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The VolSatView Information System for Monitoring the Volcanic Activity in Kamchatka and on the Kuril Islands

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Abstract—Kamchatka and the Kuril Islands are home to 36 active volcanoes with yearly explosive eruptions that eject ash to heights of 8 to 15 km above sea level, posing hazards to jet planes. In order to reduce the risk of planes colliding with ash clouds in the north Pacific, the KVERT team affiliated with the Institute of Volcanology and Seismology of the Far East Branch of the Russian Academy of Sciences (IV&S FEB RAS) has conducted daily satellite-based monitoring of Kamchatka volcanoes since 2002. Specialists at the IV&S FEB RAS, Space Research Institute of the Russian Academy of Sciences (SRI RAS), the Computing Center of the Far East Branch of the Russian Academy of Sciences (CC FEB RAS), and the Far East Planeta Center of Space Hydrometeorology Research (FEPC SHR) have developed, introduced into practice, and were continuing to refine the VolSatView information system for Monitoring of Volcanic Activity in Kamchatka and on the Kuril Islands during the 2011–2015 period. This system enables integrated processing of various satellite data, as well as of weather and land-based information for continuous monitoring and investigation of volcanic activity in the Kuril–Kamchatka region. No other information system worldwide offers the abilities that the VolSatView has for studies of volcanoes. This paper shows the main abilities of the application of VolSatView for routine monitoring and retrospective analysis of volcanic activity in Kamchatka and on the Kuril Islands.

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INTRODUCTION

Kamchatka and the Kuril Islands harbor 36 active volcanoes. Two to eight of these erupt yearly, ejecting tons of volcanic ash, gases, and aerosol into the atmosphere. In addition, large explosive events occur yearly in the region with ash rising to heights of 8 to 15 km above sea level (a.s.l.), thus posing a serious threat to flights of modern jet planes (Girina, 2012; Girina and Gordeev, 2007; Gordeev and Girina, 2014; Miller and Casadevall, 2000; Neal et al., 2009).

Efforts are made to reduce the risk of planes colliding with ash clouds by setting up volcanological observatories in various countries in order to monitor at least some of these volcanoes. The problem is that over 800 active volcanoes exist; hence, even developed countries are unable to conduct continuous monitoring of each of these volcanoes. To take an example, Japan contains 83 active volcanoes, but only 19 of these are under continuous monitoring. The operation of 79 volcanological observatories worldwide is coordinated by the World Organization of Volcano Observatories, WOVO, http://www.wovo.org) which acts under the auspices of the International Association of Volcanology and Chemistry of the Earth's Interior, IAVCEI, http://www.iavcei.org/). The WOVO issues a handbook that contains information on the locations of volcano observatories in various countries, on their monitoring programs, contact information on persons that are responsible for volcanological projects, etc. The volcano observatories use all or some of the monitoring techniques, including video and visual methods, geophysical techniques (the analysis of seismic, electrical, magnetic, gravitational and other occurrences), as well as hydrologic, gas-based, and satellite techniques (the analysis of different data, including interferometry). The International Civil Aviation Organization, ICAO, http://www.icao.int) has sought to coordinate the efforts of different surveys (volcano observatories; weather, hydrologic and other stations, and so on) to detect volcanic ash in the atmosphere and to conduct continuous monitoring of its movements in order to reduce the risk to aviation by designating nine specialized meteorological centers that offer advice on volcanic ash (Volcanic Ash Advisory Centers, VAAC: Anchorage, Buenos Aires, Washington, Wellington, Darwin, Montreal, Tokyo, and Toulouse) and by specifying their coverage areas. In addition, this global satellite-based monitoring of volcanoes contains web portals that deal with individual lines of research, such as Near Realtime Monitoring of Active Volcanoes in the East Asia Using Satellite Data, http://vrsserv.eri.u-tokyo.ac.jp/REALVOLC/); Near Real Time Volcanic HotSpot Detection System, http://www.mirovaweb.it/); the NOAA/CIMSS Volcanic Cloud Monitoring Web Portal, https://volcano.ssec.wisc.edu/); and the Support Aviation Control Service (SACS) SO_2 & Ash Notification System, http://sacs.aeronomie.be/).

In order to enhance the safety of aviation flights during explosive eruptions of volcanoes, it was decided to set up the Kamchatkan Volcanic Eruption Response Team, http://www.kscnet.ru/ivs/kvert/) in Kamchatka in 1993. The team is part of the Institute of Volcanology and Seismology (IV&S) FEB RAS; since 2010 it has been fulfilling the role a volcano observatory of the Russian Federation (WOVO no. 290111-3000001), supplying information on the volcanic activity in the Russian Far East to the international aviation community (Girina, 2012; Gordeev and Girina, 2014; Kir'yanov et al., 2001; Miller and Casadevall, 2000; Neal et al., 2009). The KVERT reduces the risk of planes colliding with ash clouds in the north Pacific by timely detection of increased volcanic activity, detecting and monitoring clouds of volcanic ash, and by rapid notification of aviation companies on the appearance of a volcanic ash threat. To do this, the KVERT scientists examine data from seismic monitoring of volcanoes conducted by the Kamchatka Branch of the Geophysical Service (KB GS) RAS and video and visual information on the state of volcanoes from a variety of sources (geologists in the field, meteorologists, pilots, tourists, mountaineers, and others). The KVERT workers began to use satellite-based monitoring of volcanoes to follow the movements of ash plumes and clouds during the eruptions of Shiveluch and Bezymyannyi volcanoes in 1993 (NOAA 11 and 12 satellite data were lent by the National Oceanic and Atmospheric Administration, NOAA, US and the Meteor-21 data by the Hydrologic and Meteorological Survey of Russia) (Girina, 2008; Kir'yanov et al., 2001). The services rendered by the satellite-based monitoring of Kamchatka volcanoes expanded over time. As an example, while the KVERT received NOAA images for the area of Kamchatka in 1997 via facsimile channels from the Alaska Volcano Observatory (AVO), United States and received information bulletins from the AVO twice every 24 hours with results from the processing of all possible satellite data from 1998 until May 17, 2013, the situation changed in 1999 when the AVO provided access to NOAA satellite images to KVERT; thus, since that time the KVERT scientists have been conducting their own satellite monitoring of volcanoes in Kamchatka and on the Kuril Islands by processing and examining satellite data (Girina, 2008, 2012, 2014).

KVERT maintains long-term relationships with various organizations that can provide satellite data; for example, it has been receiving and interpreting MODIS images (Moderate Resolution Imaging Spectroradiometer) from the DF FGUNPP *Rosgeolfond*; since 2009 it has been maintaining cooperation with the FGBU Kamchatskoe UGMS; and in 2007–2009 KVERT workers processed and examined raw TERRA and AQUA (MODIS), and NOAA (AVHRR) images that were provided by the Planeta Center (Girina, 2008, 2014).

KVERT researchers have been conducting daily real-time satellite monitoring of Kamchatka volcanoes since 2002 (Girina, 2012, 2014; Gordeev and Girina, 2014; Neal et al., 2009). This type of monitoring was necessitated by the following factors: the locations of many active volcanoes in hardly accessible areas, far from any population center; the absence of seismograph stations on most active volcanoes (for example, stations exist only on 10 of the 30 active volcanoes in Kamchatka); the fact that timely information is needed on a daily basis concerning the state of volcanoes; and the fact that flight routes traverse the Kuril–Kamchatka region (ash ejections can travel for some thousands of kilometers in different directions from volcanoes, thus impeding flights), etc.

Real-time satellite monitoring of volcanoes (the processing of satellite data as they are coming in) includes:

the detection of ash clouds and ash plumes, and the determination of their parameters (length, area, and azimuth of propagation);

the detection of thermal anomalies in areas of volcanoes, and the determination of anomaly parameters (the size and the temperatures of the anomaly and of the background);

issuing real-time notices (Volcano Observatory Notice for Aviation, VONA) on the detection of ash plumes in the areas of volcanoes and/or the prediction of an explosive eruption that can pose a threat to the population and aircraft; and

placing the VONAs and data from the real-time satellite monitoring in the KVERT database (*The Activity of Volcanoes in Kamchatka and the Kuril Islands*) and in the *Volcanoes of the Kuril–Kamchatka Island Arc* (VOKKIA) information system (IS) at the IV&S FEB RAS geoportal (http://geoportal.kscnet.ru/volcanoes/van/).

Retrospective analysis of volcanic activity based on satellite data presupposes a detailed study of the ejecta and the variation of their parameters (e.g., the variation in area, volume, and direction of movement for ash plumes and lava flows during an eruption; variation in the area and volume of the material deposited by pyroclastic flows from a volcano, as well as changes in the direction of movement of the flows during different eruptions, etc.) for assessing the behavior of volcanic activity over time (the frequency of explosive eruptions of each volcano; the change in the amount of energy that comes to the ground surface during eruptions, with one indirect piece of evidence for the energy being the volumes of ejecta) and predicting possible future threats to the population.

Owing to several different factors, the streams of satellite information that were accessible to KVERT researchers for processing and analysis constantly varied, so that a stable source of satellite data was needed for correct assessment of volcanic hazards to aircraft and to the population in the peninsula.

It goes without saying that the rate and quality of the incoming satellite information exerts a direct influence on whether our assessment of volcanic activity in the region is valid and on the reliability of forecasts of volcanic activity in the future. The leading principles that should govern the organization of satellite monitoring must be the following:

—the maximum rate of the satellite data stream and automatic acquisition of these data;

—convenient tools for data handling;

—the possibility of remote (distributed) data processing;

—the possibility of joint work and analysis of satellite and other instrumental and scientific data (for example, videos, results of mathematical simulation, etc.) from other ISs; and

—reliance on freely available non-commercial satellite data, because very large volumes of information are required.

To tackle the above problems, joint work by specialists of the IV&S FEB RAS, the Space Research Institute (SRI) RAS, the Computing Center (CC) FEB RAS, and the Planeta Far East Research Center began work to develop the Monitoring of Volcanic Activity in Kamchatka and the Kuril Islands IS (VolSatView). The system has been developed, introduced into use, and receives further improvements with partial support from projects financed by the Russian Foundation for Basic Research (project nos. 11-07-12026-ofi_m, 13-07-12180-ofi_m).

THE VOLSATVIEW INFORMATION SYSTEM

The Architecture of the System and the Main Sources of Information

The main goal of the VolSatView IS is to provide the volcanologists who are engaged in monitoring of and research on volcanic activity in Kamchatka and on the Kuril Islands with incoming and stored satellite and meteorological data and with the information products obtained from these data, as well as to provide researchers with a variety of tools for integrated processing and analysis of this information along with the data that come from other ISs (e.g., the tools for rapid simulation of ash plume propagation). Accordingly, an architecture of the VolSatView IS (http:// volcanoes.smislab.ru) was developed for the work with distributed information resources and computation systems that are used for the acquisition, processing, storage, analysis, and visualization of various instrumental and scientific data (Efremov et al., 2012, 2013, 2013a; Gordeev et al., 2014, 2015, among many others) (Fig. 1). The users can work with data that routinely come from different sources and information resources, as well as with historical information that is stored at various centers for acquisition and processing of satellite data. At present the essential centers of this system are located in Moscow, Khabarovsk, and Petropavlovsk-Kamchatskii, with data exchange between these occurring via communication channels in the Regional Computer Network of the FEB RAS, SRI RAS, and Planeta Center (Efremov et al., 2012; Khanchuk et al., 2010, 2013).

We note that one of the main goals the VolSatView is to organize access to satellite data and to make it possible to develop necessary information products on this basis, which can be used for monitoring of and research in volcanic activity. The system allows one to work with the following satellite information from:

Various meteorological satellite systems such as NOAA (the AVHRR instrument), Terra and Aqua (MODIS), Suomi NPP (National Polar-Orbiting Partnership) (VIIRS, Visible Infrared Imaging Radiometer Suite), Meteor-M (MSU-MR, multizonal scanning device of low resolution); geostationary satellites (in particular, it is envisaged to organize a routine data stream acquired from the new generation Himawari-8 Japanese satellite). This information is the basis for real-time monitoring of volcanic activity;

Natural-resource satellites of various spatial and spectral resolutions.

The system presently receives data from the following satellites: Meteor-M (multizonnal satellite imaging complex, MSIC), Landsat 7 (ETM + Enhanced Thematic Mapper Plus), Landsat 8 (OLI (Operational LamdImager), and TIRS (Thermal Infrared Sensor)), Kanopus-V (MIS multizonal imaging system), PIS (panchromatic imaging system), Resurs 1 and 2 (Geoton; KShMSA-VR and KShMSA-CR broad-aperture multispectral instrumentation of high and moderate resolution), EO-1 (Earth Observing One Mission) (Hyperion), and Sentinel 1A. Also, data from the Sentinel 2A are to be used. These data can come into the system with different periodicities and time lags.

The possibilities offered by this system for working with such diverse satellite data and the results from their processing enable one to use it for dealing with a broad class of problems involving the monitoring and study of volcanic activity (Table 1). The VolSatView IS is thus essentially different from the systems that are available at present worldwide for monitoring of volcanoes, in that it offers integrated possibilities, not only for the monitoring of volcanoes, but also for studying volcanogenic phenomena and processes. The system combines a broad range of data from different satellite systems and from different sources on the one hand and video observations of volcanoes on the other hand. It can thus provide, in the web interface using specially developed tools, joint processing of routine and retrospective satellite data, comparison of these data with video information, simulation for the propagation of ash plumes, and classification of different volcanogenic features.

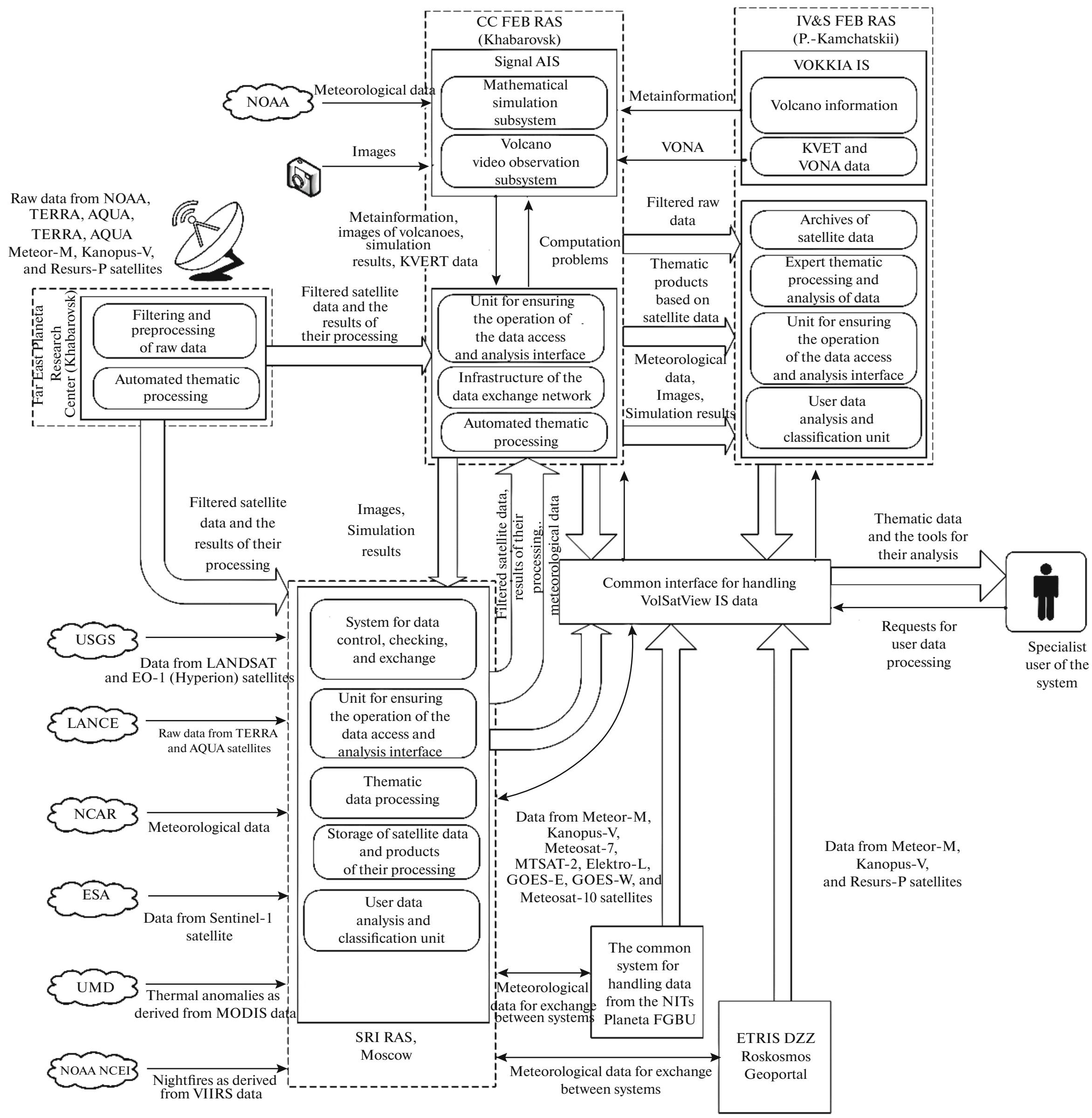

Fig. 1. VolSatView IS: Architecture and data streams. Abbreviations:
USGS United States Geological Survey, LANCE Land, Atmosphere Near real-time Capability, NCAR National Center for Atmospheric Research, ESA European Space Agency, UMD University of Minnesota Duluth, NOAA NCEI National Oceanic and Atmospheric Administration National Centers for Environmental Information (for the other abbreviations, see the main text).

At present, the data that relate to Kamchatka and the Kuril Islands from different satellite systems arrive in the VolSatView system approximately 20 times each 24 hours. The rapid development of the possibilities offered by satellite observation systems can substantially increase the rate and amount of such data in the near future. The rate at which data arrive is especially important in connection with the fact that various volcanic processes occur rapidly, as, for example, the propagation of ash plumes during volcanic eruptions. It is especially important to ensure good comparability of data from different satellite systems. As an example, the images obtained by the NOAA satellite AVHRR and by Terra and Aqua (MODIS) clearly show ash plumes as identified from the difference between infrared (IF) 10–12 μm channels (channels 4–5 at AVHRR and channels 31–32 at MODIS) (Fig. 2). The data obtained by different instruments show the good comparability and standardization of the information, which enables one to increase the rate of observations for the propagation of ash plumes. The plumes can propagate for some hundreds and thousands of kilometers from a volcano, depending on the volume and height of ash discharges, as well as on the velocity and direction of winds at different altitudes, thus posing a

Table 1. Satellite data for monitoring the volcanic activity in Kamchatka and on the Kuril Islands in the VolSatView IS

Goals	Satellites (instruments)	Data analysis using the tools developed at the IS	Daily rate of image taking
Routine monitoring of volcanic activity			
Detection of thermal anomalies	NOAA (AVHRR)	Identification of anomalies and measurement of their sizes and temperatures	15
	Terra/Aqua (MODIS)		4
	Suomi NPP (VIIRS)		4
Detection of ash clouds and plumes	NOAA (AVHRR)	Identification of ash plumes and measurement of their direction of movement (azimuth), extent, and area	15
	Terra/Aqua (MODIS)		4
	Suomi NPP (VIIRS)		4
Detection of lava flows, pyroclastic flows, rockfalls, and landslides on the slopes of volcanoes	Terra/Aqua (MODIS); Kanopus-V MSS, PSS); Meteor-M (KMSS); Landsat (ETM+, OLI, TIRS); EO-1 (Hyperion)	Determining the parameters of deposits (thickness, area, and volume), estimating the activity of volcanoes	
Retrospective analysis of volcanic activity			
Analysis of the temperature distribution within thermal anomalies	Terra/Aqua (MODIS); Landsat (ETM+, OLI, TIRS); EO-1 (Hyperion)	Identification of zonality in the temperature distribution within an anomaly	
Analysis of changes in anomaly parameters (size, temperature) on volcanoes over time	NOAA (AVHRR); Terra/Aqua (MODIS); Suomi NPP (VIIRS)	Relating changes in anomaly parameters to eruptive volcanic activity	
Analysis of changes in the direction of motion of ash plumes over intervals of time (years and months)	NOAA (AVHRR); Terra/Aqua (MODIS); Suomi NPP (VIIRS)	Relating changes in the direction of motion of ash plumes to the variation and thickness of deposits	
Analysis of changes in deposits of lava flows, pyroclastic flows, rockfalls, and landslides over time	Terra/Aqua (MODIS); Kanopus-V (MSS, PSS); Meteor-M (KMSS); Landsat (ETM+, OLI, TIRS); EO-1 (Hyperion)	Relating changes in deposits (thickness, area, volume) to variation of deposits, estimating volcanic activity	

very real threat to the peninsula population and aircraft passengers. An increased rate of observations for the propagation of ash plumes and rapid notification of interested users about their movements enable timely warning for the population on ashfall hazards and reduce the risk of aircraft running into ash clouds.

It should be noted that satellite information now travels faster because it arrives directly from the Planeta satellite data reception and processing center (http://www.dvrcpod.ru/). This center is one of the larger such centers in the Russian Far East.

VolSatView provides opportunities for working, not only with real-time satellite data, but also with stored satellite information for Kamchatka and the Kurils. As an example, users can handle data that were obtained as long ago as in the 1980s. In addition, the system provides homogeneous archives of various pieces of satellite information (for example, on the thermal anomalies that were observed in areas of active volcanoes since 2000). The main source of historical data is the archives that had been stored at the SRI RAS (http://iki.rssi.ru/) and at the Planeta center (http://www.dvrcpod.ru/) (Lupyan et al., 2014). In addition, the system provides the ability to work with data from the Roskosmos geoportal (http://gptl.ru/). Along with satellite data, VolSatView can obtain real-time weather information and its archives that have been stored since 2000 at the SRI RAS and at the Planeta center.

Tools for Operations on Data

One of the more important goals before the VolSatView IS is to provide volcanologists with tools for data analysis. Basic operations on data in VolSatView are based on the GeoSmis technology (Andreev et al., 2004; Balashov et al., 2013; Egorov et al., 2004; Efremov et al., 2004, 2012; Lupyan et al., 2004, 2011; Tolpin et al., 2011; Uvarov et al., 2013, 2014). The web interfaces can handle problems connected with the unification of data of different types that come from different information systems and resources, as well as enabling users to select the required data sets and to perform their processing and analysis. The system has a broad set of tools for handling both observational series and cartographic information (ranging from data representations in different projections to the

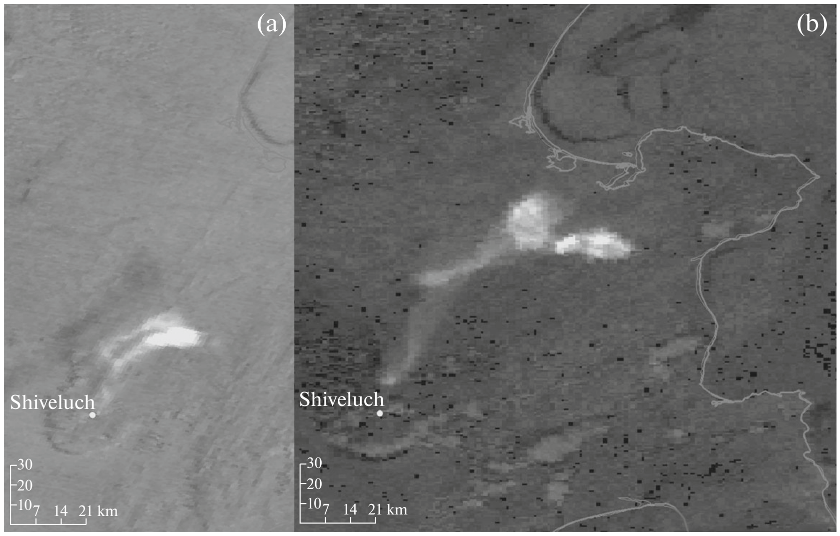

Fig. 2. The evolution of the ash plume from Shiveluch Volcano on March 22, 2015 as seen in satellite images: (a) TERRA (00:41 UTC); (b) NOAA no. 19 (01:59 UTC). The data are from the VolSatView IS.

analysis of spectral characteristics resulting from hyperspectral data and data classification).

There are also several special tools and technologies under development in the system to deal with problems that arise during the monitoring and study of volcanic activity (Efremov et al., 2012; Gordeev et al., 2014, 2015, among others). The VolSatView web interface contains tools for the analysis of temperature fields, enabling instantaneous inspection of temperature values (in Celsius or Kelvin scales) at any point of an image. This considerably reduces the time required for analysis of thermal anomalies in areas of active volcanoes. Similarly to the case of ash plumes, the temperatures of thermal anomalies in the areas of volcanoes obtained by processing images acquired by different satellite instruments show good comparability and homogeneity of the information. This is important for real-time and retrospective analysis of changes in the temperature and size of thermal anomalies in areas of volcanoes to predict the future volcanic activity and reduction of volcanic hazards for areas around volcanoes. As an example, it is known that a gradual (and occasionally very rapid) increase in the size and temperature of a thermal anomaly around the lava dome on Bezymyannyi Volcano, Kamchatka indicated the precursory process of a large explosive eruption of this volcano that ejected ash to heights of 8–15 km a.s.l. that posed serious risks to aircraft (Girina, 2012; Schneider et al., 2000). The detection and real time monitoring of changes in the parameters of a thermal anomaly in the area of Bezymyannyi Volcano based on various satellite data enabled KVERT researchers to predict such eruptions more than one time and to issue notifications to interested users a week or a few hours before the explosive event (Girina, 2012; Gordeev and Girina, 2014).

In addition, the VolSatView IS provides tools that can be used to identify ash clouds and plumes, to analyze their time series, to enter them in a database with automatic calculation of the area of the ash plume or cloud, to visualize ash plumes and clouds for specified or all volcanoes for a definite period of time (Fig. 3). The analysis of variations in the parameters of ash plumes over time will yield their velocity of propagation and the rate at which their area increases. As an example, the ash plume due to the November 22, 2014 explosive event on Shiveluch Volcano was detected on satellite images 5 h after the event (Fig. 4, Table 2). The edge of the ash plume was moving at an average velocity of 59 km/h and the average rate of increase in the area of the ash plume was 492 km^2/h (see Table 2). Statistical information on the velocity of movement for ash clouds discharged by volcanoes and on the rate of increase of their areas is useful for notifying interested users about possible ashfalls, thereby enabling a more accurate assessment of volcanic hazards for various areas.

Along with medium-resolution satellite data, VolSatView widely uses high-resolution satellite information for analysis and long-term prediction of volcanic activity. As an example, a unit has been developed to handle data from the Hyperion hyperspectrometer (HS) (High Resolution Hyperspectral imager) installed on the EO-1 satellite (http://EO1.usgs.gov). This instrument acquires information in 242 spectral channels in the 0.4–2.5 μm range (the visible + near IF ranges) with a spectral resolution of 10 nm and a spatial resolution of 30 m. The VolSatView IS has a routinely updated Hyperion data archive for Kamchatka and the Kurils since 2002. The VolSatView can be used to perform both a spatial analysis of HS data using cartographic interfaces available in the service and the analysis of spectral profiles for earth features. As well, one can compare data acquired at different times and analyze HS data together with other information in the system (Gordeev et al., 2014, 2015).

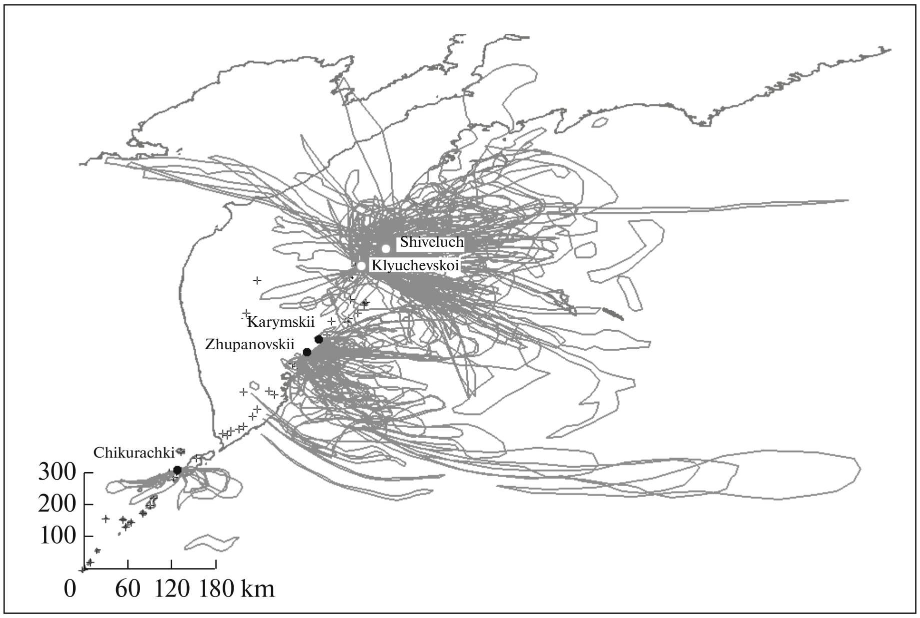

Fig. 3. Visualization of ash plumes and clouds due to explosive eruptions of Kamchatka volcanoes (Shiveluch, Klyuchevskoi, Karymskii, and Zhupanovskii) and Chikurachki Volcano on the North Kuril Is. in 2013–2015 as identified in satellite images at the VolSatView IS.

Special emphasis is placed on tools that can be used to perform a joint analysis of information from different satellite systems, on the sources of observation, and on the results of their analysis. Thus, for example, the system can be used to synthesize different data acquired at different times to detect changes in the area of a volcano. As well, one can look at information on ash plumes as observed on satellite images, along with results from numerical simulation for the propagation of these plumes.

Implementation Technologies of the System

The VolSatView system was created and is being further refined using technologies and specialized software developed at the SRI. These are intended to develop various specialized systems for remote monitoring of diverse features and resources (Andreev et al., 2004; Balashov et al., 2013; Egorov et al., 2004; Efremov et al., 2004, 2012; Lupyan et al., 2004, 2011; Tolpin et al., 2011; Uvarov et al., 2013, 2014). The main feature in these technologies and software consists in the maximum automation of data acquisition, processing, storage, and visualization for the system. This allowed us to minimize the cost of additional technical personnel who would provide constant maintenance of the system. At the present time the system is maintained in operation mostly by its developers.

INTEGRATION OF VOLSATVIEW WITH OTHER INFORMATION SYSTEMS

The VolSatView IS operates with technologies for routine handling of data from different information systems, e.g., KVERT (http://www.kscnet.ru/ivs/kvert/), VOKKIA IS at the IV&S FEB RAS Geoportal (http://geoportal.kscnet.ru/volcanoes/), and the *Signal* automated IS (AIS) (http://signal.febras.net) (Efremov et al., 2012; Romanova, 2013; Romanova et al., 2012; Sorokin et al., 2010; Khanchuk et al., 2013; Korolev et al., 2015). This enables users, e.g., to obtain access while working in the VolSatView to video observations of Shiveluch, Klyuchevskoi, Gorelyi, Avacha, and other volcanoes (at present data acquired by ten video cameras are available); information on Aviation Color Code for aircraft for each of the 36 volcanoes; the results of simulation for the paths of ash plumes from volcanoes, and so on.

A specialized service has been developed (Sorokin et al., 2014) to organize information cooperation among these systems and supply data to VolSatView; it can be treated as part of the general system that performs routine monitoring of volcanic activity in the region. The possibility of using different ISs enhances the effectiveness and quality of observations, as well as leads to the development of new information products. On these lines a number of important problems have been solved, e.g., when a KVERT VONA notification appears regarding a change in Aviation Hazard Color Code for a volcano in the VOKKIA IS database, the Signal AIS modifies the interval of image taking for the video cameras focusing on the volcano in an automatic manner using specified rules.

One important problem in the reduction of the hazard to aircraft during volcanic eruptions is to be able to predict changes in the parameters of ash plumes (their heights and direction of movement) as they travel in the atmosphere. At present we can do the following: if a

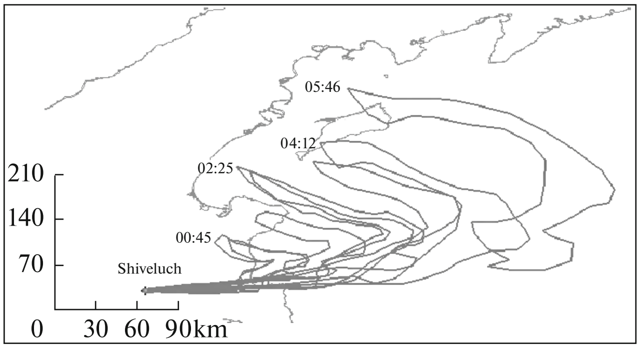

Fig. 4. The propagation of the ash plume from Shiveluch Volcano after the explosive event at 22:21 UTC November 22, 2014 (data are from the VolSatView IS).

VONA contains an indication of specific characteristics of an explosive event (the time the explosion began, the height of ash ejection, and the azimuth of travel of the ash plume) and these characteristics are received in the VOKKIA IS database, the Signal AIS automatically computes the path of the ash plume using the PUFF model (Searcy et al., 1998) and the PUFFUAF software as implemented at the University of Alaska, Fairbanks, UAF) (https://www.uaf.edu/) (Fig. 5).

THE ABILITIES OF VOLSATVIEW FOR MONITORING THE ACTIVITY OF VOLCANOES

Fast monitoring of volcanic activity essentially relies, not only on the detection of an ash plume or cloud and the estimation of its further propagation, as pointed out above (see Fig. 4, Table 2), but also on the determination of the height above sea level where it travels from the volcano. The VolSatView cartographic interface makes it possible to measure cloud temperature in different channels and to determine cloud heights from the atmospheric profile (Fig. 6). The parameters of ash plumes and clouds (height above sea level; width and extent, the direction of movement away from the volcano) as measured in the VolSatView IS cartographic interface are used in a straightforward manner to produce a VONA KVERT to notify the international aviation community about volcanic hazard to aircraft (http://www.kscnet.ru/ivs/kvert/van/). In addition, the system involves technology that is constantly refined to simulate paths of ash plumes from volcanoes based on the PUFF model and the PUFFUAF software (Searcy et al., 1998) (the paths of ash plumes are computed in the Signal AIS at the FEB RAS Computing Center) based on routine and archival satellite and meteorological data (wind direction and velocity, among other things) that constantly arrive to the system. The VolSatView IS enables visualization of results from calculated paths of ash plumes directly on satellite images where the plumes are identified (Fig. 7). In particular, one can in this way estimate the reliability of the simulation. We note that the satellite image in Fig. 7 clearly shows condensation (inversion) traces of recent plane flights, which indicates that the ash plume due to Zhupanovskii Volcano had traversed all the main aircraft routes on July 12, 2015 and posed a definite threat to aircraft.

It is known that the atmospheric circulation is very different over different areas in Kamchatka. Most of the peninsula typically shows a seasonal variation in wind that is best seen on its eastern coast. About 70 cyclones pass over Kamchatka during a year as they travel from Japan to the Aleutians or into the Bering Sea (Kir'yanov, 1992). The most pronounced changes in wind velocity, temperature, and humidity are observed in the upper troposphere in the tropopause region whose height varies between 8 and 12 km above the peninsula around the year. Kir'yanov (1992) showed that different wind directions are characteristic near the ground for different areas in Kamchatka, but the stratosphere is dominated by the eastward and southeastward transport of air masses at speeds of 20–36 m/s. The VolSatView IS enables researchers to analyze abundant data on the movement of ash plumes from volcanoes (specifically Shiveluch, Klyuchevskoi, Karymskii etc. or from all of these at the same time) during their eruptions, as well as for a definite time interval (seasons or years), and so on. This is important for identifying patterns in the seasonal propagation of ash plumes, for the analysis of changes in the velocity of movement of ash plumes over decades, and ultimately for long-term and immediate forecasts of volcanic hazards for aircraft.

The accumulated experience of American and Russian scientists in the satellite monitoring of active

Table 2. Time-dependent variation in parameters of ash plume due to Shiveluch Volcano after the explosive event at 22:21 UTC November 22, 2014 based on VolSatView data

Satellite	Nov. 23, 2014. Time of image, UTC	Time elapsed since beginning of event, min	Plume extent, km	Plume area, km^2	Velocity of plume movement, km/h	Rate of plume area increase, km^2/h
AQUA	0045	144	146.5	2825.4	61	
Suomi NPP	0134	193	198.6	4441.8	62	502
AQUA	0225	244	249.5	7156.0	61	667
Suomi NPP	0311	290	286.0	9644.8	59	515
NOAA 18	0412	351	330.7	12455.5	56	480
NOAA 18	0546	445	422.4	14646.7	57	295

volcanoes in Kamchatka allows reliable estimation of their activity using parameters (temperature and size) of thermal anomalies (Girina, 2012; Harris et al., 2000; Schneider et al., 2000, among others). The appearance of an insignificant thermal anomaly in the area of a volcano invariably points to increased activity, while for frequently erupting volcanoes like Klyuchevskoi, Shiveluch, Bezymyannyi, or Karymskii, it is a reflection of, or a precursor to, an eruptive event. For volcanoes that erupt rarely the episodic appearance of a low thermal anomaly in the area of such a volcano indicates increased gas emission, which is occasionally related to a change in meteorological conditions in the area; if an anomaly persists during 24 hours and its temperature and size begin to increase, a large explosive eruption is certain to occur. During long-continued eruptions that, e.g., discharge lava flows, the parameters of a thermal anomaly have a linear relationship with the amount of juvenile material that comes to the ground surface at the time it was recorded in a satellite image (Girina, 2012). As the eruptive activity of a volcano is about to stop, the thermal anomaly gradually shrinks, and no anomaly at all may be present between eruptions. That is to say, a thermal anomaly in the area of a volcano serves as an indicator of its activity: repose, increased activity, and eruption. The VolSatView IS can detect a thermal anomaly around a volcano, determine its size and temperature both automatically and manually, and enter the information in its database (Efremov et al., 2013, 2013a).

A retrospective analysis of volcanic activity should incorporate all of the parameters of the activity. These include temporal variations in the temperature and sizes of thermal anomalies in the areas of active vents in order to detect eruption precursors; the fact of thermal anomalies being confined to definite features like lava domes, lava flows, pyroclastic flows, slides of lava domes or active volcanoes, and so on; the zonality of temperature distributions within an anomaly for assessing the size of an imminent or ongoing eruption of the volcano (Girina, 2012; Carter et al., 2008; Oppenheimer and Francis, 1997, among others).

The VolSatView IS allows multidisciplinary analysis of any volcanogenic features around a volcano, estimation of their state, and prediction of future volcanic activity. As an example, Zhupanovskii Volcano, 70 km from Petropavlovsk-Kamchatskii, came to life in October 2013 (its last eruption occurred in 1956–1957 (Sirin, 1958)), and became quiet again after 4 days of moderate phreatic eruptive activity (Girina and Nenasheva, 2015; VONA KVERT 2013-25). On July 6, 2014 the volcano started a large explosive eruption that continued until March 2016 with some intermissions (VONA KVERT 2016-22). The large explosive events of July 12 and 14 (VONA KVERT 2015-179; VONA KVERT 2015-181), as well as those on November 27 and 30 (VONA KVERT 2015-210; VONA KVERT 2015-211) provoked a rockfall on the Priemysh active cone of Zhupanovskii. The resulting deposits near the base of the volcano that were formed on July 12 and 14 were detected on July 16, 2015 (Gorbach et al., 2015).

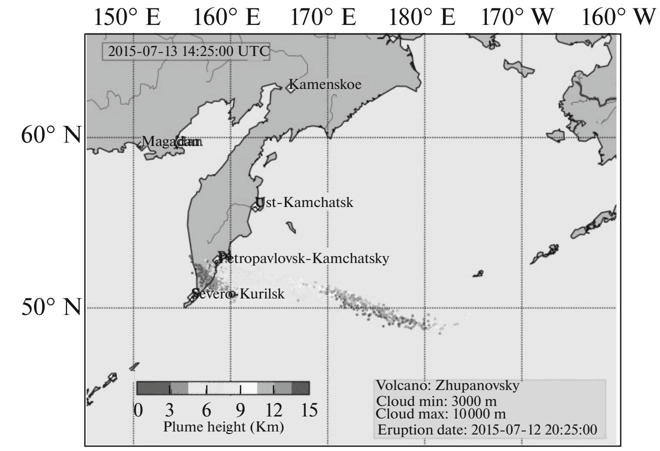

Fig. 5. Results of simulation for the propagation of the ash plume from Zhupanovskii Volcano July 12–13, 2015 using the PUFF model at the Signal AIS, CC FEB RAS.

A TERRA Aster image (NASA, JPL) (11:23 UTC, July 13, 2015) recorded a thermal anomaly on the surface of the rockfall deposits in their middle. The anomaly was 3.7 km^2 in area and its temperature varied between 9.5 and 15°C. A high resolution image acquired from Meteor-M no. 2 on July 26, 2015 clearly shows two branches of the rockfall deposits whose total area is approximately 18–20 km^2 (Fig. 8a). An analysis of rockfall images taken on July 16, 2015, Landsat-8 images before the eruption, as well as of images from Meteor-M no. 2 and Landsat-8 after the eruption showed that the average thickness of the deposits does not exceed 2 m, hence their volume must be estimated as 0.04 km^2.

The VolSatView IS was used to classify the rockfall deposits based on data recorded by the KMSS instrument (Kondrat'eva et al., 2015) installed on the Meteor-M no. 2 satellite on July 26, 2015 (see Fig. 8a). Several characteristic patches were detected on these features (see Fig. 8b). A detailed analysis of spectral characteristics for these patches was performed using data recorded on July 24, 2015 by a Hyperion instrument (EO-1 satellite). The plots of spectral reflectance (SR) based on average sets of test points on different previously identified patches on the rockfall deposits are shown in Fig. 8c.

An analysis of the SR plots shows that the lowest SR (0.09–0.13) occurred on the dark grey patch and the highest (0.14–0.20) on the black patch, with intermediate values (0.11–0.17) occurring in the light grey area (see Fig. 8c). It should be noted that the light grey field exists on all deposits of the rockfall, while the black occurs on most of the left branch and on the central part of the right (see Fig. 8b). Most of these deposits are likely to be formed during or at the end of the high explosive activity (the anomaly on the Ster image reflects the deposits of directed discharges from the Priemysh crater) of Zhupanovskii Volcano on July 12, 2015 (those parts of the rockfall light and dark grey in color in Fig. 8b). The hot material from the explosions

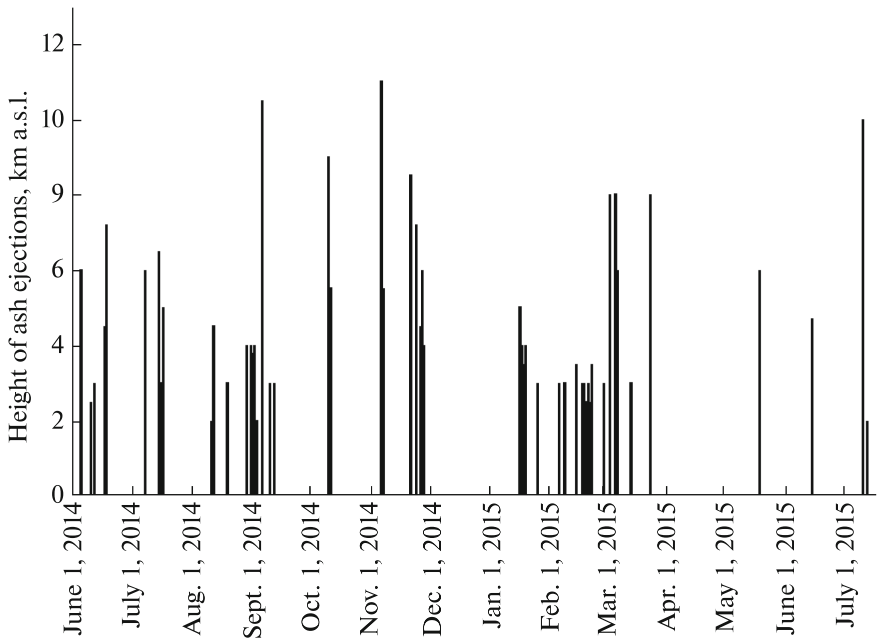

Fig. 6. Height of ash ejections from Zhupanovskii Volcano in 2014–2015 as seen in satellite images acquired at the VolSatView IS.

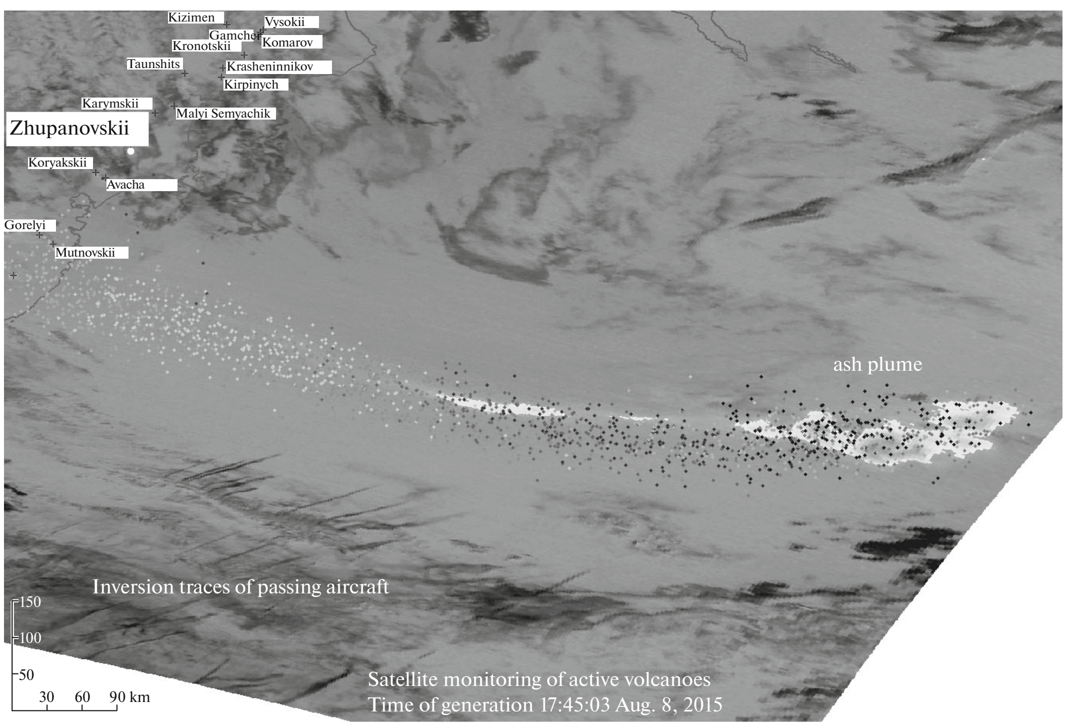

Fig. 7. Simulation results for the propagation of the ash plume from Zhupanovskii Volcano on July 12, 2015 using the PUFF model model at the VolSatView IS; the visualization is on the MODIS (AQUA) satellite image, 16:00 UTC, July 12, 2015.

fell on glaciers and snow patches, melted them, and the water-saturated, loosely lying rocks of the rockfall (or perhaps a rockfall combined with a landslide) with high concentrations of fine particles and with traces of flow on the surface covered the base of the volcano as a broad blanket. The destroyed sector of the Priemysh cone supplied additional, relatively dry (possibly still warm) rudaceous material on July 14, which was mostly deposited on the left branch of the July 12 rockfall. Some indirect evidence for the formation of the rudaceous rockfall mass on July 14 is supplied by a KVERT report on an ash cloud that that was moving east-southeast from the volcano at a height of 2 km a.s.l. at the most (VONA KVERT 2015-181). The differences in grain-size composition, water saturation, and the temperature of the rockfall deposits that were

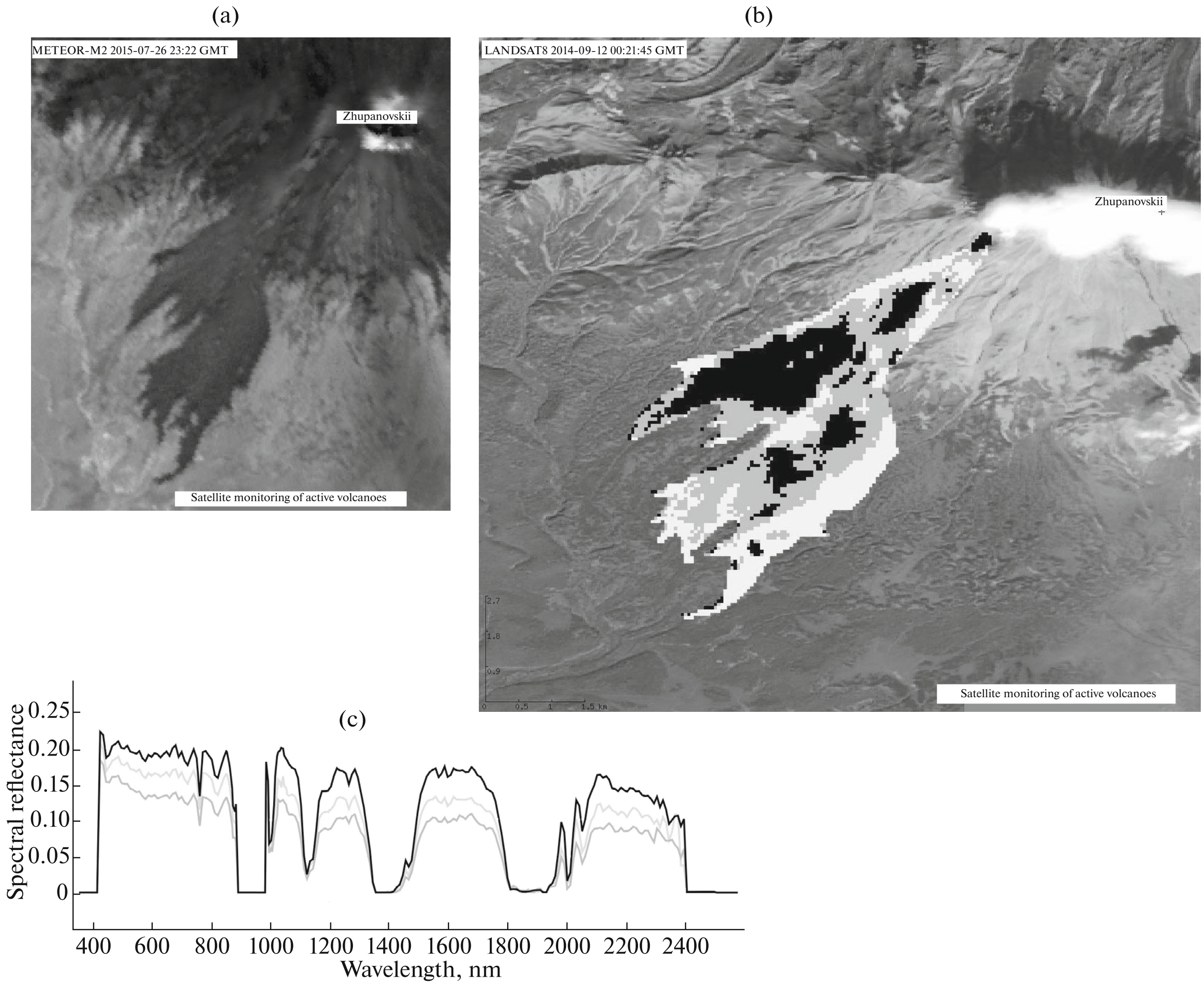

Fig. 8. Result from an analysis of rockfall deposits on Zhupanovskii Volcano that were produced on July 12–14, 2015; the analysis was performed at the VolSatView IS: (a) an image of the July 26, 2015 rockfall area (Meteor-M satellite no. 2, KMSS instrument; (b) a classification of the rockfall deposits based on data of the KMSS instrument upon the background of an image in the panchromatic channel of the OLI-TIRS instrument (Landsat 8 satellite) September 12, 2014; (c) plots of averaged SR for areas of rockfall deposits based on data from a Hyperion instrument (EO-1 satellite) July 24, 2015 (The colors of the lines in the plot correspond to the color of the rockfall areas as identified from KMSS instrument observations) (see the description in the text).

formed on July 12 and 14 produced a difference in the structure of these features, hence their SR values (see Fig. 8c).

CONCLUSIONS

The VolSatView IS was developed in 2011; during the last 5 years it has become a powerful tool for routine monitoring and retrospective study of Kamchatka and Kuril volcanoes. It was originally designed to use freely available noncommercial satellite data; at present the VolSatView IS can acquire in automatic mode various satellite data of medium and high resolution with the maximum rate of entering the system and with the ability for remote (distributed) operation on these data. As well, it can perform integrated analyses of satellite observations and other instrumental and scientific data (e.g., weather observations, videos, results of mathematical simulation, etc.) from other ISs.

VolSatView possesses a broad range of tools for operating both on series of satellite observations and cartographic information. As an example, the system web interface can access tools for the analysis of temperature fields, allowing the user an instantaneous inspection of temperature values at each point of the image, which considerably reduces the time required for the analysis of thermal anomalies in the areas of active volcanoes. Tools have been developed for the identification of ash plumes or clouds and for the visualization of ash plumes and clouds for individual or all volcanoes for a specified period of time.

VolSatView makes a wide use of high-resolution satellite data for retrospective analysis and for predicting the future activity of volcanoes. As an example, one can perform spatial analysis of hyperspectral data (Hyperion, EO-1) using the system cartographic interfaces and can analyze spectral profiles for selected features; one can compare and analyze hyperspectral data recorded at different times along with other information in the system.

The VolSatView IS has technologies for real-time handling of data from different ISs, e.g., information from KVERT at the VOKKIA IS in the IV&S FEB RAS Geoportal, the Signal AIS, and others. As an example, one can have access, while operating from the VolSatView, video observations of Shiveluch, Klyuchevskoi, Gorelyi, Avacha and other volcanoes; information on the Aviation Color Code for each of the 36 volcanoes; results of simulating the paths of ash plume propagation from volcanoes: one can simultaneously visualize the information on the ash plumes that are observed on satellite images and the results of numerical simulation for the propagation of these plumes; etc.

Based on the KVERT experience, since 2014 the SVERT (Sakhalin Volcanic Eruption Response Team) researchers at the Institute of Marine Geology and Geophysics, Far East Branch, Russian Academy of Sciences have also been using the VolSatView IS for the monitoring and study of volcanoes on the Kuril Islands.

The promising lines of development for the VolSatView IS are as follows:

—expanding the range of data that arrive from new satellite instruments (e.g., Resurs-P and Himawari-8);

—real-time determination of ash ejection heights and of the propagation of ash plumes based on the weather observations in the system;

—expanding the potential of classification for volcanogenic deposits using a variety of high-resolution satellite data; and

—creating the ability for 3-D simulation for the propagation of ash plumes from a volcano during an eruption.

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VONA KVERT 2016-22: http://www.kscnet.ru/ivs/kvert/van/index.php?n=2016-22

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