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A MODEL OF PREDICTION OF FOREST-FIRE HAZARD*

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A rather simple and physically substantiated deterministic-probabilistic expert system of prediction of forest-fire hazard, which can be used in practice, is suggested. Results of the calculation by the verified model of drying of forest combustibles, which allows for partial pressure of water vapor, are compared with results obtained by different models and experimental data.

Introduction. Annually, forest fires cause enormous damage: they destroy property and threaten the life and health of man and woodland inhabitants. Because of this, authentic prediction and timely detection of forest fires, which allows suppression of fire even at the initial stage, is of utmost importance. The main techniques of prediction of forest-fire hazard are stated in [1–3]. In [4–8], a critical analysis of the existing techniques of prediction of forest-fire hazard is presented. It is argued that the emergence of a forest fire has a probabilistic nature and depends not only on meteorological conditions and thunderstorm activity but also on the level of anthropogenic loading, wind velocity, and moisture content of forest combustibles and their reactivity. Therefore, the paper is aimed at the development of a simple deterministic-probabilistic expert system of prediction of forest-fire hazard.

A Deterministic-Probabilistic Model of Prediction of Forest-Fire Hazard. According to [4–6], there exist stationary and dynamic models of forest-fire hazard. The scheme of the emergence of forest fires is given in [8].

Using probability theory and physical grounds, we obtain the following formulas for probability of the emergence of a forest fire within the jth time range of the forest-fire period (dynamic model) and fire caused by meteorological conditions [8]:

$$P_j = \sum_{i=1}^{N} \left[P_{ij}(\mathrm{A})\, P_{ij}(\mathrm{FFi/A}) + P_{ij}(\mathrm{L})\, P_{ij}(\mathrm{FFi/L}) \right] P_{ij}(\mathrm{P})\,, \quad (1)$$

$$P_{ij}(\mathrm{C}) = \begin{cases} 0\,, \\ \dfrac{F_i}{F} \exp\left[-(\Delta\overline{\varphi}_{ij})^2\right], \end{cases} \quad F = \sum_{i=1}^{N} F_i\,, \quad \Delta\overline{\varphi}_{ij} = \frac{\varphi_{2ij} - \varphi^*_{2ij}}{\varphi^*_{2ij}}\,, \quad (2)$$

where 0 in (2) corresponds to the case where the ith area of the forest is free of forest combustibles (FC) (surface of roads, rivers, lakes, and water-saturated bogs) or more than 3 mm of precipitation fell on an FC layer.

It is evident that P_{ij}(P) takes a maximum value only when the current moisture content for the jth time range of the fire-hazard period on the ith portion φ_{2ij}, during which the FC layer is ignited and fires [9, 10], coincides with a critical moisture content φ^*_{2ij}.

To find P_{ij}(A), P_{ij}(FFi/A), P_{ij}(L), and P_{ij}(FFi/L), in formula (1) one must determine probabilities [11] in terms of the frequency of events and use statistical data for the corresponding forest husbandry:

$$P_{ij}(\mathrm{A}) \approx \frac{N_{\mathrm{À}}}{N_{\mathrm{FiHP}}}\,, \quad P_{ij}(\mathrm{FFi/A}) \approx \frac{N_{\mathrm{FiA}}}{N_{\mathrm{NFi}}}\,, \quad (3)$$

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TABLE 1. Values of P_{ij}(A) as a Function of Distance m to the Settlement

m, m	50	100	250	500	750	1000
P_{ij} (A)	0.096	0.097	0.098	0.099	0.101	0.102
m, m	2000	3000	4000	5000	7500	10 000
P_{ij} (A)	0.108	0.114	0.120	0.125	0.143	0.160

$$P_{ij}\,(\mathrm{L}) \approx \frac{N_{\mathrm{L}}}{N_{\mathrm{FiHP}}}\,, \quad P_{ij}\,(\mathrm{FFi/L}) \approx \frac{N_{\mathrm{FiL}}}{N_{\mathrm{NFi}}}\,. \tag{4}$$

The index of fire-hazard occurrence of forests near the populated area P_{ij}(A) can be determined by Table 1, borrowed from [12], where m is the distance to the populated area given in meters.

Analytical and Numerical Solutions of the Problem and Their Analysis. It is known [13] that the system of meteorological stations existing in Russia gives meteorological data about eight times a day. Therefore, three hours must be taken as a constant time step for a new system of prediction of forest-fire hazard. It is obvious that the origin of the first span of time coincides with the beginning of the fire-hazard period.

Using the formulation of the problem suggested in [14], we expand the equations for determining an FC-layer-thickness-mean dimensionless temperature of the c phase (condensed phase) and mean moisture content in this layer into a Taylor series to the second term in the vicinity of the points $\bar{\theta}_{sj}$ and $\bar{\varphi}_{2j}$. In this case, for the jth time span $\tau_j < \tau < \tau_{j+1}$ we obtain the equations

$$\frac{d\bar{\theta}_{\mathrm{s}}}{d\tau} = f_1\,(\bar{\theta}_{sj}, \bar{\varphi}_{2j}) + b_j^{(1)}\,(\bar{\theta}_{\mathrm{s}} - \bar{\theta}_{sj}) + c_j^{(1)}\,(\bar{\varphi}_2 - \bar{\varphi}_{2j})\,, \tag{5}$$

$$\frac{d\bar{\varphi}_2}{d\tau} = f_2\,(\bar{\theta}_{sj}, \bar{\varphi}_{2j}) + b_j^{(2)}\,(\bar{\theta}_{\mathrm{s}} - \bar{\theta}_{sj}) + c_j^{(2)}\,(\bar{\varphi}_2 - \bar{\varphi}_{2j})\,. \tag{6}$$

The initial conditions for the system (5)–(6) have the form

$$\theta_{\mathrm{s}}\,(0) = \theta_{\mathrm{s,in}}\,, \quad \bar{\varphi}_2\,(0) = \varphi_{2\mathrm{in}}\,, \quad \theta_{\mathrm{s}}\,(\tau_j) = \theta_{sj}\,, \quad \varphi_2\,(\tau_j) = \varphi_{2j}\,. \tag{7}$$

The expressions for the functions f_1 and f_2 and the coefficients $b_j^{(1)}$, $b_j^{(2)}$, $c_j^{(1)}$, and $c_j^{(2)}$ and other constants for the jth time span are given in the Appendix. Discarding small terms in (5) and (6), we obtain the system of two linear first-order differential equations for determining the moisture content and temperature of the FC layer. Integration of these equations with respect to time yields for each three-hour time span

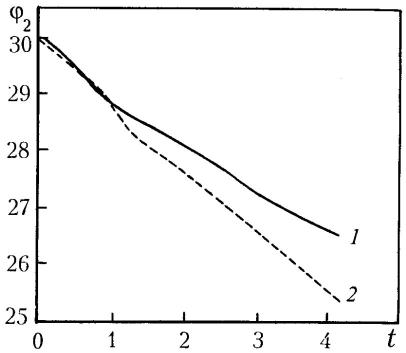
$$\bar{\varphi}_2 = \exp\,(c_j^{(2)}\tau)\,[M_j - R_j\,(\exp\,(-\,c_j^{(2)}\tau) - 1) + D_j\,(\exp\,(\tau\,[s_j^{(1)} - c_j^{(2)}]) - 1) + Y_j\,(\exp\,(\tau\,[s_j^{(2)} - c_j^{(2)}]) - 1)]\,, \tag{8}$$

$$\bar{\theta}_{\mathrm{s}} = [(\bar{\theta}_{sj} - k_j - h_j)\,\exp\,(-\,s_j^{(1)}\tau_j)]\,\exp\,(s_j^{(1)}\tau) + h_j\,\exp\,(-\,s_j^{(2)}\tau_j)\,\exp\,(s_j^{(2)}\tau) + k_j\,. \tag{9}$$

Thus, for every three hours we can obtain moisture content (by formula (8)) and temperature in the FC layer (by formula (9)) as functions of dimensionless time τ. Then the probability of the emergence of fire due to geographical and meteorological reasons at the time instant τ_j is determined by formula (1). Consequently, we succeeded in determining the probability of fire emergence at any instant of time.

It is of interest to estimate the accuracy of expressions (8) and (9).

Studies were conducted for drying pine needles under meteorological conditions typical of the Tomsk region in May and at the following parameters of the surrounding medium: wind velocity V_{e} = 0.695 m/sec at a height of 1 m, surrounding temperature T_{e} = 295 K, relative humidity of air π_{e} = 0.7, density of the flux of incident solar radiation $q_{\mathrm{R}}(h)$ = 140 W/m^2, and density of the flow of long-wave radiation J_{w} = 70 W/m^2.



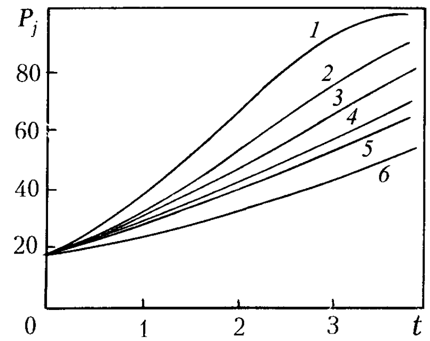


Fig. 1. Change of moisture content with time: 1) experiment [7]; 2) analytical solution. φ_2, %; t, h.

Fig. 2. Change of probability of fire hazard P_j with time for different scenarios of drying: 1) T_e = 300 K, π_e = 0.7, $q_R(h)$ = 140 W/m^2, J_w = 70 W/m^2, and V = 0.695 m/sec; 2) 295, 0.7, 500, 70, and 0.695; 3) 295, 0.7, 140, 200, and 0.695; 4) 295, 0.7, 140, 70, and 2; 5) 295, 0.7, 140, 70, and 0.695; 6) 295, 0.85, 140, 70, and 0.695. P_j, %; t, h.

It is seen from Fig. 1 how the moisture content changes during a four-hour time span. The analysis shows that from the analytical solution there follows a higher increase in the temperature of the FC layer as compared to the Runge–Kutta method; therefore, the moisture content of the layer decreases faster compared to the experiment and the Runge–Kutta method.

Figure 2 shows a change in the probability of fire hazard for different initial data. The following conclusions were drawn from the analysis of the curves presented in this figure: the temperature of the surrounding medium exerts most substantial effect on the probability of the emergence of forest fire; the probability of ignition increases with this temperature (curve 1); the probability of ignition also increases with an increase in the wind velocity and the densities of incident solar radiation and scattered long-wave radiation (curves 4, 2, and 3); as the relative humidity of air increases the probability of ignition decreases (curve 6).

These results are in agreement with the data of experimental studies of drying of forest combustibles [7] and physical grounds proceeding from the analysis of the balance of heat in the FC layer. Therefore, relations (8) and (9) can be used for developing a new expert system of prediction of forest-fire hazard [8].

APPENDIX

$$f_1 = \Bigg[\frac{1}{\delta^2} \Big\{ (\varphi_{1\text{in}} + \varphi_2)\,[c - d\,(1 + \beta\theta_s)^4] - (1 - \varphi_{1\text{in}} - \varphi_2)\,[c_0 - d_0\,(1 + \beta\theta_s)^4] -$$

$$- \text{Bi}\,(\theta_s - \theta_e) - \text{Bi}_0\,(\theta_s - \theta_0) - \frac{\varphi_2\,(b + \delta^2)}{\sqrt{1 + \beta\theta_s}}\,[\exp\,(\theta_s\,(1 + \beta\theta_s)] - \pi_e] \Big\} +$$

$$+ \frac{(1 - \varphi_{1\text{in}} - \varphi_2)\,[L - G\,(1 + \beta\theta_s)^4]}{\bar{k}_1}\,(1 - \exp\,(-\bar{k}_1)) - \bar{\alpha}_v\,(\theta_s - \theta_e) \Bigg] \Big/ (1 + a\varphi_2)\,,$$

$$f_2 = - \frac{\gamma\varphi_2}{\sqrt{1 + \beta\theta_s}}\,[\exp\,[\theta_s/(1 + \beta\theta_s)] - \pi_e]\,,$$

$$L = \frac{\rho_1 k_1 \sqrt{T_*}\,\exp\,(E/RT_*)}{q_2\,\rho_2 k_{02}}\,[(1 - A)\,q_R\,(h) + J_w]\,\cos\alpha\,,$$

$$G = \frac{\rho_1 k_1 \sqrt{T_*} \exp(E/RT_*) \varepsilon\sigma T_*^4}{q_2 \rho_2 k'_{02}},$$

$$R_j = \frac{f_j^{(2)} + b_j^{(2)} k_j}{c_j^{(2)}}, \quad D_j = \frac{b_j^{(2)} (\bar{\theta}_{sj} - k_j - h_j) \exp(-s_j^{(1)} \tau_j)}{s_j^{(1)} - c_j^{(2)}}, \quad Y_j = \frac{b_j^{(2)} h_j \exp(-s_j^{(2)} \tau_j)}{s_j^{(2)} - c_j^{(2)}},$$

$$h_j = \left[f_j^{(1)} + b_j^{(1)} \theta_{sj} + c_j^{(1)} \bar{\varphi}_{2j} - s_j^{(1)} (\bar{\theta}_{sj} - k_j)\right] \Big/ \left(s_j^{(2)} - s_j^{(1)}\right), \quad k_j = \frac{f_j^{(2)} c_j^{(1)} - f_j^{(1)} c_j^{(2)}}{c_j^{(2)} b_j^{(1)} - c_j^{(1)} b_j^{(2)}},$$

$$a_j^{(1)} - b_j^{(1)} \bar{\theta}_{sj} - c_j^{(1)} \bar{\varphi}_{2j} = f_j^{(1)}, \quad a_j^{(2)} - b_j^{(2)} \bar{\theta}_{sj} - c_j^{(2)} \bar{\varphi}_{2j} = f_j^{(2)},$$

$$s_j^{(1)}, s_j^{(2)} = \frac{b_j^{(1)} + c_j^{(2)} \pm \sqrt{(b_j^{(1)} - c_j^{(2)})^2 + 4 b_j^{(2)} c_j^{(1)}}}{2}, \quad f_1(\bar{\theta}_{sj}, \bar{\varphi}_{2j}) = a_j^{(1)}, \quad \left.\frac{\partial f_1}{\partial \bar{\theta}_s}\right|_{\substack{\bar{\theta}_s = \bar{\theta}_{sj} \\ \bar{\varphi}_2 = \bar{\varphi}_{2j}}} = b_j^{(1)},$$

$$\left.\frac{\partial f_1}{\partial \bar{\varphi}_2}\right|_{\substack{\bar{\theta}_s = \bar{\theta}_{sj} \\ \bar{\varphi}_2 = \bar{\varphi}_{2j}}} = c_j^{(1)}, \quad f_2(\bar{\theta}_{sj}, \bar{\varphi}_{2j}) = a_j^{(2)}, \quad \left.\frac{\partial f_2}{\partial \bar{\theta}_s}\right|_{\substack{\bar{\theta}_s = \bar{\theta}_{sj} \\ \bar{\varphi}_2 = \bar{\varphi}_{2j}}} = b_j^{(2)}, \quad \left.\frac{\partial f_2}{\partial \bar{\varphi}_2}\right|_{\substack{\bar{\theta}_s = \bar{\theta}_{sj} \\ \bar{\varphi}_2 = \bar{\varphi}_{2j}}} = c_j^{(2)},$$

$$M_j = \bar{\varphi}_{2j} \exp\left(-c_j^{(2)} \tau_j\right) + \frac{f_j^{(2)} + b_j^{(2)} k_j}{c_j^{(2)}} \left(\exp\left(-c_j^{(2)} \tau_j\right) - 1\right) - \frac{b_j^{(2)} (\bar{\theta}_{sj} - k_j - h_j) \exp(-s_j^{(1)} \tau_j)}{s_j^{(1)} - c_j^{(2)}} \times$$

$$\times \left(\exp\left(\tau_j \left[s_j^{(1)} - c_j^{(2)}\right]\right) - 1\right) - \frac{b_j^{(2)} h_j \exp(-s_j^{(2)} \tau_j)}{s_j^{(2)} - c_j^{(2)}} \left(\exp\left(\tau_j \left[s_j^{(2)} - c_j^{(2)}\right]\right) - 1\right)$$

are the constants for the *j*th time span.

NOTATION

P_j, probability of emergence of forest fire for the *j*th time span (time step) on the controlled forest area, %; F_i and F, forest areas covered by the *i*th-type forest (conifer or angiospermous, etc.) and areas of a certain forest husbandry, region, or district, ha; N, total number of forest types on the area F; P_{ij}(A) and P_{ij}(FFi/A), probabilities of anthropogenic loading and emergence of fire due to this loading on the area F_i, %; P_{ij}(L) and P_{ij}(FFi/L), probabilities of emergence of dry thunderstorms and forest fire due to lightning provided that dry thunderstorms can occur on the area F_i, %; P_{ij}(P), probability of the fact that to 1 p.m. of local time the moisture content of the FC layer will be less than critical (probability of emergence of fire due to meteorological conditions), %; φ_{2ij}^*, critical value of the volumetric fraction of water in the FC layer, %; N_A and N_{FiA}, number of days in the fire-hazard period with anthropogenic loading sufficient for FC ignition and of fires due to this loading; N_{NFi}, total number of fires; N_L, number of days when lightning occurs (in dry thunderstorms); N_{FiHP}, total number of days in the fire-hazard period; N_{FiL}, number of fires due to lightning in dry thunderstorms; $\bar{\theta}_s = \int_0^1 \theta_s d\zeta$ and $\bar{\varphi}_2 = \int_0^1 \varphi_2 d\zeta$, layer-thickness-mean dimensionless temperature and volumetric fraction of water; z and $\zeta = z/h$, dimensional (m) and dimensionless coordinates reckoned from the ground surface normally to the underlying surface; t and $\tau = t/t_*$, dimensional (sec) and dimensionless time; $t_* = \frac{\sqrt{T_*}\,\rho_1\varphi_{1in}c_{p1}RT_*^2}{q_2Ek_{02}s\rho_2}\exp\left(\frac{E}{RT_*}\right)$, characteristic time of drying the FC layer, sec; φ_2, current value of the volumetric fraction of water, %; φ_{1in}, initial value of the volumetric fraction of the dry organic substance, %; ρ_1 and ρ_2, densities of the dry organic substance of FC and water in the liquid-droplet state, kg/m^3; s, specific surface of macropores, 1/m; T_*, characteristic temperature (temperature of soil at the initial instant of time), K; q_2, thermal effect of water evaporation; J/kg; R, universal gas constant, J/(mole·K); k_{02}, constant pre-exponential factor in the expression for drying rate, K$^{1/2}$ m/sec; E, activation energy characterizing evaporation of bound water, J/mole; T_s and $\theta_s = \frac{(T_s - T_*)E}{RT_*^2}$, dimensional (K) and dimensionless temperatures of the c phase in the FC layer; $\delta^2 = \frac{q_2k_{02}s\rho_2h^2E}{\lambda_1\varphi_{1in}\sqrt{T_*}\,RT_*^2}\exp\left(-\frac{E}{RT_*}\right)$, analog of the Frank-Kamenetskii number [15]; h, height of the FC layer, m; λ_1, coefficient of thermal conductivity of dry FC, J/(m·sec·K); $\mathrm{Bi} = \frac{\alpha_e h}{\lambda_1\varphi_{1in}}$ and $\mathrm{Bi}_0 = \frac{\alpha_0 h}{\lambda_1\varphi_{1in}}$, Biot numbers characterizing the rate of heat exchange between the FC layer and the near-earth layer of air and the soil; α_e and α_0, coefficients of heat exchange between the near-earth layer of air and the soil, J/(m^2·sec·K); $a = \frac{\rho_2c_{p2}}{\rho_1c_{p1}\varphi_{1in}}$, dimensionless quantity; c_{p2} and c_{p1}, heat capacities of water and dry FC, J/(kg·K); $b = \frac{Eq_2k_{02}\rho_2h}{\varphi_{1in}RT_*^2\sqrt{T_*}\,\lambda_1}\exp\left(-\frac{E}{RT_*}\right)$ and $c = \frac{Eh\,[(1-A)q_R(h) + J_w]}{\lambda_1\varphi_{1in}RT_*^2}\cos\alpha$, dimensionless quantities characterizing thermal effect of water evaporation and the influx of solar radiation energy; A, albedo of the FC layer; $q_A(h)$ and J_w, densities of the flux of solar radiation and longwave radiation, J/(m^2·sec); α, angle between the underlying surface and the horizontal plane, deg; $d = \frac{\varepsilon_s\sigma T_*^2hE}{R\lambda_1\varphi_{1in}}$, dimensionless quantity characterizing emissivity of the FC layer; ε_s, emissivity of the FC layer; σ, Stefan–Boltzmann constant, J/(cm^2·K^4); $c_0 = c\exp(-k_1)$ and $d_0 = d\exp(-k_1)$, dimensionless constants; k_1 and $\bar{k}_1 = \rho_1hk_1$, dimensional (m^2/kg) and dimensionless coefficients of radiation damping in the FC layer within the framework of the Bouguer–Lambert law [16]; $\pi_e = \frac{p_{2e}}{p_{02}}\exp\left(\frac{E}{RT_*}\right)$, ratio of characteristic partial pressure of water vapor in the surrounding medium and the FC layer p_{2e} to the characteristic (equilibrium) pressure of saturated water vapor $p_{02}\exp\left(-\frac{E}{RT_*}\right)$, $\gamma = \frac{\rho_1\varphi_{1in}c_{p1}RT_*^2}{\rho_2q_2E}$, dimensionless criterion characterizing the rate of drying of FC in the layer; $\beta = \frac{RT_*}{E}$, dimensionless quantity inverse to the activation energy of the evaporation process; α_v and $\bar{\alpha}_v = \alpha_v\frac{RT_*^2\sqrt{T_*}}{q_2k_{02}\rho_2E}\exp\left(\frac{E}{RT_*}\right)$, dimensional (J/(m^2·sec·K)) and dimensionless coefficients of bulk heat exchange between the air and the c phase in the Fc layer. Indices: in, initial values, i.e., values of the parameters of state on the left-hand side boundary of the first time span; FFi, forest fire; P, period; A, anthropogenic; FiA, anthropogenic fires; NFi, number of fires; L, lightning; FiHP, fire-hazard period; FiL, fires due to lightning; i, forest type; j, right-hand side boundary of the jth time span; w, at $z = h$; 0, at $z = 0$; s, c phase; e, surrounding medium; v, volumetric; R, radiation.

REFERENCES

1. B. J. Stocks, M. E. Alexander, R. S. McAlpine, B. D. Lawson, and C. E. Van Vagner, *Canadian Forest Fire Danger Rating System*, Canadian Forestry Service (1987).
2. I. E. Deeming, I. W. Lancaster, M. A. Fosberg, R. W. Furman, and M. H. Schroeder, *The National Fire-Danger Rating System*, USDA Forest Service Research Paper RM-84, February, 1972.
3. G. N. Korovin, V. D. Pokryvailo, Z. M. Grishman, V. M. Latypin, and I. F. Samusenko, in: *Forest Fires and Fighting Them* [in Russian], Leningrad (1986), pp. 18–31.
4. A. M. Grishin, *Physics of Forest Fires* [in Russian], Tomsk (1999).
5. A. M. Grishin, *Mathematical Modeling of Forest Fires and New Methods of Fighting Them* [in Russian], Tomsk (1997).
6. A. M. Grishin, A. N. Golovanov, L. Yu. Kataeva, and E. L. Loboda, *Fiz. Goreniya Vzryva*, **37**, No. 1, 65–76 (2001).
7. E. L. Loboda, *Physico-Mathematical Modeling of Drying and Ignition of the Layer of Forest Combustibles*, Candidate Dissertation (in Physics and Mathematics), Tomsk (2002).
8. A. M. Grishin, *Modeling and Prediction of Catastrophes* [in Russian], Tomsk (2002).
9. A. M. Grishin, A. A. Dolgov, V. P. Zima, D. A. Kryuchkov, V. V. Reino, A. N. Subbotin, and R. M. Tsvyk, *Fiz. Goreniya Vzryva*, **34**, No. 6, 15–22 (1998).
10. A. M. Grishin, V. P. Zima, V. T. Kuznetsov, and A. I. Skorin, *Fiz. Goreniya Vzryva*, **38**, No. 1, 30–35 (2002).
11. N. V. Smirnov and I. V. Dunin-Burkovskii, *A Course in Probability Theory and Mathematical Statistics for Engineering Applications* [in Russian], Moscow (1969).
12. Yu. A. Andreev and G. F. Larchenko, in: *Forest Fires and Fighting Them* [in Russian], Moscow (1987), pp. 251–263.
13. *Handbook on the Climate of the USSR* [in Russian], Issue 20, Pt. 2 (1965).
14. A. M. Grishin, N. V. Baranovskii, I. V. Meinert, and Yu. Yu. Pavshuk, in: *"Forest and Steppe Fires: Origination, Propagation, Suppression, and Environmental Aftereffects"* [in Russian], Tomsk (2001), pp. 47–50.
15. D. A. Frank-Kamenetskii, *Diffusion and Heat Transfer in Chemical Kinetics* [in Russian], Moscow (1967).
16. A. V. Pavlov, *Energy Exchange in the Landscape Medium of the Earth* [in Russian], Novosibirsk (1984).