Methods of processing data from space monitoring of wild processes on the Earth’s surface

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Abstract. A methodology for modeling dynamics and controlling the fight against wild processes on the Earth's surface on basis the space technologies is proposed. Large forest fires considered as important illustration of such processes. A simple mathematical model proposed that describes the dynamics of the area covered by the spontaneous process, as well as actions to stop this process. Examples of calculating the parameters of real wildfires are given. An experiment on predicting the dynamics of a large wildfire using a neural network based on space monitoring data, as well as data from territorial divisions of forest guard enterprises and the Ministry of Emergencies are describing. It is shown how, according to the dynamics of the area occupied by the spontaneous process, is possible to estimate its configuration, as well as the intensity of the impact on it.

1. Introduction
Prediction of the wild processes parameters on the Earth’s surface and assessment of their consequences based on information obtained in satellite monitoring systems opens up significant opportunities for solving environmental monitoring tasks [1]. Examples of such processes are lava flows during volcanic eruptions, plant pest distribution, flood spread, oil spills on the sea surface, distribution of technogenic radionuclides at the bottom of the sea from sunken objects and others.

This problem is especially important in connection with the catastrophic forest fires that have become more widespread in the world - in Australia, Siberia, Canada, USA, South Europe and other regions [2]. Therefore, in this work, under the spontaneous natural process, we will mean precisely large wildfires. However, the considered methodology can be applied to other wild processes.

The difficulty of solving this problem determined by several factors.

- The complex nature and variability of the behavior of large multi-day wildfires that develop over a large area in changing forest and weather conditions.
- Insufficient or inaccurate information about the characteristics of the forest, the topography of the area, and local weather data.
- Low resolution of available satellite images of fires.
- Not always reliable reporting information from the fire location.
- Organizational complexity in the fact that when fighting forest fires near settlements and other objects of the economy, there are problems of interaction between the fire forces of various
departments: the Ministry of Emergency Situations, forest protection services, municipal and rural entities.

From the foregoing, it follows that for effective management of forest fire control, it is necessary to conduct research and evaluation of various methods for predicting fire parameters based on satellite data with the involvement, where possible, of additional information.

In this paper, we consider such methods for fires under the influence of fire fighting forces.

The initial information for the work was the data on forest fires stored in two information systems. First of them is Regional Civil Defense and Emergency Satellite Monitoring System (Krasnoyarsk) [3] and the ISDM-Rosleskhoz system created by a number of organizations under the leadership of the Space Research Institute of the Russian Academy of Sciences [4], which is used by the Federal State Aviation Protection Agency. These systems receive and process data obtained from the satellites NOAA, TERRA, AQUA, MODIS, LANDSAT and others with the help of devices operating in different radiation ranges.

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In addition, the fire managers use available data on the characteristics of the forest at the fire location, as well as weather data complexes.

Earlier, a number of authors considered various methods for predicting the spread of forest fires based on satellite information [5-7]. Fire statistics were investigated, OLAP and neural network prediction methods were used; a program for data conversion was developed, as well as a GIS-based application for visualizing forecast results.

It has been established that with the current level of information support, one of the most effective tools for predicting the parameters of large (over 200 ha) wildfires is neural network technology. Neural network models for predicting the daily increase in the area covered by the fire were proposed and verified for several regions of Eastern Siberia and the Far East [8]. The first section of this article describes one of the settings for predicting the growth of large forest fires using neural networks.

Further, in the work it is shown that, having adopted several hypotheses about the dynamics and configuration of the fire, it is possible to carry out deeper processing of the available information. Methods for predicting a fire configuration based on information on the increase in fire area, obtained by neural network processing of data stored in satellite forest monitoring systems and forest vegetation maps are considered. Based on the dynamics of the increase in the area of the fire, the moment of the beginning of the fight against the fire and the intensity of this fight are estimated.

Note that the models of fire dynamics are comparatively crude, focused mainly on obtaining qualitative estimates of the fire propagation process in the most adverse cases. Nevertheless, according to experts, such information is useful in making decisions on fighting fires. Attempts to obtain more accurate forecasts of fire dynamics undertaken, for example, by the developers of the Behave Plus system (USA) [5] with the most detailed consideration of the available data on the combustion conditions showed that even for small fires, the errors are about 30% by area and up to 50% by geometric sizes. In addition, forecast accuracy is highly dependent on the qualifications of the fire analyst. The scientists of the Forest Institute of Russian Academy of Science obtained similar results [7]. The indicated errors, among other things, are because it is impossible to predict weather conditions in the fire area, and they have a decisive influence on its distribution. This is especially true for forecasts for a long period.

2. Neural network’s forecasting the dynamics of the area of forest fires

As preliminary studies of the data stored in the forest fire monitoring system have shown, classical statistical methods do not allow establishing reliable relationships between parameters of wildfires [8]. At the same time, the use of artificial neural networks has yielded encouraging results. To implement the neural network forecasting the dynamics of the forest fire area, the NeuroPro 0.25 neuro emulator was chosen [9]. The choice of this software related to its functionality, accessibility and ease of use. The program allows you to create, train, test, and perform other necessary actions with multilayer neural networks.
The course of a typical neural network forecasting experiment includes the following steps.

- Data collection according to the conditions of the current experiment (formation of a data showcase).
- Structuring and classification of data.
- Formation of training and test samples for the neural network.
- Randomization of training data.
- Bringing data into a format suitable for processing by neuro imitators.
- The choice of the topology and configuration of the neural network, the task of forecast accuracy.
- Neural network training.
- Testing the neural network.
- Analysis of intermediate results.
- Correction of the configuration of the neural network, its change (if necessary).
- Repeated cycles of training and testing a new neural network (if necessary).
- General analysis of the results.

The data on large fires collected at ISDM-Rosleskhoz were classified according to their possible values. The classification results indicating all the selected classes, field names for the database table and sequential numbering of the fields summarized in table 1. The data were presented in dBASE IV (*.dbf) format, necessary for processing using the NeuroPro neuro-simulator.

In the course of research, to improve the quality of forecasting, the data of the meteorological service on the forecasted weather characteristics for 3 and 10 days were used. At the same time, the number of input parameters of the neural network increased to 29.

**Table 1.** Field names for the database table and sequential numbering of the fields.

| Field number | Field name | Description of field parameters |
|--------------|------------|----------------------------------|
| 1            | VAR1       | Identification field. Not involved in the sample |
| 2            | VAR2       | The average daily increase in fire area in hectares. Output field |
| 3            | VAR3       | Code of the administrative forest division |
| 4            | VAR4       | Area of fire registration in hectares |
| 5            | VAR5       | Number of days of fire observation |
| 6            | VAR6       | Code of vegetation for the fire area. |
| 7            | VAR7       | Air temperature at the start of fire °C. |
| 8            | VAR8       | Dew point at the start date of the fire °C |
| 9            | VAR9       | Deficiency of dew point °C, at the start date of the fire |
| 10           | VAR10      | Precipitation daily for the start date of the fire. mm |
| 11           | VAR11      | Integrating fire hazard indicator according to local Nesterov scales |
| 12           | VAR12      | Fire hazard class according to local Nesterov scales |
| 13           | VAR13      | Integrating fire hazard indicator for moisture index PV-1 |
| 14           | VAR14      | Fire hazard class in terms of moisture index PV-1 |
| 15           | VAR15      | Integrating fire hazard indicator for moisture index PV-2 |
| 16           | VAR16      | Fire hazard class in terms of moisture index PV-2 |
| 17           | VAR17      | A sign of rainfall during the day on the date the fire started. |
| 18           | VAR18      | Sign of rainfall at night at the start of the fire. |
More than 30 neural networks of various configurations trained and tested. The best results shown by neural networks with the next configurations: 8 hidden layers of 10 neurons and 7 hidden layers of 12 neurons.

Studies, in particular, showed that with the training sample containing data on 274 large fires and the established error in the daily increase in area equal to 10 ha, the proportion of correct answers is in the range from 86 to 94%.

3. The basic model of the wildfire area dynamics

Below are the tasks associated with further processing of data on wildfires.

Using the direct data of fire monitoring, or the growth of the fire area calculated using a neuro imitator [8], a model of the fire area dynamics may be built. When modeling, the following calculations performed.

- Fire front speed and the speed of increasing the length of the fire edge calculated.
- Based on data of wind speed and its direction the possible fire configuration is evaluated.
- The moment of the beginning of the fight against fire and the productivity of fire fighting forces are determined.

The following assumptions were made.

1. The dynamics of the area changes of a freely developing fire is determined by the expression

\[ S(t) = k_0 (t - t_0)^\alpha \]

where \( t \) – the current time, \( t_0 \) – the time of the fire starting, day, \( k_0 \) – a constant coefficient having the dimension \( ha / day \), \( \alpha \) – indicator of the growth rate of the area. As is clear from geometric considerations, the change in the speed of the fire front is associated with the indicator \( \alpha \): at \( \alpha = 2 \) this rate is constant, at \( \alpha < 2 \) the front rate decreases with time, and at \( \alpha > 2 \) the front rate increases.

2. The speed of the fire front represented as

\[ \nu(\phi, t) = v_0(t) \xi(\phi) \]

where \( v_0(t) \) – the time-dependent maximum rate of propagation of the fire front (for example, in the direction of the wind); \( \xi(\phi), (|\xi| \leq 1) \) – indicatrix of the full speed of the front, determining the configuration of the fire in accordance with the Huygens principle, \( \phi \) – the direction of propagation \( (0 \leq \phi \leq 2\pi) \).

3. The indicatrix is determined by the wind speed \( w \) and its direction, it is assumed unchanged in the estimated time period, the angle \( \phi \) in the formulas below is counted from the wind direction clockwise.

To simplify the formulas in this section, put \( t_0 = 0 \).

Consider the elementary increment of the fire area \( dS \). Figure 1 shows the edge of the fire at two close points in time \( t \) and \( t + dt \). From the figure it follows that \( dS = v_n dt \), where \( v_n \) is the normal speed of the front. The increment of the contour length, which calculated by the formula from [7]:

\[ dl = \rho d\phi = d\phi \sqrt{\xi^2(\phi) + \xi'^2(\phi)} \int_0^\phi \nu(\phi, \tau) d\tau \].

\[ \int_0^\phi \nu(\phi, \tau) d\tau \]
In turn, normal speed related to full speed by the ratio [7]

\[ v_n(\varphi, t) = \frac{v(\varphi, t)}{\sqrt{1 + \left(\frac{v'(\varphi, t)}{v(\varphi, t)}\right)^2}} = \frac{v_0(t)\xi^2(\varphi)}{\sqrt{\xi^2(\varphi) + \xi'^2(\varphi)}}. \tag{4} \]

From here

\[ dS = d\varphi dt v_0(\xi^2(\varphi)) \int_0^\varphi v_0(\tau) d\tau. \tag{5} \]

Area increment in all directions of distribution, the growth rate of the entire fire area:

\[ dS_{2\pi} = \int_0^{2\pi} dS d\varphi = 2d\xi v_0(t) \int_0^\xi d\varphi \xi^2(\varphi) \int_0^\varphi v_0(\tau) d\tau. \]

The dynamics of the total area will take the form

\[ \frac{dS}{dt} = 2v_0(t) \int_0^\xi \xi^2(\varphi) d\varphi \int_0^\varphi v_0(\tau) d\tau. \tag{6} \]

We will look for a function \( v_0(t) \) in the form \( v_0(t) = t^{\beta} \) where the quantities \( \beta \) and \( v_{0s} \) are to be determined. Then

\[ \int_0^\varphi v_0(\tau) d\tau = \frac{1}{\beta} v_{0s} t^{\beta+1}. \]

\[ \frac{dS}{dt} = 2v_{0s}^2 \frac{1}{\beta + 1} \int_0^\xi \xi^2(\varphi) d\varphi. \]

On the other hand, from the initial assumption \( S(t) = k_o t^\alpha \) it follows \( \frac{dS}{dt} = k_o \alpha t^{\alpha-1} \), and we get the equation

\[ 2v_{0s}^2 \frac{1}{\beta + 1} \int_0^\xi \xi^2(\varphi) d\varphi = k_o \alpha t^{\alpha-1}. \tag{7} \]

Equating the exponents with \( t \) we get \( 2\beta + 1 = \alpha - 1 \) where

\[ \beta = \frac{\alpha}{2} - 1. \tag{8} \]
Next, equating the factors at \( t \) we determine the value:

\[
V_{0s} = \left( \frac{\alpha k_0 (\beta + 1)}{2} \right)^{1/2} = \frac{\alpha \sqrt{k_0}}{2P},
\]

(9)

where \( P(w) = \int_0^\pi \xi^2(\varphi)d\varphi \).

Based on the formula (3), the perimeter of the fire burning edge can also be calculated. In the particular case when a fire develops from a circular focus of small radius:

\[
L(t) = 2\int_0^\pi \alpha d\varphi = 2\int_0^\pi V_0(t) d\tau \int_0^\pi \sqrt{\xi^2(\varphi) + \xi^{r^2}(\varphi)} d\varphi.
\]

(10)

The formula for the growth rate of the perimeter of the fire will take the form

\[
\frac{dL(t)}{dt} = 2V_0(t)Q(w),
\]

(11)

where \( Q(w) = \int_0^\pi \sqrt{\xi^2(\varphi) + \xi^{r^2}(\varphi)} d\varphi \).

In the case when \( \alpha = 2, \beta = 0 \) at and the front speed is constant, we have

\[
V_{0s} = \frac{\sqrt{k_0}}{P}.
\]

(12)

With circular distribution \( \xi(\varphi) = 1, \int_0^\pi \xi^2(\varphi)d\varphi = \pi \) and \( V_{0s} = \sqrt{\frac{k_0}{\pi}} \), which directly follows from the formula determining the area of the expanding circle: \( S = \pi(V_{0s}t)^2 = k_0t^2 \).

4. **Concrete expressions for indicatrix**

In this paper, we consider the following expressions for speed indicatrix [7].

1. Exponential indicatrix

\[
\xi(\varphi) = \exp(a(w)(\cos(\varphi) - 1)),
\]

(13)

where the coefficient \( a(w) \) depends on the wind speed and is estimated by the formula: \( a(w) = 0.785w - 0.06w^2 \), which is valid under the conditions: \( 0 \leq w \leq 3 \text{ m/s} \).

Then the integrals in expressions (9) and (11) take the form

\[
P(w) = \int_0^\pi \xi^2(\varphi)d\varphi = \exp(-2a(w))\int_0^\pi \exp(2a(w)\cos(\varphi))d\varphi,
\]

(14)

\[
Q(w) = \int_0^\pi \sqrt{\xi^2(\varphi) + \xi^{r^2}(\varphi)} d\varphi = \int_0^\pi \xi(\varphi)\sqrt{1 + \frac{a^2(w)}{4}} \sin^2(2\varphi) d\varphi.
\]

(15)

The calculated values of these integrals for some values of wind speed are given in Table 2.
2. Elliptical indicatrix

\[
\xi(\varphi) = \frac{1 - e(w)}{1 - e(w) \cos(\varphi)},
\]

where \( e(w) \) — eccentricity of the ellipse, depending on the wind speed. To assess the dependence of the eccentricity of the elliptic indicatrix on the wind speed, the indicatrix graphs given in the work of F. Albini \[6\] approximated by ellipses for a large range of wind speeds indicated in the first row of Table 3, and the corresponding eccentricities were calculated. The following approximation of the dependence of the indicatrix on wind speed obtained:

\[
e(w) = 1 - \exp(-0.4w).
\]

Then the values of the integrals \( P(w) \) and \( Q(w) \) were calculated, are given in table 3.

**Table 3. Calculated values of integrals P(w) and Q(w) for elliptical indicatrix**

| \( w, m/s \) | 0   | 1.25 | 2.5  | 5   | 10  | 15  |
|--------------|-----|------|------|-----|-----|-----|
| \( e(w) \)   | 0.00| 0.393| 0.632| 0.865| 0.982| 0.998|
| \( P(w) \)   | 3.142| 1.469| 0.782| 0.588| 0.539| 0.193|
| \( Q(w) \)   | 3.142| 2.151| 1.60 | 1.424| 1.379| 1.194|

Comparing tables 2 and 3, we can see that the values of the function \( P(w) \) and \( Q(t) \) for both indicatrix noticeably differ at close wind speeds. It should be borne in mind that in the first case the wind speed was calculated at a height of two meters from the ground, and in the second— at a height of ten meters, and this explains the more elongated shape of the elliptical indicatrix. Let estimate the error of the proposed methodology.

It is clear that all the initial data introduce an error into the result. However, at this stage, we restrict ourselves to the simplest calculation of errors caused by the estimation of the error in the area of the fire and its daily gain. Let the error in determining the fire area is \( \Delta S \) ha, then the error in estimating the coefficient \( k_0 \) will be in accordance with formula (5) \( \Delta k_0 = \Delta S / \Delta t^2 \).

Example. The K-1491 wildfire registered in the ISDM-Rosleskhoz system operated in the Dolgomostovsky forestry of the Krasnoyarsk Territory from May 15, 2008 to May 18, 2008. The fire registered on an area of 27 hectares, the elimination area is 1526 hectares. The air temperature was 16.7 °C, the windspeed according to the nearest weather station was 4 m/s, the wind direction counted from the north direction was 100 degrees.

We assume that the error in determining the area is \( \Delta S = 100 \) ha, \( \Delta t = 3 \) days and calculate the coefficient \( k_0 \) and its error in the model:

\[
k_0 = \Delta S / \Delta t^2 = 1499 / 9 = 166.5 \text{ ha/days}^2, \Delta k_0 = 100 / 9 = 11.1 \text{ ha/days}^2.
\]
We take an indicator of the growth rate of the fire area \( \alpha = 2 \), i.e. we assume that the speed of the fire front is constant. Since the wind speed is high enough, we use an elliptical indicatrix. For a wind speed of 4 \( m/\text{s} \), we determine the eccentricity and factors \( P(w) = 0.585, Q = 1.422 \).

In accordance with formula (12), converting hectares to square meters, we obtain:

\[
v_{0S} = \sqrt[2]{k_0^2} = \sqrt{166.5 \cdot 10^4 \cdot 0.585} = 2206 \text{ m/day}.
\] (18)

Given the possible error, the value of the front velocity will be in the following range: 
\[2195 \leq v_{0S} \leq 2217 \text{ m/day}.
\]

By the formula (11), we can estimate the growth rate of the perimeter of the fire:

\[
\frac{dL(t)}{dt} = 2v_0(t)Q(w) = 2 \cdot 2206 \cdot 1.422 = 6273 \pm 23.4 \text{ m/day}
\]

The obtained estimate of the rate of the fire front in combination with the selected distribution indicatrix allows one to construct predictive estimates of the fire contour at given intervals. For this purpose, it is convenient to use the movable grid method [7].

5 Estimation of the start time of fire extinguishing and the rate of extinguishing according to monitoring

The idea of the method described below is that an inflection point is detected on the graph of the increase in the area of the fire, and the start time and intensity of firefighting events are estimated by changing the slope of the curve.

Suppose that, according to monitoring data, the fire area was recorded at successive points in time:

\[S_1 = S(t_1), S_2 = S(t_2), \ldots, S_n = S(t_n), t_1 < t_2 < \ldots < t_n\]

We calculate the increment of the fire area for each time period (the first difference):

\[\Delta S(t_i) = S(t_i) - S(t_{i+1}), i = 2, 3, \ldots, n \text{ ha/day} \] (19)

as well as increment of increment (second difference):

\[\Delta^2 S(t_i) = \Delta S(t_i) - \Delta S(t_{i+1}), i = 3, 4, \ldots, n \text{ ha/day}. \] (20)

The analysis of quantities \( \Delta S(t_i) \) and \( \Delta^2 S(t_i) \) allows us to draw the following conclusions.

1. Values \( \Delta S(t_i) \) are always positive (or equal to zero when the fire is localized).
2. Values \( \Delta^2 S(t_i) \) are positive when the fire spreads freely, become negative when extinguishing a fire, and vanish to zero when localization is complete.

We illustrate these findings with an example.

Example. According to the Krasnoyarsk Forest protection base, a forest fire in the Turan region forestry was registered on 04/21/08 and developed as follows (in the table 4 the month and year are not indicated). The fire parameters were recorded from satellites and processed by the ISDM-Rosleskhoz system.
Table 4. Area dynamics of the Turan wildfire.

| Day $t_i$ | Fire area, $ha$ | Increment of fire area $\Delta S(t_i), ha/day$ | Second difference $\Delta^2 S(t_i), ha/day^2$ | Fire station               |
|----------|-----------------|-----------------------------------------------|---------------------------------------------|---------------------------|
| 21       | 60              | -                                             | -                                           | Free propagation          |
| 22       | 75              | 15                                            | -                                           | Free propagation          |
| 23       | 220             | 145                                           | 130                                         | Free propagation          |
| 24       | 275             | 55                                            | -90                                         | Fire extinguishing        |
| 25       | 320             | 45                                            | -10                                         | Fire extinguishing        |
| 26       | 320             | 0                                             | -45                                         | Fire extinguishing        |
| 27       | 320             | 0                                             | 0                                           | Fire is localized         |

The corresponding graph shown in Figure 3.

The analysis of the table and graph shows that from 21 to 23 days the fire developed freely, and from 24 to 26 days the fire was extinguished, and the greatest efforts to extinguish fell on the 24th. At April 27, the fire was localized.

Figure 2. Dynamics of changes the fire area in the Turan forestry on April 21-28, 2008.

6. Dynamics of a fire under the influence of fire fighting forces

It should be emphasized that in this section we are talking about the localization of the fire, and not about its elimination. According to the accepted methods of calculating the required productivity of fire fighting forces, firefighting carried out by reducing the length of the fire burning edge. We will consider a simplified model of this process, based on the hypothesis of a decrease in the growth rate of the fire area over time. We assume that firefighting forces, starting from the moment of extinguishing, reduce the growth rate of the fire area, i.e., reduce the coefficient $k_0$ value in formula (1).

In the simplest case, a linear law can be adopted:

$$k_0 = k_s(t) = k_1 - u(t - t_s), \ t \geq t_s$$ \ (21)

where $t$ is the start time of the fire, $u$ ha / day - the rate of the coefficient $k_0$ changing; when $t = t_s$ coefficient $k_0 = k_1$. 
The coefficient $u$ can be considered as an indicator of the intensity of the fight against fire, that is, as a control action from the fire forces and equipment.

Then, the area growth rate in accordance with (1) and (21) is determined by the formula

$$R(t) = \frac{dS(t)}{dt} = \begin{cases} \alpha k_1 t^{\alpha-1}, & t \leq t_S, \\ \alpha(k_1 - u(t-t_S))t^{\alpha-1}, & t \geq t_F, \\ 0, & t \geq t_F. \end{cases} \quad (22)$$

With the value of time $t_F = t_S + \frac{k_1}{u}$ and $t \geq t_F$ the growth rate of the area $R(t_F) = 0$, which means the localization (stopping the spread) of the fire. Moreover $S(t) = S(t_F)$, with $t \geq t_F$.

The total area covered by the fire at the time $t_F \geq t \geq t_S$:

$$S(t) = k_1 \int_0^{t_S} t^{\alpha-1} dt + \int_{t_S}^{t} (k_1 - u(t-t_S))t^{\alpha-1} dt = k_1 t_S^\alpha + \alpha k_1 \int_{t_S}^{t} t^{\alpha-1} dt - \alpha k_2 \int_{t_S}^{t} (t-t_S) t^{\alpha-1} dt = k_1 t_S^\alpha - \frac{\alpha}{\alpha + 1} u(t^{\alpha+1} - t_S^{\alpha+1}) + u(t^\alpha - t_S^\alpha). \quad (23)$$

In the case when the coefficient $k_1$ is known, the moments of the beginning $t_S$ and $t_F$ end of localization and, as well as $S(t_F)$, it is possible to evaluate the coefficient $u$ characterizing the rate of quenching:

$$u = \frac{k_1 t_S^\alpha - S(t_F)}{\alpha + 1} \frac{ha/days^{\alpha+1}}{t_F^{\alpha+1} - t_S^{\alpha+1} - t_S^\alpha}, \quad (24)$$

Example. We estimate the localization parameters of the fire considered above.

The approximation of the data contained in Figure 3 allows us to obtain the following estimates of the model parameters: $t_S - t_0 = 3$ days, $t_F - t_0 = 7$ days, $\alpha = 2.15$, $k_1 = 10.23$ ha/days, $S(7) = 320$ ha, then by formulas (23) and (24) we get $u = 2.771$ ha/day$^{1.15}$. Note that directly by the formula (21) with $k_o = 0$, a slightly different value of this coefficient is obtained: $u = \frac{k_1}{t_F - t_S} = 2.58$ ha/day$^{1.15}$.

The difference in values is explained by the influence of the error of the magnitude – the moment of the occurrence of the fire and the nonlinear nature of the growth of the fire area in time.
Model (21) - (23) makes it possible to evaluate the dynamics of fire parameters depending on the magnitude of the control action. Figure 3 shows the change in the parameters of the fire considered above for various values of $u$ and $t_F$. A clear picture of the extinguished fire parameters dynamics when changing $u$ can be represented in the form of phase portraits constructed in Figure 3 in the following coordinates:

- a) $S - t$
- b) $dS / dt - t$
- c) $dS / dt - S$

The magnitude of the control action varies from 0 (curve 1) to the maximum value $u$ in increments of 0.2 $u$ (curves 2 - 6).

### 7. Conclusion

The mathematical models and examples of calculations presented in the work suggest, in our opinion, the fundamental possibility of assessing the dynamics of large wildfires and performing deeper processing of data on their dynamics – both freely propagating and those under the influence of firefighting forces – in comparison with the current level of processing adopted in the above forest fire monitoring systems. We have created and successfully tested a software module for neural network forecasting of forest fire parameters based on satellite information. At present, the development of a subsystem for forecasting forest fires is underway using an expert system to select specific forces and means that carry out firefighting.

It is hoped that with the accumulation of experience, the quality of forecasting the parameters of wildfires and evaluating the effectiveness of fire-fighting measures will increase. We also hope that the
proposed methods for processing space information will find application in the analysis of other natural processes mentioned at the beginning of the article.

References
[1] Dorrer G A and Yarovoy S V 2019 IOP Conf. Ser.: Mater. Sci. Eng. 537 042052
[2] Largest wildfires of the last decade Retrieved from https://en.wikipedia.org/wiki/Wildfire
[3] Sukhinin A I, Kashkin V B and Ponomarev E I Monitoring Forest Fires in Eastern Siberia from Space Proc. of SPIE 3983 206
[4] Bartalev S A 2008 Information system for remote monitoring of forest fires of the Federal Forestry Agency of the Russian Federation (state and development prospects) Modern Problems of Remote Sensing of the Earth from Space Moscow: Space Research Institute of the Russian Academy of Sciences 5(2) 419-29
[5] Andrews P L, Bevins C D and Robert C 2008 BehavePlus fire modeling system (Ogden, UT: Department of Agriculture, Forest Service, Rocky Mountain Research Station) p 116
[6] Albini F A 1976 Estimating wildfire behavior and effects USDA Forest Service (USA: Ogden) p 72
[7] Dorrer G A 2008 Dynamics of forest fires (Novosibirsk: Siberian Branch Russian Acad. of Sci.)
[8] Berestenkova M V, Akinfeev R S, Komorowski V S 2009 The use of neural networks with a teacher to predict the increase in forest fire area on the basis of ISDM-Rosleskhoz data Problems of regional informatization PIR - 2009: Materials of the 11th All-Russian. scientific-practical conf. Krasnoyarsk pp 165-7
[9] Gorban A N 1998 Neuroinformatics (Russia: Novosibirsk: Nauka)