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The 2016 Eruptions in Kamchatka and on the North Kuril Islands: The Hazard to Aviation

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Abstract—Large explosive eruptions of volcanoes pose the highest hazard to modern jet flights, because such eruptions can eject as much as several cubic kilometers of volcanic ash and aerosol into the atmosphere during a few hours or days. The year 2016 saw eruptions on 5 of the 30 active Kamchatka volcanoes (Sheveluch, Klyuchevskoy, Bezymianny, Karymsky, and Zhupanovsky) and on 3 of the 6 active volcanoes that exist on the North Kuril Islands (Alaid, Ebeko, and Chikurachki). Effusive activity was observed on Sheveluch, Klyuchevskoy, Bezymianny, and Alaid. All volcanoes showed explosive activity. The large explosive events mostly occurred from September through December (Sheveluch), a moderate ash emission accompanied the entire Klyuchevskoy eruption in March–November, and explosive activity of Karymsky, Zhupanovsky, Alaid, and Chikurachki was mostly observed in the earlier half of the year. The ash ejected in 2016 covered a total area of 600000 km^2, with 460000 km^2 of this being due to Kamchatka volcanoes and 140000 km^2 to the eruptions of the North Kuril volcanoes. The activity of Sheveluch, Klyuchevskoy, and Zhupanovsky was dangerous to international and local flights, because the explosions sent ash to heights of 10–12 km above sea level, while the eruptions of Bezymianny, Karymsky, Alaid, Ebeko, and Chikurachki were dangerous for local flights, since the ash did not rise higher than 5 km above sea level.

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INTRODUCTION

The hazard posed by large explosive volcanic eruptions to modern jet aviation is due to the fact that such eruptions are able to eject as much as several cubic kilometers of volcanic ash and aerosol in the atmosphere and stratosphere during a few hours or days (Gordeev and Girina, 2014; Kirianov, 1992; Miller and Casadevall, 2000; Neal et al., 2009). Depending on the vigor of an eruption and wind speed, ash clouds and ash plumes can travel for some thousands of kilometers from the volcano, while still posing hazard to planes during several days, since the melting temperature of fine particles is below the working temperature of jet engines (Gordeev and Girina, 2014; Miller and Casadevall, 2000).

There are 36 active volcanoes in Kamchatka and on the Kuril Islands, with some of these being in continual activity. Two to eight volcanoes emit an annual discharge of volcanic gas and aerosol into the atmosphere; in addition, discrete powerful explosive events occur hurling ash to heights of 8–15 km above sea level (a.s.l.), thus posing serious hazards for modern airliners (Girina and Gordeev, 2007; Girina, 2012; Gordeev and Girina, 2014; Neal et al., 2009).

With the goal of achieving greater aviation safety during the explosive eruptions in 1993, it was decided to set up the Kamchatkan Volcanic Eruption Response Team, or KVERT, http://www.kscnet.ru/ivs/kvert/) based in Petropavlovsk-Kamchatsky. The KVERT has been performing as a Volcanological Observatory of Russian Federation (WOVO, no. 290111-3000001) since 2010 as part of the Institute of Volcanology and Seismology (IV&S), Far East Branch, Russian Academy of Sciences (FEB RAS) by delivering information on volcanic activities to the international aviation community (Igarashi et al., 2017; Girina, 2012; Gordeev and Girina, 2014; Kiriyanov, 1992; Miller and Casadevall, 2000; Neal et al., 2009). Modern jet airliners fly at heights of 8–13 km a.s.l., while other airplanes and helicopters rise to 6–7 km a.s.l. Different kinds of volcanic activity have different effects on international and local air transportation. The goal of the present study is to examine the 2016 explosive activity occurring in Kamchatka and on the Kuril Islands based on daily monitoring and to assess the ensuing hazards to aviation. All times are in UTC in this paper.

METHODS OF STUDY

The KVERT staff conduct daily video–visual and satellite-based monitoring of volcanoes in Kamchatka and on the Kuril Islands. Visual data on volcanoes come from a variety of sources, including our own field work, observations of other volcanologists, meteorologists, pilots, tourists, mountain climbers, and other people. In 2016 scientists could obtain data from 16 video cameras observing 11 volcanoes (Sheveluch, Klyuchevskoy, Bezymianny, Tolbachik, Kizimen, Zhupanovsky, Avachinsky, Koryaksky, Gorely, Mutnovsky, and Ebeko).

Satellite monitoring of volcanoes has been carried out by the KVERT since 2002; the *Remote Monitoring of Volcanic Activity in Kamchatka and the Kurils* information system (IS) has been in place since 2014 (VolSatView, http://volcanoes.smislab.ru) (Girina et al., 2017b; Gordeev et al., 2016a; Loupian et al., 2015; Girina, 2012; Gordeev and Girina, 2014; Gordeev et al., 2016b).

The VolSatView IS can perform real time monitoring of volcanoes and can detect objects and determine their parameters; such objects include ash clouds and ash plumes (the parameters are height, length, area, velocity, and azimuth of propagation), thermal anomalies in the areas of volcanoes (the parameters are the size and temperature of anomalies and of the background) (Girina et al., 2017b; Gordeev et al., 2016b). Based on data from this real-time monitoring, the scientists issue Volcano Observatory Notices for Aviation (VONAs), reporting ash clouds or plumes in the areas of volcanoes and/or issuing forecasts of explosive eruptions that can pose hazard to people and aviation. The information from VONAs is available at the KVERT IS database (Volcanic Activity in Kamchatka and the Kurils) (Romanova et al., 2016) and at the Volcanoes of the Kurile–Kamchatka Islands Arc (VOKKIA) IS, at the IV&S FEB RAS geoportal (http://geoportal.kscnet.ru/volcanoes/van/) (Romanova et al., 2013; Gordeev et al., 2016). Based on parameters of an ash cloud or plume as reported in VONAs and the current meteorological situation in Kamchatka and the Kurils, the Signal IS at the FEB RAS Computing Center automatically computes the trajectory for the ash cloud or plume using the PUFF model (Sorokin et al., 2017), with the result of this modeling being stored at the KVERT site (http://www.kscnet.ru/ivs/kvert/).

A BRIEF DESCRIPTION OF VOLCANIC ACTIVITY IN 2016

Five volcanoes erupted in Kamchatka during 2016 (Sheveluch, Klyuchevskoy, Bezymianny, Karymsky, and Zhupanovsky) and three on the North Kurils (Alaid, Ebeko, and Chikurachki) (Figs. 1, 2, Table 1). The Kizimen, Avachinsky, Koryaksky, Gorely, Mutnovsky and other volcanoes were in a state of moderate steam and gas activity.

Sheveluch is the northernmost active volcano in Kamchatka (see Figs. 1, 2a). The present-day structure of this volcano includes three main features, viz., Stary Sheveluch Volcano (3283 m), the caldera, and an active andesitic volcano, Molodoy Sheveluch (~2500 m) (Menyailov, 1955; Melekestsev et al., 1991). An extrusive dome has been growing since 1980 in the explosive crater produced by the November 12, 1964 catastrophic eruption of this volcano. Eruptions associated with the dome growth have been occurring since 1984, including paroxysmal eruptions that last for a few hours and discrete explosions during 10–30 min that eject ash to heights of up to 15 km a.s.l. (Girina et al., 2007, 2017b; Ovsyannikov and Manevich, 2010; Ozerov and Demyanchuk, 2004; Fedotov et al., 1985, among others).

The lava dome continued growing in 2016, involving the upward forcing of viscous lava in its northern part, with fumarole activity and incandescent avalanches accompanying the process. A thermal anomaly was recorded in the area of the volcano throughout 2016 (Fig. 3a).

The volcano showed the following types of activity: discrete ash ejections rising to heights as great as 7 km a.s.l. (up to 4.5 km above the dome) from January through April, with ash plumes traveling as far as 190 km west, north, and northeast from the volcano (Fig. 4a); May through August saw only steam and gas activity that accompanied the upward forcing of the extrusion. Since mid-September the activity became more vigorous, with explosions that sent ash to heights of 12 km a.s.l. (up to 9.5 km above the dome) nearly every week until the end of December. Large explosive events emitting ash to heights of 10–12 km a.s.l. (up to 7.5–9.5 km above the dome) occurred January 10 and 29, February 18 and 27, March 23, April 2, May 2, September 18, and December 9 and 19. Large blocks of lava collapsed in the southwestern part of the lava dome on September 18 during explosive activity of the volcano, producing deposits of pyroclastic flows as long as 10 km in the central part of the southern volcanic slope and along the Baidarnaya River bed (Gorbach et al., 2017). The time interval of December 9 through 10 saw the largest explosive event, hurling ash to heights of 12 km a.s.l. (up to 9.5 km above the dome) and driving an ash plume for a distance of over 880 km north–northeast from the volcano. The ash plumes drifted after several explosions as far as 400 km west, north, and northeast from the volcano during December 16–20. An ashfall was recorded at Klyuchi on December 17.

In addition, strong winds in the Sheveluch area formed plumes of resuspended ash that moved for 65 km southeast on July 4, 100 km east from the volcano on September 28–29, 280 km southeast and south on October 3–4, and 143 km east on November 3–4.

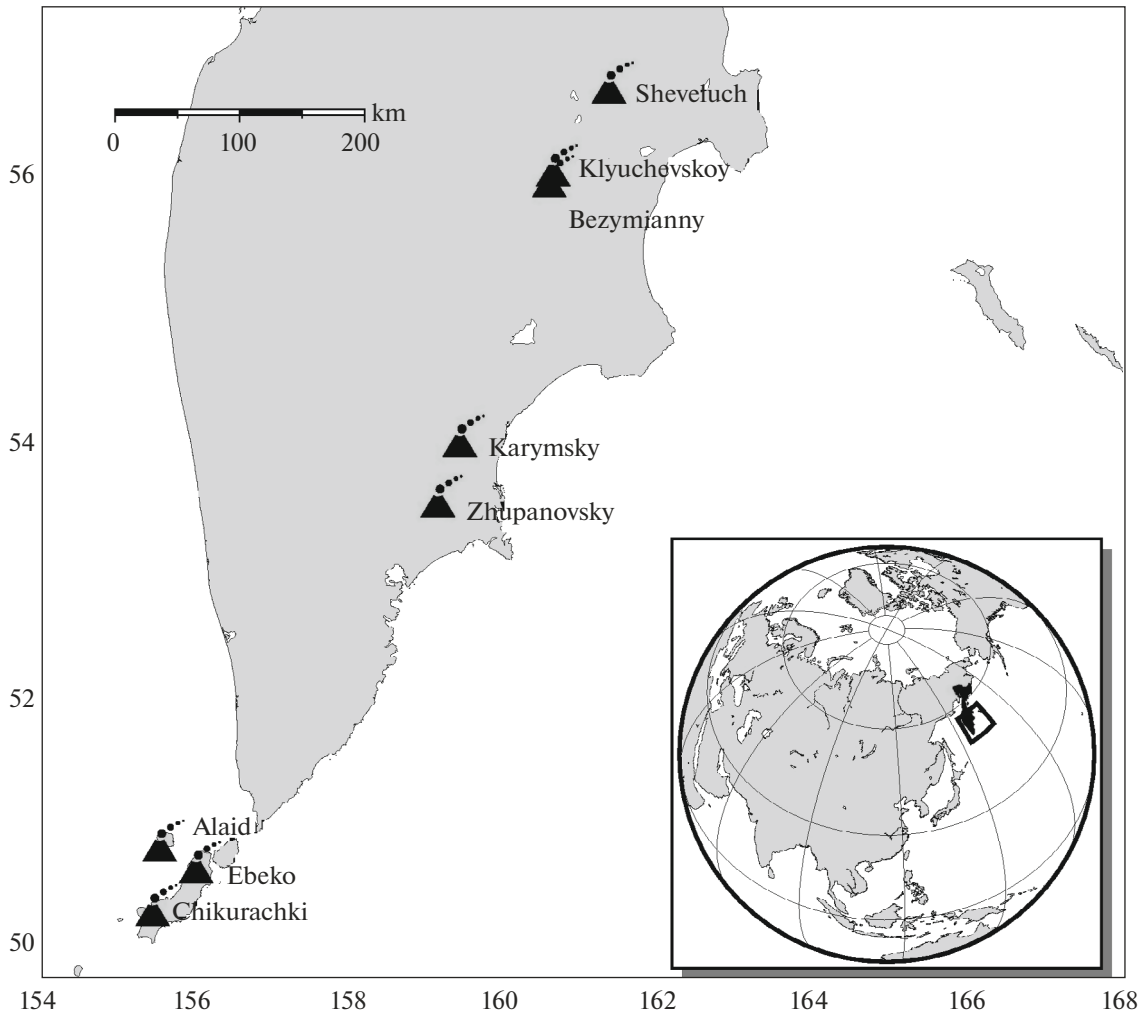


Fig. 1. The locations of the volcanoes in Kamchatka and on the North Kuril Islands that erupted in 2016.

Since the explosions hurled ash to a height of 12 km a.s.l., the 2016 Sheveluch activity posed hazards to international and local air transportation.

Klyuchevskoy (4750 m) is the most active and powerful basaltic volcano in the Kuril–Kamchatka volcanic region (Khrenov et al., 1991). It is situated in the northern Klyuchevskaya Volcanic Group approximately 360 km northeast of Petropavlovsk-Kamchatsky (see Figs. 1, 2b).

The explosive–effusive eruption of the volcano continued from April 3 through November 6, 2016 (Girina et al., 2017c). According to KVERT data, discrete episodes of Strombolian activity were recorded on March 14, 18, and 19, but the anomaly in the volcano area had negative temperatures. It should be mentioned that the volcano was heavily cloud covered March 16–17 and no incandescence was observed above the crater in late March. The Strombolian phase of the explosive eruption began on April 3, with incandescence being continually observed above the crater during discharges of volcanic bombs and cinders and the thermal anomaly being recurrently recorded from that time until the end of the eruption (see Fig. 3b). The Vulcanian phase began at 14:35 UTC April 23: explosions sent ash up to heights of 8 km a.s.l. (up to 3.3 km above the dome); the front of the ash plume was approximately 460 km southwest of the volcano at 02:28 UTC April 24 as reported by the KVERT based on satellite data. The effusive phase began April, 23–24: a lava flow began to be discharged from the summit crater of Klyuchevskoy along the Apakhonchich chute on the volcano's southeastern slope. The lava flow was approximately 0.5 km long by April 25; the size of the thermal anomaly began to increase. On April 26 mudflows were observed on the volcanic slope starting from the front of the lava flow.

A new event occurred at a height of 4.3–4.4 km a.s.l. on April 26; this was the opening of a new vent (a flank break) into the Apakhonchich chute accompanied by a sudden spike of intensity in the thermal anomaly in the volcano area (see Fig. 3b). A cinder cone began to grow at the vent discharging lava flows.

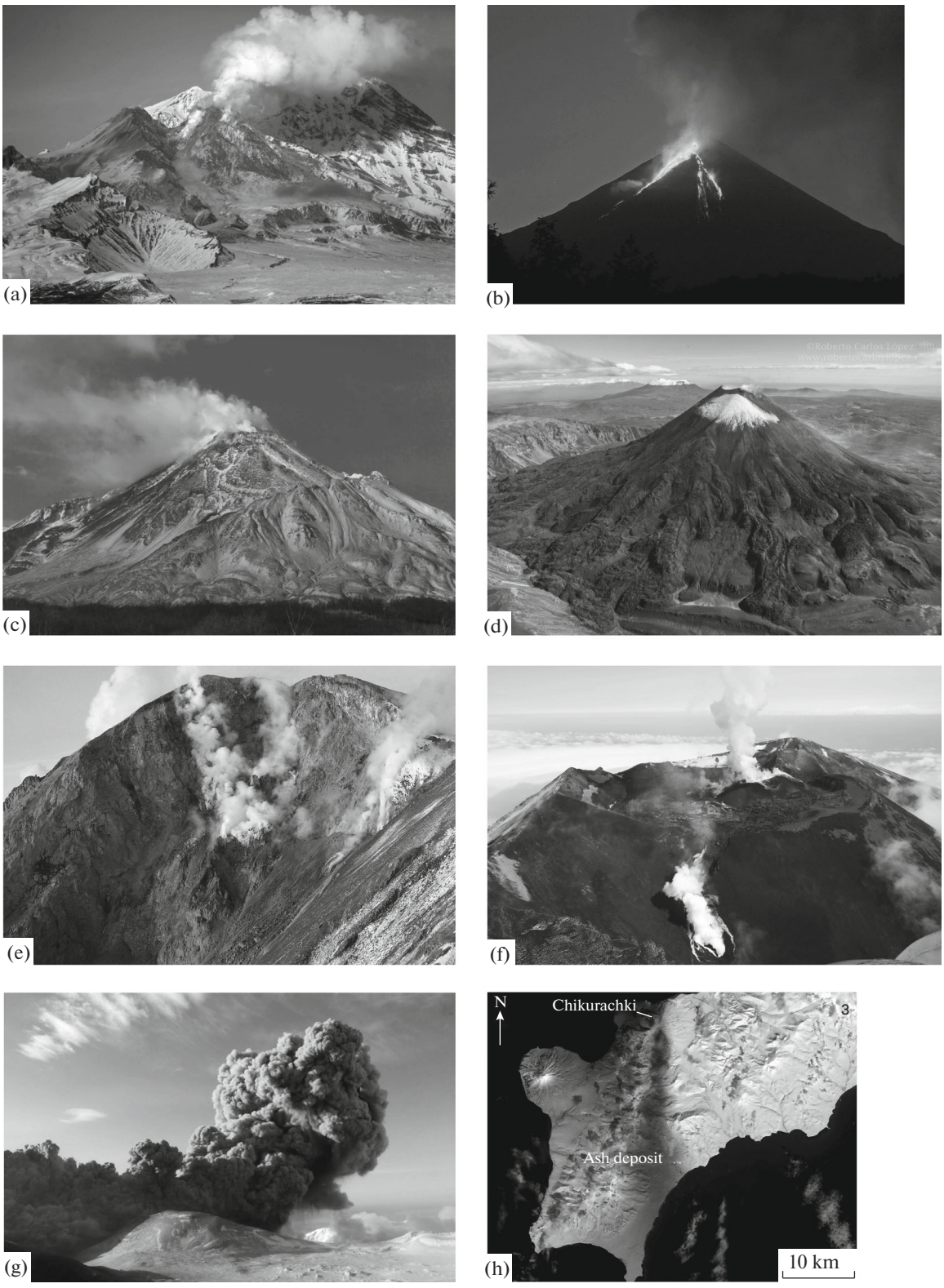


Fig. 2. The active volcanoes in Kamchatka and on the North Kuril Islands in 2016. (a) Sheveluch, March 16, photographed by Yu. Demyanchuk, (b) Klyuchevskoy, July 7, photographed by Yu. Demyanchuk, (c) Bezymianny, October 9, photographed by E. Safonova, (d) Karymsky, September 26, photographed by R.C. Lopez, (e) Zhupanovsky (the active crater of Priemysh Cone), January 23, photographed by S. Chirkov, (f) Alaid, April 28 (the cinder cone; pyroclastic material, and lava inside the 1981 crater, the lava flow on the volcano's southwestern slope), photographed by L. Figura, (g) Ebeko, December 10, photographed by L. Kotenko, (h) Chikurachki, April 4 (ash deposits on Paramushir Island), Landsat-8 OLI (raw data from https://earthexplorer.usgs.gov/).

Table 1. Eruptions of volcanoes in Kamchatka and on the North Kuril Islands in 2000–2016 according to the KVERT data

Volcano	Eruption date
Sheveluch	2000–2016; large explosive events: 19.05.2001; 09.05.2004; 27.02.2005; 22.09.2005; 29.03.2007; 27.10.2010
Klyuchevskoy	22.03.2003–03.03.2004; 15.01–10.04.2005; 15.02–26.07.2007; 08.10.2008–28.01.2009; 17.09.2009–12.12.2010; 01.09.2012–10.01.2013; 15.08–15.12.2013; 01.01–24.03.2015; 03.04–06.11.2016
Bezymianny	2000–2016; large explosive events: 13.03.2000; 01.11.2000; 06.08.2001; 16.12.2001; 25.12.2002; 26.07.2003; 13.01.2004; 18.06.2004; 11.01.2005; 30.11.2005; 09.05.2006; 24.12.2006; 11.05.2007; 14–15.10.2007; 05.11.2007; 19.08.2008; 16–17.12.2009; 31.05.2010; 13.04.2011; 08.03.2012; 01.09.2012; 15.12.2016
Tolbachik Dol	27.11.2012–15.09.2013
Kizimen	09.12.2010–09.12.2013
Karymsky	2000–2016, a large explosive event: 13–14.05.2006
Zhupanovsky	22–24.10.2013; 06.06.2014–24.03.2016; 20.11.2016
Avachinsky	05.10.2001
Koryaksky	20.12.2008–26.08.2009
Gorely	07.2010–07.2014
Mutnovsky	17.03.2000; 29.06.2000; 17.04.2007; 03.07.2013
Alaid	06.10–12.12.2012; 01.10.2015–10.08.2016
Ebeko	02–04.2005; 29.01–18.06.2009; 19.10–31.12.2016
Chikurachki	25.01–31.04.2002; 17.04–16.06.2003; 10.03–07.04.2005; 19.03–07.04.2007; 19.08–20.10.2007; 29.07–15.08.2008; 15–19.02.2015; 28–31.03.2016; 27.07.2016; 18–30.08.2016

A unique event occurred on May 3; this was the formation of a collapse cirque in the upper segment of the Apakhonchich chute that was similar to that of 1945 in the Krestovsky chute (Piip, 1956) (Fig. 5). The cirques were, however, different in that the rocks that composed the wall of the summit crater collapsed, thus making the vent open into the chute for years to come, while in 2016 the upper rim of the collapse cirque was 200 m below the crater rim, i.e., the formation of the collapse cirque was directly related to lava disgorging into the Apakhonchich chute, to the melting of buried glaciers, and to the filling of the resulting cavities with collapse material. Collapsing continued from the cirque walls during several months; for example, one strong collapse was observed on July 18, with the volcanic dust due to debris avalanches rising 0.5–1 km above the volcano slope.

The lava flows continued erupting from various boccas in the cinder cone until November 6 (Fig. 6). The lava filled the bed of the Apakhonchich chute and overflowed its walls. There were occasionally increases in steam and gas activity and ash discharges from the summit crater; as an example, ash plumes that were floating at heights of 5–6 km a.s.l. (0.3–1.3 km above the crater) extended as long as 90 km southward and southeast from the volcano on May 2–4, 13, and 16. Ash was nearly continuously discharged from the crater in the later half of the year, rising to 7–8 km a.s.l. (2.3–3.3 km above the crater) and extending for over 500 km (see Fig. 4b). Since mid-August, lava flow began to flow onto the southwestern slope of the volcano, with the source being at the level of the rim of the older Klyuchevskoy crater, i.e., from the bocca in the cinder cone that had formed on the volcano's summit during the last 10–15 years. This lava flow continued running for 1 month and was no longer observable from September 20.

The volcano showed higher activity on September 7, with the eruptive column rising to reach heights of 7.5 km a.s.l. (2.8 km above the crater) and a dense ash plume extending east–southeast from the volcano. On September 8, the ash plume of Klyuchevskoy Volcano was observed above Avachinsky and Koryaksky volcanoes at an approximate height of 4 km a.s.l.; it then moved toward the Avacha Bay and dispersed there.

The volcano's activity began to decrease gradually; as an example, ash plumes extended for 120 km east from the volcano for the last time on November 3–4.

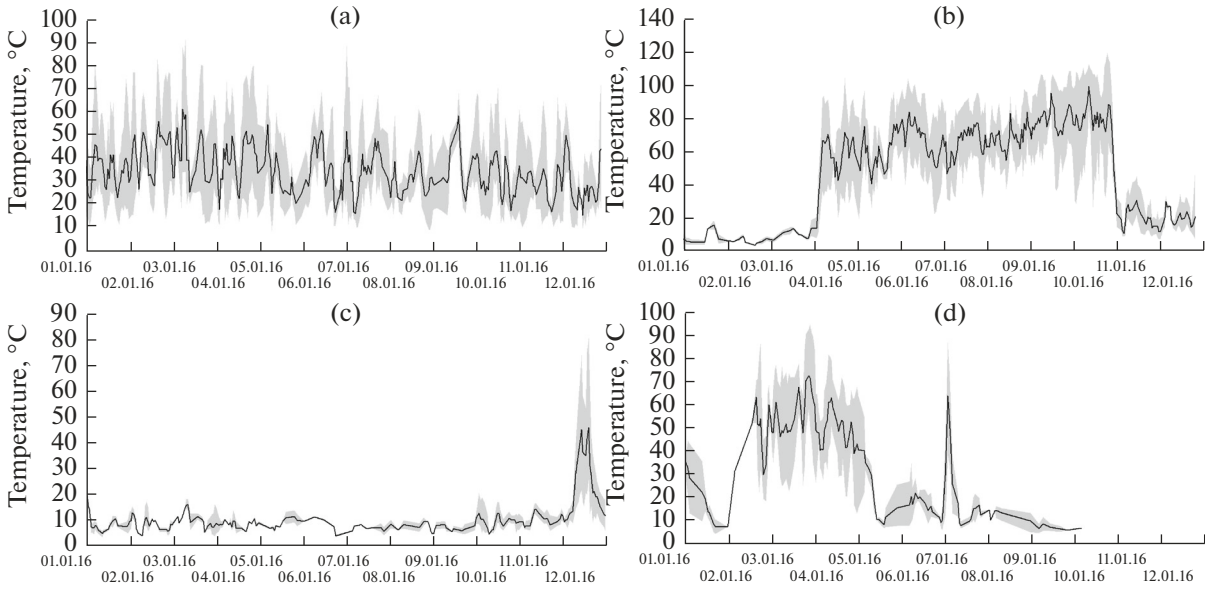


Fig. 3. Temperature variations in thermal anomalies in the areas of volcanoes in 2016. (a) Sheveluch, (b) Klyuchevskoy, (c) Bezymianny, (d) Alaid. Nighttime satellite images taken by the MODIS, AVHRR, and VIIRS instruments at intervals of 2 days were treated using the VolSatView IS. The black line represents the mean difference between the maximum temperature of a thermal anomaly and the temperature of satellite imagery background. Grey shading shows maximum and minimum differences between the maximum temperature of a thermal anomaly and the temperature of satellite imagery background.

The lava stopped flowing on November 3 and the thermal anomaly had a sudden drop in temperature on November 4, although some Strombolian activity was still observable in the Klyuchevskoy summit crater November 3–4. The eruption finished altogether by November 6.

However, some sporadic ash discharges, even series of such discharges, were observed on November 16, and on December 17 and 31; we believe that these were caused by outflow of magma from the conduit and pyroclastic materials collapsing into it from the crater rims.

Ash rose to reach 8 km a.s.l. during the explosive activity of Klyuchevskoy Volcano; this activity posed hazards to international and local aviation.

Bezymianny (2882 m) is one of the more active volcanoes in Kamchatka and worldwide (Girina, 2013). This andesitic volcano is situated in the middle of the Klyuchevskaya Volcanic Group approximately 315 km northeast of Petropavlovsk-Kamchatsky (see Figs. 1, 2c). Its previous explosive eruption occurred on September 1, 2012 (Girina et al., 2014).

The period of January through November 2016 saw some moderate fumarole activity on the volcano and a weak thermal anomaly was nearly uninterruptedly recorded around its summit, according to satellite observations (see Fig. 3c).

An extrusive body was detected in the northeastern part of the lava dome crater on August 26, with the body being continually pushed upward (Girina et al., 2017a). From December 5 the anomaly showed increasing temperature, suggesting an accelerating growth of the extrusion. Bright incandescence was recorded at the summit on December 12; a lava flow probably began to be extruded onto the west slope of the dome. An analysis of high resolution satellite data has confirmed this hypothesis. A moderate explosive event probably occurred on December 15, as a steam and gas plume with some amount of ash was noted on satellite images and extended at a height of 4 km a.s.l. for 118 km west from the volcano. The effusive eruption continued occurring until the end of the year.

The entire period of observation involved some moderate (occasionally powerful) steam and gas activity on Bezymianny, with ash rising to reach 4 km a.s.l. on December 15, thus presenting some hazard to local air transportation.

Karymsky (1486 m) is one of the more active volcanoes in Kamchatka (Ivanov et al., 1991). It is situated in the middle of the Eastern Volcanic Zone of Kamchatka, approximately 115 km northeast of Petropavlovsk-Kamchatsky (see Figs. 1, 2d).

This andesitic volcano had been in a state of explosive eruption from January 1996 through October 10, 2016. According to satellite and sporadic visual observations, the most intense activity was observed in January through February 2016, with ash rising to heights of 4–5 km a.s.l. (2.5–3.5 km above the crater) and ash plumes traveling east and occasionally reaching 300 km in length (see Fig. 4c). A thermal anomaly of a steadily decreasing temperature was occasionally recorded around the crater.

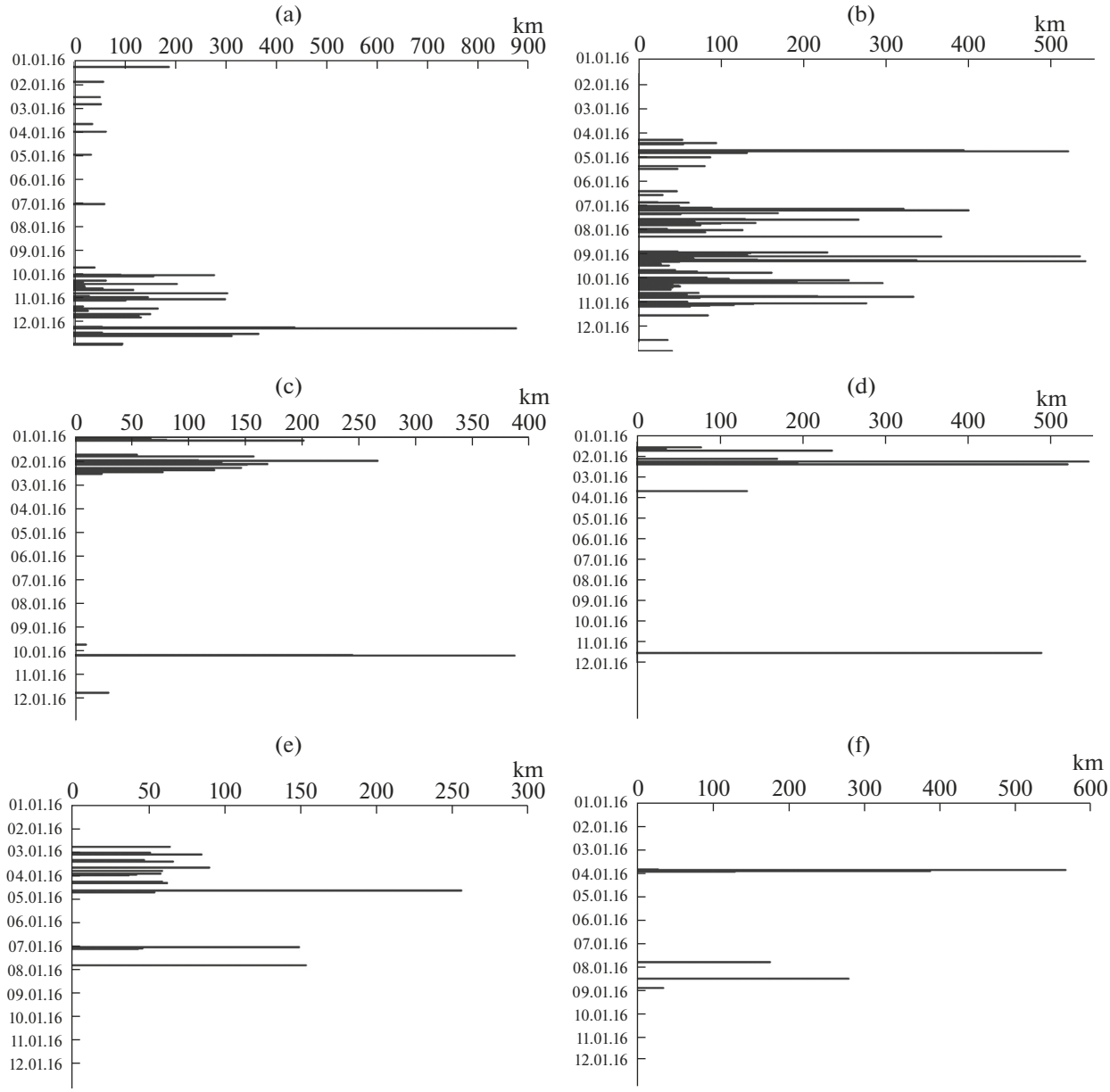


Fig. 4. The length of travel of ash clouds and plumes during the 2016 eruptions in Kamchatka and on the North Kuril Islands according to the VolSatView IS. (a) Sheveluch, (b) Klyuchevskoy, (c) Karymsky, (d) Zhupanovsky, (e) Alaid, (f) Chikurachki.

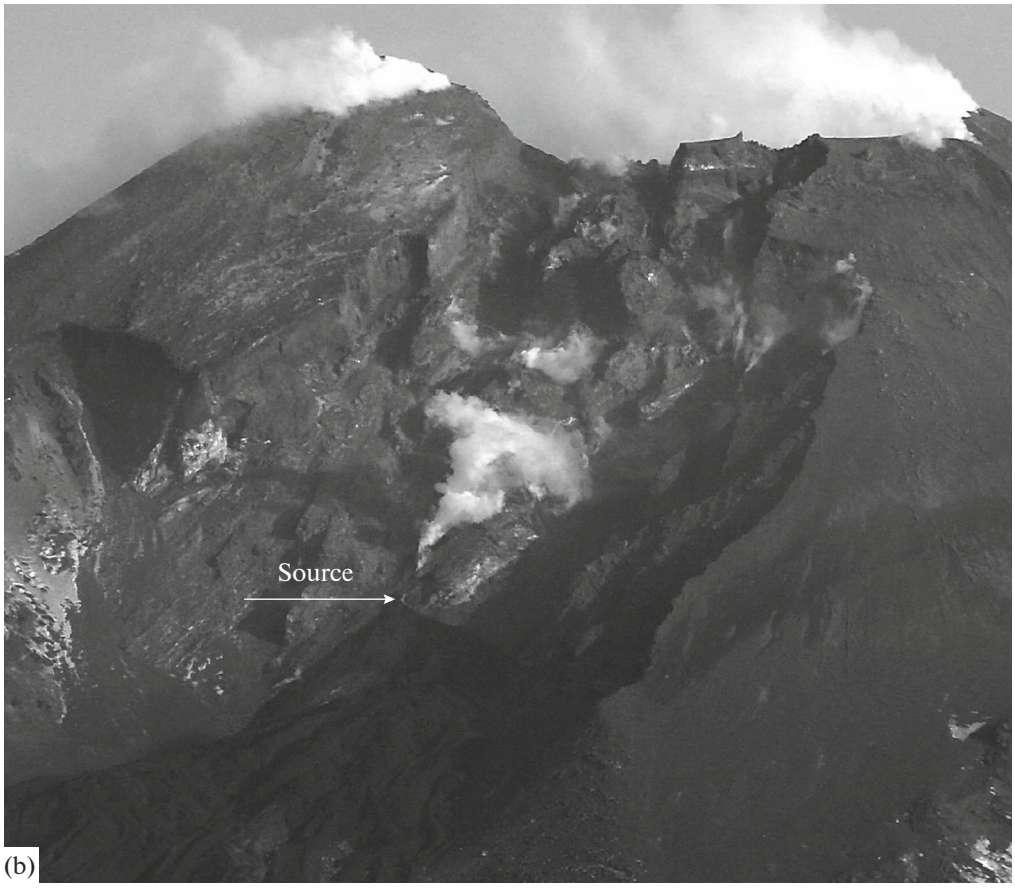
Plumes of resuspended ash were observed on satellite images October 7–8; the plumes extended for 400 km southeast from the volcano as high as 2.5 km a.s.l.

Since the ash plumes of Karymsky Volcano rose to reach heights of 5 km a.s.l., the activity of the volcano posed a hazard to local airways.

Zhupanovsky (2958 m) is situated in southeastern Kamchatka 40 km northeast of the Avachinsky–Koryaksky Volcanic Group and 70 km northeast of Petropavlovsk-Kamchatsky (see Figs. 1, 2e). This andesitic volcano is a ridge that consists of four coalesced cones of stratovolcanoes (Masurenkov et al., 1991). The active Priemysh Cone (2773 m) whose crater is 450 m across is adjacent to the Second Zhupanovsky Cone from the west. The preceding eruption on this volcano occurred in October 2013. A new explosive eruption began June 6, 2014 and ended November 20, 2016 (Girina et al., 2018).

Some discrete significant explosive events were recorded in 2016, as follows: January 19 (starting at 04:36 UTC, ash discharges rising up to 7.5 km a.s.l. and up to 4.5 km above the crater), January 21 (at 05:46 UTC, up to 7–8 km a.s.l. and up to 4–5 km above the crater), January 24 (at 00:17 UTC, up to 8 km a.s.l. and up to 5 km above the crater), February 5 (at 16:40 UTC, up to 7 km a.s.l. and up to 4 km above

(a)



(b)

Fig. 5. The collapse cirque in the upper segment of the Apakhonchich chute on Klyuchevskoy. (a) formation of the cirque resulting from a series of collapses in the chute, with ash clouds rising to heights of 5.5 km a.s.l. on May 3, 2016 according to video data of the KVERT; (b) a photograph taken on May 25, 2016 by Yu. Demyanchuk. The arrow indicates the cone of the flank break.

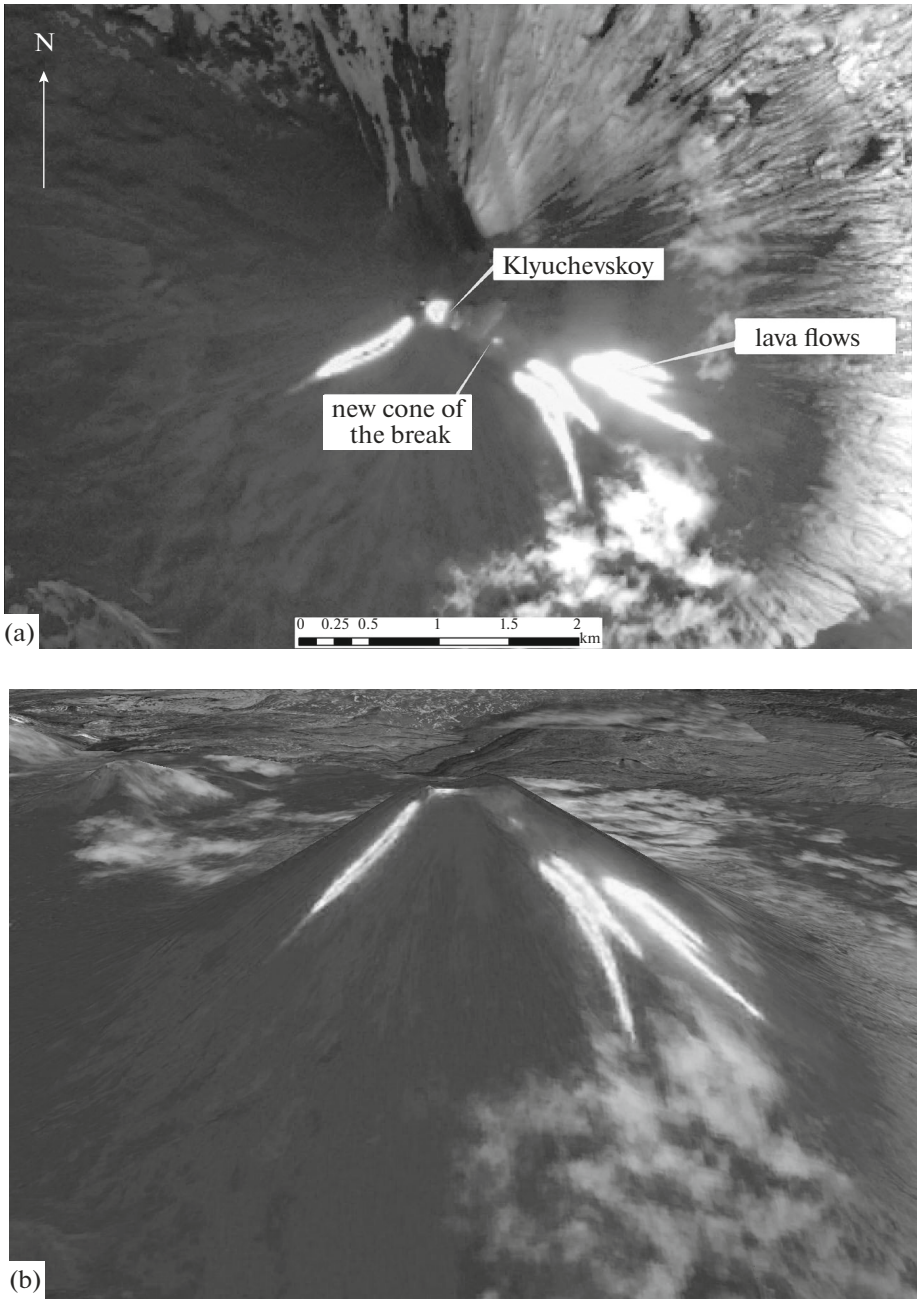


Fig. 6. The effusion of lava flows from the Klyuchevskoy summit crater onto the volcano's western slope and from various boccas of the new cinder cone in the Apakhonchich chute on the eastern slope at 00:14 UTC, September 10, 2016: (a) based on Landsat-8 data, (b) in a 3D projection.

the crater), February 7 (at 13:20 UTC, up to 5 km a.s.l. and up to 2 km above the crater), February 9 (at 07:20 UTC, up to 7 km a.s.l. and up to 4 km above the crater), February 12 (at 20:22 UTC, up to 10 km a.s.l. and up to 7 km above the crater); March 24 (at 13:50 UTC, up to 8.5 km a.s.l. and up to 5.5 km above the crater), and November 20 (at 02:29 UTC, up to 7–8 km a.s.l. and up to 4–5 km above the crater) (Girina et al., 2016b, 2018). The ash plumes extended as far as 550 km, mostly east from the volcano (see Fig. 4d). All explosive events were sudden occurrences not preceded by any precursors and preparatory phenomena.

The largest explosive event of 2016 occurred on February 12: ash rose to a height of 10 km a.s.l. (7 km above the crater) and the south wall of the Priemysh crater was finally destroyed (Girina et al., 2016b; Girina et al., 2018). According to satellite data from the VolSatView IS, the front of the ash plume was 195 km from the volcano at 23:40 UTC February 12 and 520 km at 09:30 UTC February 13. It should be noted that a

weak thermal anomaly had been recorded in the Priemysh area before that explosive event.

An intermission in the activity of this volcano that lasted 40 days was followed by explosions that sent ash as high as 8.5 km a.s.l. (up to 5.5 km above the crater) on March 24 and small deposits of pyroclastic flows and a collapse of part of the cone were formed at the base of Priemysh; ash was deposited in an area of at least 200 km^2 (Gordeev et al., 2016a). On November 20 the last explosions of 2014–2016 Zhupanovsky eruption sent ash to heights of 7 km a.s.l. (up to 4 km above the crater), with the ash plume extending for 500 km east from the volcano (see Fig. 4d).

Because ash discharged by the Zhupanovsky explosions rose to heights of 10 km a.s.l., the activity posed hazards to international and local aviation.

Alaid (2339 m) is the northernmost active volcano on the North Kuril Islands. It stands on Atlasov Island in the Sea of Okhotsk 320 km south-west of Petropavlovsk-Kamchatsky (see Figs. 1, 2f). There are more than 30 cinder cones on the slopes of this basaltic volcano, with the last of these dating back to 1972. The preceding summit eruption of Alaid occurred between October 6 and December 12, 2012 (Rashidov et al., 2012).

This eruption lasted from October 1, 2015 through August 10, 2016. A thermal anomaly was observed in the crater area as inferred from satellite imagery, lasting between January 1 and August 18, 2016 (see Fig. 3d). A first ash plume was observed on February 20; it extended at a height of 3 km a.s.l. (0.7 km above the crater) for 50 km eastward from the volcano (see Fig. 4e). Alaid showed increasing activity, the anomaly was becoming warmer, and there were more frequent ash plumes, e.g., in February through April they extended for 300 km from the volcano. A new cinder cone was detected on March 22 in the south part of the large cinder cone that was formed during the 1981 eruption and was filled with pyroclastic material by the 2012 and 2015 eruptions. The new cone had a base approximately 250 m across and a crater 75 m in diameter. The bottom of the Alaid crater (including the crater of the 1981 cone) was filled with fresh pyroclastic and lava material (Fig. 7).

The volcano showed greater explosive activity during the explosive eruption of Chikurachki Volcano on Paramushir Island between March 28 and 31, viz., Alaid's ash plumes were moving away from the volcano 60 km east, south, and southwest from March 29 until April 1. A lava flow was detected on a Landsat-8 image of May 10; the flow descended from the summit crater down the southwestern slope for an approximate distance of 300 m. The cinder cone and the lava flow were seen from a helicopter on April 28 (see Fig. 2f). Ash plumes were observed on July 3–4 to extend as far as 150 km southwest from the volcano at a height of 2.5 km a.s.l.

On July 7 satellite images showed as many as three coalesced cinder cones; two of these, whose craters are 75 m and 37 m across, originated on the southern and on the southwestern slope of the first cinder cone. The activity of these cones discharged fresh pyroclastic material onto the southern slope of the volcano covering an area of ~0.5 km^2 (Melnikov et al., 2018). By mid-July the activity of the volcano gradually began to subside and the eruption ceased altogether on August 10, 2016.

The ash discharged by the Alaid explosions rose to 3 km a.s.l.; hence, this activity posed a hazard to local airlines.

Ebeko (1156 m) is the northernmost volcano in the Vernadsky mountain range on the Paramushir Island, North Kurils. It is situated 7 km west–northwest of the town of Severo-Kurilsk and 320 km southwest of Petropavlovsk-Kamchatsky (see Figs. 1, 2g). The preceding eruption of this andesitic volcano occurred between January 29 and June 18, 2009 (Kotenko et al., 2010).

The explosive eruption of the volcano started on October 19 and continued until the end of the year. Observers reported from Severo-Kurilsk that ash was ejected from the Active Crater of the volcano at 22:30 and 22:45 UTC on October 19 and at 02:10 and 02:56 UTC on October 20, rising to reach 1.5 km a.s.l. (up to 0.4 km above the crater), with ash plumes extending for 15 km east–northeast from the volcano. Visual observation showed the resumption of ash discharges flying as high as 2.6 km a.s.l. (up to 1.5 km above the crater) from November 8, with the ash plumes moving for 15–20 km east and northeast from the volcano. According to satellite data by the KVERT, no thermal anomaly was observed in the area of the volcano during those days. The volcano showed greater activity from December 8, with ash being ejected from two craters, the Active and the Middle Crater. A weak thermal anomaly on the satellite images was observed in the area of the volcano on December 8–9 and 12, as reported by the KVERT. Ash was discharged to heights of 3 km a.s.l. (up to 1.9 km above the crater) in December (8–10, 12–14, 17, 19–27, and 31). Ashfalls were also recorded at Severo-Kurilsk during those days.

Since ash was ejected to reach heights of 3 km a.s.l. and ashfalls occurred at Severo-Kurilsk, the activity of Ebeko was hazardous for local air transportation.

Chikurachki (1816 m) is the northernmost volcano in the Karpinsky mountain range on Paramushir Island, North Kurils. It is situated 375 km southwest of Petropavlovsk-Kamchatsky (see Figs. 1, 2h). The preceding eruption of that andesitic volcano occurred on February 15–19, 2015 (Girina et al., 2016a).

The 2016 eruption of Chikurachki occurred during the period between March 28 and August 30.

The first explosive event lasted from March 28 through 31. A steam and gas plume containing a small amount of ash extending for 30 km from the volcano was first observed on a satellite image at 19:34 UTC March 28; a thermal anomaly was observed then for the first and last time during the eruption in the area

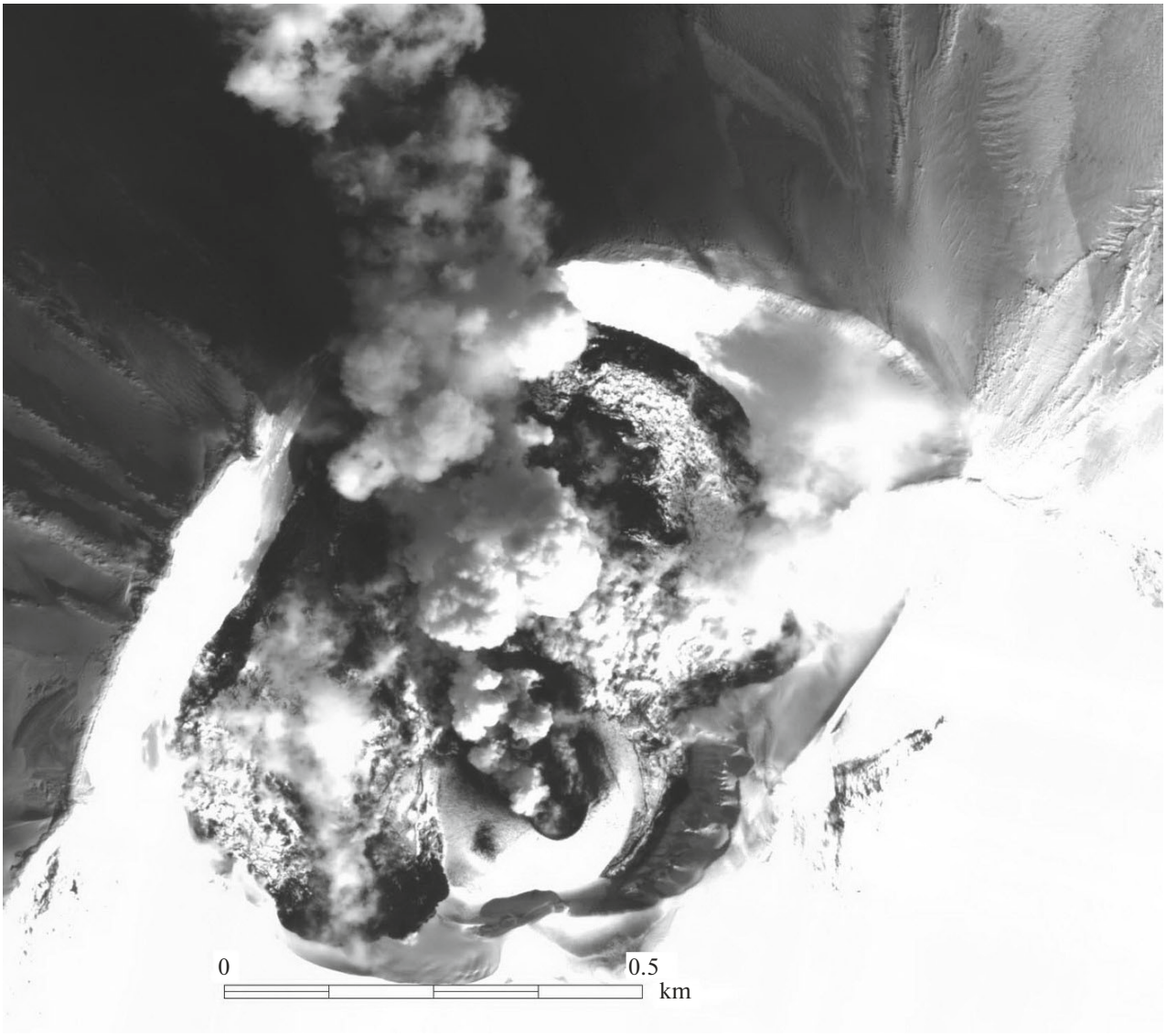


Fig. 7. The new cinder cone in the southern part of the 1981 crater on Alaid Volcano as seen on a Resurs-P image taken on March 22, 2016. The 1981 crater is filled with deposits of pyroclastic material and lava discharged by the 2015–2016 eruption.

of the crater (Girina et al., 2016c). The greatest height of the ash plume (4 km a.s.l. or 2.2 km above the crater) was recorded at 16:32 UTC March 29, while on the next day, March 30, the plumes mostly moved south–southeast and southwest of the volcano. The ash plume was dispersed after 17:00 UTC March 31 (see Fig. 4f) (Girina et al., 2016c).

The next event occurred on July 27, viz., an ash plume was detected on satellite imagery at 05:48 UTC that drifted northeastward from the volcano at heights of 4–5 km a.s.l. (2.2–3.2 km above the crater); the plume front was at a distance of 180 km from the volcano at 15:28 UTC, and a small ashfall was observed at Severo-Kurilsk.

The third explosive event was recorded on August 17–18. The volcano exhibited a powerful steam and gas activity that was recorded on satellite imagery from 23:32 UTC August 17 to 05:00 UTC August 18; ash was observed in the steam and gas discharges from 05:20 UTC August 18. Explosions sent ash flying to 2.5 km a.s.l. (0.7 km above the crater) at 06:30 UTC August 18, with the plume extending for 140 km northeast from the volcano. No ash was recorded on satellite imagery from 11:30 UTC August 19.

The last explosive episode occurred on August 30, viz., satellite imagery recorded an ash plume extending for 35 km southeast from the volcano. Between August 31 and the end of the year the volcano was quiet.

Since the Chikurachki explosive activity involved ash flying to heights of 5 km a.s.l., the activity posed a hazard to local aviation.

A DISCUSSION OF THE OBSERVATIONS. CONCLUSIONS

A daily assessment of hazards to the population and aviation posed by each of the 36 active volcanoes based on their video, visual, and satellite monitoring during 25 years, experience in surveying different types of eruption in the field, the analysis of published materials relating to volcanic activity in Kamchatka and on the Kuril Islands, producing summaries of annual activity for the volcanoes, the analysis of the dynamics of individual eruptions and of changes in the activity of each volcano over time, and comparisons between the behaviors of volcanoes that discharge ejecta of similar and dissimilar compositions onto the ground surface the year round and during decades all provide a better understanding of volcanic occurrences exhibited by volcanoes in Kamchatka and on the North Kuril Islands.

The annual level of activity of the Kamchatkan volcanoes is very high; as an example, six volcanoes were active in 2010, five in 2011, seven in 2012, seven in 2013, four in 2014, four in 2015, and five in 2016 (see Table 1) (Girina et al., 2017b). In the 21st century (2000–2016), five Kamchatkan volcanoes erupted after long quiet periods that ranged between 30 and 80 years: Koryaksky (2008–2009); Gorely (2010–2014); Kizimen (2010–2013); Tolbachik Dol (2012–2013); Zhupanovsky (2013–2016) (http://www.kscnet.ru/ivs/kvert/). The first 16 years of the 21st century saw 65 eruptions on 11 volcanoes that lasted from a few hours to 3 years in Kamchatka (Sheveluch, Klyuchevskoy, Bezymianny, Tolbachik, Kizimen, Karymsky, Zhupanovsky, Avachinsky, Koryaksky, Gorely, and Mutnovsky) and 15 eruptions on three North Kuril volcanoes that lasted between a few days and 11 months (Alaid, Ebeko, and Chikurachki) (see Table 1).

An analysis of video, visual, and satellite monitoring data of the volcanoes for 2016 provided the following information.

1. Five Kamchatka volcanoes and three North Kuril volcanoes erupted during 2016. The eruption durations were 365 days for Sheveluch, 218 days for Klyuchevskoy, 26 days for Bezymianny, 60 days for Karymsky, 50 days for Zhupanovsky, 230 days for Alaid, 74 days for Ebeko, and 8 days for Chikurachki. Every month three to five volcanoes were erupting (Sheveluch, Karymsky, Zhupanovsky, Alaid, and Chikurachki in March; Sheveluch, Klyuchevskoy, Karymsky, Alaid, and Chikurachki in August; Sheveluch, Klyuchevskoy, and Karymsky in September; Sheveluch, Bezymianny, and Ebeko in December; each of the other months saw four different volcanoes erupting, e.g., Sheveluch, Karymsky, Zhupanovsky, and Alaid in January; Sheveluch, Klyuchevskoy, Zhupanovsky, and Ebeko in November) (see Table 1).

2. Three North Kuril volcanoes erupted in 1 year for the first time during the historical period.

3. The activity of all erupting volcanoes involved an explosive phase (see Fig. 4). The Sheveluch lava dome grew during most of the year, while large explosive events were mostly observed in September through December. Ash ejections were occurring during the entire period of the Klyuchevskoy eruption. Some synchronicity of explosive events was observed on Karymsky and Zhupanovsky volcanoes, as well as on Alaid and Chikurachki (see Fig. 4). In addition, high explosive activity of Karymsky, Zhupanovsky, Alaid, and Chikurachki was mostly observed in the earlier half of the year (see Table 1).

4. Explosive events involving ejection of ash to heights of 12 km a.s.l. occurred on Sheveluch; those with 8–10 km a.s.l. on Sheveluch, Klyuchevskoy, and Zhupanovsky; those with 3–5 km a.s.l. on Karymsky, Alaid, Ebeko, and Chikurachki. The activity of Sheveluch, Klyuchevskoy, and Zhupanovsky posed hazards for international and local air transportation, while the activity of Bezymianny, Karymsky, Alaid, Ebeko, and Chikurachki was dangerous for local air transportation.

5. The total area covered by ash in 2016 (incorporating the longest ash plumes up to 1500 km long) is estimated as 600000 km^2, with 460000 km^2 being due to Kamchatka volcanoes and 140000 km^2 to those on the North Kuril Islands (Fig. 8). We note for comparison purposes that the area where ash was deposited by five volcanoes in 2015 was 1360000 km^2, with 1300000 km^2 of this area being related to eruptions of Kamchatkan volcanoes and 60000 km^2 to eruptions of North Kuril volcanoes.

6. The lava domes continued growing on Sheveluch and Bezymianny in 2016; the well-pronounced thermal anomalies that were recorded in the areas of these volcanoes reflected the extrusive and effusive processes that were occurring throughout that year on Sheveluch and on Bezymianny on December 5–31 fairly well (see Fig. 3).

7. Effusion and extrusion of lava was observed during the eruptions of Sheveluch, Klyuchevskoy, Bezymianny, and Alaid. During these periods, the average temperatures of thermal anomalies (the mean difference between the maximum temperature of a thermal anomaly and the background temperature on a satellite image) as recorded in the areas of basaltic volcanoes (Klyuchevskoy and Alaid) were 54–50°C and those for andesitic volcanoes (Sheveluch and Bezymianny) were 35–30°C (see Fig. 3). These elevated temperatures of anomalies in the areas of basaltic volcanoes were due to a comparatively low viscosity of basaltic lava and to a continuous rapid supply of it onto the ground surface, in contrast to viscous andesitic lavas that were slowly extruded onto the volcanic slopes.

8. A new vent (a flank break) was forced open at a height of 4.3–4.4.km a.s.l. in the Apakhonchich chute on April 26 during the summit eruption of Kly-

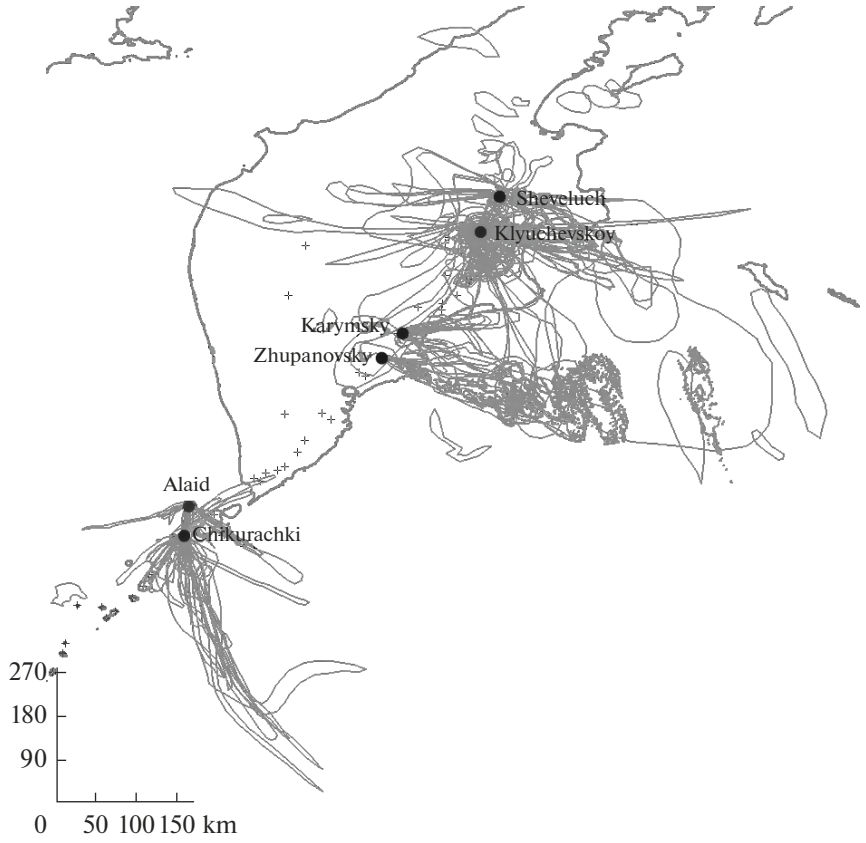


Fig. 8. Visualizing the propagation of ash plumes during the 2016 eruptions in Kamchatka and on the North Kuril Islands based on the VolSatView IS data (Gordeev et al., 2016b).

uchevskoy; the great mass of lava for this eruption was effused from this vent. This vent opening provoked the formation of a collapse cirque in the upper segment of the Apakhonchich chute on May 3; the cirque was similar to that formed in the Krestovsky chute in 1945 as described by B.I. Piip (1956). A.Yu. Ozerov, Dr. Sci. (Geol.–Mineral.) proposed naming this flank break in honor of Evgeny Konstantinovich Markhinin, Dr. Sci. (Geol.–Mineral.), a volcanologist who was known worldwide and was the author of a theory supporting a volcanic origin for the Earth's crust, hydrosphere, atmosphere, and biosphere. He was the founder of biovolcanology; he climbed Klyuchevskoy during its 1961 eruption and was the head of the Levinson–Lessing Kamchatka Volcanological Station in 1958–1962.

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REFERENCES

Fedotov, S.A., Ivanov, B.V., Dvigalo, V.N., et al., The activity of volcanoes in Kamchatka and the Kuril Islands in 1984, *Vulkanol. Seismol.,* 1985, no. 5, pp. 3–23.

Girina, O.A., Ushakov, S.V., and Demyanchuk, Yu.V., The May 9, 2004 paroxysmal eruption of Young Sheveluch Volcano, Kamchatka, *Vestnik KRAUNTs, Nauki o Zemle,* 2007, no. 2, issue 10, pp. 65–73.

Girina, O.A., On precursor of Kamchatkan volcanoes eruptions based on data from satellite monitoring, *J. Volcanol. Seismol.,* 2012, vol. 6, no. 3, pp. 142–149. https://doi.org/10.1134/S0742046312030049

Girina, O.A., Chronology of Bezymianny Volcano activity, 1956–2010, *J. Volcanol. Geotherm. Res.,* 2013, vol. 263, pp. 22–41. https://doi.org/10.1016/j.jvolgeores.2013.05.002

Girina, O.A. and Gordeev, E.I., The KVERT project: Reduction of volcanic hazards for aircraft during explosive eruptions of volcanoes in Kamchatka and on the Kuril islands, *Vestnik DVO RAN,* 2007, no. 2, pp. 100–109.

Girina, O.A., Demyanchuk, Yu.V., Davydova, V.O., and Plechov, P.Yu., The September 1, 2012 eruption of Bezymianny Volcano, its forecast, and its ejecta, in *Vulkanizm i svyazannye s nim protsessy* (Volcanism and Associated Processes), Proc. XVI science conference devoted to Volcanologist's Day, March 28–29, 2013, Petropavlovsk-Kamchatsky: IViS DVO RAN, 2014, pp. 30–35.

Girina, O.A., Manevich, A.G., Mel'nikov, D.V., et al., The 2015 activity of volcanoes in Kamchatka and on the North Kuril Islands and their hazards to aviation, in *Vulkanizm i svyazannye s nim protsessy* (Volcanism and Associated Processes), Proc. XIX science conference devoted to Volcanologist's Day, March 29–30, 2016, Petropavlovsk-Kamchatsky: IViS DVO RAN, 2016a, pp. 35–45.

Girina, O.A., Manevich, A.G., Mel'nikov, D.V., et al., The explosive activity of Zhupanovsky Volcano in 2016, in *Vulkanizm i svyazannye s nim protsessy* (Volcanism and Associated Processes), Proc. XIX regional conf. devoted to Volcanologist's Day, March 29–30, 2016, Petropavlovsk-Kamchatskii: IViS DVO RAN, 2016b, pp. 24–34.

Girina, O.A., Manevich, A.G., Nuzhdaev, A.A., and Sorokin, A.A., The 2016 eruption of Chikurachki Volcano on Paramushir Island, North Kurils, in *Sovremennye problemy distantsionnogo zondirovaniya Zemli iz kosmosa* (Modern Problems in the Remote Sensing of the Earth from Space), 2016c, vol. 13, no. 2, pp. 235–239. https://doi.org/10.21046/2070-7401-2016-13-2-235-239

Girina, O.A., Mel'nikov, D.V., Demyanchuk, Yu.VC., and Manevich, A.G., The 2016–2017 eruption of Bezymianny Volcano as reported by the KVERT, *Vulkanizm i svyazannye s nim protsessy* (Volcanism and Associated Processes), Proc. XX science conference devoted to Volcanologist's Day, March 30–31, 2017, Petropavlovsk-Kamchatskii: IViS DVO RAN, 2017a, pp. 14–17.

Girina, O.A., Mel'nikov, D.V., and Manevich, A.G., Satellite monitoring of volcanoes in Kamchatka and on the North Kurils, in *Sovremennye problemy distantsionnogo zondirovaniya Zemli iz kosmosa* (Modern Problems in the Remote Sensing of the Earth from Space), 2017b, vol. 14, no. 6, pp. 194–209. https://doi.org/10.21046/2070-7401-2017-14-6-194-209

Girina, O.A., Mel'nikov, D.V., Manevich, A.G., et al., The chronology of events during the 2016 eruption of Klyuchevskoi Volcano as reported by the KVERT, *Vulkanizm i svyazannye s nim protsessy* (Volcanism and Associated Processes), Proc. XX science conference devoted to Volcanologist's Day, March 30–31, 2017, Petropavlovsk-Kamchatskii: IViS DVO RAN, 2017c, pp. 18–21.

Girina, O.A., Loupian, E.A., Sorokin, A.A., et al., Satellite and ground-based observations of explosive eruptions on Zhupanovsky Volcano, Kamchatka, Russia in 2013 and in 2014–2016, *J. Volcanol. Seismol.,* 2018, vol. 12, no. 1, pp. 1–15. https://doi.org/10.1134/S0742046318010049

Gorbach, N.V., Gavrilenko, M.G., and Filosofova, T.M., The chemical and mineral compositions of the ejecta discharged by Young Sheveluch Volcano in September 2016, in *Vulkanizm i svyazannye s nim protsessy* (Volcanism and Associated Processes), Proc. XX science conference devoted to Volcanologist's Day, March 30–31, 2017, Petropavlovsk-Kamchatskii: IViS DVO RAN, 2017, pp. 120–127.

Gordeev, E.I. and Girina, O.A., Volcanoes and their hazard to aviation, *Herald of the Russian Academy of Sciences,* 2014, vol. 84, no. 2, pp. 134–142. https://doi.org/10.1134/S1019331614010079

Gordeev, E.I., Girina, O.A., Loupian, E.A., et al., VolSatView IS: A multidisciplinary analysis of data on explosive eruptions of Kamchatkan volcanoes, *Vestnik DVO RAN,* 2016a, no. 5, pp. 120–127.

Gordeev, E.I., Girina, O.A., Loupian, E.A., et al., The VolSatView information system for monitoring the volcanic activity in Kamchatka and on the Kuril Islands, *J. Volcanol. Seismol.,* 2016b, vol. 10, no. 6, pp. 382–394. https://doi.org/10.1134/S074204631606004X

Igarashi, Y., Girina, O., Osiensky, J., and Moore, D., International coordination in managing airborne ash hazards: Lessons from the northern Pacific, in *Advances in Volcanology,* Fearnley, C.J., Bird, D.K., Haynes, K., McGuire, W.J., and Jolly, G., Eds., IAVCEI, Barcelona: Springer, Cham, 2017, pp. 529–547. https://doi.org/10.1007/11157_2016_45

Ivanov, B.V., Braitseva, O.A., and Zubin, M.I., Karymskii Volcano, in *Deistvuyushchie vulkany Kamchatki* (Active Volcanoes of Kamchatka), vol. 2, Moscow: Nauka, 1991, pp. 182–201

Khrenov, A.P., Dvigalo, V.N., and Kirsanov, I.T., Klyuchevskoy volcano, in *Deistvuyushchie vulkany Kamchatki* (Active Volcanoes of Kamchatka), Fedotov, S.A. and Masurenkov, Yu.P, Eds., Moscow: Nauka, 1991, vol. 1, pp. 146–153.

Kirianov, V., Volcanic ash in Kamchatka as a source of potential hazard to air traffic. Volcanic ash and aviation safety, in Proc. First Intern. Symp. *Volcanic Ash and Aviation Safety*, *US Geological Survey Bull.*, 1992, vol. 2047, pp. 57–63.

Kotenko, T.A., Kotenko, L.V., Sandimirova, E.I., et al., The eruption of Ebeko Volcano in January–June 2009 (Paramushir Island, Kuril Islands), *Vestnik KRAUNTs, Nauki o Zemle,* 2010, issue 15, no. 1, pp. 56–68.

Loupian, E.A., Proshin, A.A., Burtsev, M.A., et al., The center of collective use of systems designed for storage, processing, and analysis of satellite data acquired at the Institute of Space Research, Russian Academy of Sciences for the study and monitoring of the environment, in *Sovremennye problemy distantsionnogo zondirovaniya Zemli iz kosmosa* (Modern Problems in the Remote Sensing of the Earth from Space), 2015, vol. 12, no. 5, pp. 247–267.

Masurenkov, Yu.P., Florensky, I.V., and Melekestsev, I.V., Zhupanovsky Volcano, in *Deistvuyushchie vulkany Kamchatki* (Active Volcanoes of Kamchatka), Fedotov, S.A. and Masurenkov, Yu.P., Moscow: Nauka, 1991, vol. 2, pp. 226–227.

Melekestsev, I.V., Volynets, O.N., Ermakov, V.A., et al., Sheveluch Volcano, in *Deistvuyushchie vulkany Kamchatki* (Active Volcanoes of Kamchatka), Fedotov, S.A. and Masurenkov, Yu.P., Moscow: Nauka, 1991, vol. 1, pp. 98–103.

Melnikov, D.V., Manevich, A.G., and Girina, O.A., The dynamics of Alaid eruptions in 2012 and in 2015–2016 as inferred from data acquired through remote sounding methods, in in *Vulkanizm i svyazannye s nim protsessy* (Volcanism and Associated Processes), Proc. XX science conference devoted to Volcanologist's Day, March 29–30, 2018, Petropavlovsk-Kamchatsky: IViS DVO RAN, 2018, pp. 20–23.

Menyailov, A.A., *Sheveluch Volcano: Its Geological Structure, Composition, and Eruptions,* Tr. Lab. Vulkanol. AN SSSR, Moscow: Izd-vo AN SSSR, 1955, Issue 9.

Miller, T. and Casadevall, T., Volcanic ash hazards to aviation, in *Encyclopedia of Volcanoes,* Sigurdsson, H., Ed., San Diego, San Francisco, New York, Boston, London, Sydney, Toronto: Academic Press, 2000, pp. 915–930.

Neal, Ch., Girina, O., Senyukov, S., et al., Russian eruption warning systems for aviation, *Natural Hazards,* 2009, vol. 51, no. 2, pp. 245–262.

Ovsyannikov, A.A. and Manevich, A.G., The eruption of Sheveluch in October 2010, *Vestnik KRAUNTs, Nauki o Zemle,* 2010, issue 16, no. 2, pp. 7–9.

Ozerov, A.Yu. and Demyanchuk, Yu.V., The paroxysmal eruption of Young Sheveluch Volcano on May 10, 2004, *Vulkanol. Seismol.,* 2004, no. 5, pp. 75–80.

Piip, B.I., Klyuchevskoi Volcano and Its Eruptions in 1944–1945 and in the Past, *Trudy Lab. Vulkanol.,* 1956, issue 11 (special issue).

Rashidov, V.A., Malik, N.A., Firstov, P.P., et al., The resumption of activity on Alaid Volcano, Kuril Islands in 2012, *Vestnik KRANUTs, Nauki o Zemle,* 2012, issue 20, no. 2, pp. 9–15.

Romanova, I.M., The IViS DVO RAN Geoportal as a common access point for volcanological and seismological data, *Geoinformatika,* 2013, no. 1, pp. 46–54.

Romanova, I.M., Girina, O.A., Mel'nikov, D.V., et al., *The Activity of Volcanoes in Kamchatka and on the Kuril Islands data base.* Inventor's certificate no. 2016620357, March 17, 2016, Moscow, 2016.

Sorokin, A.A., Girina, O.A., Loupian, E.A., et al., Satellite observations and numerical simulation results for the comprehensive analysis of ash cloud transport during the explosive eruptions of Kamchatka volcanoes, *Russian Meteorology and Hydrology,* 2017, vol. 42, no. 12, pp. 759–765.
https://doi.org/10.3103/S1068373917120032

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