System of the space-based monitoring of forest fires on the territory of Tomsk Region. Part 1. Organization of the space-based monitoring system

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Some organization aspects of solving the important problem of environmental protection, namely, space-based monitoring of forest fires are discussed. Space-based monitoring of Tomsk Region has been performed since 1998 at the Institute of Atmospheric Optics SB RAS, the Center for Reception and Processing of Information from NOAA satellites.

Introduction

The on-line detection and monitoring of forest fires over vast and hard-to-reach Russian forests are among urgent problems of environmental protection. In Tomsk Region, the number of forest fires for the period since 1996 until 1999 increased from 109 to 486 per year, and only for the last year this number increased by more than 100 (Fig. 1). In this connection, the necessity of using all available resources for providing the on-line detection of forest fires at the early stage of their development is doubtless. The traditional usage of airplanes for watching over regions with high fire risks requires significant funding. Therefore, the role of space-based systems of remote sensing of the Earth's surface increases. The NOAA/AVHRR information is now recognized as most efficient for fire preventing services. The AVHRR radiometer measures upward going radiation in five spectral channels: 0.58–0.68 μm (1), 0.725–1.1 μm (2), 3.55–3.93 μm (3), 10.3–11.3 μm (4), and 11.5–12.5 μm (5). The efficiency of this satellite system is explained by the following circumstances:

(a) accessibility of digital satellite information;

(b) periodicity of data recording that allows extended territories to be monitored from space no rarely than four to six times a day with a medium spatial resolution;

(c) availability of inexpensive domestically produced receiving stations.[1]

The Internet site of the Central Forest Protection Air Base has functioned since 1996. In fire-risky seasons, this site updates every hour the information about forest fires over the Russian territory. This information is based on the results of thematic processing of NOAA data in centers for receiving and processing data from space-based instruments of the Institute of Space Research RAS (Moscow) and the Institute of Solar-Terrestrial Physics SB RAS (Irkutsk). Besides, similar data are sent every day to regional offices of civil defense and emergency situations by the Laboratory of Receiving and Processing Space-based Information of the All-Russia Research Institute of Civil Defense and Emergency Situations (Krasnoyarsk).

Although the possibility exists of obtaining data on the forest fires on the territory of Tomsk Region from the above-mentioned sources, the development of the center for space-based monitoring in Tomsk was recognized to be worthwhile. In our opinion, this allows (in addition to the already available capabilities) the scientific and technical potential of Tomsk groups working in this field for development of efficient algorithms for space detection of flame zones to be used more efficiently, especially if taking into account specific conditions of space-based monitoring of the territory of Tomsk Region. One more advantage is obviously fast interaction between the regional center for space-based monitoring and regional forest protecting services. In this case, the possibilities of analyzing the results of space-based monitoring and seeking the ways to improve it open.

The system of space-based monitoring of forest fires has been developed in Tomsk Region since 1998 at the Institute of Atmospheric Optics SB RAS (IAO). By 1998, IAO already had all elements needed for space-based monitoring, namely, (a) a ScanEx station for reception of digital satellite information, (b) a wide spectrum of software tools for processing data from space-based platforms, (c) theoretical concepts and algorithms developed for complex solution of the problem, as well as experience in interpretation of satellite data.[12–18]

When developing the system of space-based monitoring of fires in Tomsk Region, we took into account both Russian[4–11] and foreign[3] experience in solving this problem. The results obtained (since 1994) at the Center for Space-Based Monitoring of the Institute of Solar-Terrestrial Physics SB RAS (Irkutsk) are of particular interest for us. A great positive experience in analogous research has been accumulated at the V.N. Sukachev Institute of Forest SB RAS.[8–11]

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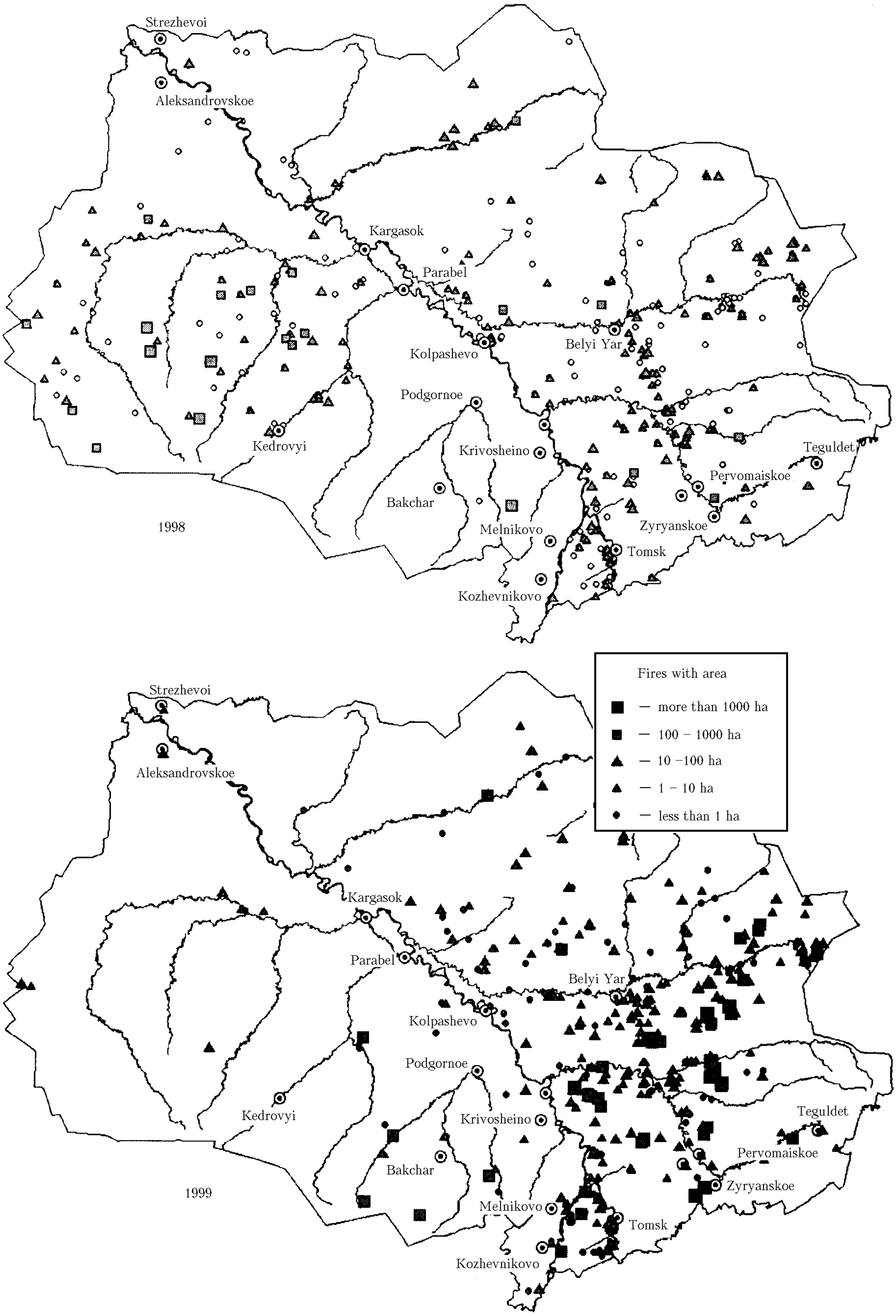

Fig. 1. Maps of forest fires on the territory of Tomsk Region.

Our efforts to develop the system of space-based monitoring in Tomsk Region, for 1998–1999 included solving the following problems:

1. For normal real-time operation of the system, we have adapted the available software and developed new programs; we also gave a workout to optimal operating conditions for the system and the channel of communication with Tomsk forest protection air base.

2. Different algorithms for automatic space-based detection of high-temperature anomalies on the surface have been tested; we have thus initially selected the algorithm that suits our conditions best of all (some results are given in Ref. 18); a new highly efficient algorithm has been developed.

3. A technique, algorithms, and computer programs have been developed for combined analysis of the data of space-based monitoring; the results of application of these algorithms will be presented in the second part of this paper.

The results of this work for 1998–1999 were positively evaluated by the Central Forest Protection Air Base, International Institute of Forest RANS (Moscow), and Institute of Solar-Terrestrial Physics SB RAS. Besides, the obtained results were reported in 1999–2000 at five scientific conferences in Novosibirsk,[19] Krasnoyarsk,[20] and Tomsk.[21–23]

1. Organization of space-based monitoring

In 1998–2000, the Laboratory of Optical Signal Propagation of the Institute of Atmospheric Optics SB RAS has organized space-based monitoring of forest fires on request of Tomsk Forest Management and Tomsk Forest Protection Air Base. Thus, about 95% of the forestland in the region is covered with monitoring. The data from the five-channel AVHRR radiometer are decoded automatically with the use of several different algorithms for detection of high-temperature anomalies on the surface. Then the data of decoded satellite pictures are analyzed by an operator, who makes a decision on whether or not there is a potential flaming zone in a picture and rejects false alarms. At the final stage, the operator using specially developed computer program makes two files (in text and graphical format) for every picture. These files contain the results of fire monitoring and are accessible via the Internet. During the whole period of space-based monitoring, the received digital data from a satellite are archived onto a magnetic tape with the use of the ARVID firmware system. Besides, for routine operation, the AVHRR data for the territory of Tomsk Region are additionally archived on a hard disk.

1.1. Reception of satellite information

NOAA–12, 14, and 15 satellites have been on polar orbits around the Earth for the period since 1998 until 1999 and by now. For each satellite, two pictures (in the forenoon and afternoon) with the maximum spatial resolution, respectively, for descending and ascending turns can be received. In 1998 space-based monitoring was based on the data of two satellites NOAA–12 and NOAA–14. So, the territory of Tomsk region was monitored four times a day. In 1999 the data from the NOAA–15 satellite were used for this purpose. This increased the number of observations up to six a day. However, during almost the entire period of works in 1999, the low quality of the data from the NOAA–15 satellite made us to abandon its morning pictures and carefully reject errors in the afternoon pictures. The general data on the conditions of observation of the territory of Tomsk Region from the NOAA satellites is given in Table 1, which presents statistical data for 1999.

1.2. Algorithms of picture decoding

After testing different satellite algorithms for automatic detection of fires using programs of numerical imitation, we came to the conclusion that the algorithm developed at the Center for Space-Based Monitoring of the Institute of Solar-Terrestrial Physics is most reliable for the specific conditions of Tomsk Region.[6] This algorithm has successfully passed evaluation test at monitoring of fires in the Irkutsk Region in 1997. We used this algorithm as a principal one in 1998 and simultaneously tested two new picture-decoding algorithms proposed by scientists from the Institute of Atmospheric Optics.

Once the fire-risky season of 1998 finished, we evaluated the efficiency of these algorithms by comparing the results obtained with the data on forest fires presented by Tomsk forest protecting services. Evaluation of the algorithm described in Ref. 6 for Tomsk Region gave rather good results and allowed determination of the conditions of its unreliable operation (for example, under conditions of semi-transparent clouds, when detecting low-intensity flaming zones, and in the presence of sun glints on the water surface of rivers and lakes). Based on the results of testing of the algorithms proposed at our Institute, we have selected one of them and improved it for further use. This algorithm provides more correct calculations of the contribution of the solar radiation to the AVHRR infrared channel No. 3 (this channel is basic for detection of the flaming zones) and the distorting effect of semi-transparent clouds. Besides, it is more sensitive to low-intensity flaming zones.

Intercomparison of this algorithm with the technique from Ref. 6 confirmed the higher efficiency of the former. This fact can be illustrated by the results of observation of flares of oil and gas fields in the pictures of Tomsk Region in 1999. Thus, the algorithm from Ref. 6 detects intense flares of the Luginetsk oil field in 36–38% pictures, whereas for our algorithm this result is higher by 5–6%. A stronger difference between the results is observed for less intense flares. In this case, the efficiency of our algorithm is 2.5–3.5 times higher. One more feature of our algorithm is higher reliability at automatic rejection of the cases of false alarm due to sun glints in the channel No. 3. This feature is very important taking into account great number of rivers and other water bodies in Tomsk Region.

Table 1. Statistical data on the geometry of observations (1999)

Satellites, turns	NOAA–12a	NOAA–12p	NOAA–14a	NOAA–14p	NOAA-15p
Time	07:52–09:37	18:04–19:49	05:39–07:30	15:44–17:36	20:01–21:40
Azimuth of scanning	104.8–108.8 106.5	69.9–75.2 73.1	105.7–110.0 107.5	68.4–74.2 72.0	69.6÷74.9 72.9
The Sun elevation angles above the horizon					
May	8.3–31.9 20.4	14.9–37.9 26.3	−7.2–12.6 2.7	34.4–52.2 43.7	1.1–23.1 11.6
June	12.2–31.5 22.2	20.4–41.1 30.9	−1.7–15.0 6.3	39.0–54.3 47.5	7.2–26.3 16.9
July	7.9–30.3 19.6	19.7–41.0 30.4	−5.9–14.2 4.5	36.6–53.6 45.5	5.3–25.7 15.3
August	1.6–25.8 13.5	10.3–35.7 23.8	−12.9–9.6 −1.6	28.9–48.2 38.5	−4.8–21.0 8.4
September	−6.4–16.6 5.6	1.0–27.3 14.0	−21.6–2.7 −9.4	15.0–36.3 27.1	−15.5–12.8 −1.8
Azimuth of direction to the Sun					
May	70.4–103.1 86.3	247.1–281.3 263.8	38.9–72.0 56.0	200.8–247.0 225.0	273.0–303.7 288.1
June	65.9–97.4 81.7	246.0–279.6 264.0	39.1–70.7 54.6	201.1–250.2 226.8	272.1–302.2 286.9
July	65.2–96.9 81.0	241.7–278.2 260.9	38.4–70.0 54.9	199.3–248.9 226.7	269.5–301.6 285.7
August	68.2–104.1 85.4	237.9–274.7 256.7	42.9–76.5 59.9	201.4–246.2 223.2	266.3–299.3 282.7
September	73.7–111.1 92.6	233.9–269.3 251.9	45.6–87.4 67.3	200.9–242.1 223.5	262.1–295.8 279.0

Notes: 1. In the row "Satellite, turns " the letters "a" and "p" are used for the morning and afternoon turn. 2. The variability ranges and the mean values are given for the scanning azimuths, the Sun elevation angles, and azimuths to the Sun.

Thus, analysis of the results obtained in 1998–1999 allowed us to use the following scheme of space-based monitoring of flaming zones:

(1) the algorithm developed at the Institute of Atmospheric Optics is used as a basic one;

(2) the algorithm developed at the Institute of Solar-Terrestrial Physics is used as a duplicate one;

(3) potential flaming zones that coincide in the detection with both algorithms are assigned the type 2, which corresponds to the higher degree of reliability;

(4) for high-temperature anomalies detected by only one algorithm, an operator visually analyzes the picture in the vicinity of the anomaly in different AVHRR channels and quantitatively analyzes the obtained values of albedo and radiative temperatures; thus the operator either supports the presence of a potential flaming zone (assigns the type 1) or rejects the case as a false alarm;

(5) stationary industrial high-temperature objects are automatically excluded from the list of potential flaming zones.

1.3. Forms of presentation of the results of picture decoding

After automatic decoding of satellite data, the operator, using auxiliary computer programs, creates two files for every picture. These files contain the results of remote monitoring of fires.

The first file has a text format and is called a monitoring protocol. Table 2 exemplifies it.

The protocol contains the following data:

– protocol identifier (name), date and time of its creation;

– type of the satellite, date and time of picture reception;

– cloud amount over the territory of Tomsk Region; this amount is determined automatically by a threshold algorithm;

– the number of potential flaming zones;

– the list of flaming zones including the following characteristics: (1) serial number, (2) latitude and longitude, (3) type of a flaming zone, i.e., the number of algorithms that detected it – 2 or 1, (4) area of the flaming zone, i.e., the number of "hot" pixels (numerical data on the spatial scale of the flaming zone), (5) the closest settlement, the distance to it, and the azimuth of the direction "settlement ц flaming zone" (using the electronic map of Tomsk Region).

The second file has a graphic format (for example, BMP). It is formed from the data of the IR channel No. 3. This file allows a user to visually analyze the spatial characteristics of high-temperature objects and simultaneously evaluate the state of cloudiness and the presence of precipitations in the flaming zones. Thus, forest protecting services can optimally plan necessary firefighting measures. An example of this file is presented in Fig. 2.

Table 2. Example of protocol with results of space-based monitoring of fires in Tomsk Region

Results of space-based monitoring of forest fires in Tomsk Region
(Laboratory of Optical Signal Propagation, Institute of Atmospheric Optics SB RAS, Tomsk)
Protocol No: 07051026 @ Date: 07/05/00 & LT = 19:14:16
Satellite: NOAA-12
Record date: 07.05.2000
Local time: 18:26
Data decoding programs: S.V. Afonin, Yu.V. Gridnev
Cloud amount index = 16.2 (%)
Number of potential flaming zones = 11

#	Latitude	Longitude	Type*	Area**	Settlement	Distance to flaming zone, km	Azimuth settlement – flaming zone	Earlier***
1	59:43.9	80:14.3	1	2	Kievskii	9.8	244.3	–/1
2	58:40.3	80:11.5	2	4	B. Griva	28.4	186.3	2/1
3	58:28.7	76:49.6	2	19	Ozernoe	13.7	208.8	1/4
4	58: 7.1	77:50.0	2	8	Charymovo	42.1	173.7	3/6
5	58: 5.0	77:57.8	2	6	Charymovo	47.4	165.0	3/5
6	57:59.6	78:20.0	2	32	Luginetskii	36.9	240.1	6/6
7	57:56.5	79:24.2	2	5	Mirnoe Ozero	36.6	47.2	3/4
8	57:53.1	78:31.2	2	13	Mirnoe Ozero	31.5	306.0	3/4
9	56:57.8	79:54.6	2	5	Chaga	44.2	273.7	–/1
10	56:53.3	82:3.0	2	2	B. Galka	5.9	133.5	
11	56:38.5	81:4.0	2	1	Pirogovka	19.4	227.4	–/1

* Number of algorithms that detected the flaming zone (=2, 1). ** Number of pixels in the flaming zone. *** Number of protocols, in which the flaming zone was detected for previous 24–48 hours/previous 24 hours.

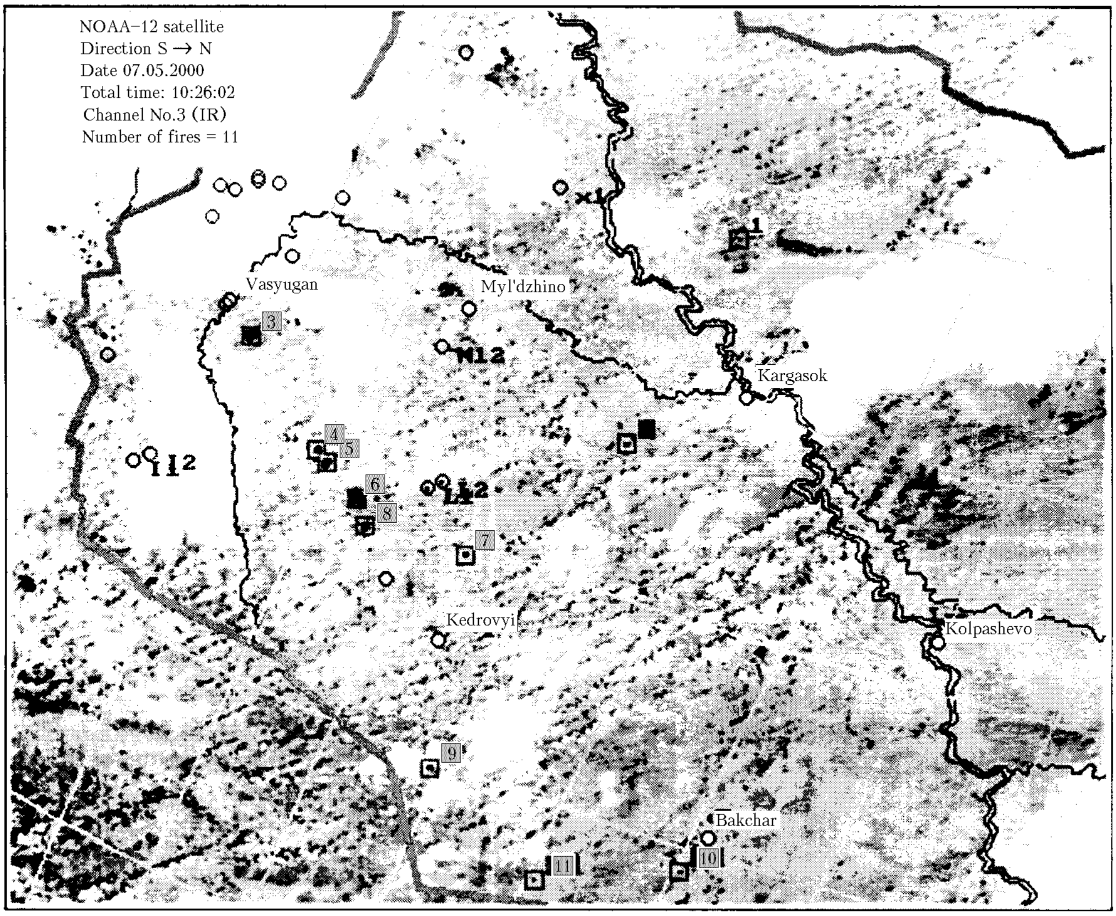

Fig. 2. Fragment of BMP file with results of space-based monitoring of fires in Tomsk Region. Potential flaming zones are marked by squares and numbers on the dark (No. 2–11) or light (No. 1) background depending on the type of a flaming zone. Stationary industrial high-temperature objects are marked by circles (in a color picture these objects have different color).

The obtained picture is supplemented with the following information:

– geographical coordinate scale, administrative border of Tomsk Region, contours of big rivers and lakes, some big settlements;

– stationary industrial high-temperature objects;

– potential flaming zones marked by red or yellow color depending on the number of algorithms that detected the flaming zone.

2. Problems of monitoring

Leaving aside the complicated problem of improving the accuracy of the algorithms of automatic detection of small-size high-temperature surface anomalies from a satellite, let us consider some problems affecting the quality of space-based monitoring of the flaming zones.

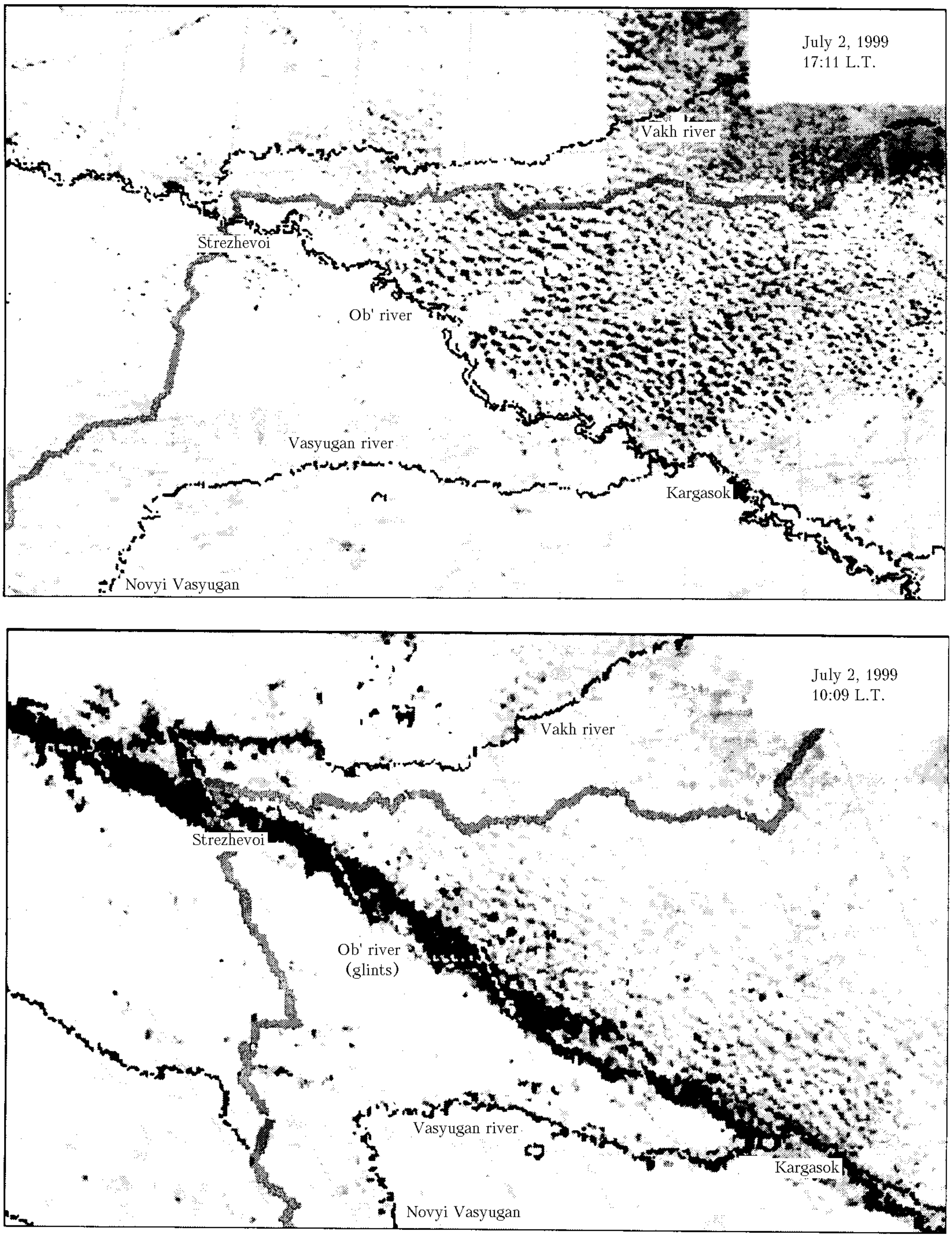

Fig. 3. Manifestation of sun glints on the surface of rivers and lakes in the third AVHRR/NOAA channel (Tomsk and Tyumen Regions).

2.1. Problem of sun glints

Analyzing the data of Table 1, we can conclude that afternoon pictures, mostly from the NOAA-12 satellite, can include sun glints on the water surface of big rivers and lakes (Fig. 3). Sun glints can lead to the anomalous increase of the radiative temperature in the third AVHRR channel (3.55–3.93 μm) and thus cause false alarms. In this case, as a rule, the intensities of upward going radiation (albedo) normalized to the spectral values of the solar constant in the first two AVHRR channels (A1 and A2, A1 > A2) increase markedly. Such a behavior is characteristic of the conditions of semi-transparent clouds.

Figure 3 shows two pictures of Tomsk Region obtained using the third AVHRR channel with the interval less than one hour. Comparing these pictures, we can see a great number of black pixels arising on the surface of the rivers Ob, Vasyugan, Vakh and numerous lakes. This is accompanied by the anomalous growth of the radiative temperatures (by 30° and higher). In this particular case, application of the algorithm from Ref. 6 gave 63 false flaming zones with the total area of 336 pixels.

No descriptions of the methods allowing an automatic identification and rejection of such false flaming zones are available in the literature. Low threshold values of the albedo A1 and A2 can seemingly be used in that case, however this restricts the applicability of satellite algorithms to the cases of weakly turbid atmosphere. At the same time, this approach does not guarantee successful rejection of false alarms for pixels that simultaneously include both land and water surface.

On the other hand, the attempt to reject false alarms based only on the known geometry conditions of formation of sun glints on the water surface in device's field of view faces the risk to reject an actual fire. The analogous problem arises when using only hydrographic maps for this purpose. Taking into account these circumstances, we use now a combined approach to rejecting the sun glints. This approach includes:

– spatial statistical analysis of satellite data;

– joint analysis of values measured in all AVHRR channels with regard for the observation geometry;

– comparison of coordinates of a potential flaming zone with hydrographic data of the electronic map of Tomsk Region.

The efficiency of this approach can be illustrated by the fact that for the hard-to-interpret situation shown in Fig. 3 our algorithms have automatically rejected all sun glints.

2.2. Problem of geographic reference

For early detection of small-size flaming zones, the accuracy of determination of the coordinates of a flaming zone is very important, since the efficiency of fire-fighting measures directly depends on it. In the fire-risky seasons of 1998–1999, geographic reference of the satellite information was made with the use of generally known computational algorithms based on TLE-NORAD Two-Line Elements Set files (TLE files) with orbital data. An operator updates these files five times a week.

Thus, we have actually used the limiting capabilities of the computational method of geographic reference. We have analyzed the accuracy of this method using satellite pictures of 1999. The results of this analysis are shown in Fig. 4; they allow some conclusions to be drawn. First, the necessity of additional corrections of computational geographic referencing becomes obvious, since computed data are often markedly displaced both along and cross the satellite trajectory (Fig. 4*a*). On the average, the deviation of the computed object's position from the actual one exceeds 4 km. This value cannot be considered as a satisfactory level of accuracy for determination of coordinates of a flaming zone.

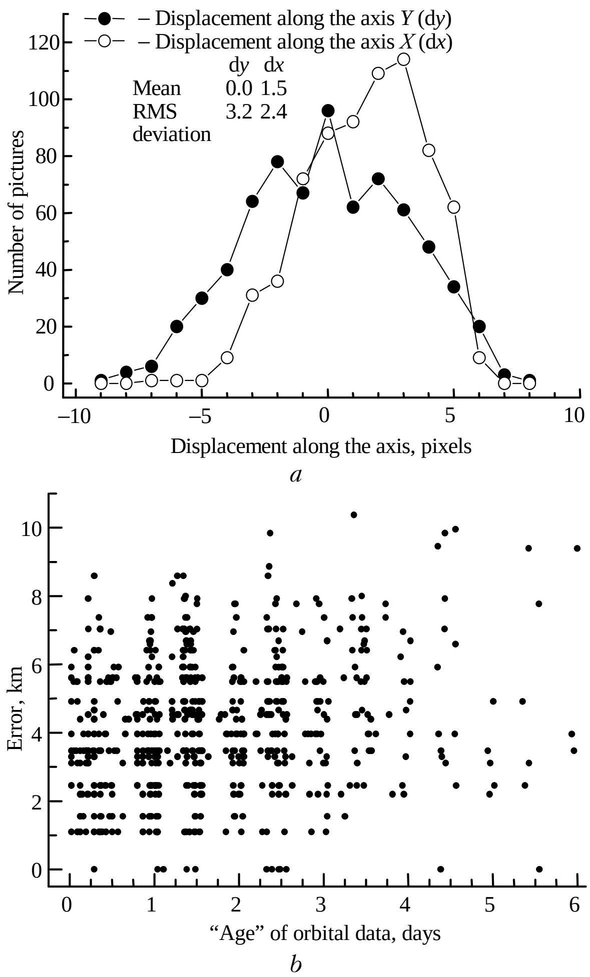

Fig. 4. Error in computation of geographic reference of satellite data (*a*) (the axis *X* is oriented from west to east along the scanning direction; the axis *Y* is oriented from south to north along the satellite trajectory); dependence of the computational error in geographic reference of the satellite data on the "age" of orbital data.

Another conclusion concerns the dependence of the accuracy of computed geographic reference on the "age" of a TLE file, i.e., the interval between obtaining the satellite and orbital data. Analysis of Fig. 4*b* demonstrates that this dependence (within 6 days) is practically absent, and even at the age of the TLE file less than 1 day the errors in computed geographic reference can achieve 7–8 km. Thus, the error of the computational method cannot be minimized simply by using "fresh" orbital data.

For solution of this problem, in 2000 we have developed algorithms and computer programs of interactive linear correction of the computational geographic reference based on the use of the set of reference points and contour hydrographic lines. The efficiency of these programs was estimated using 740 satellite pictures taken in 1999. The results showed that the geographic reference can be corrected in 95% of situations, and 5% of failures are connected with high cloud amount index. In the majority of situations, the algorithms automatically correct the geographic reference. Now these programs are already in use, and according to our estimates, they allow the error in geographic referencing to be decreased down to 1–2 km.

2.3. Problem of reliability of the results of space-based monitoring

One of the problems in analysis of the results of decoding satellite pictures is to improve the reliability of the obtained data on the potential flaming zones. Before 2000, we solved this problem based on the coincidence of the results of space-based monitoring for two independent algorithms (certainly, this not always guarantee the correctness of the solution). This problem is especially complicated in the case of low-intense temperature anomalies that, in addition, are detected by only one algorithm.

The obvious and simplest way to improve the reliability of the results in this situation is comparative analysis of the pictures closest to the analyzed one in time. The practice of such a comparison in 1999 demonstrated its laboriousness at visual processing of pictures, especially, those including a large number of such ambiguous objects. In this connection, in 2000 (after development of the algorithm of geographic correction) we have developed an additional unit in the program of analysis of decoded pictures. This unit automatically compares neighboring (in time) pictures. The results of this work are automatically presented in the column "Earlier" of the protocol of monitoring (see Table 2).

The protocol of space-based monitoring given in Table 2 contains the list of potential flaming zones, one of which (No. 1) was detected by only one algorithm. As a result, the object No. 1 cannot be reliably classified, like in the situation described above. However, the program, having analyzed the previous pictures, detected a similar high-temperature anomaly in one more picture. This allowed the operator to include the object No. 1 into the list of potential flaming zones with higher reliability.

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