System of the space-based monitoring of forest fires on the territory of Tomsk Region. Part 2. Estimation of the efficiency of space monitoring

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The efficiency of space monitoring of forest fires on the territory of Tomsk Region in the period of 1998–2000 is analyzed. Analysis is based on comparison of satellite information with data of Tomsk Forest Protection Air Base collected in the region during three fire-risky seasons. The dependence of the probability of forest fire detection from the AVHRR/NOAA data on the parameters of fires and observational conditions is examined.

Introduction

In the first part of this paper[1] we discussed organizational and some other problems of space monitoring of forest fires (SMFF), which has been performed in Tomsk Region since 1998 at the Center for Reception and Processing of Information from NOAA Satellites created at the Institute of Atmospheric Optics SB RAS (Tomsk, Russia). The aim of this paper is to analyze the efficiency of applying satellite optical systems to detection of forest fires and to compare it with the efficiency of ground-based and air forest protection services. Up to now, this problem has not yet been adequately discussed in the literature; mostly papers (see, for example, Refs. 2–4) present only general data, which are insufficient for thorough study of the problem on the efficiency of applying satellite technologies to real-time monitoring of forest fires.

Using specialized software, we have performed complex analysis of SMFF results dated by fire-risky seasons of 1998–2000 in Tomsk Region. As test information, we used the data of Tomsk Forest Protection Air Base for this three-year period. The efficiency of the SMFF system functioning in Tomsk Region was studied in relation to the following main aspects: (a) estimation of the total efficiency of the SMFF system and the efficiency of early (as compared to forest fire protection services) detection of forest fires from satellites; (b) dependence of the results of space monitoring on the fire area; (c) information content of the SMFF data in different periods of a day.

1. Characteristics of fires

When comparing the satellite and test information, we used the following key characteristics of the flaming zones:

1) geographic coordinates (latitude and longitude) complemented with azimuth and distance to the fire from the air base;

2) dates and time of fire detection (T_{det}), localization (T_{loc}), and liquidation (T_{liq});

3) fire area at the time of detection (S_{det}) and at the time of liquidation (S_{liq}).

For statistical processing of data and drawing of histograms, the range of fire areas S was divided into 14 subranges, and the range of fire durations $[T_{det}, T_{liq}]$ was divided into 11 subranges. To evaluate the efficiency of early alarm, the fire duration was extended up to $[T_0, T_{liq}]$, where $T_0 = T_{det} - dT$ (dT depends on S_{det}). Besides, execution of some blocks of the software for computer analysis involved rough estimation of the fire areas $S(T)$ at the time T of space-based monitoring sessions.

Using these characteristics, the following procedure was performed for every satellite image:

– spatial arrangement of temperature anomalies detected from space was mapped with reference to geographic coordinates;

– the map of spatial arrangement of those fires, the time interval of whose search $[T_0, T_{liq}]$ corresponded to the time of image reception, (in some cases their number reached 75) was drawn;

– two maps were compared, and the coincident pairs of objects were selected according to the preset spatial criterion with the allowance made for their size and probability of fire presence in the image processed, which was assumed equal to unity in the interval $[T_{det}, T_{loc}]$ and tending to zero at $T \to T_0$ or $T \to T_{liq}$.

To get the general pattern of forest fires in Tomsk Region, Fig. 1 presents the summarized data for 1998–2000 on some characteristics of fires: (a) maps of spatial distribution of fires over the studied territory (Fig. 1*a*); (b) histogram of distribution of fires with respect to their area S_{liq} (Fig. 1*b*); (c) distribution of fires with respect to their duration $[T_{det}, T_{liq}]$ (Fig. 1*c*).

Analysis of data shown in Fig. 1 allows the following conclusions to be drawn.

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1. Regardless of different density of the spatial distribution of fires, the dominant part of the territory is potentially fire-risky.

2. The distributions shown in Figs. 1*b* and 1*c* have relatively small (less than 6–7%) interannual fluctuations, although it should be noted that in 2000 there were no large (maximum area – 180 ha) and long fires.

3. Small fragments in the figures (integral distribution functions) suggest that the number of small-size fires each having the area less than 1 ha makes up, on the average, about 60%, and the number of short (shorter than 12 h) fires on the average exceeds 50%. Thus, we can expect that about 50% of fires have low probability to be detected from space.

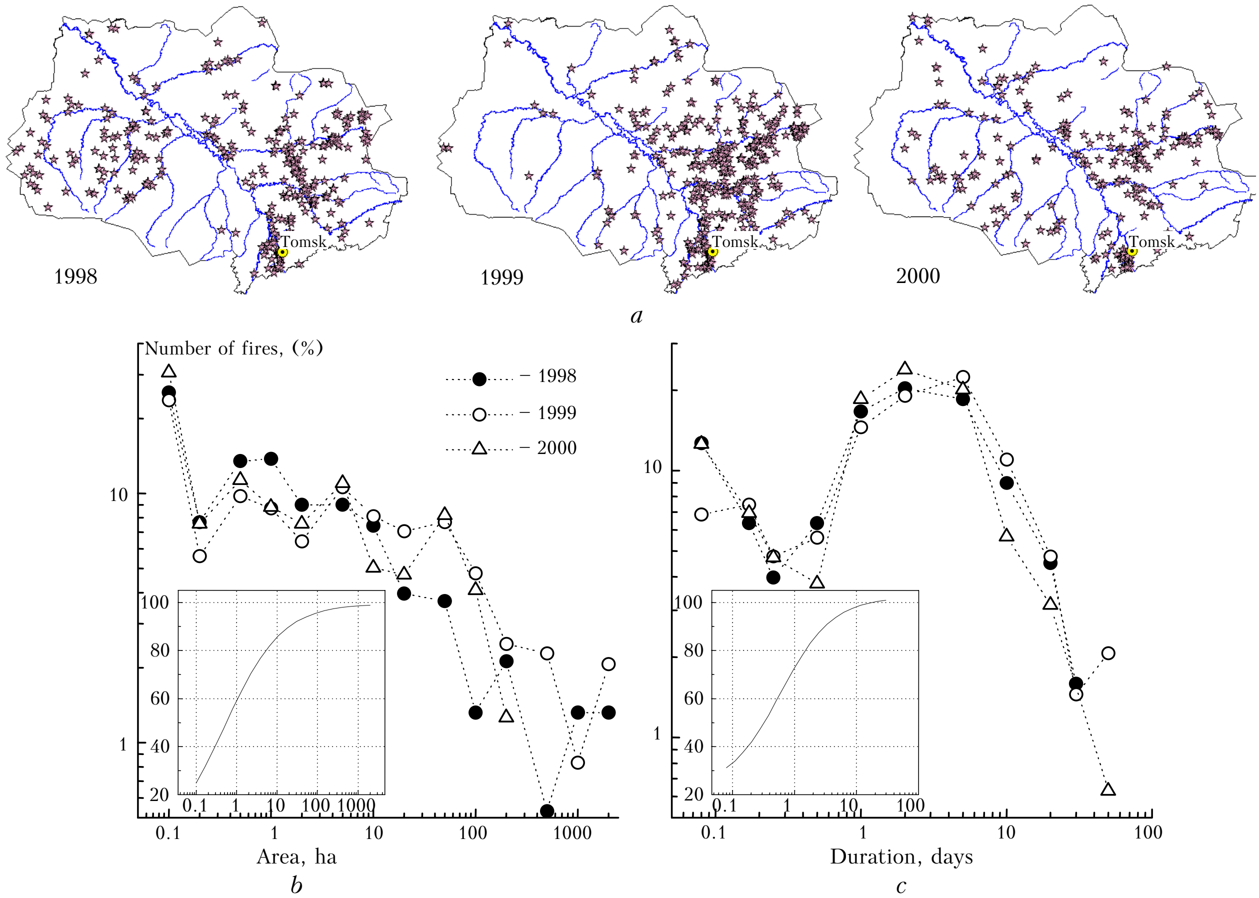


Fig. 1. Characteristics of forest fires.

Table 1. Final results of space monitoring of forest fires in 1998–2000

Characteristic	May	June	July	August	September	Total
			1998			
Number of fires	24	32	175	147	–	378 (–87)
Cloudiness, %	34.6	49.3	20.1	46.4	–	–
Fires detected	6	2	38	51	–	97
Early alarm	5	1	11	25	–	42
			1999			
Number of fires	60	31	199	132	60	482 (–80)
Cloudiness, %	45.7	55.6	28.5	49.6	61.8	–
Fires detected	39	9	72	51	22	193
Early alarm	20	0	23	33	10	86
			2000			
Number of fires	47	93	110	49	19	318 (–57)
Cloudiness, %	59.0	35.5	46.9	48.6	70.4	–
Fires detected	16	25	26	8	2	77
Early alarm	6	18	9	1	0	34
Total number of fires			1178 (–224)			
Detected			367 or 31.2% (38.5%)			
Early alarm			162 or 13.8% (17.0%)			

Note. The number of fires, which could not be detected from space, is given in parenthesis with minus sign.

2. Analysis of space-based monitoring efficiency

First, consider Table 1, which gives the results of space-based monitoring of forest fires in Tomsk Region for different months of every year (1998–2000), namely:

– number of fires detected by Tomsk forest protection services;

– monthly mean cloudiness – relative area of the territory inaccessible for space monitoring;

– total efficiency of SMFF – the total number of forest fires detected from space;

– efficiency of early alarm – the number of flaming zones that were detected from space earlier than they were fixed by forest protection services.

It follows from Table 1 that the overall efficiency of space monitoring of flaming zones varies within 24–40% in different years. A total of 367 of 1178 forest fires were detected from space in 1998–2000. It makes up more than 31% of the total number. The efficiency of early alarm varies from 11 to 18% (162 flaming zones) and makes up, on the average, about 14% for three years.

When evaluating the efficiency of space monitoring, it is worth allowing for the fact that some flaming zones (or conditions of observation) had characteristics that made their detection from space practically impossible. This is connected with the following reasons: (a) too short fire duration that the interval $[T_{\text{det}}, T_{\text{liq}}]$ lies between closest space monitoring sessions, (b) distance between flaming zones (existing in the same time) less than 2 km, i.e., they cannot be separated on images taken from space, (c) flaming zone is screened by dense clouds for the entire period $[T_{\text{det}}, T_{\text{liq}}]$. In the last column of Table 1, the number of such flaming zones is given in parenthesis for each year (15–25% of the total number of fires). In our opinion, this value is evidently underestimated. This follows, for example, from the fact that such a factor as forest canopy that is present in 96% forest fires and interferes detection of small fires is ignored here. If we subtract these fires undetectable from space, the efficiency of space monitoring increases, on the average, up to 38.5%, and the mean efficiency of early alarm makes up 17%.

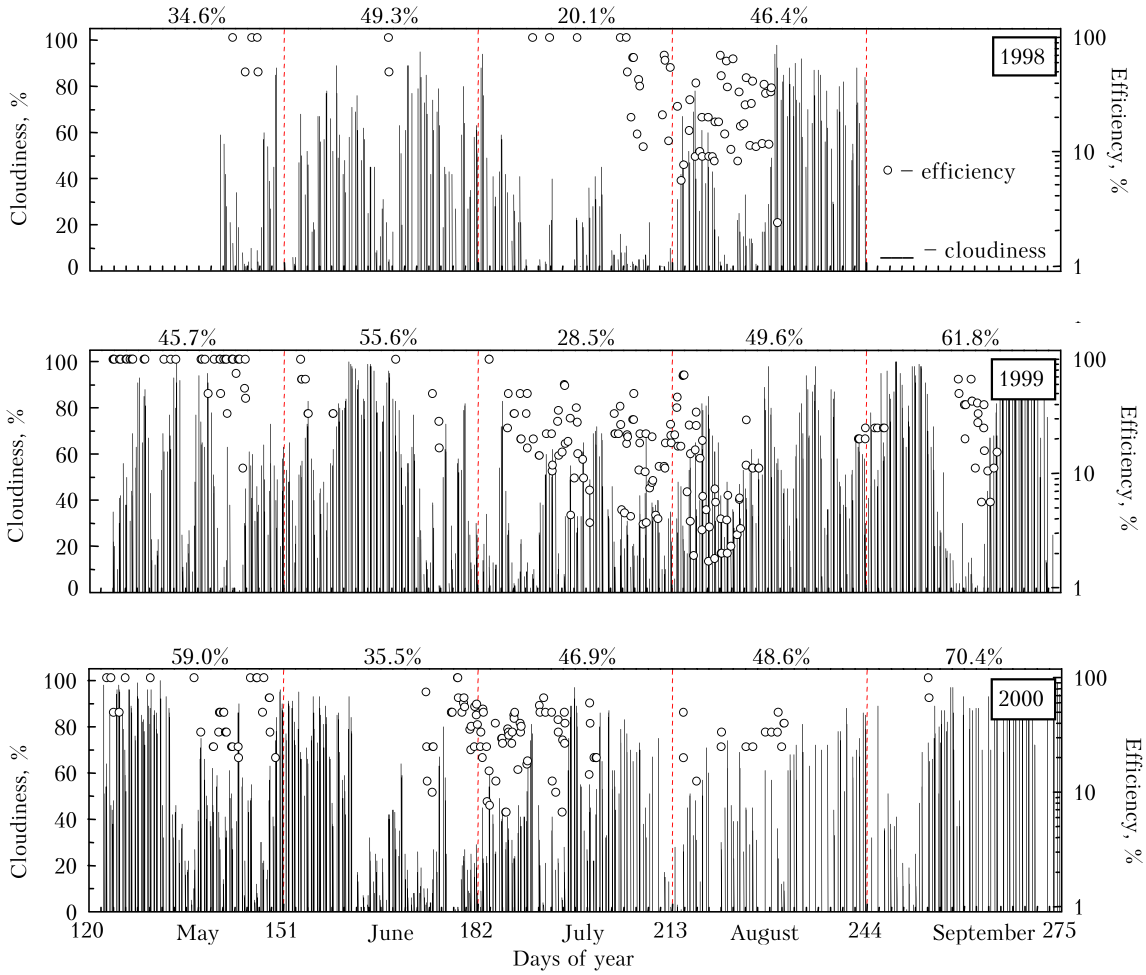
Consider now the data presented in Fig. 2. For each year, Fig. 2*a* presents time dependences of the cloud amount (the degree to which the territory is covered by clouds) and the efficiency of fire detection from space (mean cloud amounts are given for every month). It is clear that these dependences have high negative correlation: the maximum efficiency of space monitoring falls on cloudless periods. Figures 2*b* and 2*c* shows the efficiency of early alarm as a function of the area S_{det} (Fig. 2*b*) and the total efficiency of space monitoring as a function of the area S_{liq} (Fig. 2*c*). Using the data from Fig. 2*c*, we can separate the following estimates of the efficiency of space monitoring as a function of the fire area: less than 20% for S less than 1 ha, 40–55% for $S \approx 5$–10 ha, and 80–100% for S larger than 50 ha. These data agree with the conclusions of Ref. 4. The minimum size of a forest fire detectable from space is about 0.1–0.2 ha and such fires are detected with the probability about 10%.

From the experience of forest protection services, it is known that a ground fire with the area less than 5 ha can be liquidated with high probability. Turning to Fig. 2*b*, we can notice rather high (more than 20%) efficiency of early alarm already at $S \approx 2$ ha, which increases up to 30–45% at $S \approx 5$ ha. Thus, the satellite information can be used productively for early detection of forest fires already at the early stage of their development, when liquidation of such fires is relatively cheap.

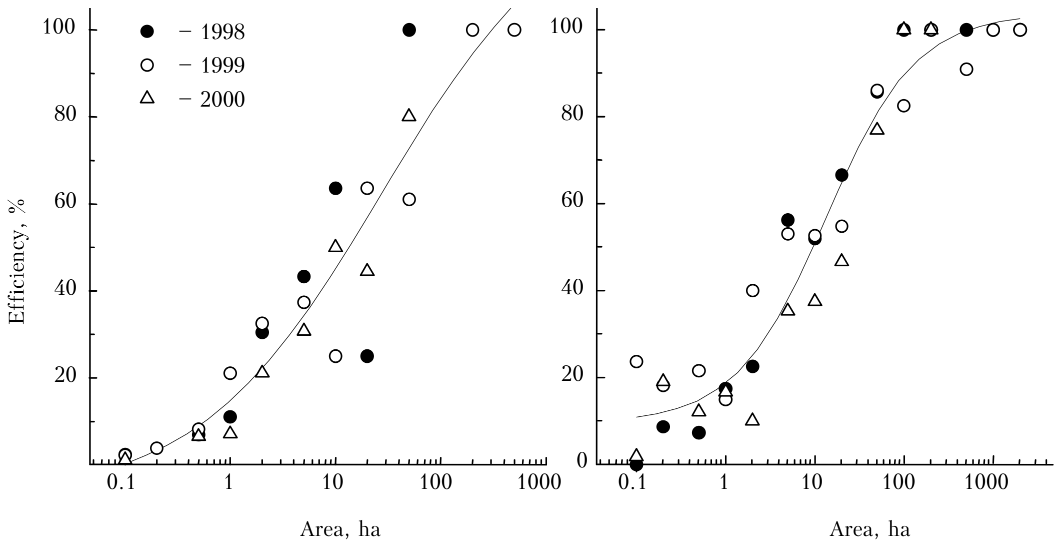
One more important illustration of the results of complex analysis is the data on the efficiency of space monitoring at different time of day that are given in Table 2. For this purpose, all data were separated for different satellites and turns (antemeridian and postmeridian). The urgency of this problem follows from the fact that there are space monitoring schemes that use only postmeridian images or even only one daytime image (for example, from NOAA-14 satellite) because postmeridian images are most informative and close in time to appearance of new flaming zones and activation of already existed fires.

The data collected in Table 2 provide an insight into the efficiency of space monitoring in different time of a day: morning images have relatively low efficiency and afternoon images are characterized by far (two to three times) higher efficiency. However, it becomes clear that the use of only one (even most informative) image decreases the efficiency of space monitoring by 20–25%, and the efficiency of early alarm decreases by 1.4–1.8 times. The last column of Table 2 gives the total values of the efficiency of space monitoring with the use of only afternoon images. It follows from these data that afternoon images in sum provide for about 95% of the total efficiency of space monitoring and more than 85% of the efficiency of early alarm. Thus, in spite of the high informativeness of afternoon images, rejection of morning images still causes the loss of a part of useful satellite information and the marked decrease in the efficiency of early alarm. Consequently, only a complete scheme of space monitoring including all satellite images regardless of time of a day provides for maximum efficiency of space monitoring, real-time observation of the flaming zone dynamics, and the state of cloudiness in the zone of fire.

The forest protection service of Tomsk Region evaluated the results obtained at the Institute of Atmospheric Optics SB RAS in the field of application of satellite technologies to detection of forest fires. The leadership of Tomsk Forest Protection Air Base decided to complement airborne watch of forested territories with the data of satellite images obtained at the Institute of Atmospheric Optics.



a



b *c*

Fig. 2. Results of space monitoring of forest fires.

Table 2. Results of space monitoring of fires in different time of day

Turns	Antemeridian			Postmeridian			Total
Satellites	NOAA-12	NOAA-14	NOAA-15	NOAA-12	NOAA-14	NOAA-15	
				1998			
Time	08:14–10:02	04:56–06:50	–	18:28–20:12	15:08–16:47	–	
Number of images	91	93	–	86	83	–	
Fires detected	24, 24.7%	33, 34.0%	–	74, 76.3%	78, 80.4%	–	92, 94.8%
Early alarm	4, 9.3%	10, 23.3%	–	15, 34.9%	31, 72.1%	–	36, 85.7%
				1999			
Time	07:52–09:37	05:39–07:30	–	18:04–19:49	15:44–17:36	20:01–21:40	
Number of images	150	148	–	153	152	153	
Fires detected	43, 22.2%	46, 23.7%	–	145, 74.7%	130, 67.0%	112, 57.7%	186, 96.4%
Early alarm	17, 19.8%	12, 14.0%	–	47, 54.7%	45, 52.3%	42, 48.8%	79, 91.9%
				2000 г.			
Time	07:31–09:45	06:21–09:00	09:51–12:01	17:44–19:45	16:20–18:20	19:59–21:54	
Number of images	121	132	81	126	141	83	
Fires detected	10, 13.0%	12, 15.6%	20; 26.0%	51, 66.2%	58, 75.3%	36, 46.8%	73, 94.8%
Early alarm, %	2, 5.9	0, 0.0	11; 32.4	19, 55.9	19, 55.9	12, 35.3	29, 85.3

Note: (a) Time is the local time of reception of space images; (b) efficiency of space monitoring and early alarm is given in per cent of the total amount for year (see Table 1).

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