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Field Experiment on Studying Solar Radiation Passing through Aerosol Layers

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Abstract—Results of a field experiment on studying solar radiation passing in the visible wavelength range are described with the model aerosol media created in the surface atmosphere. High-efficiency thermocondensation generators were used for creating model aerosol media. The index of refraction and an average size of the aerosol particles formed are close to those characteristic of the natural stratospheric aerosol. The composition and technical characteristics of the equipment complex used in the experiments to control aerosol optical and microphysical parameters and meteorological conditions of the experiment are considered. The Gaussian model of impurity dispersion in the boundary layer is used for the analysis and interpretation of measurement results. It is found that with a number concentration of aerosol particles of $\sim 10^2$–10^3 cm^{-3} (which corresponds to the aerosol density in the deposited layer of about 1–10 mg/m^2 with the layer thickness along the ray path of about 100 m) the solar radiation attenuation with artificial aerosol layers accounts for 1 to 10%. Model estimates are in satisfactory agreement with the measurement results.

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1. INTRODUCTION

Due to the ever-increasing tendency toward climate warming in recent years, the world community feels concern about possible measures for climate stabilization. One of such measures is the acceptance of the Kyoto Protocol, which requires reducing greenhouse gas emissions from industrial enterprises into the atmosphere. However, a positive effect of this measure could be pronounced over centuries, when irreversible consequences of climate change can take place.

As early as in the 1970s, a well-known Soviet scientist M.I. Budyko [4] put forward an idea concerning climate management with finely dispersed aerosol particles injected into the stratosphere, which would reduce part of the incoming solar radiation onto the Earth's surface in order to compensate warming. According to the estimates, approximately 1% attenuation of solar radiation is sufficient to reduce a mean temperature over the Earth's surface by about 0.6–1°C (which is sufficient to maintain the present-day climate [8]). It is recognized that injection of reflecting aerosol submicron particles into the stratosphere can be an optimal option to compensate warming [9, 12].

Such studies have been initiated in the Russian Federation. They include a search for optically active aerosols, theoretical investigations of optical characteristics of aerosol layers, and experiments in special imitation chambers. Optical characteristics of stratospheric aerosol layers modeled with sulfuric aerosol with parameters (the index of refraction and diameter) close to the natural stratospheric aerosol are studied in these experiments. It is found that with the formation of the aerosol media with a particle number concentration of 10^2 cm^{-3} and a particle diameter of about 0.5 μm when the layer thickness (along the ray paths) is about 100 m, the radiation attenuation at the wavelength of 0.63 μm, which is close to the wavelength of the solar radiation maximum, amounts to about 1%. The next stage in these studies is to perform limited field experiments in the atmosphere on measuring the solar radiation attenuation with artificial aerosol layers of known optical and microphysical parameters close to the stratospheric aerosol characteristics.

This article is devoted to describing such an experiment, where solar radiation passing in the visible range was studied with a model aerosol media created in the surface atmospheric layer.

2. EQUIPMENT AND METHODOLOGY

The experiments in the surface atmospheric layer were conducted with an equipment complex that provided measuring basic meteorological variables in the surface atmosphere (stratification, temperature, air humidity, and wind speed) and microphysical and optical characteristics of aerosol particles.

The meteorological unit consisted of two meteorological complexes that provided simultaneous meteorological measurements at two separate points. The meteorological complexes are used to continuously measure meteorological parameters at a height of up to 4 m and above the underlying surface and to record instantaneous values of three components of the wind velocity vector, temperature, humidity, and pressure. Mean, maximum, and minimum wind speed and direction, temperature, humidity, pressure, and turbulent characteristics are calculated.

Aerosol microphysical parameters were measured with a photoelectric aerosol counter, which has the following characteristics:

—the range of measured sizes (in diameter) from 0.3 to 10 μm;

—the upper limit of measured concentrations 6×10^3 cm^{-3};

—the lower limit of measured concentrations 1 cm^{-3};

—the diameter measurement error 20%;

—the concentration measurement error 10%.

Weakening properties of aerosol layers were controlled with two ground-based automatic photometers (developed at Taifun Scientific Industrial Association and an automated system for recording the total and direct solar radiation (developed at Central Aerological Observatory). The photometers were developed based on the ground-based automatic UV-meters [10] and are intended to measure the direct solar radiation intensity at the wavelength of 0.53 μm with data recording on a personal computer. The photometers have the following characteristics:

—angle of vision 2°;

—minimally required angular altitude of the solar disk 20°;

—the Sun tracking error for six hours of operation 1°.

The automated system for recording total and direct solar radiation consisted of three actinometrical measuring modules. Each module consisted of two pyranometers, and analog-digital transducer, and a personal computer. One of the pyranometers measured the total (total in the entire semi-sphere of 180°) solar irradiance, the second one measured the direct (in the sector of 90°) irradiance. The irradiance measurement range is from 0.01 to 1.6 kW/m^2, and the wavelength range is from 0.3 to 2.4 μm. The instrument sensors were 10–15 m away from the control boards and a recording point and were installed on the grassy ground at a height from 1 to 2 m and 4 m above the earth level.

The sources of aerosol were mobile high-efficiency submicron aerosol thermocondensation generators that formed voluminous aerosol plumes. Aviation and ground-based aerosol generators mounted on the helicopter and on the car chassis were used in the experiments (Fig. 1). In the aviation aerosol generators, the aerosol was formed from combustion of metal-chloride pyrotechnic compounds, and in the ground-based generators it was formed as a result of condensation of the overheated vapor-gas mixture of individual fractions of petroleum products released at a high rate. The ground-based thermocondensation aerosol generator has the following parameters:

—the linear rate of the substance removal from the generator $w_0 = 200$ m/s;

—the nozzle radius $R_0 = 0.3$ m;

—the inclination of the generator nozzle to the horizon $\alpha = 12°$;

—the air overheat at the generator output compared to the environmental air temperature $\Delta T = 425°C$;

—the nozzle height above the earth level $H_0 = 2$ m;

—the aerosol generator output $Q = 0.1$ kg/s;

—the mass cross-section of the solar radiation attenuation with the generated aerosol particles σ_a is 8.7 m^2/g.

Fig. 1. Aerosol generators installed (a) on the helicopter and (b) on the car chassis.

During the experiments, the atmospheric stratification was close to neutral, the air temperature T was of about 20°C, the mean wind speed at a height of 2 m u_2 = 5 m/s and at a height of 4 m u_4 = 7 m/s, the measurements were carried out at distances of up to 1.5 km from the aerosol generator.

Figure 2 shows schemes of experiments on measuring solar radiation passing through aerosol formations. When the aviation generators were used, the helicopter created the aerosol plume when flying over the measurement area in the contrary directions at heights from 200 to 50 m (Fig. 2a) The width of the plume from the helicopter with aerosol generators was equal to the path length of the helicopter from turn to turn and amounted to about 5–6 km.

The ground-based aerosol generator, after the wind direction and speed were measured with meteorological complexes, was located downwind and oriented in a way that the aerosol jet passed with its edge through the measurement point and the solar sighting line passed through the aerosol jet thickness. Photometers and pyranometers together with the aerosol counter were located at a measurement point on the periphery of the jet, at a distance of 1 km from the aerosol generator downwind. Schematically, the solar ray path through the aerosol jet is shown in Fig. 2b.

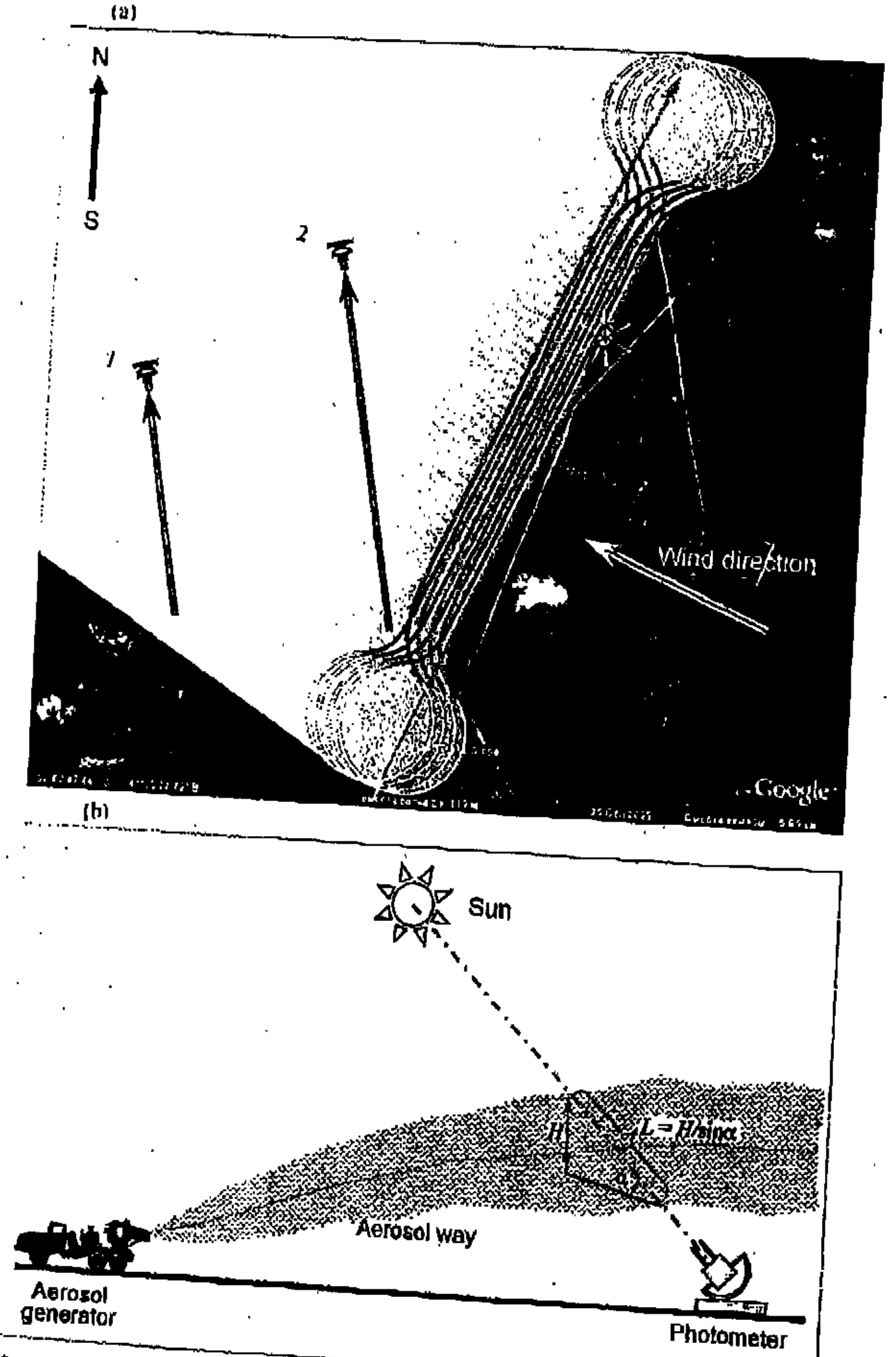

Fig. 2. Schemes of experiments with (a) air aerosol generators (the view from above against the background of the satellite picture of the locality and (b) with an aerosol generator on the car chassis. In panel (a) *1* and *2* denote the points of the photometer and other measuring devices locations; the arrows leading to photometers denote the solar beam directions.

3. RESULTS OF THE FIELD EXPERIMENT

Figure 3 shows a separate series of photometer measurements of direct solar radiation transmission when the peripheral part of the jet passes across the measurement point located at a distance of 1 km from the ground-based aerosol generator. The radiation attenuation in these measurements ranges from 1 to 20% on the periphery of the jet, and, when the central part of the jet passes across the measurement point, the radiation attenuation reaches 100%.

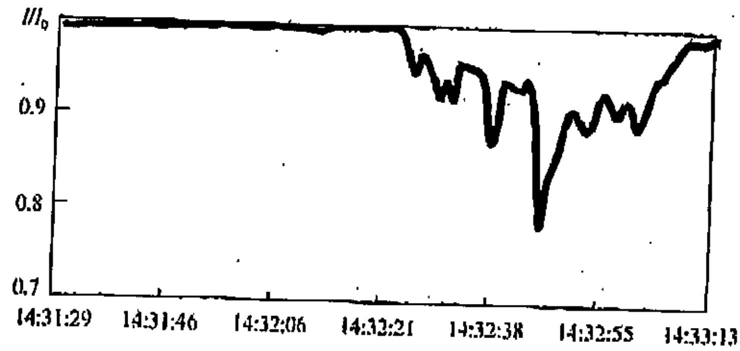

Fig. 3. Dependence of the I/I_0 passage through the aerosol layer on the time of the periphery jet passing through the measurement point.

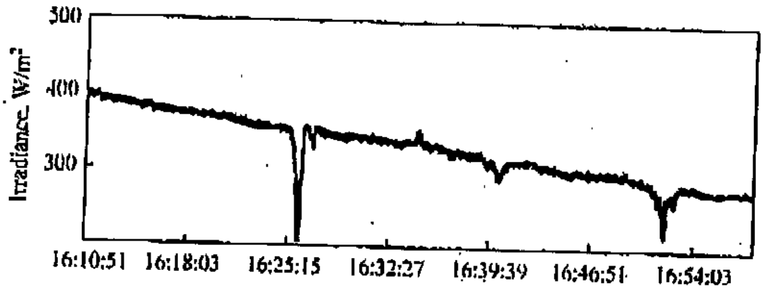

Fig. 4. Changes in the total irradiance when the aerosol jet is formed at the surface.

Generally, a basic equation for the intensity I of light that passed through the aerosol layer of thickness L is used to estimate the direct solar radiation attenuation.

$$I = I_0 \exp\left[-\frac{1}{6}\pi D_3^3 N\rho\sigma_a L\right], \quad (1)$$

where I_0 is the intensity of the incident light; $\frac{1}{6}\pi D_3^3 N\rho = M$ is the aerosol mass concentration; D_3 is the mean cubic diameter; N is the aerosol number concentration; ρ is the aerosol particle density; and σ_a is the mass cross-section of attenuation (see the generator parameters given above).

Figure 4 shows irradiance values obtained with a pyranometer included into an actinometrical complex. The curve in the figure presents values of the total irradiance measured with a completely open pyranometer, which recorded the total solar radiation attenuation of 41%.

Figure 5 shows data on irradiance measurements when an aerosol plume was generated by the helicopter. In the experimental area, cloudy weather with sky clearing was observed. It made difficult to detect a possible change in the solar radiation caused by the artificial aerosol sample passing over the instrument complex against the background of natural changes associated with cloud windows. A high degree of variability of the data obtained can be noted. The arrows in the figure denote the areas with the changed irradiance caused by the passage of the aerosol formation over the instruments. Possible changes in the irradiance are estimated in this case rather approximately. The irradiance reduction in this case was about 28%.

4. ANALYSIS OF THE FIELD EXPERIMENT RESULTS

To calculate the field of a mass aerosol concentration in the aerosol plume formed by the thermocondensation generators, in practice, we use models developed for describing dispersion of plume emissions from industrial chimneys in the surface atmosphere [3, 7, 11]. When describing the dynamics of the aerosol jet, the whole interval of its motion is usually divided into two: the initial portion is between the jet injection point and the point where the jet velocity becomes equal to the mean wind speed and a jet

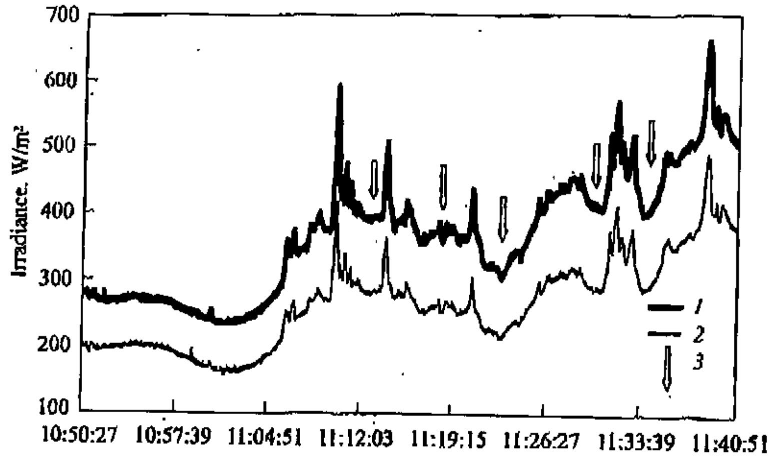

Fig. 5. Changes in irradiance when the aerosols are formed with the help of the helicopter. (*1*) Total radiation; (*2*) direct radiation; arrows (*3*) denote the sections where the irradiance is measured when passing above the instruments of aerosol formation.

rises to some effective height due to the initial velocity and jet overheat. This portion is mainly characterized by parameters of the aerosol generator used. The second is a basic portion with a jet-free motion along the mean wind direction.

In the initial portion of the aerosol jet motion, the initial rate of emissions ω_0 and their overheat ΔT relative to the environmental air temperature cause its rise. The effective height of the aerosol jet rise is determined from the following expression:

$$H_{ef} = H + \Delta H, \tag{2}$$

where H is the height of the generator nozzle above the surface and ΔH is the height of the jet rise above the nozzle plane.

The empirical expressions for ΔH take into account the relation between the vertical component of the aerosol jet motion rate w_z and a horizontal transport speed, i.e., the mean wind speed u, assuming that at a height of ΔH above the source the value of w_z is small compared to u [3]:

$$\Delta H \cong \frac{K_1 w_0 R_0 \sin\alpha}{u} + \frac{K_2 w_0 g R_0 \Delta T}{T_0 u^3}, \tag{3}$$

where $K_1 \approx 4$, $K_2 \approx 5$ are the numerical coefficients; g is the gravity acceleration; T_0 is the environmental temperature. The rest of parameters (w_0, R_0, α) are determined above.

Further estimates will be made for the aerosol generator (its experimental data are given in Figs. 3 and 4) operating in the regime of a constant source. The effective jet height, calculated with formulas (2) and (3) with allowance for the aerosol generator elevation above the surface is about 40 m.

At high mean wind speeds, when the main contribution to relation (3) is made by the first term on the right-hand side of the equation, i.e., the role of the thermal lift is comparatively small, for calculating the section of the outgoing gas jet in the initial gas portion, the model of drowned flow can be used; according to this model changes in the section S_1 can be described with the following relation [1]:

$$S_1 = S_0(Ax + 1)^2, \tag{4}$$

where $S_0 = \pi R_0^2$ is the nozzle section; $A \cong 3.4a\sqrt{S_0/\pi}$; a is the coefficient characterizing the intensity of the induced turbulence in the jet ($a \sim 0.1$); $x \approx \Delta H/\sin\alpha$ is the distance from the generator.

Then, the effective jet section at the end of the initial portion, according to the calculations with formula (4), for the aerosol generator will be close to 3×10^3 m^2.

At the basic site, the aerosol jet evolution in the atmosphere is affected by the particle turbulent diffusion that results in the jet broadening. The aerosol particle number concentration is determined at the beginning

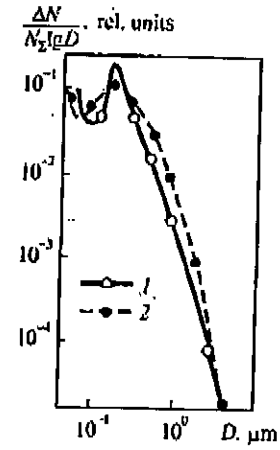

Fig. 6. Normalized functions of aerosol particle size distribution (*1*) in the plume at the beginning of the basic portion and (*2*) at 1 km windward from a permanent aerosol source [11].

of the basic jet portion from a known relation of $N_1 = Q/S_1 u V_a \rho$, where $V_a = \pi D_3^3/6$ is the aerosol particle volume. Generally, the aerosol thermocondensation generators produce aerosol particles of tenths parts of a micron in diameter [6]. In the preliminary experiments with the aerosol generator, according to measurements, the mean cubic particle diameter was $D_3 \sim 0.16$ μm [11]. Hence, we shall obtain the estimate of the total particle concentration $N_1 \approx 10^6$ cm^{-3} at the beginning of the basic portion of the jet. It can be seen from Fig. 6 that the contribution of the fraction of the optically active aerosol with diameter $D \geq 0.3$ μm, measured in these experiments with a photoelectric counter, amounts to about $5 \times 10^{-2} N_\Sigma$ at the beginning of the basic portion of the jet, which corresponds to the number concentration of about 5×10^4 cm^{-3} (N_Σ is the total aerosol concentration in the diameter size range from 10^{-3} to 10 μm).

To analyze the evolution of the aerosol jet considered and describe changes in the mass aerosol concentration in the jet, we shall use the known Gaussian model [2, 7]. For a point continuous source elevated to the height H_{ef}, the expression for a mean aerosol concentration is as follows:

$$M(x, y, z) \cong \frac{Q\exp[-y^2/2\sigma_y^2]}{2\pi u \sigma_y(x)\sigma_z(x)}\left[e^{-\frac{(z-H_{ef})^2}{2\sigma_z^2}} + e^{-\frac{(z+H_{ef})^2}{2\sigma_z^2}}\right], \tag{5}$$

where x, y, and z are the coordinates of the observational point in the coordinate system with the origin at the point where the source is located (the axis X is directed along the mean wind, the axis Y is perpendicular to the axis X in the horizontal plane; and Z is the vertical axis); $M(x, y, z)$ is the mass aerosol concentration; $\sigma_y(x)$ and $\sigma_z(x)$ are standard deviations (turbulent diffusion parameters).

For the characteristic conditions of the neutral stratification of the surface atmospheric layer and diffusion times $t \geq 3H_{ef}/u_*$, where u_* is the friction velocity and $t = x/u_2$, the following standard deviations $\sigma_y(x)$ and $\sigma_z(x)$ will be used [2]:

$$\sigma_y(x) = 0.08x(1 + 0.0001x)^{-0.5}, \quad \sigma_z(x) = 0.06x(1 + 0.0005x)^{-0.5}. \tag{6}$$

The friction velocity u_* will be estimated in the approximation of the logarithmic wind profile

$$u/u_* = \frac{1}{\kappa}\ln(z/z_0), \tag{7}$$

where $\kappa = 0.4$ is the von Karman constant and $z_0 \approx 3$ cm is the roughness parameter of the surface of a rural locality [2, 5].

Taking into account the fact that in the experiments the mean wind speed u_4 at an altitude of 4 m was 7 m/s, we shall get from formula (7) that u_* is about 0.57 m/s and from formula (6) we obtain turbulent dispersion parameters $\sigma_y(x) = 80$ m and $\sigma_z(x) = 50$ m.

Let us return to Fig. 6, where the shape of the normalized aerosol distribution function is shown in the process of the jet motion. The conservation of a distribution function is indicative of an insignificant role of coagulation processes in the jet portion considered, while a comparatively small dispersion of the particle size distribution function makes it possible in the future to use the monodispersity approximation, assuming that $D_3 \approx 0.16$ μm [6]. Accordingly, the Stokes's particle deposition can be ignored, and for the calculation of the aerosol number concentration a simple relation can be used

$$N(x, y, z) = 6M(x, y, z)/\pi\rho D_3^3, \tag{8}$$

where the mass particle concentration $M(x, y, z)$ along the route of spreading is found from relation (5).

The calculation with formula (8) of the number concentration of particles near the jet axis gives an estimate $N_\Sigma \sim 4 \times 10^6$ cm^{-3} for the aerosol generator at the beginning of the basic portion and $N_\Sigma \sim 10^5$ cm^{-3} at 1 km from the generator. Taking into account the contribution of the optically active aerosol of ≥ 0.3 μm in diameter, equal to $\sim 5 \times 10^{-2}\, N_\Sigma$, these concentrations near the jet axis will amount to $\sim 10^5$ cm^{-3} for the beginning of the basic portion and $\sim 5 \times 10^3$ cm^{-3} at 1 km from the generator. The calculated values are in satisfactory agreement with the experimental data derived with the help of photoelectric counters ($\sim 10^4$ cm^{-3}) near the jet axis at 1 km from the generator.

Since the aerosol jet is much meandered, its peripheral part, at a distance from $1\sigma_y(x)$ to $3\sigma_y(x)$ from the axis, passed through the measurement point, where photometers, pyranometers, and aerosol counters were located. In accordance with (5), the total particle number concentration changes from $e^{-0.5}N_\Sigma$ at $y = \sigma_y(x)$ to $e^{-2}N_\Sigma$ at $y = 2\sigma_y(x)$ and to $e^{-4.5}N_\Sigma$ at $y = 3\sigma_y(x)$, which is in satisfactory agreement with the experimental data measured with a photometric counter. The length L of the solar radiation absorption layer in the aerosol jet is determined by the jet height H and the Sun elevation α: $L = H/\sin\alpha$. The mean α value during experiments was about 30°. The jet height, according to estimates, was approximately $2\sigma_z(x) \approx 100$ m. From the calculations with formula (1), when the mass cross-section of attenuation σ_a is 8.7 m²/g for the aerosol used and $L \approx 200$ m, the mass aerosol concentration on the jet periphery at a distance of $y = 3\sigma_y(x)$ can be obtained from the attenuation data in Fig. 4. The total number concentration derived from the mass concentration (in the monodisperse aerosol approximation) agrees well with the measurements obtained with the photoelectric counter. The respective aerosol mass concentration in the layer of about 100 m thick is about 1 mg/m².

5. CONCLUSIONS

At the first stage of field experiments on studying solar radiation attenuation with aerosol layers, the methodologies were optimized and measuring equipment was tested to control optical and microphysical characteristics of aerosol formations in the surface atmospheric layer. For the first time, the data were obtained on the solar radiation attenuation with the artificially injected aerosol layers. With the number aerosol concentration of about 10^2–10^3 cm^{-3}, which corresponds to the aerosol density in the deposited layer of about 1–10 mg/m² with the layer thickness (along the ray path) of about 100 m, the solar radiation attenuation with the artificial aerosol layers ranges from 1 to 10%.

Based on the experimental results obtained in our work, it is shown how it is principally possible to control solar radiation passing through artificially created aerosol formations in the atmosphere with different optical thickness.

REFERENCES

1. G. E. Abramovich, *Theory of Turbulent Jets* (Fizmatgiz, Moscow, 1960) [in Russian].
2. *Atmospheric Turbulence and Pollution Dispersion Modeling*, Ed. by F. T. M. Newstadt and Kh. Van Don (Gidrometeoizdat, Leningrad, 1985) [Transl. from Engl.].
3. M. E. Berlyand, E. L. Genikhovich, and R. I. Onikul, "On the Calculation of the Atmosphere Pollution with Emissions from Power Plant Chimneys," Trudy GGO, No. 158 (1964) [Trans. Main Geophysical Observatory, No. 158 (1964)].
4. M. I. Budyko, *Climate Change* (Gidrometeoizdat, Leningrad, 1974) [in Russian].
5. N. L. Byzova, *Typical Characteristics of the Lower 300-m Atmospheric Layer from Measurements at the High-altitude Mast* (Gidrometeoizdat, Moscow, 1982) [in Russian].
6. L. Yu. Visnapuu and V. V. Smirnov, "Studying the Gas Flow–Unipolar Ions–Aerosol Particle Systems," Trudy IEM, No. 44 (134) (1987) [Trans. Inst. Experimental Meteorol., No. 44 (134) (1987)].

7. E. K. Garger, "Calculation of Diffusion Characteristics of the Concentration Field of Weightless Pollution in the Surface Atmospheric Layer," Trudy IEM, No. 29 (103) (1984) [Trans. Inst. Experimental Meteorol., No. 29 (103) (1984)].
8. Yu. A. Izrael, "An Efficient Way to Regulate the Global Climate is the Main Objective of the Solution of the Climate Problem," Meteorol. Gidrol., No. 10 (2005) [Russ. Meteorol. Hydrol., No. 10 (2005)].
9. Yu. A. Izrael, I. I. Borzenkova, and D. A. Severov, "Role of Stratospheric Aerosols in Maintenance of the Present-day Climate," Meteorol. Gidrol., No. 1 (2007) [Russ. Meteorol. Hydrol., No. 1, 32 (2007)].
10. N. K. Nikiforova and N. V. Tereb, "High-frequency Variations of the Total Ozone Content," Meteorol. Gidrol., No. 1 (1991) [Meteorol. Hydrol., No. 1 (1991)].
11. A. V. Savchenko, V. V. Sminov, and A. D. Uvarov, "Dynamics of the Plume of Charged Aerosol Particles in the Surface Atmospheric Layer," Trudy IEM, No. 51 (142) (1989) [Trans. Inst. Experimental Meteorol., No. 51 (142) (1989)].
12. P. J. Crutzen, "Albedo Enhancement by Stratosphere Sulfur Injection: A Contribution to Resolve a Policy Dilemma?" Climate Change, 77 (2006).