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Monitoring the Thermal Activity of Kamchatkan Volcanoes during 2015–2022 Using Remote Sensing

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Abstract: The powerful explosive eruptions with large volumes of volcanic ash pose a great danger to the population and jet aircraft. Global experience in monitoring volcanoes and observing changes in the parameters of their thermal anomalies is successfully used to analyze the activity of volcanoes and predict their danger to the population. The Kamchatka Peninsula in Russia, with its 30 active volcanoes, is one of the most volcanically active regions in the world. The article considers the thermal activity in 2015–2022 of the Klyuchevskoy, Sheveluch, Bezymianny, and Karymsky volcanoes, whose rock composition varies from basaltic andesite to dacite. This study is based on the analysis of the Value of Temperature Difference between the thermal Anomaly and the Background (the VTDAB), obtained by manual processing of the AVHRR, MODIS, VIIRS, and MSU-MR satellite data in the VolSatView information system. Based on the VTDAB data, the following "background activity of the volcanoes" was determined: 20 °C for Sheveluch and Bezymianny, 12 °C for Klyuchevskoy, and 13–15 °C for Karymsky. This study showed that the highest temperature of the thermal anomaly corresponds to the juvenile magmatic material that arrived on the earth's surface. The highest VTDAB is different for each volcano; it depends on the composition of the eruptive products produced by the volcano and on the character of an eruption. A joint analysis of the dynamics of the eruption of each volcano and changes in its thermal activity made it possible to determine the range of the VTDAB for different phases of a volcanic eruption.

Keywords: remote sensing; volcano eruption; thermal activity; Sheveluch; Klyuchevskoy; Bezymianny; Karymsky; Kamchatka

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1. Introduction

The powerful explosive eruptions with large volumes of volcanic ash are very dangerous to modern jet aviation, e.g., [1–7]. Due to the high air traffic in the Northern Pacific, there is an increased risk of an encounter with volcanic ash that could lead to in-flight engine failure and other damage to aircraft systems. To avoid aircraft-related disasters caused by volcanic ash clouds, a framework for the International Airways Volcano Watch (IAVW) was established in 1993 by the International Civil Aviation Organization (ICAO). Under this framework, a total of nine Volcano Ash Advisory Centers (VAACs) were designated to monitor volcanic eruptions and provide information on the locations and movement of volcanic ash clouds, as well as an outlook for their regions of responsibility. There are four VAACs in the Northern Pacific region: Anchorage, Montreal, Tokyo, and Washington. The volcanoes located on the Kamchatka Peninsula and the Kurile Islands are the responsibility

of the Tokyo VAAC, which covers the East Asia and Northwest Pacific regions. The Tokyo VAAC has been monitoring volcanoes 24 h a day and issuing Volcanic Ash Advisories since 1997, e.g., [8]. The Kamchatka Volcanic Eruption Response Team (KVERT), on behalf of the Institute of Volcanology and Seismology (IVS) Far East Branch (FEB) of the Russian Academy of Sciences (RAS), provides to VAACs timely eruption information about volcanoes in the Kamchatka Peninsula and Kurile Islands since 1993, e.g., [6–9]. KVERT goal is to reduce the risk of aircraft encountering volcanic ash clouds in the Northern Pacific region by timely detection of volcanic unrest, tracking of ash clouds, prognosis, and rapid notification of airlines, civil aviation authorities, and other interested parties about the volcanic hazards, e.g., [6–10]. The comprehensive analysis of data published about volcanic activity and the data from 30 years of KVERTs continuous monitoring of volcanoes allow an expert evaluation of the hazards posed to aviation by volcanoes. When KVERT issues a Volcano Observatory Notice for Aviation (VONA), it is automatically disseminated to VAACs Anchorage, Darwin, Montreal, Tokyo, and Washington, and different international and local users of the Northern Pacific region such as ICAO, Alaska Volcano Observatory (AVO), Smithsonian Institution, the Elizovo Airport Meteorological Center (Elizovo AMC), the Kamchatka Branch of the Ministry for Emergency Situations, and mass media. It is also automatically uploaded on the KVERT website: http://www.kscnet.ru/ivs/kvert/van/ (accessed on 10 July 2023) [10].

In addition to an operative response to volcanic eruptions with ash emissions, in order to assess the situation in the area of a particular active volcano in Kamchatka and the Kurile Islands, it is very important to forecast its activity and danger for air flights in the near future (days, weeks). Monitoring of changes in the thermal anomaly parameters (size, temperature) of each volcano is successfully used to predict its future activity, including strong explosive eruptions, e.g., [10–15].

The Kamchatka Peninsula of Russia, with 30 active volcanoes, is one of the most volcanically active regions in the world. In the 20th century, more than 100 eruptions of 14 volcanoes occurred in Kamchatka (Sheveluch, Klyuchevskoy, Bezymianny, Tolbachik, Kizimen, Karymsky, Zhupanovsky, Avachinsky, Koryaksky, Gorely, Mutnovsky, Ksudach, Zheltovsky, Iliinsky), e.g., [10,16–21]. Since the beginning of the 21st century (over 22 years), more than 80 eruptions have been recorded from 12 volcanoes (Sheveluch, Klyuchevskoy, Bezymianny, Tolbachik, Kizimen, Karymsky, Zhupanovsky, Avachinsky, Koryaksky, Gorely, Mutnovsky, Kambalny), e.g., [10,19,22–28]. The duration of the paroxysmal explosive eruptions of the volcanoes varies from several hours (Bezymianny) to several days (Sheveluch), while extrusive eruptions continue for more than sixty years (Bezymianny).

The volcanoes in the Northern group of Kamchatka are the most active. They are characterized by a contrasting composition of volcanic rocks: Klyuchevskoy and Tolbachik are the basaltic andesites and basalts, respectively; Bezymianny and Sheveluch are the andesites and dacites, respectively. These volcanoes have explosive and effusive eruptions, but the activity of Bezymianny and Sheveluch is also associated with the extrusive ones, with the growth of the lava domes in explosive craters formed during catastrophic eruptions in 1956 and 1964, respectively, e.g., [16,18,20]. The composition of volcanic products predetermines their effusive eruptions: Klyuchevskoy volcanoes usually effuse agglomerate lava flows, while Bezymianny and Sheveluch volcanoes are characterized by extruding viscous lava onto the lava dome's slopes. The continuous growth of the Bezymianny lava dome has been observed since April 1956, and the Sheveluch lava dome − since August 1980, e.g., [16,17,29,30]. The summit and lateral eruptions of Klyuchevskoy volcano have been known since 1697 [31] and Tolbachik since 1740 [32].

A thermal anomaly in a volcanic area is one of the main indicators of volcanic activity. Any magmatic eruption (extrusive, explosive, or effusive) is a process of high-temperature juvenile material entering the earth's surface. The highest temperature of the thermal anomalies reveals itself during explosive eruptions of the Strombolian (basaltic and basaltic andesite volcanoes) and Vulcanian types (any volcanoes), as well as lava lakes and effusive eruptions of basaltic volcanoes, e.g., [27,33–36]. The extrusive eruptions with the hot

avalanches collapsing from the lava domes of andesitic and dacitic volcanoes have a lower temperature, e.g., [37–39].

Due to the development of satellite observations, a lot of attention has been paid to the thermal activity of Kamchatka volcanoes. For example, some articles considered the thermal activity of the Bezymianny and Sheveluch volcanoes during separate eruptions on the AVHRR (Advanced Very-High-Resolution Radiometer) and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) data, e.g., [12,23,40–45]. The other works are devoted to the analysis of the thermal activity of the different volcanoes of Kamchatka according to the AVHRR data during 1993–2008, e.g., [46–48].

KVERT has been continuously monitoring the thermal anomalies in the Kamchatka volcanoes using satellite data since 2002 [10]. The following satellite data were mainly processed: AVHRR (NOAA—National Oceanic and Atmospheric Administration, and NOAA-N-Prime), and MODIS—Moderate Resolution Imaging Spectroradiometer (Terra and Aqua). Since 2012, this monitoring has been carried out using the "Remote Monitoring of the Activity of the Volcanoes of the Kamchatka and the Kuriles" (the VolSatView, http://kamchatka.volcanoes.smislab.ru, accessed on 10 July 2023) Information System (IS), e.g., [10,49–51].

During 2015–2022, we collected detailed volcanological and satellite data about the activity and eruptions of the Kamchatka and Kurile Islands volcanoes. For example, daily monitoring of the thermal activity of volcanoes in manual mode allowed us to determine the beginning and end of almost all eruptions that occurred during this period. Based on the volcanological information, in this study we present an extensive analysis of the thermal state of the most active Kamchatkan volcanoes: Sheveluch, Klyuchevskoy, Bezymianny, and Karymsky during 2015–2022 (Figure 1).

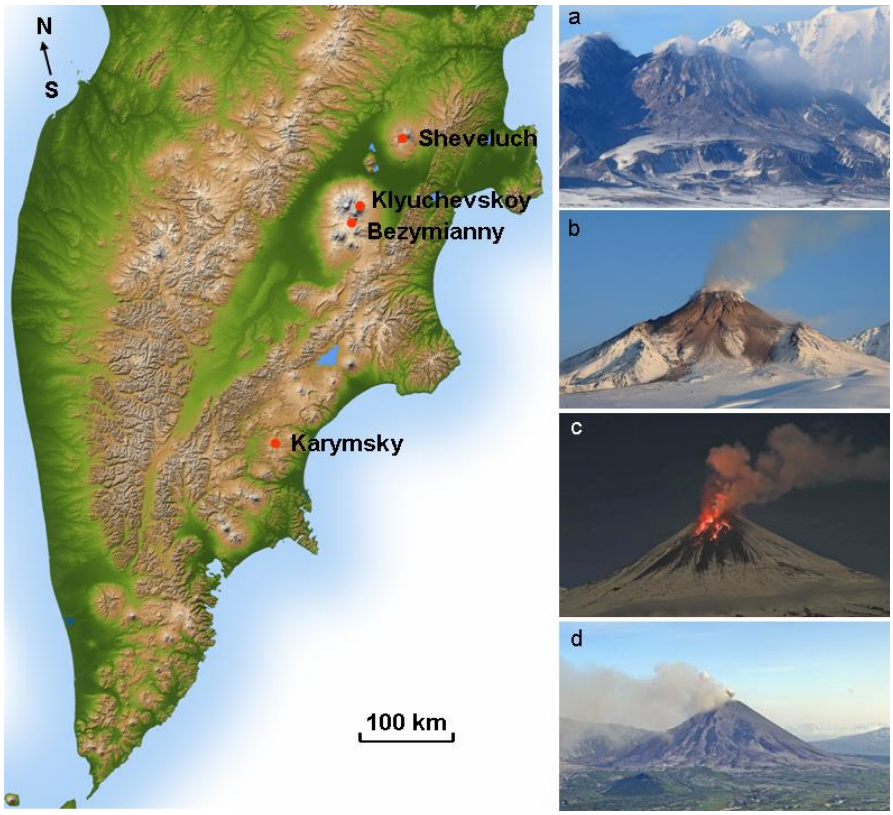

Figure 1. Location of volcanoes Sheveluch, Bezymianny, Klyuchevskoy, and Karymsky at Kamchatka (**a**) Sheveluch: the lava dome, a view from south, photo by Yu. Demyanchuk on 24 May 2020; (**b**) Bezymianny: the lava dome, a view from southeast, photo by Yu. Demyanchuk on 20 April 2022; (**c**) Klyuchevskoy: the stratocone, a view from east, photo by Yu. Demyanchuk on 14 October 2016; (**d**) Karymsky: the stratocone, a view from southwest, photo by A. Sokorenko on 30 June 2020.

2. Methods

2.1. The VolSatView Information System

The VolSatView Information System was created in cooperation with the Space Research Institute RAS (IKI), the Institute of Volcanology and Seismology FEB RAS, the Computing Center (CC) FEB RAS, and the Far-Eastern Center of State Research Center for Space Hydrometeorology (FEC SRC) "Planeta", e.g., [10,49–51]. The VolSatView provides volcanologists with operational and archival satellite and meteorological data and information products derived from them, as well as various tools for complex processing and analysis of the above information together with data from other information systems. Because the system uses significant amounts of data, its architecture is focused on distributed information storage and utilizing computing resources in various scientific centers. The VolSatView provides users with tools designed for distributed data processing and analysis. The VolSatView is based on technologies for working with various data developed at IKI RAS, IVS FEB RAS, CC FEB RAS, and FEC SRC "Planeta", including technologies for building remote monitoring systems created at IKI RAS, e.g., [10,52–57]. In addition, computer algorithms for managing networks of specialized observations and processing instrumental data were used, developed at CC FEB RAS, e.g., [10,58–60].

The monitoring system has the weather data integrated using a specially developed Application Programming Interface (API), which allows users to quickly select information from the archives for further processing, analysis, and display [61]. This API is focused on the use of remote monitoring systems based on the GEOSMIS technology, which includes VolSatView [10,62].

The data analysis system in the VolSatView is based on the approaches, technologies, and solutions that are developed and supported at the IKI RAS as a core part of the system for collective use of extra-large distributed archives of satellite data and the results of their processing, primarily in the interests of the Shared Services Center "IKI-Monitoring" [50] and its information service "VEGA-Science" (http://sci-vega.ru/, accessed on 10 July 2023) [63].

The VolSatView cartographic web interface is focused on working with spatial information, allowing setup parameters for data searching, displaying, and analyzing. The interface allows you to receive and visualize various satellite data available in the system, as well as products obtained by their processing, including so-called "virtual" ones that are formed "on the fly" upon user request, e.g., [10,56].

2.2. The Analysis of a Thermal Anomaly in the Volcano Area

The VolSatView includes the following satellite data for continuous monitoring of the thermal activity of Kamchatka volcanoes: AVHRR (NOAA-N-Prime), MODIS (Terra and Aqua), VIIRS—Visible Infrared Imaging Radiometer Suite (JPSS-1 (Joint Polar Satellite System), and Suomi NPP (National Polar-Orbiting Partnership), and MSU-MR—Multispectral scanner low-resolution (Meteor M-2).

Automated detection of the thermal anomalies based on the AVHRR and MODIS (MOD14 and MODVOLC) algorithms, e.g., [64–71], was implemented in the VolSatView based on the AVHRR, MODIS, and VIIRS satellite data.

There is an option in VolSatView to interactively (in manual mode) process the satellite images available in the system to analyze the thermal anomalies in the area of each active volcano. The processing of thermal anomalies includes measuring the temperature of each of the anomaly pixels, the number of anomaly pixels, and the background temperature. The calculation of radio brightness temperatures for all image pixels occurs at receiving stations during the calibration of satellite observation data (the processing level is not lower than L1B) [72]. Thanks to that, the VolSatView automatically determines the value of a given pixel on pre-processed images upon receiving a corresponding user request. To determine anomaly temperature, the AVHRR, MODIS, VIIRS, and MSU-MR instrument data are used for the 3.7 μm, 11 μm, and 12 μm bands.

We consider only nighttime data on all the available satellite images, e.g., Figure 2. Images in Supplementary Materials Addition S1 (section to Figure 2) illustrate the eruptive activity of volcanoes on 8 November 2020 or so, which corresponds to the brightness of the thermal anomalies shown in Figure 2.

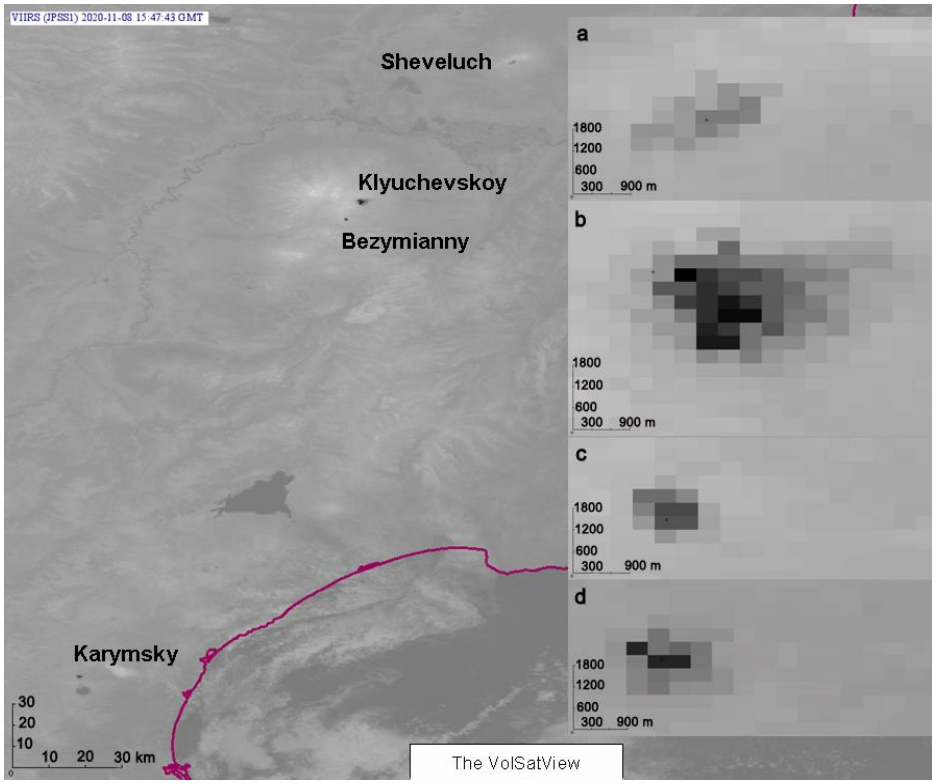

Figure 2. The thermal anomalies over the Kamchatkan volcanoes at 15:47 UTC on 8 November 2020 on JPSS-1 (I4 channel) satellite image; these thermal anomalies on an enlarged scale: (**a**) Sheveluch; (**b**) Klyuchevskoy; (**c**) Bezymianny; (**d**) Karymsky. The pink line is the border of the Kamchatka Peninsula.

The information obtained interactively about the number of pixels of the thermal anomaly, the maximum temperature of its pixel, and the average background temperature near the anomaly is recorded in the KVERT IS database, which contains tools for analyzing the thermal activity of the Kamchatka and Kuril volcanoes [10]. It is possible to present data on the thermal activity of all volcanoes in Kamchatka and the Kuriles or a separate volcano for any period starting in 2003, as well as data on all or separate satellite instruments. Figure 3 shows an example of information representation about the thermal anomaly in the area of the Karymsky volcano: the Value of Temperature Difference between the thermal Anomaly and the Background (the VTDAB), obtained interactively in the VolSatView using various satellite data. It is clearly seen that only the last graph (all instruments) provides the most complete information on the thermal anomaly of the volcano. In each of the four upper graphs, information about the thermal anomaly differs from others due to the features of each of the satellite instruments.

2.3. Video and Visual Observation

Visual monitoring of volcanoes gives the most reliable information to volcanologists; therefore, KVERT has been conducting such observations of the Kamchatkan volcanoes since 1993. KVERT receives information about the volcanoes of the Northern group of the Kamchatka: Sheveluch, Klyuchevskoy, and Bezymianny (see Supplementary Materials) from the Kamchatka Volcanological Station after F. Yu. Levinson-Lessing in Klyuchi. Visual observations of the Karymsky volcano are carried out by volcanologists mainly during

field work. In addition, visual information about active volcanoes comes to KVERT from pilots of local and international airlines, meteorologists, tourists, etc. [10].

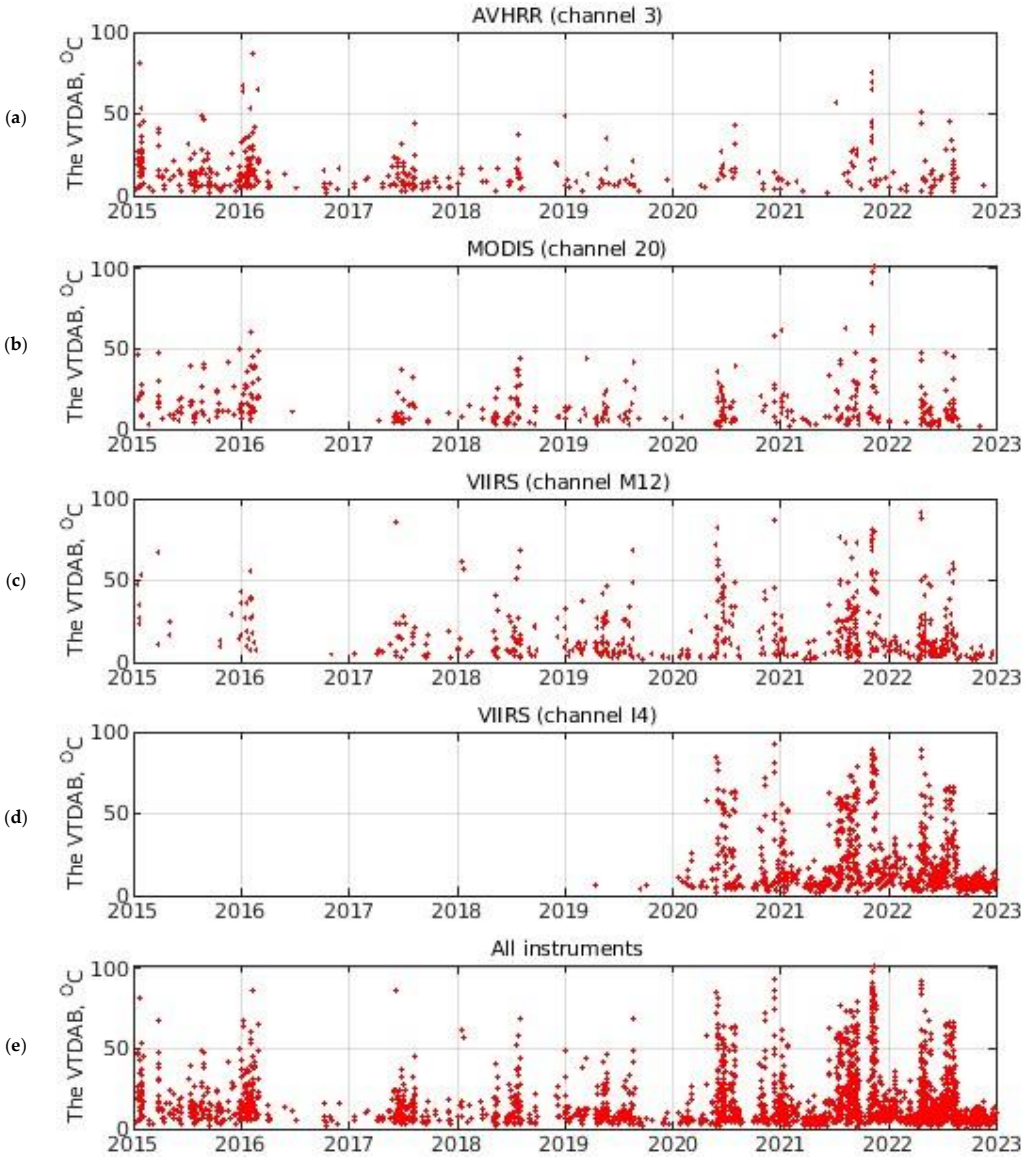

Figure 3. The value of the temperature difference between the thermal anomaly and the background in the area of the Karymsky volcano, obtained interactively in the VolSatView on the satellite data: (**a**) AVHRR; (**b**) MODIS; (**c**) VIIRS, M12 channel; (**d**) VIIRS, I4 channel; (**e**) all instruments.

KVERT has begun to use video cameras since the beginning of the 21st century. The first video cameras were pointed at the Klyuchevskoy volcano on 9 October 2000, at the Sheveluch on 17 May 2002, and at the Bezymianny on 20 August 2003 [10]. In 2010–2017 IVS FEB RAS installed video cameras with infrared-cut filters and different scales on the volcanoes: the Sheveluch (12 July 2011, 1 December 2011, and 1 November 2017) and the Klyuchevskoy (28 October 2010 and 1 December 2011). Images are captured from those cameras in real time mode with one frame/min frequency and then published on the KVERT website of IVS FEB RAS. Since 2011, video data from volcanoes has been accumulated and archived on the IVS FEB RAS server using the developed algorithm [10].

3. Results

The KVERT IS database contains 23,675 records of the VTDAB for thermal anomalies in the areas of the Sheveluch, Bezymianny, Klyuchevskoy, and Karymsky volcanoes for

the period 2015–2022 (Table 1). Each volcano has a unique frequency of occurrence of the VTDAB, which is mainly unimodal for the Sheveluch, Bezymianny, and Karymsky volcanoes and bimodal for the Klyuchevskoy, as can be noted in Figure 4.

Table 1. The number of the VTDAB in KVERT IS and corresponding statistics data for the Sheveluch, Bezymianny, Klyuchevskoy, and Karymsky volcanoes in 2015–2022.

Volcano	Quantity	VTDAB, °C		
		Min	Max	Mean
Sheveluch	10,236	0.8	119	39
Bezymianny	6442	0.3	117	19.5
Klyuchevskoy	5073	1.5	132	52.9
Karymsky	1924	0.7	102	17.9

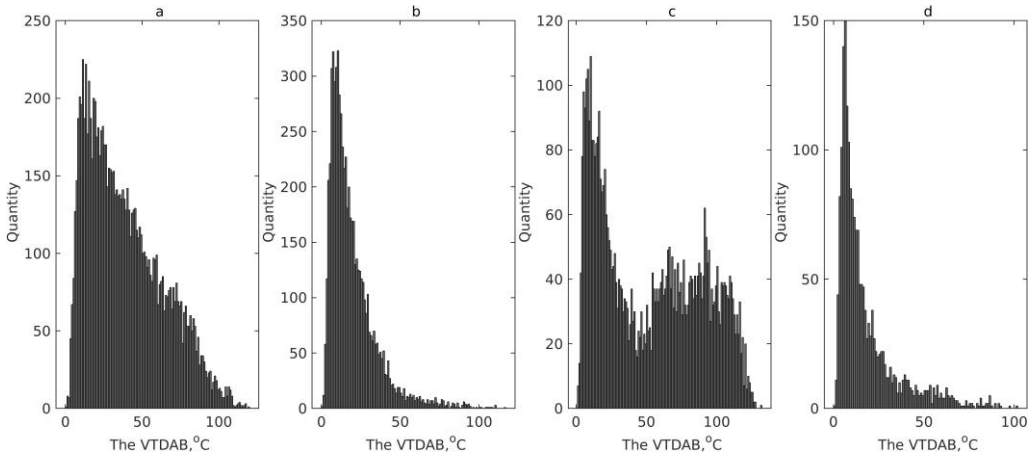

Figure 4. The frequency of occurrence of the VTDAB of the volcanoes in 2015–2022: (**a**) Sheveluch; (**b**) Bezymianny; (**c**) Klyuchevskoy; (**d**) Karymsky.

3.1. The Background Activity of the Volcano

The eruptive activity is unique for each active volcano in Kamchatka. There are periods of very strong activity and periods of relative rest for each of them. The value of the difference between the maximum temperature of the anomaly in the area of the volcano and the average background temperature near the anomaly during periods of its relative rest can act as a kind of "background of activity of the volcano". It should be clarified that our definition of "the background of activity on the volcano" is based on the VTDAB and differs from the one described in [73].

Let us consider changes in temperatures of the thermal anomalies of the Sheveluch, Bezymianny, Klyuchevskoy, and Karymsky volcanoes during 2015–2022.

For example, the Sheveluch volcano was relatively quiet from 10 February to 1 November 2018, only its fumarole activity was noted. The VTDAB varies from 1.9 to 22.4 °C; its average value is 10.1 °C; however, not more than 20 °C in most cases (only 4% of VTDAB is over 20 °C) (Figure 5a). It can be assumed that the VTDAB of 20 °C is the background of the Sheveluch volcano activity. The highest temperature of the Sheveluch thermal anomaly is associated with explosive activity of the Vulcanian-type and intensive growth of the lava dome (extrusion of lava blocks and lava flows), accompanied by the collapse of hot avalanches, e.g., (Supplementary Figures S1–S4 in Addition S1).

The Bezymianny was relatively quiet from 4 January 2015 to 1 October 2016, with predominantly fumarole activity on the volcano noted (Figure 6a). The VTDAB varies from 1.7 to 27.4 °C. The average value in the range from 16 to 27.4 °C is 20 °C, while 5% of VTDAB is above 20 °C (Figure 6a). It can be assumed that VTDAB of 20 °C is the background of the Bezymianny volcano activity. The highest temperature of the volcano thermal anomaly is

associated with explosive activity of the Vulcanian-type and the extrusion of lava flows onto the lava dome slopes, accompanied by the hot avalanches' collapses, e.g., (Supplementary Figures S5 and S6 in Addition S1).

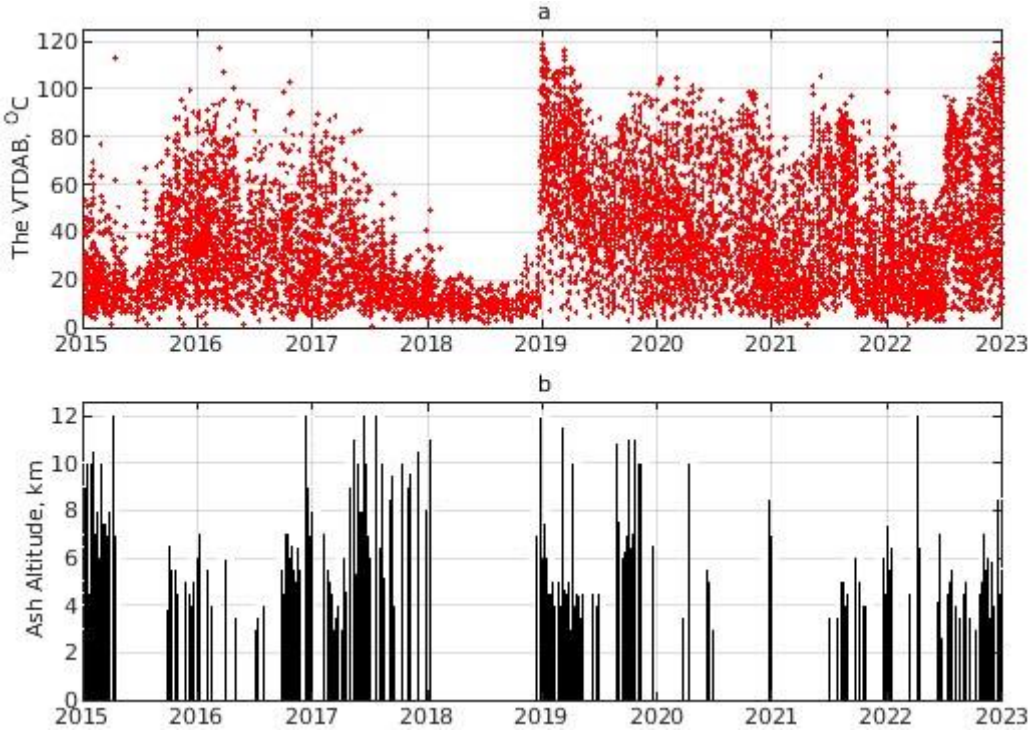

Figure 5. The 2015–2022 eruptions of the Sheveluch volcano: (**a**) the value of the temperature difference between the thermal anomaly and the background, and (**b**) the height of ash emission.

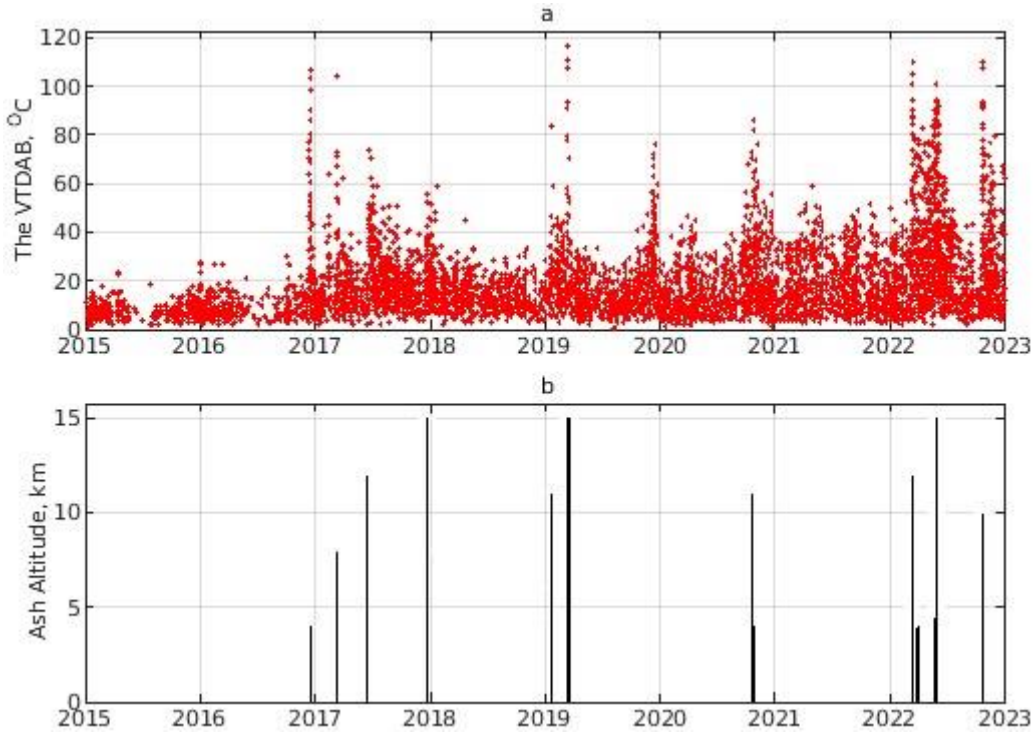

Figure 6. The 2015–2022 eruptions of the Bezymianny volcano: (**a**) the value of the temperature difference between the thermal anomaly and the background; (**b**) the height of ash emission.

In the period from 16 June 2018 to 13 June 2019 the Klyuchevskoy volcano was in a state of inter-eruptive activity, in the stage of cooling of the lava flow that erupted in 2016 (Figure 7a). The VTDAB during this period varies from 3 to 16.5 °C. The average of VTDAB in the range from 10 to 16.5 °C is 12 °C, while 5% of the VTDAB is greater than 12 °C (Figure 7a). It can be assumed that the VTDAB of 12 °C is the background of the Klyuchevskoy volcano activity. The highest temperature of the volcano thermal anomaly is associated with the summit and lateral effusive eruptions and explosive activity of the Strombolian and Vulcanian types of the craters, e.g., (Supplementary Figures S7–S11 in Addition S1).

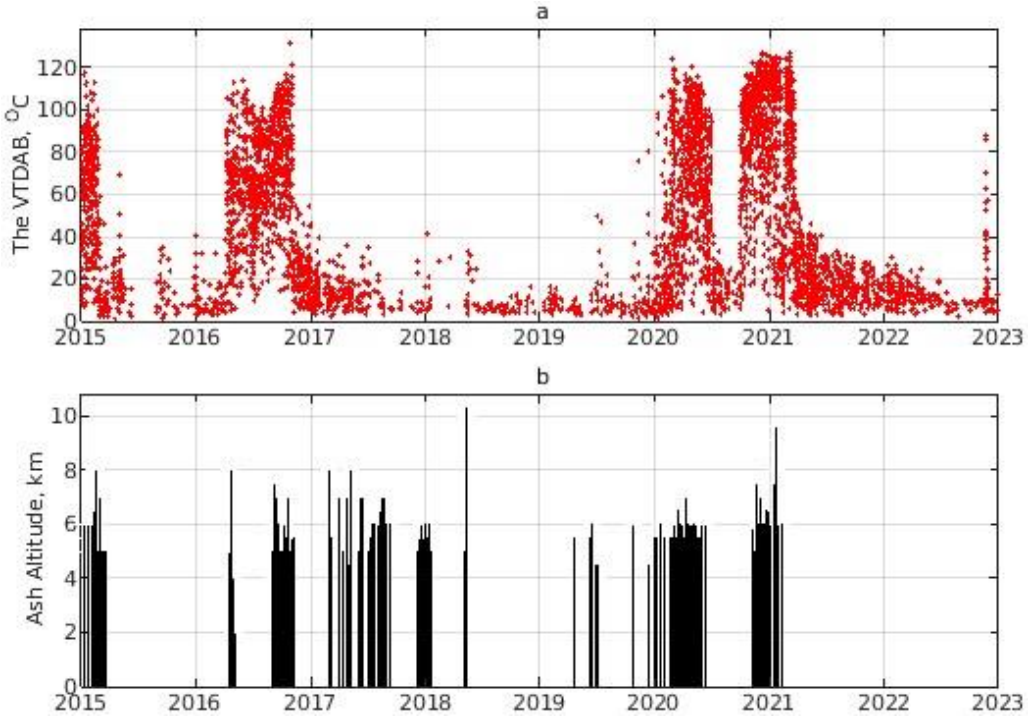

Figure 7. The 2015–2022 eruptions of the Klyuchevskoy volcano: (**a**) the value of the temperature difference between the thermal anomaly and the background; (**b**) the height of ash emission.

Several relatively quiet periods can be identified on the Karymsky volcano (Figure 8a). For example, from 28 March 2016 to 17 May 2017, the VTDAB varies from 1.7 to 16.1 °C; the average value is 8 °C, and 6% of the VTDAB is more than 15 °C. From 22 August to 28 December 2022, VTDAB varies from 1.4 to 16.8 °C; the average value is 7 °C, and 7% of VTDAB is more than 13 °C. Generally, the VTDAB of 13–15 °C can be taken as the background of the Karymsky volcano activity. The highest temperature of the thermal anomaly of the Karymsky volcano is associated with the explosive activity of the Strombolian and Vulcanian types; the temperature of the anomaly is much lower for the lava dome in the crater, e.g., (Supplementary Figures S12–S14 in Addition S1).

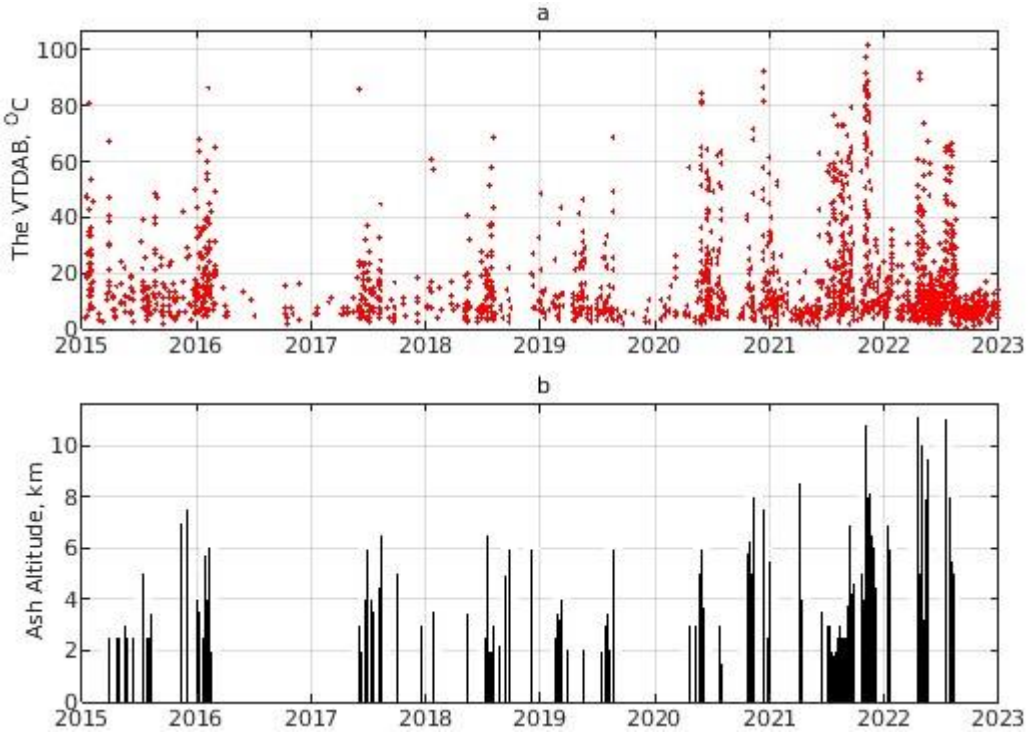

Figure 8. The 2015–2022 eruptions of the Karymsky volcano: (**a**) the value of the temperature difference between the thermal anomaly and the background; (**b**) the height of ash emission.

4. Discussion

4.1. Sheveluch Volcano Activity in 2015–2022

Sheveluch is one of the largest and most active Kamchatkan volcanoes, with at least 60 large eruptions during the Holocene, e.g., [74]. The catastrophic eruption in 1964 formed the modern amphitheater within which the active lava dome is now growing since late August 1980, e.g., [18,20,29]. Lava blocks and lava flows are extruded constantly onto the slopes of the Sheveluch dome; that is, magmatic matter, andesite, and dacite compositions enter the earth's surface all the time. Five paroxysmal explosive eruptions of the Sheveluch volcano occurred in 2001, 2004, 2005, 2010, and 2023, e.g., [30,75–78].

A long-lived eruption of the Sheveluch continued during 2015–2022, and the persistent thermal anomaly corresponds to the area of the growing lava dome. Strong gas-steam activity, ash explosions up to 10–15 km a.s.l., and hot avalanches accompanied the extrusion of viscous lava.

In the first half of 2015, the lava dome was actively growing: lava flows continued to fill the explosive crater, e.g., (Supplementary Figure S15 in the Addition S2), which was formed during the paroxysmal eruption in October 2010, e.g., [78–80]. From January to mid-April, 16 explosive events occurred with ash removal up to 12 km a.s.l., e.g., (Supplementary Figure S16 in the Addition S2), and ash plumes spread for 840 km in various directions from the volcano (Table 2) [79,81]. From mid-May to the end of June, the dome was in a state of relative rest; the temperature of the anomaly decreased to the background values (see Methods) (Figure 5a). Since the beginning of July, the extrusion process has intensified up to mid-September, when a new block of lava began to be extruded in the northern part of the lava dome, e.g., Supplementary Figure S17 in the Addition S2; this was accompanied by the collapse of hot avalanches, e.g., Supplementary Figure S18 in the Addition S2 (Figure 5b); the temperature of the anomaly was high all this time (Figure 5a) [81,82]. By 6 December 2015, the VTDAB had reached 100 °C, and it stayed the same until mid-October 2016, which indicates that magmatic matter was constantly coming to the earth's surface all this time.

Table 2. Strong explosive events of the Sheveluch volcano in 2015–2022 according to satellite data.

Date of Explosive Event	UTC	Ash Altitude, km	Length, km	Direction of Ash Plume
7 January 2015	01:42	9	325	NW
12 January 2015	15:42	7	178	WSW
15 January 2015	18:06	10	180	W
26 January 2015	06:28	10	360	ESE
1 February 2015	15:12	10.5	780	ENE
8 February 2015	04:33	7	180	NW
17 February 2015	18:30	8	840	SE
28 February 2015	01:10	10	460	ENE
4 March 2015	00:53	7	607	NE
8 March 2015	04:20	7.5	790	E
16 March 2015	15:00	7.5	190	SE
21 March 2015	04:30	7	225	NE
26 March 2015	00:17	8	610	SW
7 April 2015	14:20	12	430	NE
12 April 2015	04:23	7	480	E
15 April 2015	03:14	7	216	E
9 January 2016	21:53	7	190	W
10 October 2016	20:42	7	55	E
14 October 2016	05:22	7	206	NW
17 October 2016	02:45	7	60	W
9 December 2016	21:40	12	910	NNE
16 December 2016	23:20	7.5	190	W
19 December 2016	07:52	9	315	NE
24 December 2016	04:20	7	60	SW
30 December 2016	15:55	7	100	NE
31 December 2016	07:14	8	100	N
4 February 2017	23:00	7	112	NW
2 May 2017	23:30	9	342	NW
11 May 2017	20:30	10	980	NW
16 May 2017	07:44	11	146	E
24 May 2017	20:30	10	544	ESE
31 May 2017	02:30	8	650	SW
3 June 2017	01:00	8	1300	SE
7 June 2017	02:30	7.5	338	SW
8 June 2017	00:20	8	1554	SW
10 June 2017	02:12	8	328	SW
11 June 2017	04:50	7	466	SW
14 June 2017	16:30	12	3000	N, E
18 June 2017	16:59	10	1430	SE
27 June 2017	01:20	7	1380	SE
23 July 2017	18:00	12	1400	E
8 August 2017	16:31	10	530	S
7 September 2017	13:30	8.5	115	SE
7 September 2017	21:30	8	1666	E
8 September 2017	10:35	9.5	240	N
11 September 2017	19:09	9	210	E
12 September 2017	20:27	9.5	113	SE
13 September 2017	00:30	9	390	SE
11 October 2017	00:01	10	252	N
2 November 2017	06:00	9	995	NE
7 November 2017	19:10	9.6	990	ENE
4 December 2017	21:06	10.5	500	ENE
26 December 2017	02:10	8	302	NE
9 January 2018	22:40	11	2000	E
26 December 2018	20:30	12	420	NW
29 December 2018	21:30	8	400	SW
30 December 2018	00:50	12	340	SE

Table 2. *Cont.*

Date of Explosive Event	UTC	Ash Altitude, km	Length, km	Direction of Ash Plume
9 January 2019	23:50	7	528	W
10 January 2019	07:50	7.5	110	W
9 March 2019	05:55	12	380	N
5 April 2019	22:30	7.5	550	NW
10 April 2019	04:40	10	1280	S
29 August 2019	05:54	11	520	SW
30 August 2019	07:57	7.5	125	SE
26 September 2019	21:20	7	170	SE
2 October 2019	00:05	9	1400	E
6 October 2019	01:36	11	1100	ENE
13 October 2019	12:50	7	400	ENE
21 October 2019	12:30	11	1234	SE
3 November 2019	05:10	10	640	WNW
5 November 2019	19:20	7	500	WNW
11 November 2019	18:53	10	1300	SE
8 April 2020	19:30	10	530	SE
22 December 2020	00:20	8	623	ESE
29 December 2020	00:10	7	254	W
9 April 2022	11:00	12	1980	NE
19 June 2022	20:47	7	255	NE
7 November 2022	07:20	7	60	N
16 December 2022	00:20	8.5	110	NE

By mid-March 2016, the northern block of the dome was covered by lava flows, e.g., Supplementary Figure S19 in Addition S2. Against the background of the growth of the lava dome and the collapses of hot avalanches, single explosions were observed from January to April with the removal of ash up to 7 km a.s.l. (Table 2); however, in May–August only gas-steam activity of the dome was noted [27]. On 18 September 2016, high explosive activity caused the collapse of large lava blocks in the northwestern part of the lava dome, e.g., (Supplementary Figure S20 in Addition S2). As a result, deposits of pyroclastic flows up to 10 km long were formed in the central part of the volcano's southern slope and along the Baidarnaya riverbed [83]. Explosions were observed almost weekly from mid-September to the end of December, e.g., (Supplementary Figure S21 in the Addition S2) (Table 2, Figure 5b). For example, on 9 December, the eruptive column rose to 12 km a.s.l., and on 9–10 December, the ash plume extended for 910 km to the north-northeast of the volcano.

During January–May 2017, the VTDAB stayed at 80–90 °C, then it began to slowly decrease (Figure 5a), and by mid-February 2018, the activity of the volcano dropped to the background level (see Methods). The strongest explosive events with the rise of eruptive columns up to 8–12 km a.s.l. occurred from May to December 2017 (Table 2, Figure 5b). Examples of such explosions are the events on 14 June 2017 [84] and 4 December 2017 (Supplementary Figure S22 in Addition S2). During explosive events on 16 May, 14–18 June, and 27 June, the pyroclastic flows deposits were formed. In 2017, the greatest extent of ash clouds and plumes was noted in June, July, and September (Table 2).

On 11 June 2017, an unusual meteorological situation was observed in the south of Kamchatka: the Sheveluch ash plumes moved over the area of the Elizovo airport in the form of several strips. Due to that, two flights SU1730 and PL6385, en route from Moscow to Petropavlovsk-Kamchatsky, were delayed [85].

A powerful explosion with ash removal up to 11 km a.s.l. was observed on 9 January 2018 (Table 2, Figure 5b). The ash plume moved over 2000 km to the northeast and then to the east of the volcano. Because of the cyclone, the ash plume turned towards the Kamchatka Peninsula, and two ash fall bands passed over the Commander Islands, both

associated with one explosive event. From 10 February to 1 November 2018, the volcano was in a state of relative rest [86].

From mid-December 2018, the temperature of the thermal anomaly began to rise sharply, and the VTDAB reached 119 °C by the end of the month (Figure 5a). This indicated an intensification of the extrusive volcanic eruption associated with the influx of fresh magmatic matter to the earth's surface. An activation of the growth of the lava dome was accompanied by strong explosive events on 26, 29, and 30 December with the rise of eruptive columns up to 8–12 km a.s.l., e.g., (Supplementary Figure S23 in the Addition S2), ash clouds, and plumes stretching for 2000 km in various directions from the volcano. The VTDAB was in the range of 100 to 119 °C until 1 May 2019, that is, at that time, the extrusion process was the most powerful (Figure 5). Strong explosive events with ash removal up to 9–12 km a.s.l. took place on 9 March, 10 April, 29 August, 2, 6 and 21 October, and 3 and 11 November 2019, e.g., (Supplementary Figure S24 in the Addition S2) (Table 2, Figure 5b). During the 10 April explosive event, an ash plume extended over 1200 km south of the volcano. On the territory of the Kamchatka Peninsula, a strip of ash 55 to 85 km wide and 240 km long stayed on the snow for a long time, e.g., (Supplementary Figure S25 in the Addition S2). As a result of strong explosions on 29 August 2019, with ash removal up to 11 km a.s.l., a field of pyroclastic flow deposits was formed on the southeastern slope of the volcano, covering an area of about 10 km^2 [87]. Although the temperature of the anomaly decreased by August, the VTDAB did not drop below 75 °C (Figure 5). From the beginning of September 2019, the temperature of the anomaly began to rise again, and the VTDAB was close to 100 °C from the beginning of October 2019 until 10 November 2020 (Figure 5a).

The unique phenomenon of the Sheveluch volcano was observed in 2020: from late April to early May, a plastic block of lava began to be extruded in the eastern part of the lava dome. By 11 June, it rose above the dome by 50–80 m, by 30 September by 100 m, and by 14 October, its size reached 170 × 100 m. The roundness of the outlines of the lava block was first noted on 6 June; and smooth surfaces of the lava block were observed on 28 September (Supplementary Figure S26 in Addition S2). This lava block was named "Dolphin" [88]. On 31 October, fissures were noted on the lava block, and it collapsed by 8 December 2020 (Supplementary Figure S27 in Addition S2). The collapse of the upper part of the "Dolphin" occurred without explosive events, probably due to the deflux of lava from its base. The explosive events in 2020 were recorded on 8 April (up to 10 km a.s.l.) and 22 and 29 December (up to 8 km a.s.l.) [89], that is, they occurred before and after the end of the extrusion of a plastic lava block.

From 29 December 2020 to 5 May 2021, the VTDAB averaged 75 °C (Figure 5a). On 14 February 2021, on the site of the southern wall of the destroyed "Dolphin", a new plastic lava block, named "Dolphin-2", began to rise; by 21 March, its height above the dome exceeded 50–60 m [88,90]. That is, there was a resumption of lava extrusion through the "Dolphin" channel. On 15 May, the height of "Dolphin-2" was 150 m (Supplementary Figure S28 in Addition S2). The afflux of juvenile matter increased, resulting in an increase in the temperature of the anomaly (Figure 5a). By 15 June, the height of "Dolphin-2" had reached 200 m. A fissure with intense steaming was observed on its surface, which may have appeared on 13 June during a strong explosion that raised the ash up to 5 km a.s.l. By 23 June 2021, the number of fissures on the surface of "Dolphin-2" increased, it began to collapse, and the VTDAB also gradually decreased to 75 °C (Figure 5a). Starting from 28 July 2021, the VTDAB increased again to 95–99 °C and stayed above 75 °C until 23 January 2022 (Figure 5a). At that time, an intensive growth of a hard lava block was observed in the southern part of the dome, which was accompanied by almost continuous collapses of hot avalanches from its slopes, e.g., (Supplementary Figure S29 in Addition S2) [91]. Subsequently, the VTDAB gradually decreased to 50 °C until mid-June 2022 (Figure 5a).

Against the background of predominantly gas-steam activity of the lava dome, on 9 April 2022, explosions raised ash to 12 km a.s.l. and on 19 June to 7 km a.s.l., e.g., (Supplementary Figure S30 in the Addition S2) (Table 2) [92]. Since mid-June, the temperature of the anomaly in the area of the lava dome began to rise, which indicated

the resumption of an active extrusive process in the southern part of the dome, e.g., (Supplementary Figure S31 in the Addition S2). By 7 July, the VTDAB had increased to 97 °C; by 21 October it exceeded 100 °C. By 10 December, the VTDAB had reached 114 °C and stayed at this level until the end of 2022 (Figure 5a). By mid-September, the extrusive process in the southern part of the dome changed to an effusive one; by mid-October, lava flows blocked the southern part of the dome, e.g., (Supplementary Figure S32 in the Addition S2). In November, the number of hot avalanches increased. Under the action of extrude new lava blocks in the central part of the dome, the frontal lava flows gradually collapsed. Explosions raised ash up to 8.5 km a.s.l. on 16 December (Figure 5b), and the growth of the lava dome continued uninterrupted until the end of 2022, e.g., (Supplementary Figure S33 in Addition S2).

4.2. Bezymianny Volcano Activity in 2015–2022

The Bezymianny is one of the most active volcanoes in the world, located in the central part of the Klyuchevskaya group of volcanoes in Kamchatka (Figures 1 and 2). The composition of its products is andesite. After the catastrophic eruption on 30 March 1956 [16,17], the growth of the extrusive dome in its explosive crater occurred almost continuously [10,19,93,94]. In 1977–1984, the explosive phases of the Bezymianny eruptions ended in effusive ones: the extrusion of lava flows onto the slopes of the dome, which lasted up to several months. After the strong explosive eruption in July 1985, the lava flow was extruded onto the northeastern slope of the dome for 4 years [19]. Hereinafter, explosive eruptions and subsequent extrusion of lava flows began to be registered again. In January 2005, a deep crater formed at the top of the lava dome [22,95], and that crater remained the same after the strong explosive eruptions of the volcano in 2006–2012. By 2012, lava had armored all the slopes of the dome. From December 2012 to December 2016, the volcano was in a state of relative dormancy, probably due to the high effusive activity of the basaltic volcanoes of the Klyuchevskaya group: the Tolbachik (the Tolbachik fissure eruption in name of the 50th anniversary of IVS FEB RAS: from 27 November 2012 till 15 September 2013), and the Klyuchevskoy (the eruptions from 1 September 2012 till 15 January 2013; from 15 August till 15 December 2013; from 1 January till 24 March 2015; and from 3 April till 6 November 2016) [96]. In 2016–2022, there were ten explosive eruptions at Bezymianny volcano (Figure 6b, Table 3).

Table 3. Parameters of the Bezymianny explosive eruptions in 2015–2022 according to satellite data.

Date of Explosive Paroxysm	UTC	Ash Altitude, km	Length of Ash Plume, km	Direction of Ash Plume	Maximal VTDAB, °C	Days before Previous Paroxysm
15 December 2016	10:00	4	120	W	106.4	1566
9 March 2017	03:23	8	442	NW	104.6	83
16 June 2017	04:53	12	620	E	cloudy	98
20 December 2017	03:40	15	320	NE	56, cloudy	188
20 January 2019	16:10	11	870	NW	83.9	394
15 March 2019	17:30	15	1300	E	117	63
21 October 2020	20:22	11	1160	SE	72.9	584
15 March 2022	12:53	12	1310	ENE	105.5	509
28 May 2022	08:15	15	3040	SE	101	72
23 October 2022	11:40	10	1860	NE	110	147

In 2015–2016, moderate fumarole activity in Bezymianny was observed, and a weak thermal anomaly was constantly recorded on satellite images in the area of the volcano. The VTDAB of this period has been taken as "the background of activity on the volcano" (see Methods). On 26 August 2016, an extrusive body was discovered in the northeastern part of the volcano crater; a month later, the extrusion rose above the edge of the dome [97]. Since 10 December 2016, the temperature of the anomaly has begun to rise; that is, the intensity of the extrusive process in the crater of the volcano has increased, and an explosive volcanic eruption is expected soon.

On 15 December 2016, a gas-steam column with some amount of ash lifted up to 4 km a.s.l. and a plume stretched for 120 km to the west of the volcano. The VTDAB reached 106.4 °C during this event (Figure 6a). On 15–23 December, lava flow extruded onto the southern slopes of the dome, accompanied by powerful gas-steam activity, the glow of the volcano top, and hot avalanches on the eastern slope of the dome. By the end of the year, the eastern part of the dome was covered with snow, and the activity of the volcano had dropped to background levels (see Methods). On 20 January 2017, a powerful lava flow 500 m wide, 570 m long, and with a total area of 0.21 km^2 was noted in the Geoton-P image (Resurs-P1 data from the VolSatView) [97]. On 5–13 February 2017, a growth in the temperature of the anomaly resumed; at that time, a flow of low-viscous lava was noted on the southern slope of the dome. For example, according to MSI (Sentinel-2A) satellite data for 12 February 2017, flow parameters were as follows: the length—550 m, the width—up to 120 m, a thickness of about several meters, and an area of about 0.06 km^2 [97]. The effusing of two flows of low-viscous lava continued onto the western slope of the lava dome until the end of February 2017.

In 2017, there were three powerful explosive eruptions of the volcano. According to satellite data, the first explosive eruption began on 9 March 2017, e.g., (Supplementary Figure S34 in Addition S3). Five large explosions occurred from the volcano crater with ash rising to 7–8 km a.s.l. (Table 3, Figure 6b). The ash plume was moving to the northwest from the volcano [97]. The VTDAB reached 104.6 °C during this event (Figure 6a). Immediately after the explosions, a lava flow began to be extruded onto the slope of the dome; that was confirmed by the bright glow of the volcano at night, and the VTDAB reached 71.5 °C (Figure 6a). As of 16 March, lava was being extruded at a rate of about 0.2 m^3/s [97]. In April and May, the volcano was relatively quiet; however, the thermal anomaly continued to be recorded over the lava dome, and the VTDAB reached 39 °C (Figure 6a). During 12–15 June 2017, there was a slight increase in the temperature of the thermal anomaly over the volcano (Figure 6a), as well as an increase in the number of hot avalanches and a gas-steam activity [98]. The explosive eruption with the rise of an ash cloud up to 12 km a.s.l. started at 04:53 UTC on 16 June (http://www.kscnet.ru/ivs/kvert/van/?n=2017-138, accessed on 10 July 2023). According to the data from the Himawari-8 satellite, the area of the eruptive cloud increased from 05:00 to 21:00 UTC on 16 June from 103 to 65,065 km^2, and the ash plume extended eastward from the volcano [84,85]. It should be noted that due to dense cloudiness in the area of the Klyuchevskoy group of volcanoes, this explosive event did not result in a sharp increase in the VTDAB (Figure 6a). In June–September 2017, a glow was constantly observed in the area of the volcano at night, and a bright thermal anomaly was recorded on satellite images (the VTDAB reached 73.6 °C) (Figure 6a), i.e., a lava flow extruded onto the northwestern slope of the dome. In October–November, the temperature of the anomaly dropped slightly; however, the VTDAB was above 30 °C (Figure 6a). Since 14 December 2017, a gradual increase in the temperature of the anomaly in the area of the volcano, its relatively powerful gas-steam activity, as well as the glow of the lava dome top at night, have been recorded. At 03:40 UTC on 20 December, a powerful explosive eruption occurred, carrying ash up to 15 km a.s.l. [99]. During the eruption from 03:40 to 07:20 UTC on 20 December, more than five large explosive events occurred, accompanied by the formation of deposits of pyroclastic and mud flows in the Vostochnaya valley and on the northern slope of the volcano, e.g., (Supplementary Figure S35 in Addition S3). It should be noted that this explosive event, such as the previous one, did not result in a sharp increase in the VTDAB (Figure 6a). The reason is the daytime of the eruption as well as the powerful ash clouds that covered the dome of the volcano. For example, from the beginning of the eruption until 09:00 UTC on 20 December, the area of the ash cloud increased from 72 to 42,000 km^2, and the ash plume extended northeast of the volcano [99]. After the end of the eruption, a bright thermal anomaly was recorded over the volcano for several months, and new lava flows continued to be extruded onto the northern and northwestern slopes of the dome.

A new extrusive body in the volcano crater was discovered on 9 July 2018, e.g., Supplementary Figure S36 in Addition S3). Moderate gas-steam activity of the volcano was constantly observed; a thermal anomaly was noted in the area of its summit; the VTDAB exceeded 30 °C, sometimes reaching 44.7 °C (Figure 6a).

In 2019, two powerful explosive eruptions of the volcano occurred [87]. No significant increase in the temperature of the anomaly in the area of the Bezymianny in January was noted; however, on 20 January at 16:10 UTC, the explosions sent ash up to 11 km a.s.l., and the ash plume moved to the northwest of the volcano, e.g., (http://www.kscnet.ru/ivs/kvert/imgs/2409.gif, accessed on 10 July 2023) (Table 3) [87]. After the end of the explosive eruption, lava flows continued to be extruded onto the southern and southwestern slopes of the dome. The temperature of the anomaly in the volcano area was constantly high; the VTDAB exceeded 45 °C (Figure 6a). In the last week of February, the activity of the volcano began to increase again: the glow of the volcano was observed at night, and hot avalanches collapsed from the dome. A strong explosive eruption began at 17:30 UTC on 15 March: the VTDAB reached 117 °C (Figure 6a). Explosions raised ash to 15 km a.s.l., and a huge ash cloud was moving northeast of the volcano, e.g., (Supplementary Figure S37 in Addition S3) [100,101]. The explosive eruption continued, ash clouds rose to 5–6 km a.s.l., and ash plumes with a higher concentration of ash, compared to the first large explosions, moved to the east of the volcano. As a result of the eruption, deposits of pyroclastic flows 8–9 km long were formed on the eastern flanks of the volcano. After the end of the explosive eruption, lava flows began to extrude again on the western and northwestern slopes of the dome; the VTDAB exceeded 25–30 °C (Figure 6a). From 23 November to 23 December 2019, an intensification of an effusive eruption was registered: the VTDAB reached 76.4 °C (17 December), but no explosive events were noted.

From mid-February until 30 April 2020, the VTDAB rose to 46.8 °C (27 March) and then did not drop below 30 °C (Figure 6a). It is likely that the sharp increase in the temperature of the anomaly is associated with the arrival of higher-temperature portions of the lava flow to the surface of the dome. Since 26 July, hot avalanches began to be observed on the eastern slope of the lava dome; on 26 August, a block of plastic lava was found in the lava dome crater, e.g., (Supplementary Figure S38 in Addition S3). From 25 September, the temperature of the anomaly began to rise, and occasionally small hot avalanches were observed on the eastern slope of the dome. Observations of the preparation and development of the eruption were complicated by dense clouds covering Kamchatka for several weeks. A powerful explosive volcanic eruption with ash removal up to 11 km a.s.l. and the spread of ash plumes to the southeast of the volcano began at 20:22 UTC on 21 October 2020 [28,89,93]. The VTDAB was 72.9 °C at that time (Figure 6a). By 24 October lava had filled the crater of the dome, and two tongues of lava flow began to overflow onto its northern slope, e.g., (Supplementary Figure S39 in Addition S3). The effusion of lava flows on the dome slopes continued until March 2022, the VTDAB did not drop below 35 °C (Figure 6a). In the periods from 7 April to 22 May, and from 25 September to 1 November, as well as 30 December 2021, the VTDAB exceeded 49 °C (Figure 6a), probably due to the effusion of fresh lava onto the surface of the dome.

In 2022, three powerful explosive eruptions of the volcano occurred [92,94]. Since 9 March, satellite images have demonstrated an increase in the size and temperature of the thermal anomaly in the area of the dome; since 11 March, the number of hot avalanches on the southern and southeastern slopes of the dome has increased dramatically. Observations indicated an active extrusive process that precedes an explosive volcanic eruption. The explosive eruption with ash removal up to 12 km a.s.l. occurred at 12:53 UTC on 15 March: the VTDAB reached 105.5 °C (Figure 6a). An eruptive cloud was moving east-northeast of the volcano. Small deposits of pyroclastic flows were formed in the Vostochnaya and Yuzhnaya valleys. Since 15 March, lava flows have been extruded onto the southern and southwestern slopes of the dome, e.g., (Supplementary Figure S40 in Addition S3). The VTDAB exceeded 75 °C and reached 83.1 °C on 16 April (Figure 6a). From 20 May, hot avalanches began to be noted again on the eastern slope of the lava dome; their

number was increasing, and a new explosive eruption was being prepared. Since 27 May, avalanches have been collapsing from the dome almost continuously; ash clouds have risen up to 5 km a.s.l. and stretched southeast of the volcano. On 28 May at 07:26 UTC, the strong explosions raised ash up to 12 km a.s.l. and at 08:15 UTC to 15 km a.s.l. (http://www.kscnet.ru/ivs/kvert/van/?n=2022-47, accessed on 10 July 2023; http://www.kscnet.ru/ivs/kvert/van/?n=2022-48, accessed on 10 July 2023), e.g., (Supplementary Figure S41 in the Addition S3) [94]. On 28–30 May the ash plume moved to the southeast of the volcano (Table 3). Deposits of pyroclastic flows 7 km long were formed in the Vostochnaya and Yuzhnaya valleys. The extrusion of lava flows onto the southern and southeastern slopes of the dome continued until 20 September: on 28 May the VTDAB reached 101 °C; it decreased to 50 °C by the end of June and to 30 °C by mid-September (Figure 6a). From 21 September to 15 October, the activity of the volcano decreased to the background level; the VTDAB did not exceed 15.7 °C (Figure 6a). From 21 October, the activity of the volcano began to increase again; the temperature of the thermal anomaly in the area of the volcano began to rise gradually. On 22 October, a gas-steam column with a height of 2 km above the lava dome was observed for several hours. The strong explosive eruption of the volcano began at 11:40 UTC on 23 October: explosions sent ash up to 10 km a.s.l. (http://www.kscnet.ru/ivs/kvert/van/?n=2022-143, accessed on 10 July 2023), e.g., (Supplementary Figure S42 in Addition S3) [94], the VTDAB reached 110 °C (Figure 6a). The ash plume moved northeast of the volcano on 23–24 October (Table 3). Small deposits of pyroclastic flows were formed on the northern slope of the volcano, and mudflow deposits 15 km long were observed in the canyon of the Sukhaya Khapitsa River. After the end of the explosive eruption, the lava flow continued to be extruded on the southeastern slope of the dome until the end of 2022, sometimes accompanied by the collapse of hot avalanches. The VTDAB always exceeded 65 °C, sometimes reaching 79.8 °C (29 November) (Figure 6a).

4.3. Klyuchevskoy Volcano Activity in 2015–2022

The Klyuchevskoy volcano is one of the most active volcanoes in the world. It is a typical stratovolcano with a regular cone composed of lava flows and pyroclastic material of basalt and basaltic andesite composition. The productivity of the volcano reaches an average of 60 million tons per year [25,31,102]. The volcano is located in the northeastern part of the Klyuchevskaya group of volcanoes (Figures 1 and 2). The summit crater of the volcano, with a diameter of about 700 m, constantly changes its morphology both during eruptions (different depths of the crater, the presence of a different number of centers of removal of magmatic matter in it) and during periods of rest (magma outflow leads to the formation of a deep crater). The volcano is characterized by summit eruptions with the formation inside the crater of up to two cinder cones up to 50 m high and lava flows on its various slopes (mainly in the Krestovsky, Apakhonchichsky, or Kozyrevsky chutes) up to 3.5 km long, as well as by lateral breakthroughs at altitudes from 500 up to 4500 m with the formation of 1–10 cinder cones up to 100 m high and lava flows with a length of 11 km from the center of the eruption [25,31,102,103]. The duration of explosive-effusive eruptions reaches 1.5 years; information about them has been known since 1697 [31,102]. One of the results of the eruptive activity of Klyuchevskoy in the 20th–21st centuries is that by May 2011, the Krestovsky deep chute, which was formed during the 1944–1945 eruption, was filled with lava material [25,31,104].

In 2015–2022, there were five summit eruptions of the Klyuchevskoy volcano (from 1 January till 24 March 2015; from 3 April till 6 November 2016; from 2 March till 30 August 2017; from 1 November 2019 till 3 July 2020; from 30 September 2020 till 8 February 2021), and two lateral breakthroughs (from 26 April till 6 November 2016; and from 17 February till 20 March 2021) [10,25,27,79,84–87,89,103–109] (Figure 7).

After the end of the previous explosive-effusive eruption of the Klyuchevskoy in 2013, which lasted from 15 August to 15 December [25,104], the volcano was in a state of relative

rest until the end of 2014. In the last week of December 2014, the gas-steam activity of the volcano increased.

On 1 January 2015, a thermal anomaly was noted for the first time on satellite images in the area of the Klyuchevskoy crater. The VTDAB was 35.1 °C (Figure 7a). From that day on, the eruption developed rapidly: the VTDAB rose to 91 °C on 3 January and to 118 °C on 7 January (Figure 7a). According to ground-based observations, Strombolian-type activity occurred at that time: lava fountaining in the crater with the release of volcanic bombs up to 200–300 m above the crater rim, e.g., (Supplementary Figure S43 in the Addition S4) [80,104]. In the first days of the eruption, lava fountains were observed from the crater of the cinder cone, which formed on the top of Klyuchevskoy during previous eruptions. Later, bocca formed on the southeastern slope of the cinder cone, and two lava fountains and a lava flow covering the crater resulted in a sharp increase in the temperature of the anomaly, e.g., (Supplementary Figure S44 in Addition S4) (Figure 7a). According to video and satellite data, a lava flow began to pour out of the bocca of the summit cinder cone along the Apakhonchich chute onto the southeast slope of the volcano on 8–9 January; its length exceeded 2.5 km by 18 January, e.g., (Supplementary Figure S45 in the Addition S4) [104]. On 10 January, ash appeared in the gas-steam plumes (Figure 7b). The paroxysmal phase of the Vulcanian-type eruption began on 15 February: explosions sent ash up to 8 km a.s.l. during five hours, and ash plumes drifted for about 1000 km mainly to the southeast of the volcano, e.g., (Supplementary Figure S46 in the Addition S4) (Table 4) [80,104]. In the following days, the rise of ash clouds did not exceed 5.5 km a.s.l. (Figure 7b). The VTDAB was above 75 °C until 24 February (Figure 7a). In the last week of February, the activity of the volcano slightly decreased; ash plumes did not rise above 5 km a.s.l. [104]. Since 25 February, the temperature and size of the thermal anomaly in the area of the volcano crater have begun to decrease (Figure 7a). From 26 February, the VTDAB did not exceed 50 °C, and it dropped to the background level by 24 March (Figure 7a). Ash plumes were last recorded on 10 March; however, gas-steam plumes containing a small amount of ash were observed on 16–17 and 22–23 March. We considered that the explosive eruption of Klyuchevskoy finished on 24 March [104]. Until the end of 2015, there were several episodes when the VTDAB exceeded the background level: up to 30.4 °C on 13–17 April, up to 68.9 °C on 1–13 May and up to 34.6 °C on 9 September–11 October (Figure 7a). Probably, the changes in temperature of the thermal anomaly were associated with the uneven lowering of magma through the channel deep into the volcano edifice. High fumarole activity on the volcano was observed at that time almost constantly.

At the beginning of 2016, Klyuchevskoy was relatively quiet; a weak thermal anomaly was sometimes observed in the area of the crater, associated with its gas-steam activity. The VTDAB did not exceed 31.7 °C (Figure 7a). The explosive volcanic eruption began on 3 April: Strombolian-type activity (lava fountaining in the summit crater) was visually observed, e.g., (Supplementary Figure S47 in the Addition S4) [27,105]. From 5 April, the temperature of the thermal anomaly began to rise: the VTDAB reached 84.1 °C on 8 April, and 105.7 °C on 9 April (Figure 7a). The Vulcanian phase of the eruption began at 14:35 UTC on 23 April: explosions sent ash up to 8 km a.s.l. (Table 4); the front of the ash plume was approximately 460 km southwest of the volcano at 02:28 UTC on 24 April according to satellite data. The effusive phase of the eruption began on 23–24 April: a lava flow was effusing from the summit crater of Klyuchevskoy along the Apakhonchich chute on the southeastern slope of the volcano, e.g., (Supplementary Figure S48 in the Addition S4). The lava flow was approximately 0.5 km long by 25 April [27,105]. The VTDAB has been above 100 °C from 9 April till 31 October (Figure 7a).

A new event occurred on 26 April 2016: there was the formation of a new vent (a lateral breakthrough) at a height of 4.3–4.4 km a.s.l. into the Apakhonchich chute, accompanied by a sudden spike of intensity in the thermal anomaly in the volcano area. The VTDAB reached 113 °C (Figure 7a). A cinder cone began to grow over the vent discharging lava flows, e.g., (Supplementary Figure S49 in Addition S4) [27,105]. A unique event occurred on 3 May 2016 (Supplementary Figure S50 in the Addition S4). This was the formation of

a collapse cirque in the upper part of the Apakhonchich chute that was similar to one in 1945 in the Krestovsky chute [31]. However, the cirques were different: in 1945, the rocks that composed the wall of the summit crater collapsed in, thus making the crater 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 for several months; for example, the strong collapse was observed on 18 July, with the volcanic dust due to avalanches rising 1 km above the volcano slope [27,105].

Table 4. Strong explosive events at the Klyuchevskoy volcano in 2015–2022 according to satellite data.

Date of Explosive Event	UTC	Ash Altitude, km	Length of Ash Plume, km	Direction of Ash Plume
15 February 2015	03:24	8	1000	SE
1 March 2015	02:30	7	450	SE
23 April 2016	14:35	8	522	SW
6 July 2016	10:40	7.5	400	E
9 August 2016	17:55	7	264	ESE
7 September 2016	03:29	7.5	40	ESE
15 September 2016	21:40	7	40	NE
20 September 2016	21:27	8	50	ENE
14 October 2016	04:32	7	40	NW
21 October 2016	01:11	7	60	NW
30 October 2016	00:36	8	60	NE
2 March 2017	02:05	9	25	NE
29 March 2017	20:58	7.5	312	SE
30 March 2017	03:20	7	65	NNW
23 April 2017	21:07	7	72	WSW
6 May 2017	04:31	8	85	E
10 June 2017	00:23	7	162	WSW
11 June 2017	21:20	7	584	ESE
12 June 2017	05:35	8	130	SE
15 June 2017	06:40	7	85	WSW
17 August 2017	22:03	7	55	NW
20 August 2017	04:42	7	252	WNW
21 December 2017	04:16	7	68	E
6 January 2018	01:33	7	20	SW
14 May 2018	16:00	10.5	45	NE
13 April 2020	02:17	7	155	SE
30 April 2020	21:50	7	210	NW
18 November 2020	21:00	7.5	50	S
19 November 2020	00:38	7	104	SE
29 November 2020	20:50	7	50	NE
5 December 2020	02:10	7	103	NE
20 December 2020	21:50	7.5	154	SSE
18 January 2021	11:20	7.5	490	W
24 January 2021	06:00	9.6	42	NNE

The Strombolian activity of the summit crater and lateral cone named after the volcanologist E.K. Markhinin continued, and the number of lava flows increased. Lava filled the bed of the Apakhonchich chute and poured over its sides; e.g., (Supplementary Figure S51 in Addition S4), the temperature of the thermal anomaly was constantly high (Figure 7a). Since mid-August, lava flow began to run 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 summit during the last 10–15 years, e.g., (Supplementary Figure S52 in the Addition S4). This lava flow continued running for one month and was no longer observed since September 20 [27,105]. There were occasionally increases in gas-steam activity and ash explosions from the summit crater; as an example,

ash plumes rose up to 5–6 km a.s.l. and extended for 90 km to the south and southeast from the volcano on 2–4, 13, and 16 May. Ash was almost continuously discharged from the crater in the second half of the year, rising to 7.5 km a.s.l. and extending for over 500 km (Figure 7b). The activity of the volcano significantly increased on 7 September, with the eruptive column rising up to 7.5 km a.s.l. and a dense ash plume extending to the east-southeast of the volcano (Table 4). On 8 September, the ash plume of the Klyuchevskoy volcano was observed above the Avachinsky and Koryaksky volcanoes at an approximate height of 4 km a.s.l.; it then moved toward the Avacha Bay and dispersed there [27,105]. The effusion of lava flows continued, e.g., (Supplementary Figure S53 in Addition S4). The VTDAB continued rising and reached 132 °C on 28 October (Figure 7a). The volcano activity began to decrease gradually; as an example, ash plumes extended for 120 km east from the volcano on 3–4 November. The lava stopped flowing on 3 November but the VTDAB was 76.2 °C. The VTDAB had a sudden drop to 27.4 °C on 4 November (Figure 7a), although some Strombolian activity was still observable in the Klyuchevskoy summit crater on 3–4 November. The eruption finished on 6 November [27,105]. However, until the end of the year, the VTDAB stayed above 50 °C (Figure 7a), this was probably due to the cooling of a large volume of lava that erupted in 2016. Separate ash explosions were observed on 16 November, and 17 and 31 December.

The VTDAB decreased from 29.6 °C on 3 January to 10 °C by 7 August 2017, and stayed at this level until the end of 2017, sometimes reaching 34–35 °C (Figure 7a). Against the background of a gradual decrease in the temperature of the thermal anomaly, the irregular explosive activity of the volcano was noted all year, the main events of which occurred from 2 March to 30 August (Table 4) [106]. Ash plumes rose to 6–8 km a.s.l., e.g., (Supplementary Figure S54 in Addition S4), and extended more than 600 km to the different directions of the volcano. Unique events in the area of the Northern group of volcanoes of the Kamchatka were observed on 14–18 June 2017: against the background of a continuous moderately explosive eruption of the Klyuchevskoy volcano, a powerful paroxysmal event of the Bezymianny volcano, and six explosive events of the Sheveluch volcano (two of them powerful) [84].

The VTDAB almost did not exceed 10 °C in 2018; it was above 30 °C for four days only (Figure 7a). The moderate explosions of the volcano sent ash up to 5–6 km a.s.l. on 1–18 January, 8 May, and 6 and 15 June 2018. The event associated with the collapse of pyroclastics from the walls of the Apakhonchich chute and the rise of ash up to 10.5 km a.s.l. occurred on 14 May (Table 4). Ash plumes extended over more than 300 km in the eastern and southwestern directions from the volcano [86]. According to the low temperatures of the thermal anomaly observed in the area of the volcano summit in 2017–2018, we suggest there was no juvenile matter in the explosions (Figure 7a). The explosive activity of the volcano was probably associated with the uneven lowering of magma through the channel deep into the volcano's edifice.

The VTDAB was not above 16 °C from 1 January until 25 October 2019, except for 3 and 19 July, when the VTDAB rose to 50 °C (Figure 7a). Moderate ash explosions were observed in these days, e.g., (Supplementary Figure S55 in the Addition S4). According to the video data, the Strombolian activity of the volcano has been observed constantly since 14:09 UTC on 1 November. The VTDAB in the area of the Klyuchevskoy crater has shown stable growth since that day (Figure 7a). So, we consider 1 November 2019 to be the beginning of the explosive-effusive eruption in 2019–2020 [107]. In addition to episodes of Strombolian activity, the Vulcanian ones were also observed: explosions raised ash to 5.5 km a.s.l. on 11, 22, and 29–30 December, ash plumes stretched for 150 km in different directions from the volcano. In February–March 2020, the Strombolian activity of the volcano intensified: lava fountains reached 500 m above the crater with the spread of volcanic bombs along the slopes of the volcano below 3.5 km a.s.l., e.g., (Supplementary Figure S56 in the Addition S4). The VTDAB reached 106.4 °C on 28 January and 124 °C on 27 February 2020, and it was above 100 °C until 21 June 2020 (Figure 7a). In 2020, ash explosions were observed almost every day from January until June [107]. Explosions raised ash mainly to 5.5 km a.s.l.,

sometimes up to 6 km a.s.l. (for example, on 2, 20, and 29 March; 9–10, and 13–16 March; 21–22 and 30 April; 10 and 28 May; and 9 June) (Figure 7b). The strong explosive activity of the volcano was noted on 13 and 30 April: ash rose to 7 km a.s.l. (Table 4) [107]. The lava flow from the summit crater of the volcano began to effuse on 18 April 2020. The wall of the crater began to collapse under the pressure of lava at 07:42 UTC on 18 April, and lava gushed out into the Apakhonchich chute on the southeastern slope of the volcano. Pyroclastic masses began to collapse from the slopes of the chute, and a dense ash cloud was forming over the volcano, where resurgent ash predominated in composition, e.g., (Supplementary Figure S57 in the Addition S4). On 12–14 May the lava flow migrated to the northern side of the chute, and deposits of the lava flows of 2020 partially covered those of 2016, e.g., (Supplementary Figure S58 in Addition S4). Collapses of pyroclastics from the right side of the chute, phreatic explosions, and mud flows accompanied the movement of the lava flow until the end of the volcanic eruption. The VTDAB decreased rapidly from 97 °C on 1 July to 16.8 °C on 3 July, when the lava stopped flowing (Figure 7a). Although the VTDAB rose to 40.4 °C on 6 July, we consider 3 July as the end of the eruption [107].

The VTDAB stayed below 25 °C from 30 July to 29 September 2020 (Figure 7a). The new summit eruption of the volcano began on 30 September 2020 and ended on 8 February 2021 [103]. On September 30, a sharp increase in the temperature of the thermal anomaly was noted in the area of the volcano crater. The VTDAB increased from 7.5 °C on 29 September to 34.4 °C on 30 September, to 86.5 °C on 2 October, and to 102.2 °C on 3 October (Figure 7a). The VTDAB was above 100 °C from 3 October 2020 to 5 February 2021 (Figure 7a). Strombolian-type activity on the volcano occurred all the time during the eruption [103]. From 4 October, a lava flow began to move along the Apakhonchich chute on the southeastern slope of the volcano; its length was 2.8 km by 10 November 2020, e.g., (Supplementary Figure S59 in the Addition S4) [103]. Since 8 October, Vulcanian-type activity has occurred from time to time: explosions sent ash mainly up to 6 km a.s.l. An increase in the explosive activity of the volcano was observed on 18 November and 20 December 2020, and 18 January 2021: ash clouds rose up to 7.5 km a.s.l. (Table 4) [103]. The lava flows moved from the summit crater of the volcano along the Apakhonchich chute from 4 October to 8 December 2020. From 7 December 2020 to 28 January 2021, lava also effused along the Kozyrevsky chute on the southwestern slope of the volcano, e.g., (Supplementary Figure S60 in Addition S4), on 4 January, the length of lava flows was 1.7 km. From 22 January to 8 February 2021, the lava flows moved again along the Apakhonchich chute, e.g., (Supplementary Figure S61 in Addition S4). Because lava flows effused continuously during the eruption, a large, bright thermal anomaly was constantly recorded in the area of the volcano. The VTDAB reached 124–127 °C on 10, 12, and 24, December 2020, 3, 12, 15, and 21, January and 5 February 2021 (Figure 7a). The area of lava flow deposits was about 0.5 km^2 [103].

During the eruptions of the Klyuchevskoy volcano in 2016–2020, due to the effusions of numerous lava flows, the Apakhonchichsky chute deepened and expanded more and more, glaciers and snowfields buried in the pyroclastic strata were exposed, and their contact with new lava flows led to phreatic explosions and collapses of tephra deposits from the chute boards. For example, as a result of a phreatic explosion on 6 October 2020, a gas-steam column with ash rose from the slope of the volcano to 5 km a.s.l. and up to 6 km a.s.l. on 23 January 2021 [103]. The most powerful collapses of tephra deposits from the boards of the Apakhonchich chute were observed at 05:38 UTC on 24 January 2021: a dense ash cloud rose up to 9.6 km a.s.l. (Table 4), and moved northwest of the volcano, e.g., (Supplementary Figure S62 in Addition S4). By 06:00 UTC this day, the ash cloud had descended to 5 km a.s.l. The eruption of the Klyuchevskoy volcano had suddenly finished on 8 February: since explosive events were not registered on this day, the effusion of lava flows stopped [103]. The VTDAB was 124 °C on 5 February, 47.8 °C on 6 February, and 43.2 °C on 8 February (Figure 7a). The VTDAB stayed high.

On 17 February 2021, between 23:00 and 24:00 UTC, a lateral breakthrough named after volcanologist G.S. Gorshkov occurred on the northwestern slope of the volcano, e.g.,

(Supplementary Figure S63 in Addition S4) [103,108,109]. Lava effused from two parallel fissures of northwest strike, at an altitude of 2800 m. The VTDAB reached 118 °C on 20 February, 124 °C on 24 February, and 127 °C on 8 March (Figure 7a). Due to the explosive activity of the Strombolian type, a cinder cone about 60 m high grew by 18 March, e.g., (Supplementary Figure S64 in the Addition S4) [109]. By 23 February, the 1.2-kilometer-long lava flows had reached the Erman Glacier. Along the Krutenkaya River, a mudflow began to pour out, the deposits of which formed an alluvial fan 2 km wide, 28–30 km from the volcano. The VTDAB from 100.8 °C on 20 March decreased to 68.1 °C on 21 March (Figure 7a). On 20 March, the explosive and effusive activity of the cone ended; that is, the eruption was finished. The lava flow area was 1.36 km^2 by 26 February [109]. The lava deposits gradually cooled: the VTDAB was above 50 °C until 6 April; it decreased to 25 °C by the end of November 2021 and to 10–12 °C by 10 May 2022 (Figure 7a). The VTDAB stayed at the level of the background activity of the volcano until 18 November 2022, when it increased from 14.9 °C to 42.4 °C (Figure 7a). The VTDAB reached 85.6 °C on 19 November, and 87.8 °C on 20 November. By 28 November, the VTDAB had dropped to the level of the background activity of the volcano and stayed the same until the end of 2022. Probably the sharp rise in the temperature of the thermal anomaly on 18–20 November is not associated with the eruption of new lava; however, it is associated with the uneven lowering of magmatic matter through the channel deep into the volcano edifice.

4.4. Karymsky Volcano Activity in 2015–2022

Karymsky is one of the most active volcanoes in Kamchatka [110]. It is situated in the middle of the Eastern Volcanic Zone of Kamchatka, approximately 115 km northeast of Petropavlovsk-Kamchatsky (Figures 1 and 2). This andesitic volcano had been in a state of uneven explosive eruption from January 1996 through the end of 2022. In 2015, the moderate explosive activity of the Karymsky volcano was registered throughout the year, e.g., (Supplementary Figure S65 in Addition S5). The thermal anomaly was noted almost all the time on satellite images in the area of the volcano crater. The VTDAB was mostly above 40 °C during the explosions; however, on 22 January and 25 March, it reached 81.2 and 67 °C, respectively (Figure 8a). The explosions send ash mainly up to 3–5 km a.s.l., and on 15 and 30 November up to 7–7.5 km a.s.l. (Table 5, Figure 8b). Ash plumes extended more than 300 km, mostly in the eastern direction of the volcano [79,80]. The explosive events occurred irregularly, with interruptions ranging from several days to a month. The highest intensity of the eruption was noted in January–April, July–August, and October–November; the temperature of the thermal anomaly and the extent of ash plumes had higher values at that time [80] (Figure 8a).

According to satellite and sporadic visual observations, the most intense activity was observed in January through February 2016, with ash rising mainly to 4-5 km a.s.l. and ash plumes traveling for about 300 km to the east of the volcano [27]. The VTDAB reached 67.7 °C on 6 January and 86.6 °C on 10 February (Figure 8a).

The Karymsky volcano was in a state of relative rest from 28 March 2016 to 17 May 2017, e.g., (Supplementary Figure S66 in Addition S5). The VTDAB matched the background activity of the volcano at that time (Figure 8a). The explosive activity of the volcano resumed on 3 June 2017 [85,106]. The VTDAB increased to 85.8 °C on 5 June (Figure 8a). A strong explosive event with ash rising up to 6 km a.s.l. occurred on 26 June. Subsequently, ash plumes rose mostly up to 4-5 km a.s.l. and extended more than 400 km in different directions from the volcano [85,106]. The 13 explosive events were registered during June–December, confirmed by satellite data [85]. The VTDAB was below 20 °C from 9 August 2017 to 18 January 2018 (Figure 8a). The strong explosive events were observed on 18 and 23 January 2018; the VTDAB was 61 °C and 56.8 °C, respectively (Figure 8a). Then the VTDAB was again below 20 °C until 13 May (Figure 8a). The explosions sent ash up to 6.5 km a.s.l. on 14 July (Supplementary Figure S67 in Addition S5), and on 22 July, and up to 6 km a.s.l. on 7 and 26 August, 10, 22, and 30 September, and 1 December 2018 (Figure 8b) [86]. The VTDAB reached 68.5 °C on 4 August 2018 (Figure 8a).

Table 5. Strong explosive events of the Karymsky volcano in 2015–2022 according to satellite data.

Date of Explosive Event	UTC	Ash Altitude, km	Length of Ash Plume, km	Direction of Ash Plume
15 November 2015	23:00	7	15	E
30 November 2015	03:55	7.5	80	ESE
8 November 2020	14:08	8	27	NE
9 December 2020	22:30	7.5	60	NW
3 April 2021	23:30	8.5	255	ENE
10 September 2021	15:10	7	75	E
3 November 2021	07:48	11	1250	E
6 November 2021	03:40	8	61	ENE
14 November 2021	03:30	7.5	22	NE
18 November 2021	09:00	8	368	NE
12 January 2022	12:00	7	172	W
14 April 2022	12:50	7	78	N
19 April 2022	20:10	11	2000	NE
28 April 2022	02:10	10	722	W
14 May 2022	01:08	8	264	ENE
18 May 2022	16:13	9.5	252	E
19 May 2022	00:37	8.5	463	ENE
13 July 2022	10:50	11	346	SW
31 July 2022	01:30	8	57	E

The volcano was in a state of relative rest from 1 January to 15 February 2019 [87]. The explosive activity of the volcano was occasionally recorded from 16 February to 23 August. Ash removal was noted mainly up to 2.5–3.0 km a.s.l. [87]; however, explosions sent ash up to 6 km a.s.l. on 14 August (Supplementary Figure S68 in the Addition S5) [28]. Ash plumes extended more than 450 km in different directions from the volcano [98]. The VTDAB reached 43.4 °C on 10 March, 46.2 °C on 20 May, and 68.3 °C on 21 August (Figure 8a). The volcano was in a state of relative rest from 22 August 2019 to 20 April 2020. The VTDAB was below the background activity of the volcano at that time, except on 4 March, when the VTDAB was 26.1 °C (Figure 8a).

In 2020, ash explosions were observed from one (in June) to seven (in October) days a month. The eruptive activity was observed from April until July and from October until December, e.g., (Supplementary Figure S69 in the Addition S5). The VTDAB reached 57.9 °C on 21 April, and 84.6 °C on 26 May; and the VTDAB was above 60 °C from 26 May till 29 July (Figure 8a). The volcano was quiet for the next two months and 20 days in October. The VTDAB increased to 40.5 °C on 21 October, to 71.8 °C on 8 November, and to 92.7 °C on 10 December (Figure 8a). According to the high temperature of the thermal anomaly of the Karymsky volcano, juvenile magmatic matter arrived on the earth's surface when the strong explosions sent ash up to 8 and 7.5 km a.s.l. on 8 November, and 9 December, respectively (Table 5). Ash plumes and clouds drifted for 380 km in the different directions of the volcano [89]. The VTDAB did not exceed 30 °C until the end of 2020.

In 2021, the VTDAB was 61.1 °C on 1 January and 52.5 °C on 23 January; it was below 20 °C from 2 February until 9 June (Figure 8a). The explosions raised ash to 6 km a.s.l. in January, April, and from June until December, e.g., (Supplementary Figure S70 in Addition S5). The strong explosive events of the volcano were observed on 3 April, 10 September, 6, 14, and 18 November (up to 7–8.5 km a.s.l.), and on 3 November (up to 11 km a.s.l.) (Table 5, Figure 8b). Ash plumes and clouds traveled over 2700 km in different directions from the volcano [90,91]. The VTDAB increased to 62.6 °C on 11 June, and it was again below 20 °C until 5 July (Figure 8a). The VTDAB was above 55 °C from 6 July till 18 September and then rapidly decreased to the background level and stayed the same until 22 October (Figure 8a). Probably, as a result of strong explosive events, the VTDAB increased to 102 °C on 10 November, that is, juvenile magmatic matter arrived on the earth's surface at this time (Figure 8a). We suggest that a series of powerful explosions that occurred in September and November indicate the destruction of the lava dome that formed in the crater of the

Karymsky volcano. The VTDAB did not exceed 20 °C from 18 December until the end of 2021.

In 2022, four periods of explosive activity on the volcano were observed: from 11 to 17 January with the removal of ash up to 7 km a.s.l.; from 17 April to 19 May: up to 11 km a.s.l.; from 13 to 15 July: up to 11 km a.s.l.; and from 27 July to 8 August: up to 8 km a.s.l. (Table 5, Figure 8b) [92]. The strongest explosive events occurred on 19 April and 13 July, e.g., (Supplementary Figure S71 in Addition S5). Due to the high cyclonic activity in the Kamchatka region, ash clouds from the Karymsky volcano were moved to the Arctic on 19–20 April [111]. Ash plumes and clouds drifted in different directions from the volcano at distances greater than 2000 km on 19–21 April, 1160 km in July and 550 km in August. Ashfall was noted in the vicinity of Elizovo airport on 13 July [92]. The VTDAB was below 35 °C from 1 January until 18 April, and it reached 91.9 °C on 22 April and 73.7 °C on 5 May (Figure 8a). The VTDAB did not exceed 25 °C from 26 May to 28 June, and it was below 31 °C until 12 July (Figure 8a). The VTDAB increased to 65.2 °C on 13 July, and it stayed above 60 °C till 6 August. The temperature of the thermal anomaly decreased to match the background activity of the volcano by 20 August, and the volcano was quiet until the end of 2022.

We suggest that long breaks in the 2020–2022 activity of the Karymsky volcano are associated with the growth of lava domes in its crater. Only powerful explosive events with ash removal up to 11 km a.s.l. could destroy the domes ("plugs") in the crater, which was observed. One of the confirmations of the existence of a dome in the crater of the volcano, for example, until July 2022, was that because of a series of explosions on 13 July, the operation of the seismic station located at the foot of the volcano was disrupted, and piles of lava blocks up to 1.5 m in size were observed near it [92]. When the crater of the volcano is open (not filled with a dome), explosions remove mainly ash, lapilli, and volcanic bombs not larger than 0.5 m in size.

4.5. Summary of Volcanoes Activity in 2015–2022

The extrusive-effusive eruption of the Sheveluch volcano lasted from 2015 to 2022, with a break of almost 9 months from 10 February to 1 November 2018. The VTDAB during the eruption mostly exceeded 80 °C. The resumption of the extrusive process was preceded by powerful explosions with the removal of ash up to 12 km a.s.l., while the VTDAB reached 119.1 °C (Figure 5a). The extrusive-effusive eruption of the volcano was often accompanied by strong and moderately explosive Vulcanian-type events (Figure 5b). In addition, the intensive growth of the dome was accompanied by the collapse of hot avalanches; the VTDAB reached 117 °C during such phenomena (Figure 5a).

It is known that the Bezymianny volcano is characterized by three phases of activity: extrusive, explosive, and effusive. In 2015–2022, the extrusive eruptions lasted up to 6 months with a gradual increase in the VTDAB from the level of the background activity of the volcano (20 °C) to 50 °C. During paroxysmal explosive eruptions lasting up to 6 h, the VTDAB exceeded 100 °C and reached 117 °C. The effusion of viscous lava flows onto the slopes of the dome lasted from 2 months to 1.5 years, and the VTDAB varied from 30 to 80 °C. One can note the constantly high VTDAB from October 2020 until the end of 2022 (with a tendency to gradually increase): probably, lava flows were effused onto the slopes of the lava dome almost continuously (Figure 6a). Against the background of the effusion of lava flows, explosive eruptions occurred to remove cooled lava from the volcano channel and open the way for new portions of juvenile magmatic matter.

In 2015–2022, there were five summit eruptions of the Klyuchevskoy volcano and two lateral breakthroughs, which ended on 20 March 2021. The summit eruptions of the volcano were represented by four explosive-effusive eruptions and one explosive eruption. All explosive-effusive eruptions of the volcano started with explosions of Strombolian-type. The Vulcanian-type explosions began from 8 to 149 days (in 2020–2021 and 2015, respectively) after the beginning of the eruptions. The effusion of lava flows started from 4 to 170 days (in 2020–2021 and 2019–2020, respectively) after the start of the eruptions.. When

the explosive eruption of Strombolian-type was observed, the VTDAB reached 80–106 °C; when lava flows moved along volcanic slopes in the time of summit eruptions or lateral breakthroughs, the VTDAB increased to 132 °C (Figure 7a). The explosive eruptions of Vulcanian-type sent ash up to 8 km a.s.l.; the VTDAB did not exceed 45 °C. The strongest rise of ash up to 10.5 km a.s.l. is associated with the collapse of pyroclastic masses from the walls of the Apakhonchich chute, not with the volcano eruption. The temperature of the thermal anomaly had not increased during those events. Note that the general overview of temperature changes in the thermal anomaly of the Klyuchevskoy volcano during 2015–2022 is similar to the one presented in [45]. However, the manual processing of satellite data allowed us to show the activity of the volcano in more detail.

The explosive activity of the Karymsky volcano occurred irregularly in 2015–2022 (sometimes the volcano was in a state of relative rest from several days to 13.5 months), with a tendency to increase the power of explosive events in 2020–2022 (Figure 8a). The maximal VTDAB was 102 °C on 10 November 2021, when the strong explosions produced juvenile magmatic matter on the earth's surface. Our data agrees with the data of the Karymsky volcano activity in 2005–2010 [73]: the temperature of the thermal anomaly has the highest values during the strongest ash explosions. We suggest that long breaks in the 2020–2022 activity of the Karymsky volcano are associated with the growth of lava domes in its crater. The powerful explosive events with the removal of ash up to 11 km a.s.l., which were observed after long breaks in the activity of the volcano, confirm our assumption that lava domes were located in its crater.

4.6. The Relationship of the Volcano Activity of the Northern Group of Kamchatka in 2015–2022

There is no constant correlation between the changes in the activity of the volcanoes in the Northern group of Kamchatka in 2015–2022. However, the following may be noted:

1. A vivid response to each other's explosive events was observed in June 2017 [96]. Against the background of moderate explosive activity of the Klyuchevskoy volcano with ash removal up to 7–8 km a.s.l. on 12–20 June, strong explosions of the Sheveluch volcano raised ash to 12 km a.s.l. on 14 June, strong explosions of the Bezymianny volcano also sent ash up to 12 km a.s.l. on 16 June, and then the explosions of the Sheveluch volcano raised ash to 10 km a.s.l. on 18 June (Tables 2–4). Similar events were observed in December 2017: the Bezymianny volcano explosions raised ash to 15 km a.s.l. on 20 December, the Klyuchevskoy volcano sent ash up to 7 km a.s.l. on 21 December, and the explosions of the Sheveluch volcano raised ash to 8 km a.s.l. on 26 December (Tables 2–4).
2. Paroxysmal explosive eruptions of the Bezymianny volcano occurred more often against the background of high activity at the Sheveluch volcano (for example, in 2016 and 2019–2020), but sometimes they happened against the background of a decrease in its activity (for example, on 15 and 28 May 2022). Explosive events of Bezymianny and Sheveluch with ash removal up to 4 and 7.5 km a.s.l. sometimes occurred close to each other: for example, on 15 and 16 December 2016, respectively (Tables 2 and 3).
3. The explosive eruption of the Bezymianny volcano sometimes began after the end of the explosive-effusive eruption of Klyuchevskoy (for example, on 15 December and 6 November 2016, respectively). Moreover, sometimes the explosive eruption of Bezymianny (on 21 October 2020) occurred against the background of the explosive-effusive eruption of Klyuchevskoy (from 30 September, 2020, to 8 February 2021). The cases of a simultaneous increase in the VTDAB for the Bezymianny and Klyuchevskoy volcanoes were registered, for example: the VTDAB was 27.4 and 40.6 °C, respectively, on 1 January 2016; it was 39.2 and 41.4 °C, respectively, on 3 January 2018; and it was 77.2 and 87.8 °C, respectively, on 20 November 2022 (Figures 6a and 7a).
4. Analysis of the data showed that during the eruption of the Klyuchevskoy volcano, the VTDAB of the Sheveluch volcano slightly decreased. The Sheveluch had the highest VTDAB when the Klyuchevskoy was quiet.

5. In 2017–2019, volcanoes of the Northern group of the Kamchatka were in a state of relative rest: the Sheveluch volcano—from 10 February 2018 to 1 November 2019; the Klyuchevskoy volcano − from 16 June 2018 to 13 June 2019; and the Bezymianny volcano—from 20 December 2017 to 20 January 2019. Therefore, all active volcanoes in the Northern group of Kamchatka were quiet from 16 June to 1 November 2018 (Figures 5–7).

5. Conclusions

In this paper, we have presented the thermal activity of the most active volcanoes in Kamchatka. Our study is based on the analysis of the Value of Temperature Difference between the thermal Anomaly and the Background (the VTDAB), obtained by manual processing of the AVHRR, MODIS, VIIRS, and MSU-MR satellite data in the VolSatView information system. Based on the VTDAB data, we determined "the background of activity of the volcanoes": 20 °C for the Sheveluch and Bezymianny, 12 °C for Klyuchevskoy, and 13–15 °C for Karymsky.

This study shows that the highest temperature of the thermal anomaly corresponds to the juvenile magmatic material that arrived on the earth's surface. The VTDAB of the basaltic andesite volcano Klyuchevskoy reaches 132 °C, that of the andesite and dacite volcanoes Bezymianny and Sheveluch reaches 119 °C, and that of the andesite volcano Karymsky reaches 102 °C.

A joint analysis of the dynamics of the eruption of each volcano and changes in its thermal activity allowed us to determine the range of the VTDAB for different phases of a volcanic eruption. For example, the VTDAB of the Bezymianny volcano eruption reaches 50 °C for the extrusive phase, 117 °C for the explosive phase, and 80 °C for the effusive phase.

All active volcanoes in the Northern Group of Kamchatka were quiet during the period from 16 June to 1 November 2018.

According to the low temperatures of the thermal anomaly observed over the Klyuchevskoy volcano summit in 2017–2018, we suggest that there was no juvenile material in the explosions. The explosive activity of the volcano in 2017–2018 was probably associated with the uneven lowering of magma through the channel deep into the volcano edifice.

The manual processing of the different recent satellite data (NOAA-N-Prime, Terra, Aqua, Suomi NPP, JPSS, Meteor M-2) allowed us to show the activity of the Kamchatkan volcanoes in more detail than it was done before.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs15194775/s1, Addition S1: To Figure 2, and to Section 3.1; Addition S2: Sheveluch volcano activity in 2015–2022; Addition S3: Bezymianny volcano activity in 2015–2022; Addition S4: Klyuchevskoy volcano activity in 2015–2022; Addition S5: Karymsky volcano activity in 2015–2022.

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