances by quantities, sizes along the ray path. And further, we need to know chemical compositions of aerosols as absorbing substances. These can be identified only very roughly. It is hard to obtain the scattering parameters as well. Currently it is possible to identify most probable statistical structure of the mentioned parameters through multiple measurements and this can be done for the given region only. Experimentally, it would be relatively simple and practically reasonable to introduce single integral parameter instead of the mentioned parameters to describe radiant energy extinction and this parameter is valid for the given region only. Such parameter can be the so-called extinction factor that is frequently used to study light propagation ion in the atmosphere and can be expressed by well-known Angstrom's formula [9]:

$$^{2}\text{-}(^{a}|\sim) = \quad ^{a-n}. \tag{7}$$

Expression (7) is a monotonically decreasing function of wavelength and parameter determines relative concentration and *n* expresses aerosol distribution by sizes.

Formation of the aerosol optical density takes place in the entire atmosphere and its significant change within the small area is unlikely. In Georgia and *n* have been measured for many years and their values are mostly provided in [10, 11]. According to the measurements, variation of value is within 0.02-0.22 range, with 0.10 maximal probability. The range of value n is within 0.2 -2.6 with the most probable value of 0.80. These values basically change with the altitude above sea level and this could be accommodated by the expression exp(–*z*/1.2) where 1.2 is the reduced height of the aerosols in vertical direction (*z* is expressed in km) [12]. Thus, formula (7) can be written as:

$$^{2}\text{-}(^{a}|\sim) = 0.1\ ^{a-0.8}\exp(-z/1.2). \tag{8}$$

Formulas (4), (5), (7) and (8) allow calculation of integral (2), i.e., determine spectral distribution of direct radiation after passing of optical mass *m* in the atmosphere, if spectral composition of direct radiation beyond the atmosphere is known, as well as total quantities of the water vapor and ozone, along the sun ray path, optical density of the atmosphere aerosols, altitude of the location over the sea level and reduced heights of the ideally pure atmosphere and aerosols. Using the information about these parameters provided in the literature, we have calculated spectral distributions of direct radiation on summer solstice apparent noon, i.e. for expected maximal radiation value for 28 regions of Georgia. Obtained spectral distributions for three regions with the low-

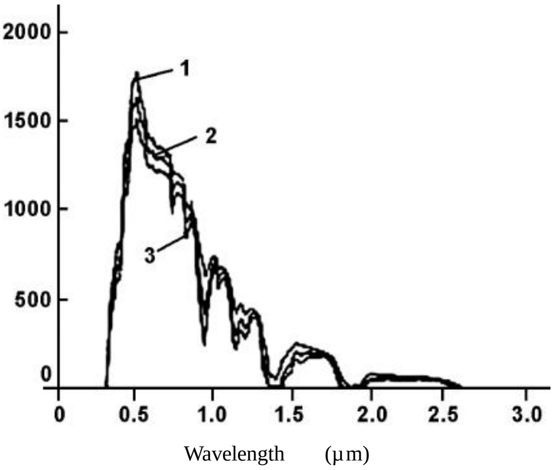

Fig. 1. Distribution of direct radiation by wave lengths at a time of apparent noon on 15 June, with clear sky, for Batumi (1), Pasanauri (2) and high mountain Kazbegi.

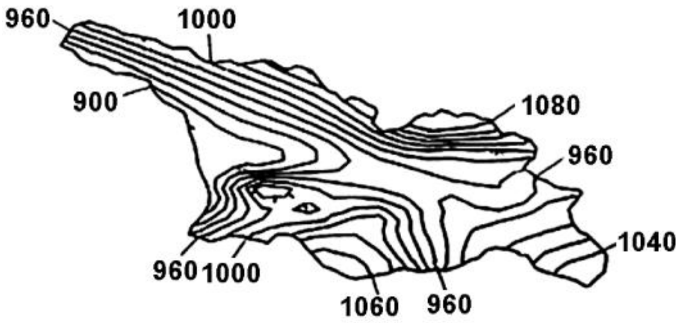

Fig. 2. Distribution of direct radiation intensity on the surface perpendicular to the sun ray (W/m^2) on the territory of Georgia, with clear sky, at apparent noon on summer solstice.

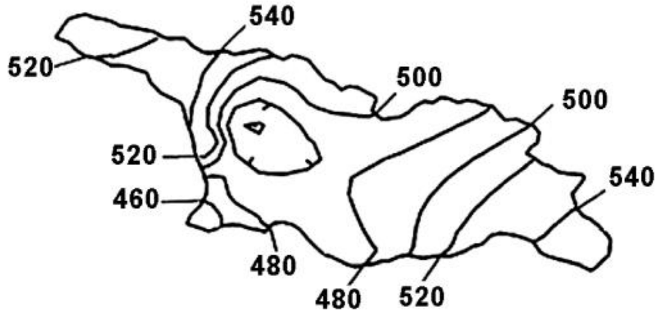

Fig. 3. Distribution of direct radiation intensity on the surface perpendicular to sun ray (W/m^2) in the territory of Georgia, with cloud cover, at apparent noon on summer solstice.

est, average and highest altitudes above the sea level are provided in Fig.1.

For three regions provided in Fig. 1 the integral values of direct radiation are 879.0, 977.2 and 1100.9 W/m^2 respectively, for one of these regions, in particular, for high mountain Kazbegi and for four more regions of 28 the calculation results can be compared with the actual values provided in the reference book [12]. Irrespective of significant time difference, the difference between the mentioned values is within 6-7%. At the same time, the values provided in the reference book are in all cases higher than the calculated ones. This may be due to the fact that radiation, beyond the considered wavelength range is also different from zero and it is neglected due to its low value.

Direct radiation intensities resulting from the calculations for clear sky the schematic map of their distribution structure in the territory of Georgia is provided for apparent noon on summer solstice in Fig.2. This is the maximal radiant energy reaching the underlying surface perpendicular to the rays.

Energy I' on the horizontal surface depends on the angle and can be expressed as:

$$I' = \mathrm{Sin}\,h. \qquad (8)$$

Actual energy that the surface can receive depends on the presence of clouds. Presence of clouds and their impact on radiation can be provided by the expression [13]:

$$\begin{aligned} I'(n,s) = I'[0.78+9.60\cdot10^{-4}\cdot s- \\ (7.43\cdot10^{-4}+1.00\cdot10^{-5}\cdot s)n], \end{aligned} \qquad (9)$$

where n and s are general sly cover in points and sunshine duration in hours, respectively.

Relying in the available information on cloud cover and sunshine time on the territory of Georgia, we have calculated values of direct radiation intensities on the horizontal surface, regarding cloud cover and sunshine time at apparent noon on summer solstice and built the schematic map as provided in Fig.3

ფიზიკური გეოგრაფია

მზის პირდაპირი რადიაციის განაწილება საქართველოს ტერიტორიაზე ჭეშმარიტი შუადღისას ზაფხულის მზებუდობის დროს

კ. თავართქილაძე* და დ. მუმლაძე*

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(წარმოდგენილია აკადემიის წევრის თ. ჭელიძის მიერ)

შექმნილია პირდაპირი რადიაციის სპექტრული განაწილების თეორიული გამოთვლის სქემა მოწმენდილი ცის შემთხვევაში, რომლის საშუალებით გამოთვლილია მართობულ ზედაპირზე მოწმენდილი ცის დროს და ჰორიზონტალურ ზედაპირზე ღრუბლიანობის გათვალისწინებით პირდაპირი რადიაციის ინტენსიურობა, ჭეშმარიტი შუადღისას, ზაფხულის მზებუდობის დროს. აგებულია საქართველოს ტერიტორიაზე მათი განაწილების სქემატური რუკები.

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