ISSN 0010-9525, Cosmic Research, 2023, Vol. 61, Suppl. 1, pp. S182–S187. © Pleiades Publishing, Ltd., 2023.
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Analysis of the Development of the Paroxysmal Eruption of the Sheveluch Volcano on April 10–13, 2023, Based on Data from Various Satellite Systems

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Accepted April 27, 2023

Abstract—The Sheveluch volcano is the most active volcano in Kamchatka. The paroxysmal explosive eruption of the volcano that destroyed the lava dome in the volcanic crater continued on April 10–13, 2023. According to various satellite data, the height of the separate eruptive clouds probably exceeded 15 km above sea level. A powerful cyclone, which dominated the entire Kamchatka Peninsula, pulled the eruptive cloud to the west, turned it to the south, stretched it to the north, and directed it to the east from the volcano. The dynamics of the development of ash and aerosol clouds of this eruption is reflected in the animations made from a series of *Himawari-9* satellite images in the VolSatView IS from 08:00 UTC on April 10 to 07:00 UTC on April 14 (http://d33.infospace.ru/jr_d33/materials/2023v20n2/283-291/1683110898.webm) and of the Arctica-M1 satellite from 16:00 to 21:30 UTC on April 10 (http://d33.infospace.ru/jr_d33/materials/2023v20n2/283-291/1683821166.webm). It was noted that the eruptive column was not vertical: for example, at the initial moment of the eruption on April 10 at 13:20 UTC, it deviated to the north–northeast; on April 11, at 12:00 UTC to the northwest; and, on April 12, at 7:00 UTC to the southwest. During the paroxysmal eruption, sulfur dioxide continuously entered the atmosphere, the maximum amount of which was released on April 10–11, as a result of the explosive destruction of the lava dome of the Sheveluch volcano. Ash clouds along with aerosol clouds on April 10–13 were stretched into a strip more than 3500 km long from west to northeast. On April 21–22, the Sheveluch aerosol cloud was observed in the region of the Scandinavian Peninsula. The total area of the territory of Kamchatka and the Pacific Ocean where ash and aerosol plumes and clouds were observed during the April 10–13 eruption was about 3280000 km^2. The paroxysmal eruption of Sheveluch volcano belongs to the sub-Plinian type because it is characterized by a large height of the eruptive cloud and a long event duration. For this eruption, the Volcanic Explosivity Index is estimated to be 3–4. A detailed description of the paroxysmal explosive eruption of the Sheveluch volcano and the spread of the eruptive cloud was performed based on data from various satellite systems (*Himawari-9*, *NOAA-18/19*, *GOES-18*, *Terra*, *Aqua*, *JPSS-1*, *Suomi NPP*, *Arctica-M1*, etc.) in the information system "Remote Monitoring of Kamchatka and Kuril Islands Volcanic Activity" (VolSatView, http://kamchatka.volcanoes.smislab.ru).

Keywords: volcano, Sheveluch, paroxysmal explosive eruption, satellite monitoring, VolSatView, KVERT, Kamchatka

DOI: 10.1134/S0010952523700533

INTRODUCTION

Sheveluch is the most active volcano in Kamchatka, located in the northern part of the Central Kamchatka Depression, 50 km from the village of Klyuchi and 450 km from Petropavlovsk-Kamchatsky (http://www.kscnet.ru/ivs/kvert/volc?name=Sheveluch). It is one of the largest volcanic structures in Kamchatka, with a base diameter of 45–50 km and an area of at least 1300 km^2 [12]. The present structure includes three main elements: Old Sheveluch (3283 m), an ancient caldera, and Young Sheveluch (2800 m). In the crater of Young Sheveluch, a lava dome has been growing since August 1980, with its activity characterized by extrusive, effusive, and explosive (Vulcanian type) eruptions [12, 13]. The most powerful explosive

eruptions of the volcano, associated with the growth of the lava dome, were observed in 2001, 2004, 2005, and 2010 [1, 2, 6, 7].

Satellite monitoring of the volcano has been carried out by scientists from the Kamchatka Volcanic Eruption Response Team (KVERT) of the Institute of Volcanology and Seismology of the Far Eastern Branch of the Russian Academy of Sciences since 2002 [3, 8]. Since 2014, it has been conducted using the information system "Remote Monitoring of Kamchatka and Kuril Islands Volcanic Activity" (VolSatView) (http://kamchatka.volcanoes.smislab.ru) [3, 4, 9, 11].

Sheveluch is characterized by periods of very strong activity and periods of relative quiet. For example, from February 10 to December 17, 2018, only fumarolic activity was observed at the volcano. In early 2022, the volcano was also relatively quiet, but, from June 10, the intensity of the lava dome's growth began to increase, with an increased number of hot avalanches falling on its slopes. From October 21 until the beginning of the paroxysmal eruption on April 10, 2023, the value of temperature difference between the thermal anomaly and the background, as determined from medium-resolution satellite images, remained consistently above 100°C. This clearly indicated the emergence of juvenile material on the Earth's surface and the possibility of a major explosive eruption of the volcano at any time.

A detailed description of the paroxysmal explosive eruption of Volcano Sheveluch and the spread of its ash and aerosol clouds was carried out based on the analysis of data from various satellite systems, including *Himawari-9*, *NOAA-18/19* (National Oceanic and Atmospheric Administration), *GOES-18* (Geostationary Operational Environmental Satellite), *Terra*, *Aqua*, *JPSS-1* (Joint Polar Satellite System), *Suomi NPP* (National Polar-orbiting Partnership), *Arctica-M1*, and others in the VolSatView system.

PAROXYSMAL EXPLOSIVE ERUPTION OF SHEVELUCH VOLCANO ON APRIL 10–13, 2023

According to data from the *Himawari-9* satellite in the VolSatView system, at 10:10 UTC on April 10, an aerosol cloud with a size of 12 × 30 km^2 emerged, rising to an altitude of 6 km above sea level and moving for 35 km to the north–northwest at an azimuth of 354° from the volcano by 10:50 UTC. Starting from 12:10 UTC on April 10, the volcano began to emit ash; a gas-steam plume containing ash extended to the northwest (azimuth 309°), reaching 40 km by 13:00 UTC.

At 13:10 UTC on April 10, a paroxysmal explosive eruption of the Sheveluch volcano began, severely destroying the lava dome in its crater. On a satellite image from *Himawari-9* in the VolSatView system at 13:20 UTC, an ash cloud measuring 35 × 20 km^2 with a "cap" of aerosols was observed, with its far edge located to the northeast (azimuth 15°) of the volcano (Fig. 1a). Subsequently, the eruptive cloud unfolded and began to move west-northwest of the volcano (see Fig. 1). According to *Himawari-9* satellite data at 13:20 UTC on April 10, the eruptive cloud rose to an altitude of approximately 10 km above sea level. The Tokyo Volcanic Ash Advisory Center determined the height of this ash cloud at 13:10 UTC at 15.8 km above sea level (https://ds.data.jma.go.jp/svd/vaac/data/TextData/2023/20230410_30027000_0192_Text.html). Scientists from KVERT issued a Volcano Observatory Notice for Aviation warning of the eruption's aviation danger, changing the aviation color code from orange to red at 19:29 UTC on April 10 (http://www.kscnet.ru/ivs/kvert/van/?n=2023-51).

The explosive eruption proceeded almost continuously from April 10 to 13. A powerful cyclone, which covered the entire Kamchatka Peninsula, carried the ash cloud westward, turned it south, stretched it north, and directed it eastward from the volcano. The dynamics of the development of the ash and aerosol clouds from this eruption are presented in animations created using VolSatView from *Himawari-9* satellite data from 08:00 UTC on April 10 to 07:00 UTC on April 14 (http://d33.infospace.ru/jr_d33/materials/2023v20n2/283-291/1683110898.webm) and data from the *Arctica-M1* satellite from 16:00 to 21:30 UTC on April 10 (http://d33.infospace.ru/jr_d33/materials/2023v20n2/283-291/1683821166.webm).

In addition to the continuous emission of ash from the volcano's crater and the formation of an expanding eruptive cloud, primarily constrained by the tropopause (around 10 km above sea level), powerful explosions occasionally occurred, sending ash clouds into the stratosphere. For example, according to *Himawari-9* satellite data, such explosions were recorded at 15:10 UTC (cloud area $S = 110$ km^2), 15:30 UTC ($S = 826$ km^2), 16:50 UTC ($S = 430$ km^2), 17:50 UTC ($S = 975$ km^2), 19:00 UTC ($S = 82$ km^2), and 19:20 UTC ($S = 177$ km^2) on April 10. Comparing data from the MODIS (Moderate Resolution Imaging Spectroradiometer) instrument (*Aqua* satellite) at 14:50 UTC and the advanced Himawari imager instrument (*Himawari-9* satellite) at 15:10 UTC allowed for a preliminary estimate of the explosion's height at approximately 15–16 km.

From 16:50 UTC on April 10, as a result of a series of powerful explosions, the eruptive cloud began to expand, and a dense ash plume was directed to the south of the volcano. At 19:00 UTC, another powerful ash explosion occurred, with its height exceeding 13 km above sea level, according to a joint preliminary analysis of data from the *Arctica-M1* (http://d33.infospace.ru/jr_d33/materials/2023v20n2/283-291/1682090840.webm) and *Himawari-9* (http://d33.infospace.ru/jr_d33/materials/2023v20n2/283-291/1681247449.webm) satellites. An estimation of the explosion's height based on data from the *GOES-18*

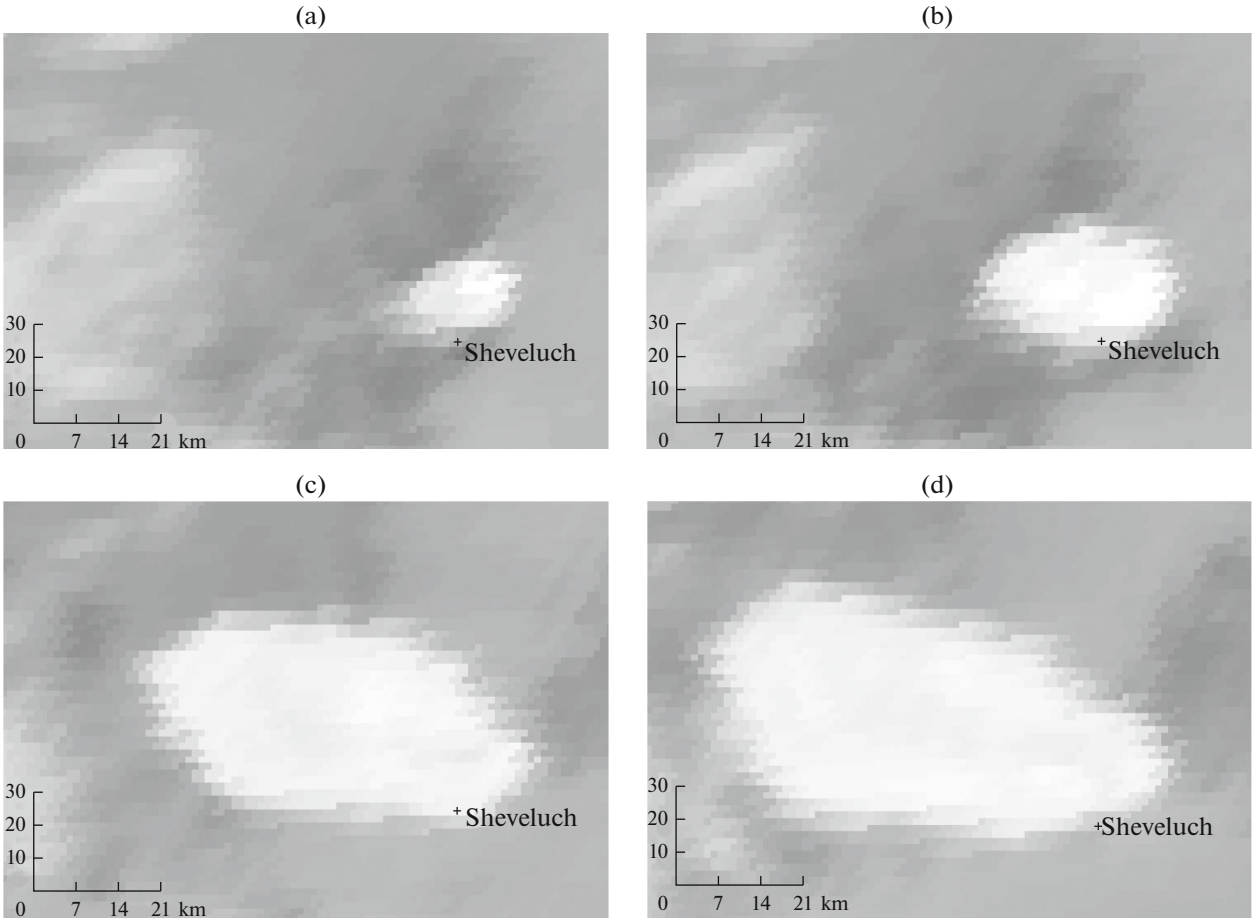

Fig. 1. Changes in the configuration and propagation azimuth of the Sheveluch eruptive cloud during the April 10, 2023, eruption. Data from the VolSatView Information System: eruptive clouds on *Himawari-9* satellite images in channel 14 at (a) 13:20, (b) 13:30, (c) 14:00, and (d) 14:20 UTC on April 10, 2023.

satellite using the method from [10] indicated a height of ~18 km above sea level. These and other powerful explosions led to the formation of a dense ash plume directed southwest from the volcano, and ash deposits were observed in the village of Klyuchi and its surroundings, with a layer of about 8 cm. Throughout April 10–13, the ash plumes from the volcano changed direction according to the development of the cyclone in the Kamchatka region. The areas covered by these plumes and clouds were approximately as follows: April 10, 172000 km^2; April 11, over 942000 km^2, including 205000 km^2 on the Kamchatka Peninsula; and April 12, up to 2115000 km^2.

The *Sentinel-2A* satellite image at 00:40 UTC on April 12 features a visible plume of ash extending southwest from Sheveluch volcano (see Fig. 2). Pyroclastic flows were likely still forming at this time, as there was a haze of dispersed ash to the east of the plume in the vicinity of the volcano. The image also highlights a zone covered by a significant layer of ash during the eruption on April 10–11. The estimated area of this zone was over 60000 km^2. The total area of the territory in Kamchatka and the Pacific Ocean covered by volcanic ash and aerosol plumes during the Sheveluch eruption from April 10 to 13, as of April 14, was approximately 3280000 km^2.

It is worth noting that the eruptive column during the eruption was not vertical. For example, at the beginning of the eruption on April 10 at 13:20 UTC, it deviated to the north-northeast; on April 11 at 12:00 UTC, it deviated to the northwest; and on April 12 at 07:00 UTC, it deviated to the southwest.

Throughout the eruption, explosive events were accompanied by the emission of a large amount of sulfur dioxide (SO_2). According to the Support Aviation Control Service (SACS) SO_2 and Ash Notification System (http://sacs.aeronomie.be) with data from the TROPOMI (Tropospheric Ozone-Monitoring Instrument), clouds of sulfur dioxide with heights exceeding 20 km above sea level were recorded over Kamchatka. As of 01:42 UTC on April 11, these clouds covered an area of 165967 km^2, contained 214.46 kt of SO_2, and had a sulfur dioxide concentration of 471.9 DU. By 01:22 UTC on April 12, the area covered by such

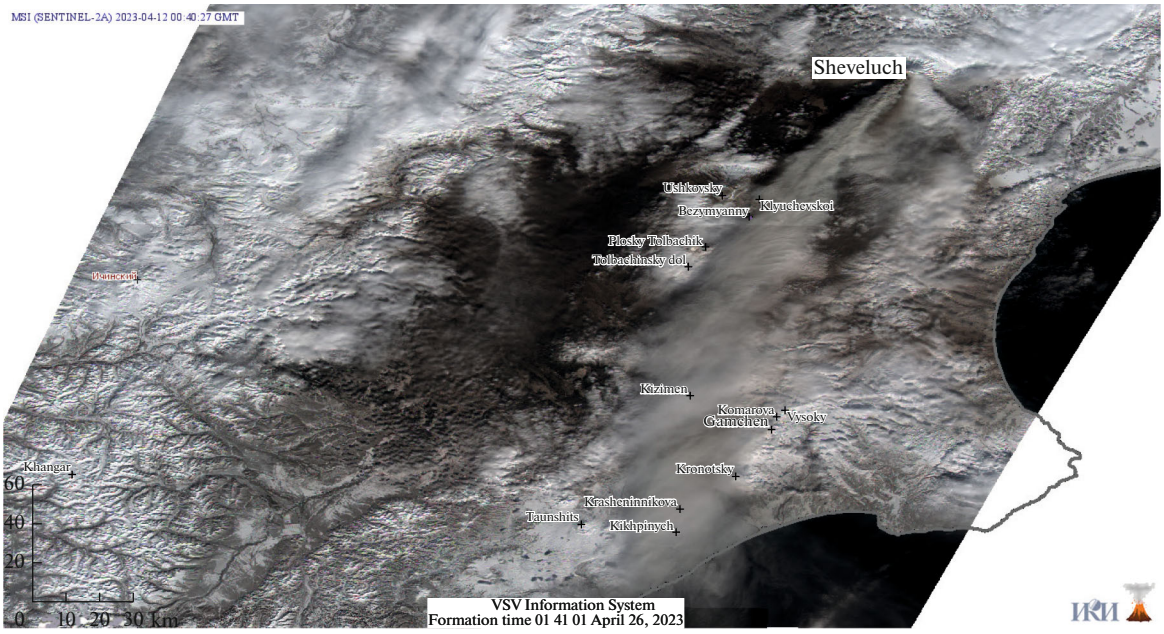

Fig. 2. Powerful ash plume of the Sheveluch volcano and ashfall-related pollution zone in the *Sentinel-2A* satellite image at 00:40 UTC April 12, 2023.

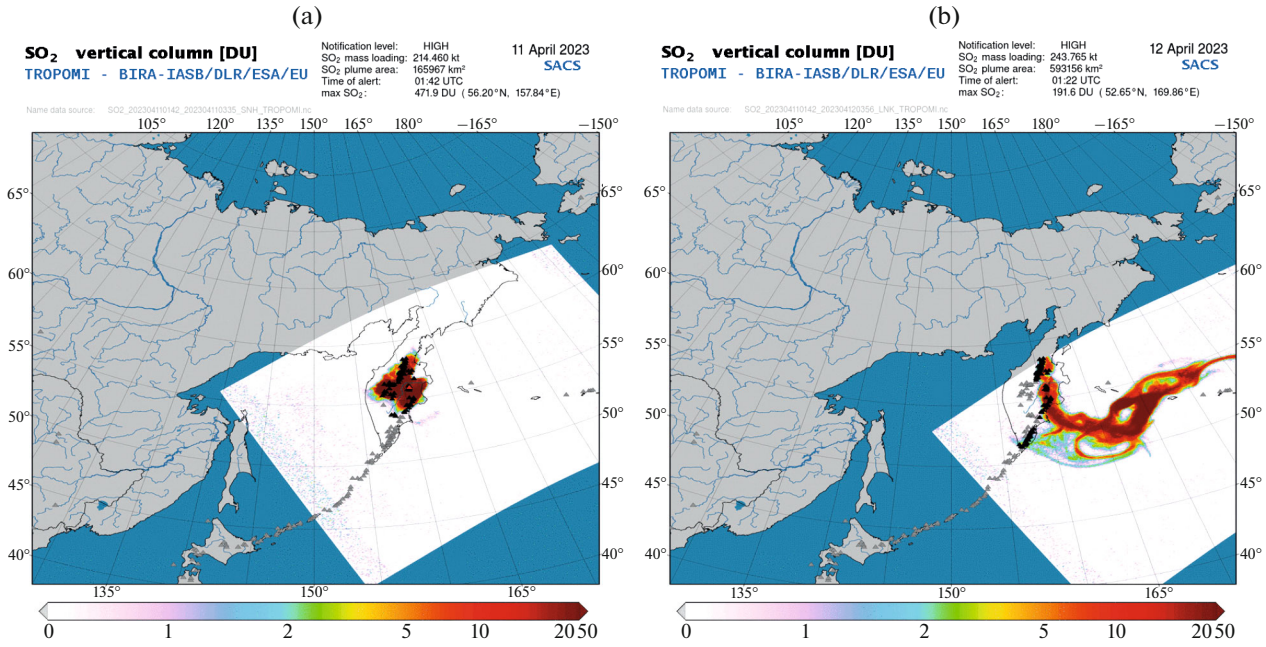

Fig. 3. SO_2 content in the aerosol plume during the Sheveluch volcano eruption on April (a) 11 and (b) 12, 2023, according to SACS data (http://sacs.aeronomie.be/).

clouds had increased to 593156 km^2, with 243.765 kt of SO_2 and a sulfur dioxide concentration of 191.6 DU (Fig. 3). In the following days, the area covered by aerosol clouds continued to expand, but the concentration of SO_2 in them decreased (e.g., https://sacs.aeronomie.be/nrt/TropomiNrt/2023/04.orb/12/tropomi_vcd20230412_112_lr.gif, https://sacs.aeronomie.be/nrt/TropomiNrt/2023/04.orb/13/tropomi_vcd20230413_101_lr.gif, https://sacs.aeronomie.be/nrt/TropomiNrt/2023/04.orb/14/tropomi_vcd20230414_102_ lr.gif).

By April 20, the aerosol cloud had reached the western part of Greenland (https://sacs.aeronomie.be/nrt/TropomiNrt/2023/04.orb/20/tropomi_vcd20230420_105_lr.gif), and on April 21, it stretched in a band from Iceland along the Scandinavian Peninsula (https://sacs.aeronomie.be/nrt/TropomiNrt/2023/04.orb/21/tropomi_vcd20230421_106_lr.gif).

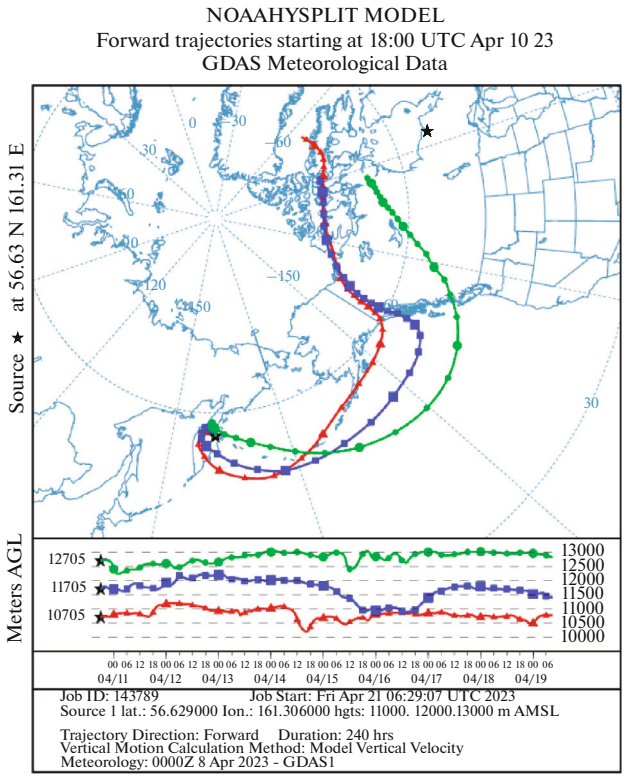

Fig. 4. Trajectories of aerosol clouds movement of the Sheveluch volcano eruption at levels 11, 12, and 13 km above sea level in the period from April 10 to 18, 2023, according to the HYSPLIT model (https://www.ready.noaa.gov/HYSPLIT.php).

According to NOAA HYSPLIT model data, aerosol clouds in the vicinity of Greenland on April 19 were located at altitudes of 11–13 km above sea level (see Fig. 4).

The April eruptive event of Sheveluch was one of the most powerful explosive eruptions associated with the growth of the lava dome since 1980. Preliminary estimates suggest a Volcanic Explosivity Index (VEI) of 3–4 for this eruption.

CONCLUSIONS

Paroxysmal explosive eruption of Sheveluch volcano continued uninterrupted from April 10 to 13, 2023. It began against the backdrop of constant ash emissions from the volcano, which had been observed for 3 h. The height of the rise of separate ash clouds likely exceeded 15 km above sea level, with some estimates suggesting that occasional explosions could raise ash clouds to heights of up to 18 km above sea level. Exact values for the height of eruptive clouds can be estimated based on a detailed analysis of data from various satellite systems.

According to satellite data, the eruptive column during the eruption was not vertical. At the initial moment of the eruption, it had a tilt to the northeast, and subsequently, it mainly tilted to the west and southward. During the occurrence of subsequent explosions, eruptive clouds were observed not directly above the volcano's crater but to the side of it.

Due to the high cyclonic activity prevailing over the Kamchatka Peninsula, the Sheveluch eruptive cloud stretched into a band more than 3500 km long from west to northeast of the volcano. An aerosol cloud was observed in the vicinity of the Scandinavian Peninsula on April 21–22. Sulfur dioxide was constantly released into the atmosphere during the paroxysmal eruption, with the highest amount emitted on April 10–11, coinciding with the explosive destruction of the Sheveluch volcano's lava dome. As of April 14, the total area covered by volcanic ash and aerosol plumes in Kamchatka and the Pacific Ocean during April 10–13 was approximately 3 280 000 km^2.

This eruption of Sheveluch is classified as sub-Plinian, because has high parameters for the rise of eruptive clouds and the duration of the event. The Volcanic Explosivity Index for this eruption is estimated as 3–4.

FUNDING

The study was primarily conducted using the VolSatView Information System [3, 4, 9, 11]. The work was made possible through the resources of the Far East Center of the Scientific Research Center "Planet" and the Center for Collective Use "IKI-Monitoring," which is supported and developed by the Institute of Space Research of the Russian Academy of Sciences under the theme "Monitoring," with state registration no. 122042500031-8 [5]. The research also involved the scientific equipment of the Center for Processing and Storage of Scientific Data of the Far East Branch of the Russian Academy of Sciences, which is funded by the Ministry of Science and Higher Education of the Russian Federation under agreement no. 075-15-2021-663 and supported and developed by the Computing Center of the Far East Branch of the Russian Academy of Sciences [14].

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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Translated by M. Chubarova