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On Precursor of Kamchatkan Volcanoes Eruptions Based on Data from Satellite Monitoring

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Abstract—Kamchatka is one of the most active volcanic regions on the planet. Large explosive volcanic eruptions, in which the ash elevates up to 8–15 km above sea level, occur here every 1.5 years. Study of eruptions precursors in order to reduce a volcanic risk for the population is an urgent problem of Volcanology. The available precursor of strong explosive eruptions of volcanoes, identified from satellite data (thermal anomaly), as well as examples of successful prediction of eruptions using this precursor, are represented in this paper.

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STUDY OF THE KAMCHATKA VOLCANOES

Kamchatka Peninsula is home to 30 active and potentially active volcanoes. Four of them are producing nearly continuous weak or moderate eruptions accompanied by paroxysmal explosive events. Klyuchevskoy Volcano has been active for hundreds of years; Molodoy Sheveluch has been active since August 1980 when a lava dome started to grow inside the explosive crater caused by the catastrophic eruption in November 12, 1964; Bezymianny Volcano has been active since October 22, 1955 after a thousand years of repose; Karymsky Volcano has been active since its new stage of activity, which started on January 1, 1996. Avachinsky, Mutnovsky, and Gorely volcanoes also sporadically become active. In average one strong explosive eruption which sends ash columns to altitudes of 8–15 km above sea level (a.s.l.) and even higher is produced once every 1.5 years (Girina and Gordeev, 2007).

Kamchatka volcanoes have been studied for hundreds of years, but it all began with the first scientific research made by Stepan P. Krasheninnikov. The Levinson-Lessing Volcanological Station was established in Klyuchi settlement, Kamchatka, in 1935 giving birth to complex research of each volcano in the peninsula and resulted in published numerous data on geology, tectonics, rocks composition, eruption characteristics, history of evolution of many Kamchatka volcanoes (Gorshkov and Bogoyavlenskaya, 1965; Dubik and Volynets, 1972; Melekestsev, et al., 1997; Naboko, 1963; Piip, 1956; Vlodavets, 1984; Vlodavets and Piip, 1957; etc). Seismological investigations of active volcanoes have been developed since 1946 (Chubarova, et al., 1983; Fedotov, 2008; Gorshkov, 1956, 1961; Gontovaya, et al., 2004; Gordeev, 1992; Gorelchik, 2001; Tokarev, 1966, 1981; Shirokov, 2009; etc).

In order to improve safety for aviation during explosive eruptions, KVERT (Kamchatkan Volcanic Eruption Response Team) was created in 1993 (Girina, 2008; Girina and Gordeev, 2007; Miller and Casadevall, 2000; Neal, et al., 2009). The goal of KVERT is to reduce the risk of aircraft encounters with volcanic ash clouds in the North Pacific region through timely detection of volcanic unrest, tracking of ash clouds, and prompt notification of airline authorities and others about volcanic ash hazards. Volcanic ash is extremely hazardous to flying jet aircraft. Encounters of a jet aircraft with ash clouds can pose a real threat to passengers. Jet engines can fail suddenly, because ingested ash particles can melt and then accumulate as re-solidified deposits in the engine (the melting temperature of ash is lower than the operating temperatures of modern jet engines) (Girina and Gordeev, 2007; Miller and Casadevall, 2000). Ash particles cause abrasion damage to forward-facing surfaces, including windshields and fuselage surfaces; obstruction of vent and fuel systems and airspeed tube; erosion of compressor fan blades; failure of critical navigational and operational instruments and others.

Recently the Institute of Volcanology and Seismology Far East Branch of the Russian Academy of Sciences (IVS FEB RAS) has the authority for discharge obligations as the Volcano Observatory of the Russian Federation[2]. Namely, on behalf of IVS, KVERT is

[1] The article was translated by the author.

[2] The Agreement on providing information about volcanic activity in the Far East to international air navigation services for the airspace users, signed December 06, 2010 between the Federal Agency of Air Transport, the Russian Academy of Sciences and the Federal Service for Hydrometeorology and Environmental Monitoring, the Institute of Volcanology and Seismology (IVS) FED RAS.).

Color	State of volcano
GREEN	Volcano is in normal, non-eruptive state *or, after a change from a higher level:* Volcanic activity considered to have ceased, and volcano reverted to its normal, non-eruptive state.
YELLOW	Volcano is experiencing signs of elevated unrest above known background levels. *or, after a change from higher level:* Volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.
ORANGE	Volcano is exhibiting heightened unrest with increased likelihood of eruption. *or,* Volcanic eruption is underway with no or minor ash emission. [specify ash-plume height if possible]
RED	Eruption is forecast to be imminent with significant emission of ash into the atmosphere likely. *or,* Eruption is underway with significant emission of ash into the atmosphere. [specify ash-plume height if possible]

Fig. 1. The Aviation Color Code.

responsible for providing information on volcanic activity to international air navigation services for the airspace users. KVERT scientists perform seven days in week in work time analysis of monitoring data of Kamchatka active volcanoes: seismic data provided by the Kamchatka Branch of the Geophysical Survey of the Russian Academy of Sciences (KB GS RAS), data from video and visual observations provided by both IVS FEB RAS and KB GS RAS, and satellite imagery provided by both IVS FEB RAS and the Alaska Volcano Observatory (AVO) of the US Geological Survey. The complex analysis of the published data on volcanic activity and the data from 18 years of KVERT continuous monitoring of volcanoes allows to reliably evaluate hazard posed by volcanoes to aviation and population community.

The level of hazard to aviation at each of Kamchatkan active volcanoes is communicated by KVERT using the Aviation Color Code developed by ICAO – International Civil Aviation Organization (Fig. 1). KVERT issues a weekly hazard forecast of Kamchatka active volcanoes to aviation (VONA - Volcano Observatory Notice for Aviation), but in case when ash explosions and ash plumes within Kamchatka area or built-up and beginning of strong explosive eruptions are detected, KVERT issues eruption alerts to aviation VONA any time and any day of the week regardless holidays and weekends. VONAs are available on the KVERT web-site - http://www.kscnet.ru/ivs/kvert/index.php

VOLCANO ERUPTION PRECURSORS

Those who live near volcanoes have always tried to reveal any precursors of eruptions. Volcanic rumble and glow above the crater may indicate that a volcano is ready to erupt. Scientists have revealed many precursors of explosive eruptions detected by different methods. These are rapid increasing of fumarolic activity or increasing number of observable hot avalanches on volcano extrusions which erupt andesite and dacite lavas; deformations on volcano flanks registered by tiltmeters, GPS and satellite data; increasing temperature of volcanic gases and higher concentration of HCl measured on a volcano; etc (Tokarev, 1985, etc). Realizing that strong eruptions can pose a serious hazard to residents resulted in development of remote methods for volcanoes research and searching for precursors of eruptions.

Careful seismological study of volcanoes resulted in first descriptions for seismic precursors in 1950–1960. Thus, Minakami (1960) divided volcanic earthquakes into 4 types: A, B, C and a volcanic tremor. According to Minakami (1960), increased frequency of B-type earthquakes suggests that an andesite volcano is likely to erupt soon and a vent at basaltic volcanic field are likely to be breached. Monograph by

P.I. Tokarev (1966) characterizes seismicity of active Klyuchevskoy and Bezymianny volcanoes, distinguishes several types of earthquakes typical for these volcanoes, and describes their eruption precursors. For example, build up of Bezymianny eruption according to seismic data by Tokarev (1966) is preceded by gradually increasing number of the second-type earthquakes, gradual and steady increasing in rate of conditional deformations. Energy of volcanic earthquakes decreases just prior to an eruption. Because the build-up of a new Bezymianny eruption has remained nearly unchanged for many years, routine seismic monitoring allows predicting its eruptions.

P.I. Tokarev contributed a lot into development of seismology. He was a creator of a method for eruption forecast using data on seismology, described characteristics of different seismic signals and revealed seismic precursors for eruptions of Klyuchevskoy, Plosky Tolbachik, and Bezymianny volcanoes (Gorelchik, 2001; Tokarev, 1966, 1976, 1981, 1985, 1988). He made some short-term forecasts using his methods for the Large Tolbachik Fissure Eruption in 1975, the 1983 flank cinder cone of Klyuchevskoy Volcano, and Bezymianny eruptions in October 1959, April 1960, and March 1961 (Gorelchik, 2001). Later, the method of short-term eruption forecast was updated by V.I. Gorelchik[3].

Progress in space research and creation of Internet allowed detecting eruption precursors using data from satellites. Satellite observation is very important because some volcanoes can be unavailable for other types of monitoring. For example, 19 active volcanoes in Kamchatka have no seismic stations. These are Ichinsky, Vysoky, Gamchen, Komarov, Kronotsky, Krasheninnikov, Kikhpinych, Taunshits, Maly Semyachik, Zupanovsky, Opala, Ksudach, Zheltovsky, Il'insky, Koshelev, Kambalny, Khodutka, Khangar, and Dikiy Greben volcanoes. Sometimes seismic monitoring of volcanoes is unavailable for some technical reasons. Thus, current satellite monitoring in Kamchatka remains one of the most effective methods for monitoring of volcanic activity.

SATELLITE MONITORING OF KAMCHATKA

Monitoring of active volcanoes in various countries of the world involves data from National Oceanographic and Atmospheric Administration (NOAA) satellites which are equipped with Advanced Very High Resolution Radiometers (AVHRR), Geostationary Operational Environmental Satellites (GOES), Geostationary Meteorological Satellites (GMS), TERRA and AQUA equipped with Moderate Resolution Imaging Spectroradiometer (MODIS), data from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and some other satellites (Carter, et al., 2000; Dehn, et al., 2000; Girina and Gordeev, 2007; Kearney, et al., 2008; Miller and Casadevall, 2000; Ramsey and Dehn, 2004; Schneider, et al., 2000; Watson, et al., 2004; Yu, et al., 2002). Processing of satellite signal varies from 15 min for GOES to 1.5 hours for GMS to complete.

Over the period of more than 20 years polar-orbiting satellites NOAA (AVHRR) have been providing data necessary for on-line monitoring of volcanic activity (tracking of thermal anomalies over volcanoes and ash plumes from explosive eruptions) (Glaze et al., 1989; Miller and Casadevall, 2000; Prata, 1989; Ramsey and Dehn, 2004; Schneider et al., 2000; Schneider and Rose, 1994; Watson et al., 2004; Wen et al., 1994). Simultaneously several (up to 4) satellites are on their orbits, each passes any territory approximately at the same time (Garbuk and Gershenzon, 1997; Kronberg, 1988; Tertyshnikov and Kucheiko, 2010; Tolmacheva and Shklyaeva, 2006). Satellites orbit at about 800 kilometers above the surface of the Earth. Their orbits near Earth's poles allow obtaining of a broad overview of areas (a swath width of review is 3000 km) and ensure that any part of the surface (a spatial resolution is 1.1 km, and pixel-size is of 1.1×1.1 km at nadir) is captured at least 4 times per 24 hours by each satellite. Scanning AVHRR Radiometer forms an image of the underlying surface in 5 spectral bands: 1 (0.58–0.68 μm) - measurement of radiation reflected by the earth's surface; 2 (0.725–1.1 μm) - measurement of radiation in the near infrared (IR) area; 3 (3.55–3.93 μm) - measurement of the own radiation and radiation reflected by the earth's surface; 4 and 5 (11.5–12.5 and 10.5–11.5 μm) - measurement of the own thermal radiation by the earth's surface. Precision is 10 bits/pixel/channel. Bit rate from the AVHRR is 665.4 Kbit/s. Data from NOAA is available online at www.saa.noaa.gov (Satellite Active Archive) to all users. Besides, according to "Open Sky" concept, the World Meteorological Organization provides free access to satellite data by any ground stations around the world.

In 1999 AVO granted KVERT access to data from NOAA for monitoring of Kamchatka active volcanoes and trained KVERT scientists to process satellite images. Since 2002 KVERT scientists have been able to process and analyses various satellite data from MTSAT, NOAA (AVHRR), TERRA and AQUA (MODIS), OMI, ASTER etc. nearly real-time in order to detect ash plumes and thermal anomalies on active Kamchatka volcanoes. A revealed ash plume poses a real threat to aviation within an area of the volcano. Therefore KVERT issues an eruptive alert which includes information about the plume size and location and sends it via e-mail to all users. In 2002–2007 scientists from KB GS were also conducting satellite

[3] V.I. Gorelchik, V.T. Garbuzova, V.I. Levina, O.S. Chubarov, Razrabotka i oprobovaniye sistemy prognoza vulkanicheskikh izverzheniy na Kamchatke. Otchot o NIR. VNTITsentr; GR 81068164; Reg. number 528. M. 1986. Chapter 3.1. Pages 63–141) (1985 and 1986) and other scientists.

monitoring of Kamchatka volcanoes in frames of KVERT Project (according to agreement with IVS FEB RAS), but they never mentioned the Project in any papers (Senyukov, 2006).

Scientists from KVERT continue to exchange information with AVO colleagues and communicate problems concerning satellite monitoring. For example, the ash cloud from the Bezymianny eruption on October 5, 1995, was tracked using satellites over a distance of 5000 km on its way from the volcano to Unalaska Island, the Aleutians. Close collaboration of scientists from KVERT and AVO in use of satellite data along with seismic data (from KB GS) and ground observations resulted in reduced risk to aviation in Kamchatka. Fifteen flights were canceled due to the Bezymianny eruption (Girina and Gordeev, 2007).

VOLCANIC ERUPTIONS PRECURSOR, BASED ON DATA FROM SATELLITE MONITORING (THERMAL ANOMALY)

Flows of heat transmitting to the atmosphere from the area of active volcanoes during their eruption (during explosions of hot volcanic products in Strombolian, Vulcanian, Pelean, Plinian activity; from the surface of lava lakes, effusing lava flows, descending pyroclastic flows and so on) or during inter-eruptive period (gas and steam emissions from fumaroles and solfataras) are well-studied at present (Dehn, et al., 2000; Glaze, et al., 1989; Harris, et al., 1995, 2000; Oppenheimer, et al., 1993, 1997; Schneider, et al., 2000; Watson, et al., 2004; Wright, et al., 2002; etc).

The articles on satellite monitoring of evolution of the 1997 and 1998 eruptions of Bezymianny Volcano (Dehn, et al., 2000; Schneider, et al., 2000) are one of the first works in which variations of temperature and size of a thermal anomaly in the area of a volcano are considered to be operative precursor of explosive eruption. The 20-year experience of American and Russian scientists on satellite monitoring of active Kamchatka volcanoes (KVERT Project) proved this precursor to be effective not only for Bezymianny Volcano but also for volcanoes with different composition of erupted volcanic products.

This precursor is based on the classical definition of the term “volcanic eruption”: an eruption is a process when a magma matter reaches the Earth’s surface (Macdonald, 1975; Vlodavets, 1984). When hot magma matter (900–1200°C) rises toward the Earth’s surface a flow of heat transmitting to the atmosphere increases and is observed in satellite images as thermal anomaly. Both size and temperature of the anomaly are linearly associated with the amount of juvenile material which comes on the Earth’s surface at the moment of the anomaly detection in satellite image.

Thermal anomaly which appears in a volcanic area evidences on warning signs of explosive eruption or that explosive event is likely in the nearest future. Hazard that poses such eruption to people and environment depends on composition of magma matter of the volcano. There are several examples.

Klyuchevskoy Volcano

(rock composition – basalts, andesibasalts)

2005. From the end of October 2004 to January 11, 2005 seismicity of the volcano (on data of KB GS RAS) was at background level, and only fumarole activity with steam and gas plume at an approximate altitude of 5 km a.s.l. were detected. On January 12 seismicity of the volcano increased, volcanic tremor began to record. Since January 15 satellite imagery had been showing thermal anomaly, resulted from the rise of fresh lava towards the summit crater (Fig. 2a) (Girina, et al., 2007). *Thermal anomaly in the area of the summit crater evidenced of the beginning of a new eruption of the volcano.* For the first time incandesce above the volcano was observed on January 16, which gave evidence for lava inside the crater, and the beginning of the volcano Strombolian activity. Fumarole column reached 6 km a.s.l.; visual observation revealed a small amount of ash inside the column. Satellite images showed ash plumes drifted 40 km to the north-east of the volcano. Within 8 days incandesce was detected but only on January 21 visual observations established Strombolian activity of the volcano. However, explosive phase of the eruption began on January 16 (a time of incandesce above the volcano). On January 16 at 00:25 UTC the Aviation Color Code was raised to Orange (high level of volcano hazard to aviation) (KVERT Information Release 05-05 (http://www.kscnet.ru/ivs/kvert/updates/).

2007. From December 14, 2006 a weak thermal anomaly was detected in the area of the summit crater (Fig. 2b). It was evident that the volcano would erupt soon, and on December 19 at 01:05 UTC the Aviation Color Code was raised from Green to Yellow (KVERT Information Release 58-06). From January to the middle of February KVERT detected mainly moderate fumarole activity of the volcano, but the temperature of the anomaly gradually increased. Seismicity of the volcano (data from KB GS RAS) was rather low, but since February 1 it increased because the beginning of volcanic tremor was recorded (Girina, et al., 2009). On February 15 visual observation revealed first Strombolian activity of the volcano, evidencing of the beginning of the eruption explosive phase. On February 15 at 09:10 UTC the Aviation Color Code was raised to Orange (KVERT Information Release 07-07).

In these two cases thermal anomaly in the crater area was for the first time revealed 8 day (2005) and two months (2007) prior to the active Strombolian phase of the eruption. In 2003–2007 Klyuchevskoy erupted: from April 16, 2003 to February 15, 2004; from January 15 to May 19, 2005; from February 15 to July 27, 2007. During the 2003–2004 continuous eruption the volcano did not produced any lava flows, and only a cinder cone grew inside the crater and it

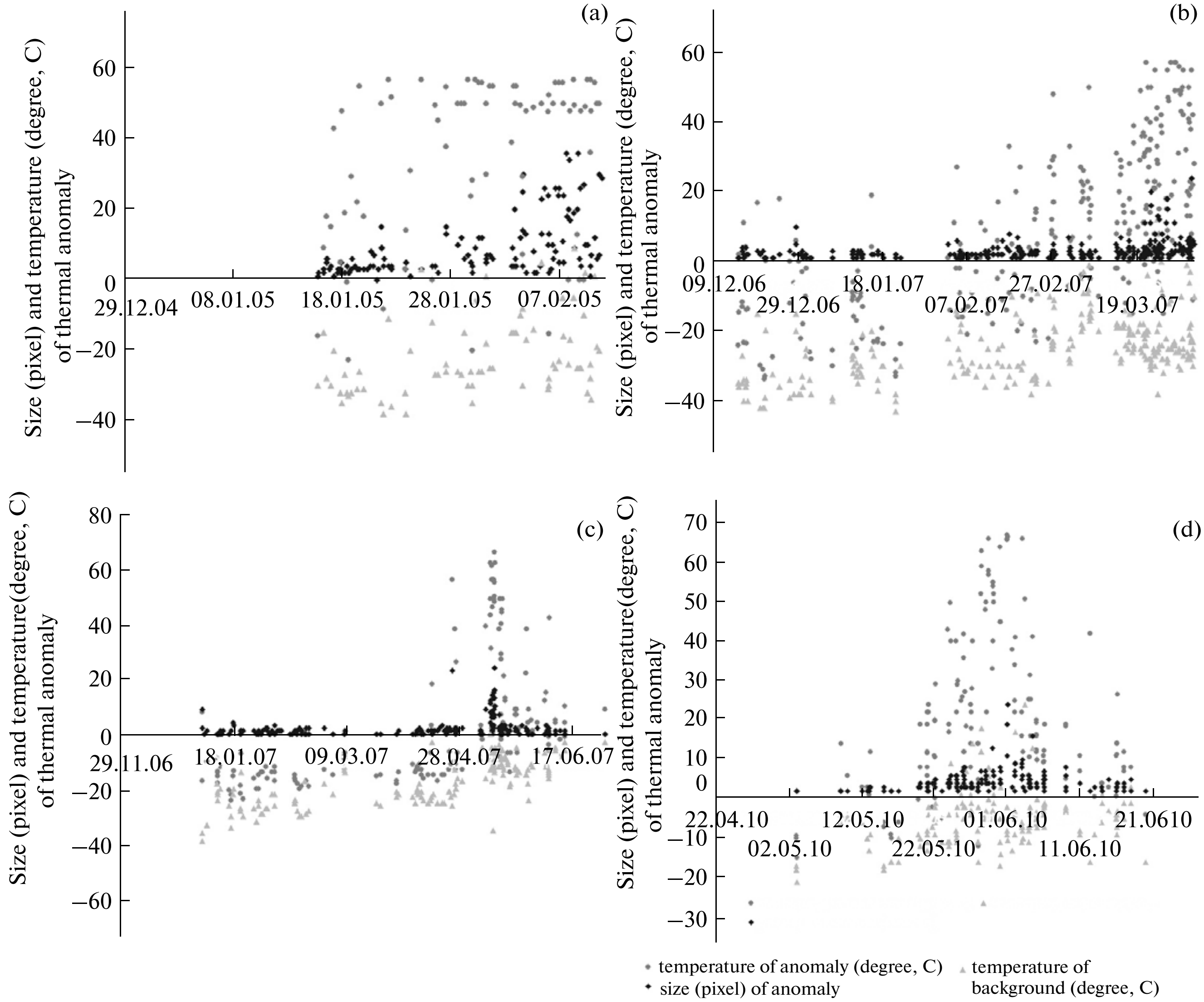

Fig. 2. Change of temperature and size of thermal anomaly over Klyuchevskoy volcano in 2005 (a) and 2007 (b), and Bezymianny in 2007 (c) and 2010 (d).

kept before the start of the next 2005 eruption (the interval between the eruptions was ~10 months). New lava relatively easy travelled through pyroclastic deposits in the volcanic channel, therefore thermal anomaly was detected nearly simultaneously with Strombolian activity. During the 2005 eruption rather a small amount of lava effused into Krestovsky chute (Girina, et al., 2007). Besides, the 2007 eruption was preceded by 20-month period of repose, during which a deep funnel at the summit of the volcano probably resulted in collapsing of lava-pyroclastic material inside volcanic channel. During two months new lava filled the crater of the volcano, and only than Strombolian activity became visual. These examples demonstrate that in any case whether the crater is filled with cinder material or it is empty, thermal anomaly in the area of the volcano evidences that the volcano is likely to start explosive eruption soon.

On initial stage explosive eruptions of Klyuchevskoy volcano as a rule, pose a hazard only to local airlines, as ash plumes drift first tens km of the volcano at altitudes of 6–7 km a.s.l.

By the end of any terminal Klyuchevskoy eruption its explosive activity *always* increases accompanied by ash plumes which can rise up to 8–10 km and drift to 5000 km of the volcano (Girina, et al., 2007; Girina, et al., 2009).

During such periods the volcano poses a serious hazard to international aviation. Ash probable falls in the nearest to the volcano settlements, the hazard poses to population depends on the power of the eruption and duration of the ash fall.

Bezymianny Volcano (rock composition is andesites)

After the catastrophic eruption on March 30, 1956 the lava dome has been *continuously* growing in its crater. It is well known that seismic activity of the volcano between culminations is very weak, though slow extrusion of lava flows on the dome flank is observed, and a weak thermal anomaly is detected in satellite images (Chubarova, et al., 1983; Girina, et al., 2007; Girina, et al., 2009; Tokarev, 1966). Gradual increase of amount and energy of seismic events directly indicates on warning signs of strong explosive eruption of the volcano (Chubarova, et al., 1983; Tokarev, 1966). There are cases when a preparation of Bezymianny eruption is accompanied by strong explosive eruption of Klyuchevskoy which strong seismic activity obscures all seismic events in the area of the neighboring volcanoes. In that case the most effective precursor of Bezymianny volcano eruption is the size and variation of temperature of the thermal anomaly in the lava dome area.

2002. Moderate fumarole activity of the volcano was observed on December 1–24. On data from KB GS RAS on December 9–22 singular weak shallow volcanic earthquakes were recorded. From December 23, seismicity began to increase rapidly, on December 25 weak volcanic tremor and a swarm of earthquakes (over 70 events) were recorded. On December 23 it was detected for the first time a one-pixel thermal anomaly with temperature of 18°C (the difference of temperatures of anomaly and the background). On December 24 the temperature of a two-pixel anomaly increase from 18°C to 33°C. Based on the increase of seismic activity, and the size and the temperature of the thermal anomaly on December 25 at 03:25 UTC the Aviation Color Code was raised to Yellow (KVERT Information Release 61-02). Later the size of the anomaly comprised 10 pixels and the temperature reached +50°C (the background temperature was –25°C). Besides, on December 25 at 01:21 UTC the author detected a very bright plume 15 km long, which 2.5 hours later drifted 200 km to the west of Bezymianny volcano. KVERT raised the Aviation Color Code to Orange. KVERT reported of soon eruption based on the increase of the thermal anomaly temperature and size and the bright plume (KVERT Information Release 62-02). Strong explosive eruption of the volcano started on December 25 at 19:15 UTC. In Kozyrevsk Village ash started to fall about two hour after the beginning of the eruption. The ash layer was ~3 mm thick.

2007. From January 1 to May 10 weak or moderate fumarole activity of the volcano and also sometimes weak thermal anomaly in the lava dome area were detected. The Aviation Color Code was Yellow. On May 6 it was a 2-pixel anomaly with a temperature of 4°C. On May 8 KVERT detected rapid growth of the size (10 pixels) and the temperature (40°C) of the thermal anomaly (Fig. 2b). Based on these data on May 10 KVERT raised the Aviation Color Code to Orange and reported of possible ash explosions up to 10 km a.s.l. in any time (KVERT Information Release 16-07, http://www.kscnet.ru/ivs/kvert/updates/). Strong eruption of Klyuchevskoy at this very time did not allow to record the increase of seismic activity of Bezymianny and to forecast its eruption on seismic data. The author reconstructed the sequence of events of Bezymianny eruption on indirect data and on May 13 published in KVERT Information Release 17-07. The explosive Vulcanian-type eruption occurred on May 11 from 14:30 to 15:00 UTC (data from KB GS RAS) (Girina, et al., 2009). Satellite imagery showed dense ash plume drifted to the north-east of Bezymianny volcano and thin ash plume drifted to the east-north-east of Klyuchevskoy volcano. 20–30 km from the volcanoes the ash plumes jointed together and further drifted as single plume. Satellite images showed different directions of the ash plumes motion associated with strong cyclone in the area of the Northern group of volcanoes. On May 11 from 16:00 to ~22:00 UTC in Klyuchi Village ash fall occurred, it was predominantly gray ash from Bezymianny with some amount of black ash from Klyuchevskoy.

2010. Based on the analysis of change of the temperature and the size of the thermal anomaly, on May 20 the author reported the forecast for strong eruption of Bezymianny volcano for the period from May 21 to July 10. On May 19 the temperature of the thermal anomaly in the lava dome area was 18°C, on May 23 it increased to 49°C (Fig. 2d). On May 24 at 02:20 UTC KVERT raised the Aviation Color Code to Orange, and reported of new explosive eruption warning sings (KVERT Information Release 23-10). The main phase of this strong eruption was recorded (on data of KB GS RAS) on May 31 from 12:34 to 12:50 UTC. First ash emissions probably did not exceed 10 km a.s.l., ash plume drifted 250 km to the west of the volcano and ash fell in Kozyrevsk Village. During further explosive activity of the volcano ash reached more than 10 km a.s.l., ash plumes drifted 160 km to the north-north-east of the volcano. Later on June 1–4 singular ash cloud ~200 × 50 km in size drifted more than 700 km to the south-west and south to the area of the Northern Kurile Islands (http://www.kscnet.ru/ivs/kvert/updates/).

Continuous satellite monitoring of Bezymianny volcano has been conducted by KVERT scientists since 2002, episodic monitoring since 1998 (Girina, 2008; Girina and Gordeev, 2007; Girina, et al., 2007; Girina, et al., 2009). Thanks to our observations of variations of size and temperature of a thermal anomaly in the area of the lava dome in 2001–2010 KVERT scientists predicted 8 eruptions of Bezymianny volcano (on December 16, 2001; on December 25, 2002; on January 11, 2005; on May 9, 2006; on May 11, 2007; on October 14–15, 2007; on August 19, 2008, on May 31, 2010). Published in Internet KVERT Information Releases, containing the Aviation Color

Code Orange or Red and warning of impending strong eruption *before the eruptions* realize forecasts in real-time.

Fumarole activity at Bezymianny between explosive eruptions poses threat only to local aviation. Eruption build-up and especially paroxysmal stage of an explosive eruption is extremely dangerous for international airlines because such eruptions usually evolves rapidly, producing ash plumes which raise up to 8–15 km a.s.l. and can drift up to 5000 km far from the volcano (Girina, et al., 2007; Girina, et al., 2009). Ashfalls are possible in Kozyrevsk and Klyuchi Villages, but ash is usually as thick as a few millimeters.

CONCLUSIONS

Advances of remote sensing methods allow recent 24/7 satellite monitoring of active volcanoes. This helps to detect a thermal anomaly over any active volcano and track its growth and temperature in time. Experience of daily satellite monitoring of active Kamchatka volcanoes for the last 9 years and knowledge on peculiarities of their eruptions allows to predict strong explosive eruptions.

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