DEVELOPMENT OF GIS TO ESTIMATE FOREST FIRE DANGER CAUSED BY LIGHTNING ACTIVITY

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ABSTRACT

Lightning activity is the main natural reason to start forest fires. An ignition during lightning activity is caused by cloud-to-ground lightning discharge. Initiation of the forest fire ignition determines by chemical and physical processes during discharge influence. There are differences in electric current conduction within a tree trunk for coniferous and deciduous species. The main part of fire incidents occurs in the coniferous forest stands. It is necessary to simulate tree ignition by the cloud-to-ground lightning discharge. The simple heat transfer mathematical model is used to simulate coniferous tree ignition. Probabilistic criterion is used to assess forest fire danger level caused by lightning activity and forest conditions. In general, forest fire danger depends on lightning activity, meteorological conditions and vegetation on the forested territory. Meteorological parameters like environmental temperature are used in the mathematical model of tree ignition. Tree breed is taking into account using tree trunk structure and thermophysical parameters of coniferous wood. Also model uses electric current parameters of the cloud-to-lightning discharge. In principle, a mathematical model may take into account multi-stroke of the lightning discharge. It is suggested to use a specific geoinformation system developed for forest fire danger assessment. Using of the ArcGIS or QGIS software is not suitable for realization of the program instruments of tree ignition and probabilistic estimation. It is suggested to use high-level programming language for program realization of the mathematical models of forest fire initiation during lightning activity. Dialog mode is used in developed software to organize the interaction with users. The Origin Pro Software is used to visualize prognostic information on forest fire danger levels. Contours options can be used to map lightning activity, forest conditions and forest fire danger level using probabilistic estimation. The Origin Pro Software is applied in conjunction of the executable files of developed software to simulate forest fire danger. This software package can be used in forestry to implement decision-making function during fire season.

Keywords: *forest fire danger, GIS, estimate, Origin software, lightning activity*

INTRODUCTION

Currently, both soft and hard calculations are used to analyze the processes of forest fires [1]. It should be noted that the use of most soft computing methods based on neural networks or classification algorithms with training, allows us to analyze the forest fire danger in relatively constant conditions. But from time to time there are sharp weather and climate changes that cannot be noted within the framework of soft computing technologies. It is necessary to focus on the methods of deterministic forecast of forest fire danger and probabilistic criteria [2].

Today, various software products are used for the analysis of spatial data on forest fire danger (geo-information systems) [3]: ArcGIS, QGIS, Grass, GeoDMA, eCognition. At the same time, the authors of [3] propose to use the R language library [4] as a GIS system. In this paper, it is proposed to use the Origin Lab software package by Origin Lab as a host system for GIS data analysis. This is due to several reasons, including the cost of development and the software used as the host system. Moreover, the cost of the final workplace of a forest protection engineer is more advantageous when using the Origin Pro package. The package also offers advanced features for data analysis.

The purpose of this work is to design and create a system of geoinformation analysis of forest fire danger based on the application for the Origin Pro package.

System requirements

Currently, the problem of forest fires is relevant for many regions of Russia and other states with forested areas. A particularly tense situation with forest fires is taking place in remote areas where there are no settlements or accessible transport routes. As a rule, in such territories forest fire danger is caused by the action of thunderstorm activity in the region. The cause of fire is a cloud-to-ground lightning discharge. One of the possible mechanisms for the occurrence of a forest fire from a thunderstorm is characterized by the destruction of wood as a result of the impact and fallout of heated charred particles onto a layer of ground cover and its further ignition. Due to a variety of forest and meteorological conditions, it is advisable to monitor, evaluate and predict forest fire danger at the regional level, taking into account local peculiarities. At the regional level, there should be a computational resource providing forecasting of forest fire danger in a mode ahead of the real time of development of the catastrophic phenomenon. A prerequisite for an adequate forecast is the presence of a specific system of requirements:

- availability of a tool network for monitoring meteorological parameters in a controlled forest area (for example, in the Roshydromet structure);
- the presence of physically sound mathematical models of drying of the ground cover under environmental conditions;
- the presence of physically sound mathematical models of ignition of forest fuels (in this case as a result of ground lightning discharge);
- availability of operational information on the development of the storm front in a controlled forest area (using satellite technology and the WWLLN network);
- availability of tools for the spatial analysis of information on forest conditions, meteorological parameters and thunderstorm activity;
- availability of visualization tools for forecasting information in the form of a layer-by-layer structure of a system of various parameters characterizing the level of forest fire danger in a controlled forest area in conditions of thunderstorm activity;
- availability of methods for ranking the level of forest fire danger based on a probabilistic approach;

- availability of an output system of parameters that is available for understanding and making management decisions for employees of the forest fire protection service (possibly without a specialized physical and mathematical education).

This is a set of minimum conceptual requirements for organizing physically sound monitoring, assessment and forecasting of forest fire danger at a regional level. Foreign experience shows that the use of forest fire danger forecasting systems brings a significant economic effect from use.

STUDY AREA

Timiryazevskiy forestry of the Tomsk region is located between the Ob river and the Tom river on the territory of three administrative districts of the Tomsk region: Tomsk, Shegarsky and Kozhevnikovsky. The length of the forest area from north to south is 64 km, from west to east is 50 km. Timiryazevskiy forestry was founded in 1966. Forestry forests are mainly represented by a single forest. According to the forest vegetation zoning of Western Siberia, the territory of Timiryazevsky forestry belongs to the zone of Southern taiga (Ob-Tomsk cedar-pine forest vegetation district). The territory of the forest is referred to a moderately wet area. The growing season is 120 days. The predominant main species is pine (39.6%), aspen (26.2%) and birch (21.2%). Cedar, larch, spruce and fir make up 13% [5]. Therefore, pine can be selected for research as a typical representative of deciduous trees.

Since 2008, in the Timiryazevskiy forestry of the Tomsk region during the fire danger season, observations are made annually in the forests during thunderstorms. The most susceptible places are selected on the basis of statistical data or WWLLN data analysis (2016,2017) [6]. Timiryazevskiy forestry is covered by a network of roads (asphalted, unpaved, country, forest-carrying). For observation of thunderstorms in the forests are organized mobile stations equipped with video cameras, as well as on the roads organized travel vehicles equipped with DVRs. The latter are installed on the rear and windshield of the car to enable coverage of the forest massif behind and in front of the car. Significant material of field observations has been accumulated, the analysis of which allows us to conclude about the possible physical mechanism of occurrence of a fire in a forest in conditions of thunderstorm activity.

In general, it can be concluded that the analysis of the accumulated factual material confirms the hypothesis of a possible mechanism for the occurrence of fires in forests. According to the hypothesis, small particles heated to high temperatures (mainly accompanied by the combustion process of the gaseous products of pyrolysis of dry organic matter) are one of the causes of forest fires, especially in remote forested areas. It should be noted that in order to clarify the theory of the occurrence of forest fires, it is necessary to continue monitoring the thunderstorm activity and forests using stationary and mobile observation points.

The probability of wood ignition is estimated by the formula, taking into account the discharge power

$$P_{ign} = \begin{cases} 1, & ignition \\ 0, & no\ ignition \end{cases}.$$

The WWLLN receiver consists of a VLF antenna, a VLF preamp (mounted at the bottom of the antenna). A separate small GPS antenna is also installed. In addition, the service node is connected. All these components are connected to a personal computer using various cables [7], [8]. Such a node can be built in any country to detect lightning discharges at a distance of up to 10 thousand km. The maximum signal from a lightning discharge is fixed at frequencies of about 10 kHz. Each node transmits data to a central computer, where centralized data processing takes place.

Specialized GIS-system is a distributed information and computing system. In Gorno-Altaisk, the WWLLN reception station processes information on lightning discharges across the territory of the Timiryazevskiy forestry of the Tomsk region, highlighting the time, spatial coordinates and energy of a lightning discharge. This information comes in the form of a data file in Tomsk. A special data processing center has been created in Tomsk for predicting forest fire danger. The mathematical model of ignition of a conifer tree is implemented in a high level language in the RAD Studio system from Embarcadero. In addition to data on lightning discharges, the program (which is a console application running in the interactive mode) uses data on typical sizes of tree, as well as thermophysical and thermokinetic characteristics for calculating the process of starting a tree ignition by the cloud-to-ground lightning discharge. A one-dimensional mathematical model has been implemented, taking into account the structural heterogeneity of the conifer tree trunk. After calculating the ignition delay time and local ignition parameters, the data is transferred to the Origin Pro package, which is used to process and visualize them.

The physical model is formulated with the following assumptions and assumptions:

1) A coniferous tree grows on the surface of the earth (for definiteness - pine);
2) A cloud-to-ground lightning discharge of a certain polarity strikes a tree trunk;
3) The electric current of the cloud-to-ground lightning discharge passes through the trunk. It is assumed that in different sections of the trunk the current parameters are the same and it passes in the subcortical zone of the coniferous tree;
4) Wood is heated due to the release of Joule heat as a result of cloud-to-ground lightning discharge;
5) When critical values of heat flow from the subcortical zone of the trunk and temperature are reached, cracking of the thin surface layer of the trunk occurs;
6) The effect of wood moisture on the process of its heating is neglected.
7) Thermal decomposition of the dry organic matter of the tree trunk wood is not taken into account.

The processes of wood ignition are well studied when exposed to the material of radiant heat fluxes of varying intensity [9]. These results can be extrapolated to the case of high-energy impact of cloud-to-ground lightning discharges on a tree trunk in conditions of thunderstorm activity. Due to the high energy of lightning discharges, when formulating a task, thermochemical processes may not be considered, accompanied by heating the wood to high temperatures (thermal decomposition, oxidation of gaseous and solid products of pyrolysis by air). It is assumed that the conditions for heating wood in the "core-subcortical zone-bark" system can be satisfactorily evaluated by mathematical modeling of heat transfer in the conductive model, taking into account the source term responsible for the heat production according to the Joule-Lenz law. Moreover, an equation in the subcortical zone should be immediately written, taking into account the energy characteristics of a thunderstorm discharge, available in the data from the WWLLN network. Typical data network WWLLN presented in Table 1.

The WWLLN network is a tool for localizing lightning discharges in time and space over long distances. The network uses very low frequency radio waves (VLF) receivers distributed throughout the planet and a central processor that combines individual data to determine the source of a signal from a lightning discharge on top of a spherical Earth. These networks have been used in recent studies to analyze cosmic processes [10], in meteorology [11], and also to analyze lightning physics [12]. Currently, the WWLLN network consists of more than 50 stations around the world. Since 2010, the network has been looking for discharges with a spatial resolution of 10 km and less than 10 ms.

Table 1. Typical WWLLN data available to node owners

Date	time	Latitude	Longitude	Resid	Nstn	energy	energy uncertainty	Nstn_energy
2012/4/23	00: 00: 00.149517	26.5463	135.4961	13.2	9	2741.38	332.49	5
2012/4/23	00: 00: 00.834707	10.7970	125.8763	06.2	7	1744.95	131.47	6
2012/4/23	00: 00: 00.943868	19,4564	-070,9303	17,2	6	298,00	118,10	4
2012/4/23	00: 00: 00.922768	14.1879	-090.7451	24.0	16	507.86	136.14	13
2012/4/23	00: 00: 00.943845	19.3481	-070.9295	16.4	5	212.37	48.31	4
2012/4/23	00: 00: 01.205949	14.2636	-090.4189	14.0	11	140.89	33.33	9

According to [13], the power of the switched signal of a lightning discharge is associated with the peak value of the current strength according to the formula: $P_{stroke} = 1676 \times \left|J_{peak}\right|^{1.62}$

Where P_{stroke} is the power of the bearing signal, J_{peak} is the peak value of the current.

The problem is solved for a cylinder that simulates a tree trunk. A specific section of the trunk is considered. The diagram of the solution area is shown in Figure 1.

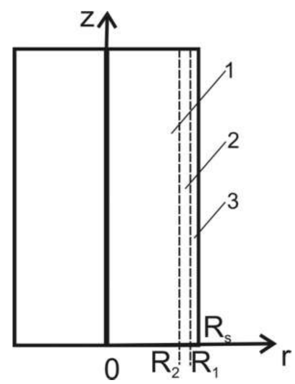

Fig. 1. Diagram of the solution area: 1 - core, 2 - subcortical zone, 3 - bark of a tree trunk; Rs is the outer radius of the trunk, R1 is the boundary between the subcortical zone and the cortex, R2 is the boundary between the core and the subcortical zone.

The process of warming up a tree with a cloud-to-ground lightning discharge is described by a system of nonstationary differential heat conduction equations:

$$\rho_1 c_1 \frac{\partial T_1}{\partial t} = \frac{\lambda_1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_1}{\partial r}\right),$$

$$\rho_2 c_2 \frac{\partial T_2}{\partial t} = \frac{\lambda_2}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_2}{\partial r}\right) + \left(\frac{E_{WWLLN}}{1676 t_l}\right)^{0.617} U,$$

$$\rho_3 c_3 \frac{\partial T_3}{\partial t} = \frac{\lambda_3}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_3}{\partial r}\right),$$

Boundary conditions:

$$r=0,\ \lambda_1 \frac{\partial T_1}{\partial r} = 0,$$

$$r=R_2,\ \lambda_1 \frac{\partial T_1}{\partial r} = \lambda_2 \frac{\partial T_2}{\partial r},\ T_1 = T_2,$$

$$r=R_1,\ \lambda_2 \frac{\partial T_2}{\partial r} = \lambda_3 \frac{\partial T_3}{\partial r},\ T_2 = T_3,$$

$$r=R_3,\ \lambda_3 \frac{\partial T_3}{\partial r} = \alpha_e (T_e - T_3),$$

Initial conditions:

$$t=0,\ T_i(r) = T_{i0}(r),\ i=1,2,3,$$

where T_i, ρ_i, c_i, λ_i are temperature, density, heat capacity and thermal conductivity, respectively, of the core (i=1), subcortical zone (i=2), and the bark (i=3) of the trunk; α_e is the heat transfer coefficient; E_{WWLLN} is the energy of the taped signal; Jpeak - peak current; tl is the time of registration of the lightning discharge signal; U is the lightning discharge voltage. r - coordinate, t - time. Indices "e" and "0" correspond to the parameters of the external environment and the parameters of wood at the initial moment of time.

Initial data (pine wood, core): ρ=500 kg/m^3; c=1670 J/(kg·K); λ=0.12 W/(m·K). Parameters of the subcortical layer: ρ=500 kg/m^3; c=2600 J/(kg·K); λ=0.35 W/(m·K). Thermal characteristics of the bark: ρ=500 kg/m^3; c=1670 J/(kg·K); λ=0.12 W/(m·K). Geometrical characteristics of the solution area: R_s=0.25 m; R_1=0.245 m; R_2=0.235 m. Environmental parameters: T_e=300 K, α_e= 80 W/(m^2·K).

CONCLUSION

The circumferential and axial compressive stresses arising from the intense very fast (t <0.5 s) heating of the near-surface layer of the wood of the trunk significantly exceed the compressive strength. In this regard, there are grounds for concluding that there is a very high probability of intense cracking followed by dispersing the near-surface wood layer heated to high temperatures. The analysis showed that the temperature of dispersed particles of wood reaches 1200 K. It was previously established that littering of litter of coniferous and deciduous trees is possible at temperatures above 1113 K. Consequently, it can be concluded that forest combustible materials located on the ground surface are highly likely to fire lightning discharge with the subsequent formation of particles heated to high temperatures.

Thus, this paper presents a description of an application that works in interactive mode and uses the capabilities of the Origin Pro package. In addition, the capabilities of the package allow you to analyze the calculated temperature fields in a tree exposed to a cloud-to-ground lightning discharge, in order to make decisions about fire prevention measures in the territory controlled by Timiryazevskiy forestryt of Tomsk Region. A description of the probabilistic criterion is proposed. The description of the operating mode of the new specialized geographic information system, which can be used to predict, monitor and assess forest fire danger from thunderstorms, is presented.

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