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Wave perturbations in the atmosphere accompanied the eruption of the Raykoke volcano (Kuril Islands) 21–22 June, 2019

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Abstract. Infrasound signals (IS), accompanied the most powerful episodes of the Raykoke volcano of the 21–22 June 2019, were registered by the network of observation stations, located at the distances of 335 to 974 km from the volcano. We identified IS of two frequency ranges: f = 0.08–0.5 Hz and f = 0.004–0.012 Hz. The first one was caused by magma fragmentation and non-stationary processes, appeared during the ash-gas mix outflowing from the crater. The second IS range is associated with an eruptive column forming and an eruptive cloud appearance. In this case the separate eruption episodes are considered as a continuous heat source. On the base of kinematic and dynamic parameters of IS of the first range, we carried out the detailed reconstruction of the eruption course, there 11 separate episodes (explosions) were distinguished. Wave pattern of IS allowed to defined four episodes (no. 1, 5, 6, 8) as explosions, in other cases a high-speed outflow of ash-gas mix ("blow") occurred from the volcano vent. The most long "blow" (no. 9) lasted for ~3.5 hr. On the base of IS of the second range, we estimated the minimal volume of the ash ejected into the atmosphere (by the methodology of Yu.A. Gostintsev and Yu.A. Shatskih) as >0.1 km^3, that allows us to assign the index of explosive activity VEI – 4 for this eruption.

Keywords: Raikoke volcano, explosive eruption, infrasound, eruptive cloud, ejected ash volume.

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Introduction

By the data of Sakhalin volcanic eruption response team (SVERT) (http://www.imgg.ru/ru/teams/svert), 21 June 2019 approximately in 18:05:00* in the Middle Kurils, the powerful explosive eruption of the Raykoke volcano have begun (fig. 1). The description of this eruption is given in the works [Girina et al., 2019; Rashidov et al., 2019; Degterev, Chibisova, 2019].

The Raykoke andezitodacite volcano (48.29° N, 153.25° E) is a stratovolcano on the island of the same name with a diameter of ~2 km, its summit crater is ~700 m wide and 200–250 m deep [Gushenko, 1979]. It forms a single volcanic massif of the northern-west strike with an area of 15 × 21 km (1200 m isobath) together with the quaternary submarine volcano 3.18, which flat top is located approximately in 7 km from the Raykoke volcano's top at the depth of ~245 m [Pushcharovskii, 1992]. Sudden powerful explosive eruptions are specific for the Raykoke volcano. The last such eruption has been occurred

*Here and after the time in UTC, format – hh:mm:ss.

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in 1924, when the underwater eruption has also been observed [Tanakadate, 1925].

The beliefs about the eruption dynamics were mainly received on the base of images, being in open access, from the Himawari-8 satellite of the Japan Meteorological Agency. The major equipment in this satellite is the Advanced Himawari Imager 16-channel multispectral thermal imager, operating in both visible and infrared bands. A geostationary orbit of the satellite allows to scan the Asian-Pacific region with a resolution of 500 m and a maximum frequency of 0.1 cycle/min. (http://ds.data.jma.go.jp/svd/vaac/data/vaac_list.html).

The eruptive cloud (EC) development can be traced in the images of the Himawari-8 satellite during the 18-hour interval from 20:20 of the 21.06.2019 to 14:20 of the 22.06.2019 (fig. 2). Within the first two hours the EC has been moving westward at an altitude* of 10.2 km at a speed of ~28 m/s (~100 km/h). For the next 18 hours, the cloud has been keeping move on the same course, with an average speed of ~20 m/s (~72 km/h) (fig. 2 b, c). At the end of this time interval, the EC front moved off 1500 km, and its altitude reached for ~13 km (fig. 2d).

Then the EC became twisting by the cyclone, prevailing in the area of the Commander Islands in the northern part of the Pacific Ocean. Under the influence of circulation processes in the atmosphere, the EC has become free of an ash, and then just the aerosol cloud continued spreading for long distances up to 5000 km (http://sacs.aeronomie.be/; [Girina et al., 2019]). Such wide spreading of the Raykoke volcano eruption products is an evidence of this event significance. Besides, in the works [Girina et al., 2019; Rashidov et al., 2019] the reasoned assumption, that eruption of the underwater volcano 3.18 might simultaneously occurred, is stated. In the more later work [Degterev, Chibisova, 2019] on the base of a detailed study of the images from satellite the dynamics of the eruptive process of this eruption was more accurately traced.

Fig. 1. The moment of the explosive eruption of the Raikoke volcano on 21 June 2019, at 22:45, the picture was taken from the international space station (https://earthobservatory.nasa.gov/images/145226/raikoke-erupts).

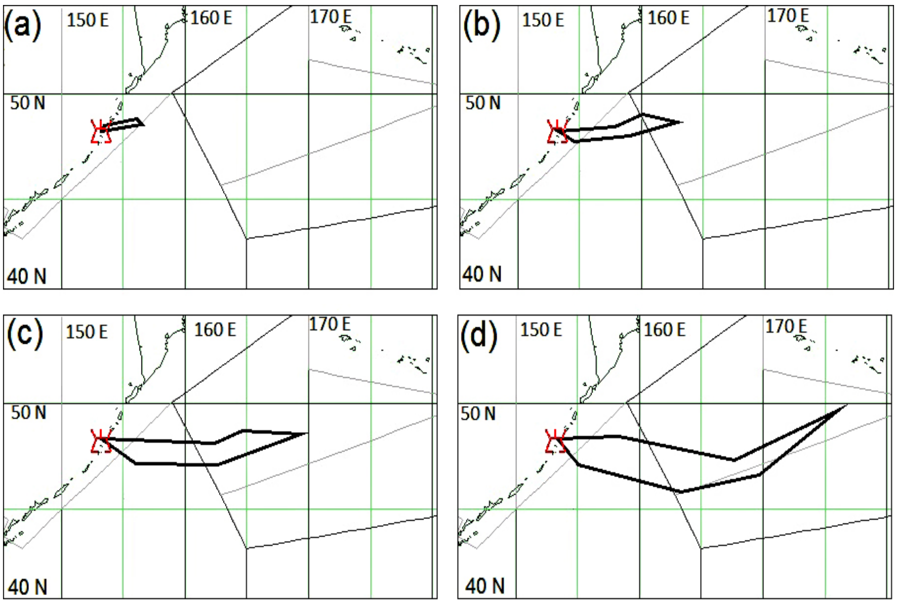

Fig. 2. Dynamics of the development of an eruptive cloud during the eruption of the Raikoke volcano, based on images of the Himawari-8 satellite: (a) 21.06.2019, 20:20; (b) 22.06.2019, 02:20; (c) 22.06.2019, 08:20; (d) 22.06.2019, 14:20.

*Here and after the altitude above sea level.

The remote methods such as seismic and acoustic were proved for gathering the information about the dynamics of eruption. Thus, during Sarychev Peak volcano eruption in the Middle Kurils in June, 2009 infrasound signals (IS) accompanied the eruption, were registered at the distances up to 6400 km [Matoza et al., 2010]. Unfortunately, there is no any seismic station near the Raykoke volcano, but the IS, accompanied the volcano eruption, were registered in the North Kurils and Kamchatka at the distances from 330 to ~1000 km.

It should be noted, that in the last two decades appeal to acoustics of volcanic eruptions has suddenly increase due to the international monitoring system (IMS) of the network of a regime of compliance with the Comprehensive Nuclear-Test–Ban Treaty. More than 60 infrasound stations, distributed by the Earth surface, are included in this network. In the numerous foreign works, the capabilities of infrasound range for monitoring of explosive eruption of volcanos worldwide are demonstrated [Fee, Matoza, 2013; Pichon et al., 2019; and other].

In the works [Lamb et al., 2015; Fee et al., 2017] it was made an attempt to apply IS to ascertain the amount of an ejected material. The IS, registered in the nearest zone at the distance up to 15 km, were used. They represent the air impulsive waves, into which the weak air shock-waves, accompanying directly the process of explosion and magma fragmentation, are turned. The separate explosions were considered on the Redoubt (Alaska Peninsula) and Sakurajima (Japan) volcanos. The calculations of ash amount were compared with the geological data received by the fallen ash isopachs. In our case, the IS were registered at the distance of several hundred kilometers from the source, that is why the approach, based on the theory of IS generation from a source with powerful mass and heat release, was applied [Gostintcev, Shatskih, 1989].

This work is devoted to the peculiarities of generation and distribution of infrasound signals and the evaluation of amount of ash, ejected into the atmosphere by the Raykoke volcano eruption, based on them.

Equipment and observation methodology

To study the wave perturbations in the atmosphere accompanied the volcanic eruptions, several registration stations of the Kamchatka Branch of the “United geophysical service of the Russian Academy of Sciences” Federal Research Center (KB FRC UGS RAS) function on the Kamchatka Peninsula. These stations are equipped with the channels of IS registration (fig. 3), that allows to monitor the strong explosive volcanic eruptions [Gordeev et al., 2013].

The ISGM-03M (Russia) differential microbarograph with an operation frequency range of 0.002–4.0 Hz is used on the SKR, PRT and KOZ stations as sensors for infrasound channels. Besides, in Nachiki station the IS44 IMS (fig. 3) acoustic station works. It has an installed antenna array of 4 M-2000 microbarographs (France) and with an aperture of ~1.8 km, allowing to register IS in the frequency range of 0.003–5 Hz and ascertain the azimuth to the source.

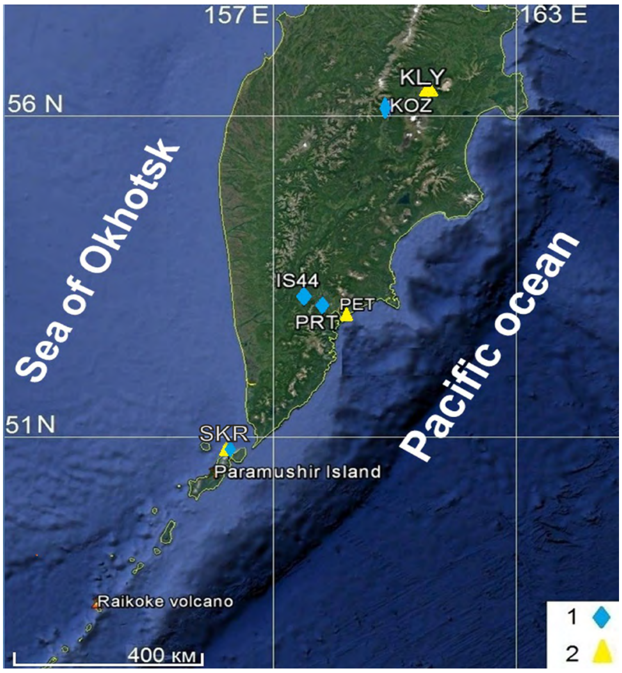

Fig. 3. The location of the Raikoke volcano, registration stations for infrasound vibrations (1) and weather stations (2), where balloon sounding is carried out, on the Kamchatka Peninsula and the Northern Kuril Islands. Infrasound registration stations: SKR – village Severo-Kurilsk, PRT – Paratunka, IS44 – an international station in Nachiki village, KOZ – Kozyrevsk village. Weather stations: SKR, PET – Petropavlovsk-Kamchatsky City, KLY – Klychi village.

To study the conditions of infrasound signals propagation it is important to know the atmosphere stratification in order to obtain a vertical profile of the effective sound speed (C_{eff}). In the studied area balloon sounding is carried out at three stations (fig. 3). The fig. 4 demonstrates the stratification of the atmosphere parameters (temperature, speed and wind direction) by the data of balloon sounding in the time neighborhood of the eruptions in the SKR station. From the fig. 4 it is evident, that during the whole eruption there were no abrupt changes of the stratification and the effective sound speed in the tropospheric wave-guide, calculated on the Raykoke-SKR trace, was constant $C_{eff} \approx 0.31$ km/s, while in the surface layer it was about 0.33–0.34 km/s.

Detailed idea about the dynamics of the Raykoke volcano eruption 21–22 June, 2019 can be got on the base of kinematic and dynamic parameters of IS, registered by the network of infrasound stations at the distance of 336–974 km (fig. 3). P.P. Firstov [Firstov, 2003; Firstov, 1994] offered the phenomenological classification of shock-wave and acoustic effects of the volcanic eruptions in the atmosphere, where the specific frequency range and physical processes, generating them, are taken as the main characteristic of the classes.

As a result of nonstationary processes in the crater of volcano air shock-waves appear, which evolve and transit into IS during the propagation process. Strong convection processes, related to eruptive clouds forming, generate another IS class. Besides, powerful eruptive clouds begin oscillating near a hover point, as a rule, at the tropopause height (10–12 km), exciting acoustic-gravity waves with Brunt–Väisälä frequency ($N_Z > 0.02$ s^{-1}), that was observed when disastrous eruption of the Shiveluch volcano 12 November, 1964 [Firstov, 1996].

Taking the scale of the considering eruption into account, it can be supposed, that it was accompanied with the acoustic signals of all classes, it is proved with the fig. 5, 6. On the record of infrasound oscillations in the SKR station (R = 336 km) (fig. 5b) it is clearly shown increasing of low-frequency infrasound oscillations after the paroxysmal phase of the eruption, while in the PRT station (R = 629 km) it is not observed (fig. 5a).

At the same time on the spectrograms of power density in the frequency band ≤ 1 Hz, calculated for the infrasound oscillations in the SKR station for the period of 21–22 of June, 11 well-marked and time-separated IS are clearly distinguished (fig. 5c).

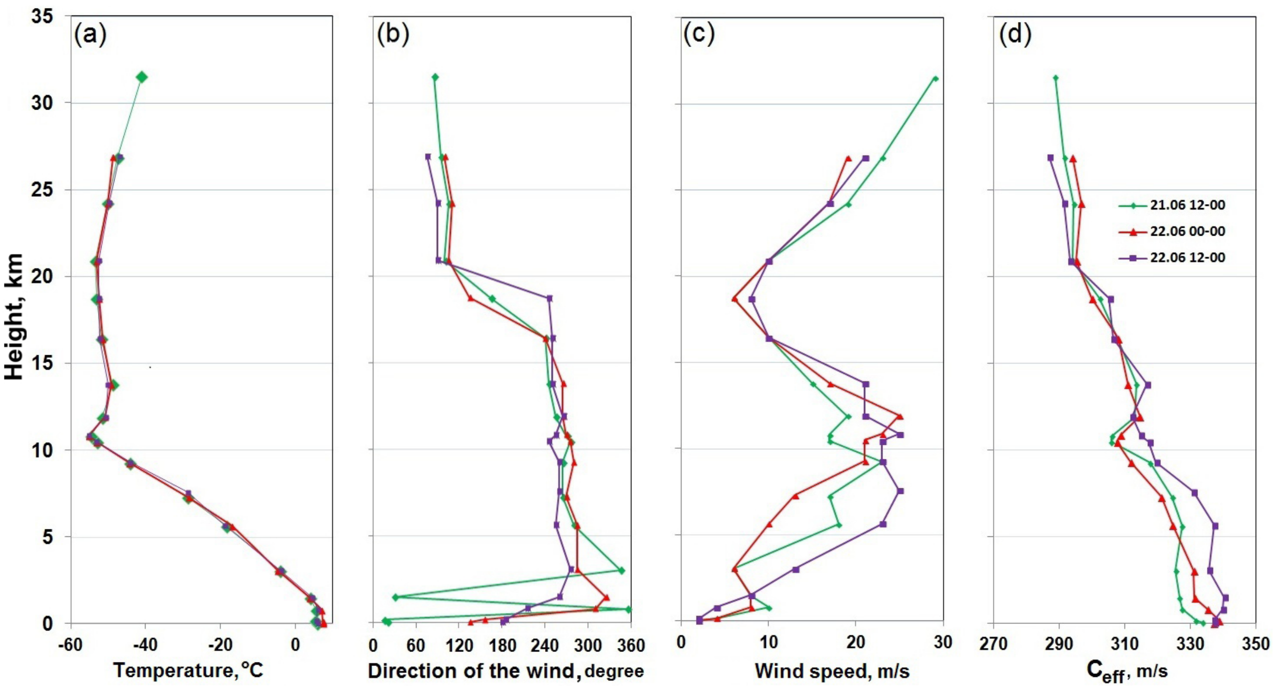

Fig. 4. Stratification of the atmosphere on 21–22 June, 2019 in accordance with the data of balloon sounding from the SKR weather station. Vertical sections: (a) air temperature, (b) wind direction, (c) wind speed, (d) effective speed of sound.

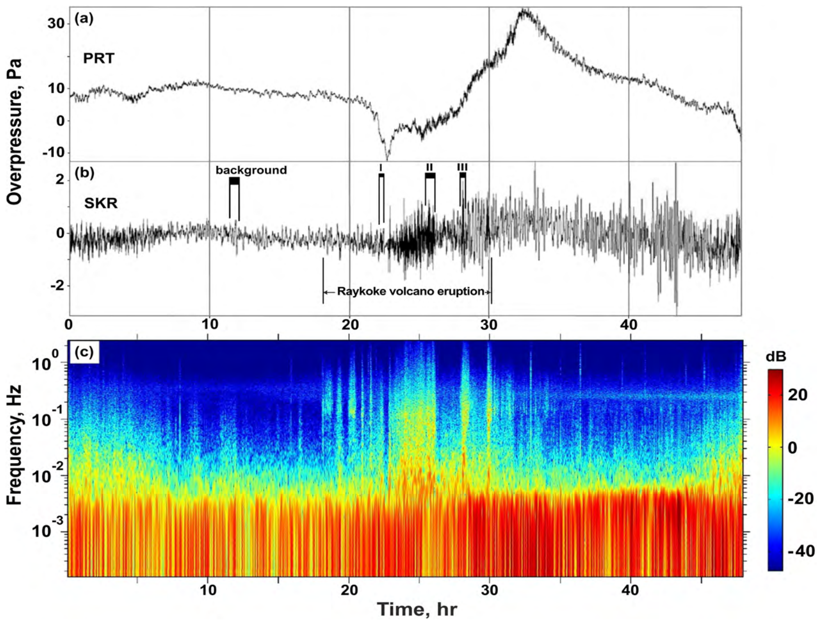

Fig. 5. The record of infrasound vibrations at the PRT (a) and SKR (b) stations with a spectrogram in the frequency band ≤ 1 Hz (c) during the eruption of the Raikoke volcano on 21–22 June, 2019. The sections, for which the power spectral density was calculated, are marked with the black rectangles. The countdown starts on 20 June, 2019, 23:59:04.

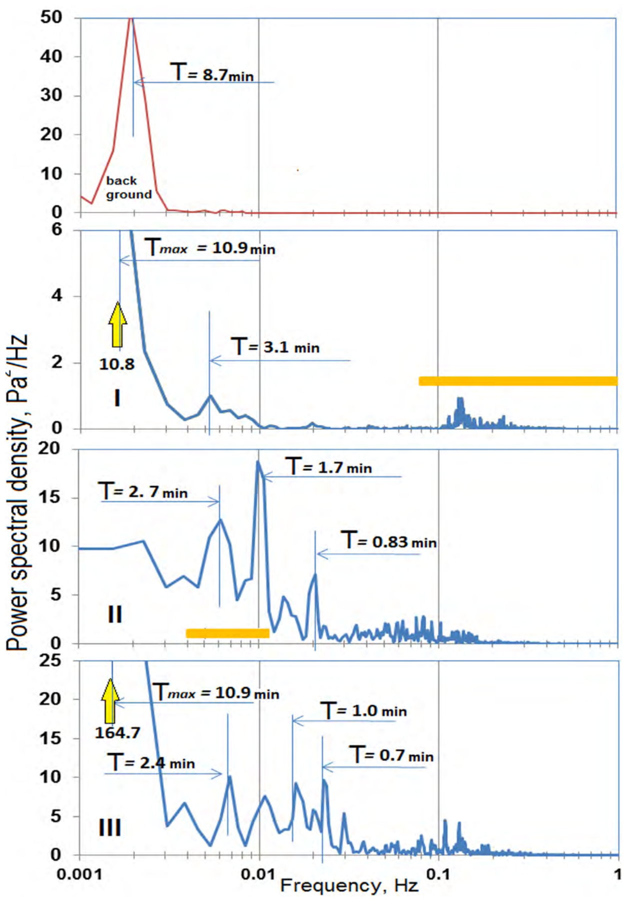

Fig. 6. The spectral power density for the background and three IS from the separate episodes of the eruption of the Raikoke volcano. Rectangles mark the frequency ranges in the band of which the IS, generated by the explosions of the Raikoke volcano were studied in detail.

For the background and three recording areas in the SKR station of a duration ≥ 5 min, containing IS, accompanied the separate long eruption events, the spectral power density (SPD) was calculated (fig. 6).

For calculation of the background SPD, the record with rather intense oscillations was selected. Spectral peak for the background falls on a frequency $f = 0.00192$ Hz (T = 8.7 min). Major part of IS energy for I and III areas falls at more lower frequencies $f = 0.00153$ Hz (T = 10.9 min). Especially, the considerable value of the SPD spectral peak $S(\omega) = 164.7$ Pa^2/Hz draws the attention at this frequency for III area, significantly exceeding background. Apparently, due to forming a plume from the eruptive cloud the acoustic-gravity waves of Brunt–Väisälä frequency appears, they are observed only at SKR the nearest station. On all SPD-curves the "high-frequency" spectral peaks are distinguished in 0.08–0.5 Hz frequencies range (fig. 6).

All details of the most powerful episodes of the volcano activity are clearly followed on the records of IS, filtered by the bandpass filter with 0.08–1.0 Hz cutoff frequencies, that, from the one hand, separated the signals and, from the other hand, provided a good signal-noise ratio at all infrasound stations (fig. 7). The 11 marked separate strong episodes of explosive activity of the Raykoke volcano eruption 21–22 June, 2019 [Degterev, Chibisova, 2019; Girina et al., 2019; Rashidov et al., 2019] are accompanied with IS of different intensity and duration.

Specifics of IS waveform were considered by the records of SKR the nearest station (336 km). IS signals of the Raykoke volcano eruption were divided into two groups (see the table) by the arrival form. The IS no. 1, 5, 6, 8 had clear arrivals, that usually appears during the explosions of the "burst" type (fig. 8). Evidence of this fact is shown on the fig. 1, on which eruptive cloud forming from obviously point source, coinciding by the time with IS no. 8 appearance.

Table. **Parameters of acoustic signals accompanying the eruption of the Raikoke volcano, and assessment of ejected ash**

Episode no.	Date, time of separate eruption episodes beginning		Parameters of acoustic signal and assessment of ejected ash						Note
	Date	Time	$\Delta\overline{P}$, Pa	T, s	τ, min	$E_a \times 10^6$, kJ	$Q \times 10^9$, kW	$V \times 10^6$, m^3	
1	21.06.2019	18:05:52	0.10	6.7	3	–	–	–	«Burst», two arrivals of IS are clearly distinguished with a delay of ~03:20
2		18:15:45	0.08	6.7	34	–	–	–	Continuous outflow of ash-gas jet from the crater with smooth increasing of IS amplitude
3		19:04:51	0.10	7.1	20	–	–	–	
4		19:57:52	0.28	7.1	32	–	–	–	
5		20:54:51	0.30	7.1	3	–	–	–	«Burst», two arrivals of IS are clearly distinguished with a delay of ~03:20
6		21:30:06	0.35	7.1	3	0.33	1.32	0.52	
7		22:08:56	0.08	8.3	9	0.31	1.27	1.17	Continuous outflow of ash-gas jet from the crater with smooth increasing of IS amplitude
8		22:51:03	0.16	5–9	6	0.48	1.70	0.59	«Burst», two arrivals of IS are clearly distinguished with a delay of 3:27. This episode evolution was shotted from the international space station (fig. 1)
9_1	21.06.2019	22:57:21	0.24	10	53	4.25	7.24	17.71	Continuous (3 hr.) powerful outflow of ash-gas mixture. Pulsatory mode with a period of ~20 min is observed
9_2		23:50:26	0.45	8–10	21	3.79	6.70	6.49	
9_3	22.06.2019	00:09:39	0.31	6–12	68	11.51	14.05	44.10	
9_4		01:00:16	0.48	7–12	26	4.42	7.43	8.92	
9_5		01:25:52	0.52	7–12	24	2.31	4.82	5.34	
9_6		01:48:52	0.55	6–12	18	3.67	6.57	5.46	
10		03:52:22	0.57	7–10	29	2.41	4.96	6.65	Continuous outflow of ash-gas jet from the crater with smooth increasing of the IS amplitude
11		05:46:28	0.75	9–12	21	3.23	6.03	5.84	Powerful explosion closing the eruption
			Total: $V = 102.79 \cdot 10^6$ m^3						

Notes. Eruption episodes numbers are corresponded to the numbers in the fig. 7. The parameters of IS after filtration with a bandpass filter of 0.08–0.1 Hz: $\Delta\overline{P}$ – an average overpressure, T – prevalent period, τ – signal duration. Calculated values of the acoustic source energy and amount of ash ejected into the atmosphere by IS after filtration with a bandpass filter of 0.004–0.012 Hz: E_a – the acoustic source energy, Q – power of heat release, V – calculated ash volume. Dash – for these episodes there was no any registered IS.

Two clear-cut arrivals with $t_2–t_1 \approx$ 00:03:20, which are, apparently, associated with coming of the waves along the earth surface and by the stratospheric wave-guide, are distinguished in the records of these signals.

Time of the clear-cut first arrival for no. 1 infrasound signal is 18:05:52. If we assume, that in this case the wave has come, with propagation speed C_{eff} = 0.34 km/s according to the fig. 4d, then the first explosion time will be 17:49:24.

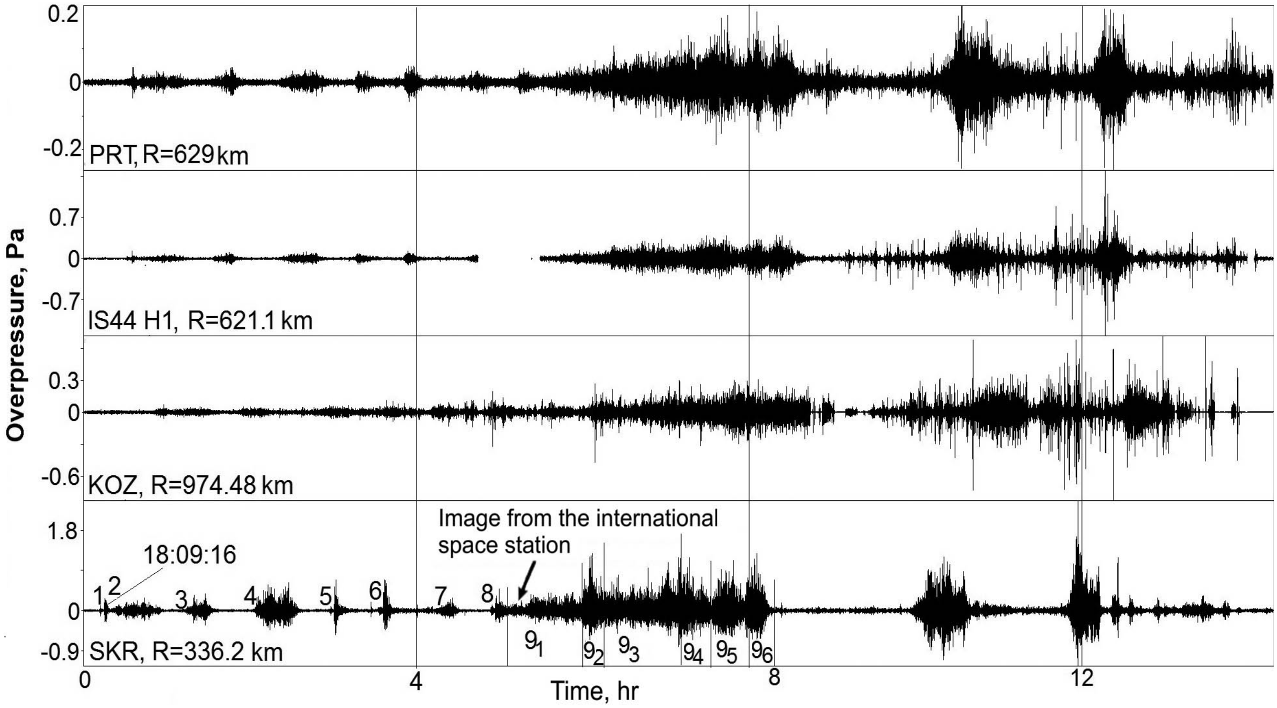

Fig. 7. Record of the IS accompanying the eruption of the Raikoke volcano on 21–22 June, 2019, filtered in the 0.08–1.0 Hz band at various stations. The numbers indicate the separate episodes of the eruption, defined by the records at SKR. The countdown starts on 21 June 2019, 17:53:54.

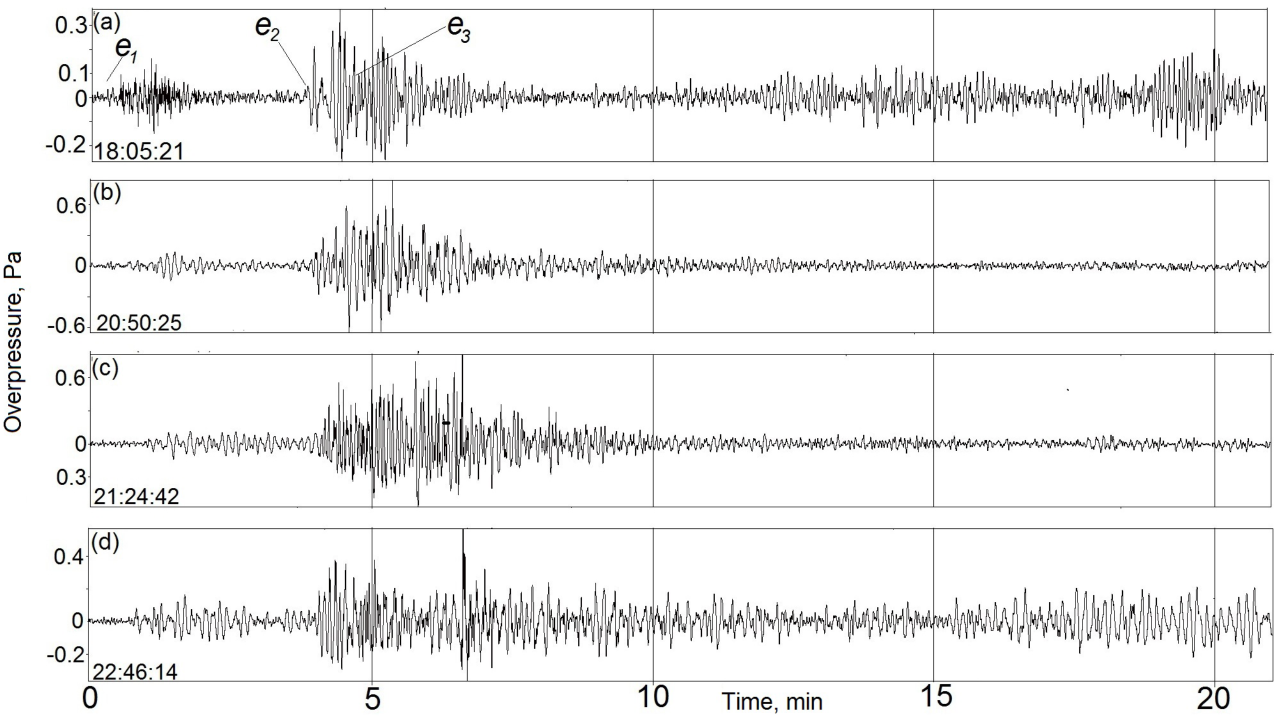

Fig. 8. The wave pattern of the IS in the SKR station from the separate "burst" explosions with an initial countdown: no. 1 – 18:05:21 (a); no. 5 – 20:50:28 (b); no. 6 – 21:24:42 (c); no. 8 – 22:46:14 (d).

This time differs from the time of the eruption beginning, specified in the works [Degterev, Chibisova, 2019; Girina et al., 2019; Rashidov et al., 2019].

In other cases, IS were characterized with the smooth amplitude increasing and more large duration (τ). The IS no. 9 had $\tau \approx 200$ min, that was an evidenced of a continuous outflow of ash-gas mixture, that were accompanied with nonstationary processes (explosions, supersonic outflow), in which result the air shock-waves were generated. Owing to the evolution, at the large distances they turned into IS, which were registered at all stations (fig. 7).

Arrangement of 4 microbarographs at the IS44 station makes the antenna array in the form of the isosceles triangle with the side of ~1.8 km and the median point, that allows to calculate the azimuth to the source, apparent speed and glide angle by measured time delays between the signals for the microbarographs pairs in a standard way by means of cross-correlation analysis. These parameters were ascertained for 7 first IS from the Raykoke volcano (fig. 9) till the interruption in the IS44 work.

The azimuth from the IS44 to the Raykoke volcano is 212.2°. High values of the azimuths (215°–223°) for first and second signals are noteworthy, i.e. the source is slightly displaced to the west with regard to the IS44 (fig. 9b). This fact can make in favor of the assumption, stated in the works [Girina et al.., 2019; Rashidov et al., 2019], that on the initial phase of the Raykoke volcano eruption, activation of the underwater volcano 3.18 might occur as well.

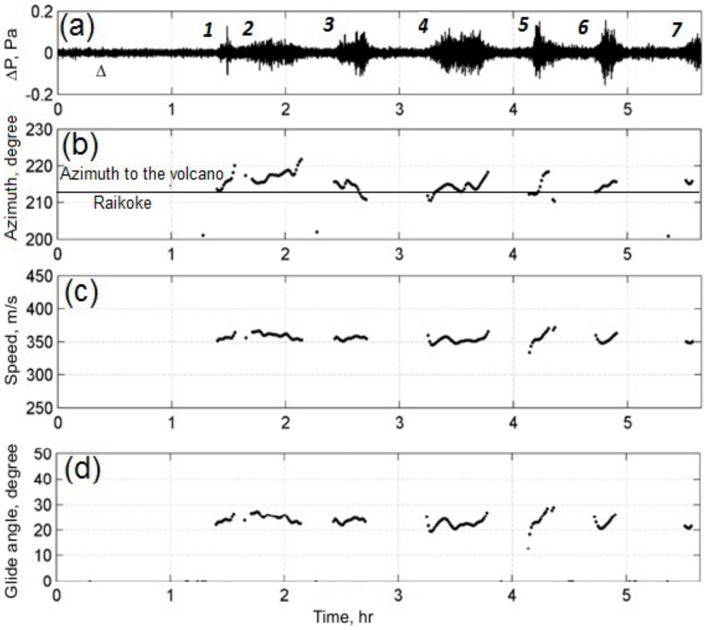

Fig. 9. The fragment of the infrasound recording for 22 June, 2019 by the H1 microbarograph of station IS44 filtered in the band of 0.08–0.8 Hz (a), the azimuth to the source of the IS input (b), the apparent speed (c), the slip angle (d). The initial countdown is 22 June, 17:00:00.

Calculation of ash amount ejected into the atmosphere on the base of acoustic emission

During the Raykoke volcano eruption fine-dispersed ash settled in the Pacific Ocean basin. In this case assessment of the volume of ash ejected into the atmosphere, without considering coarse-grained pyroclastics, can be carried out on the base of eruptive cloud height and IS intensity only. It should be noted, that maximum eruption intensity falls on the no. 9 episode, when a high-speed outflow of ash-gas mixture was occurring. This episode duration was ~210 min, and the eruptive cloud height – 13 km [Degterev, Chibisova, 2019].

In the classic work of S.A. Fedotov [Fedotov, 1982] there is a nomogram for assessment of ash amount at the height of the eruptive cloud. According to the nomogram, for the most intensive episode no. 9 a heat power will amount to $3.2 \cdot 10^{12}$ W, that corresponds to ash carrying of $5 \cdot 10^{6}$ kg/s. By the ash density $\rho_a = 1.3 \cdot 10^{3}$ kg/m^3 and this episode duration ~3.5 hr., the volume of ejected ash is evaluated at 0.048 km^3. It should be noted, that this assessment of ejected matter is minimal, because it does not take a coarse-grained pyroclastics into account.

Let us consider the possibility of ejected ash estimation on the grounds of the works [Gostintsev et al., 1983 a, b; Gostintsev, Shatskih, 1989], in which a theoretical reasoning of energy of an acoustic source $E_{a.s.}$ dependence on heat power Q within the center of powerful explosions and areal fires is given:

$$E_{a.s.} = 90\frac{\pi\rho_0\alpha}{\chi h C_0}\left(\frac{g\beta}{\pi\rho_0 c_p}\right)^{3/2} Q^{3/2}N^{-3/2},$$

where: $a = dh/dx = 0.15$ – a tangent of the jet expansion angle; $\rho_0 = 1.23$ kg/m^3 and $c_p = 1000$ J/(kg·K) – air density and heat capacity respectively; $\beta = 1/T_a = 3.6 \cdot 10^{-3}$ – a coefficient of thermal expansion; T_a – an ambient air temperature; $C_0 = 0.3$ km/s – sound speed in the air; $h = 10$ km – an effective height, dependent on the atmosphere stratification; $N = 0.003$ 1/s – Brunt–Väisälä frequency; $\chi = 1.9 \cdot 10^{-5}$ m^2/s – a turbulent coefficient of the thermal diffusivity.

The energy of an acoustic source was calculated by the well-known formula:

$$E_{a.s.} = \frac{2\pi HR}{\rho_0 C_0} \int \Delta P^2 dt,$$

where $H = 10$ km – a height of the homogeneous layer; $R = 336$ km – a distance between the source ang registration point; ΔP – an overpressure.

We can turn from heat power to assessment of the ejected ash volume proceeding from the assumption, that in the case of explosive eruptions heat power in the eruptive column at the automodel area are mainly provided with heat, brought to the atmosphere with the hot fine pyroclastics (volcanic ash). In the work [Fedotov, 1982] it is shown, that flowrate of pyroclastics of 1 kg·s^{-1} corresponds to the average heat power of 10^6 W, i.e. $\gamma = 10^{-6}$ kg·(s·W)$^{-1}$. The process time (τ) is estimated by IS duration. If ash density is known (it was taken as $\rho_a = 1.3 \cdot 10^3$ kg/m^3), then the volume of ash ejected into the atmosphere (V) can be calculated by the following formula:

$$V = (Q \cdot \tau \cdot \gamma)/\rho_a.$$

After filtration with the bandpass filter with cut-off frequencies 0.004–0.012 Hz the long-period IS, related to the eruptive column forming, were being distinguished. Such IS have begun to be registered just since no. 6 episode (see the table). Total minimal volume of the ash, ejected into the atmosphere during the Raykoke volcano, estimated on the base of IS, amounted more than 0.1 km^3. The major error in the calculation of ash amount, of course, is introduced with conditions of infrasound waves propagation. Relying on the atmosphere stratification, authors suppose the ash volume estimation error to be 30 %.

For volcanic explosive eruptions and their influence on the atmosphere classification, in the work [Newhall, Self, 1982] the volcanic explosivity index (VEI) was offered. VEI gradation from 0 (for nonexplosive eruptions) to 8 (disastrous eruptions with the volume of 10^3 km^3) is defined by two following parameters: the volume of ejected tephra and the height of eruptive column. According to the ejected ash volume $0.1 < V$ km^3 < 1.0, as well to the height of eruptive cloud, the Raykoke volcano eruption should refer to the VEI – 4.

Conclusions

In the network of infrasound monitoring stations at the Kamchatka Peninsula, which are placed at the distances of 336–974 km from the Raykoke volcano, infrasound signals, accompanied the most powerful episodes of its eruption in 21–22 June, 2019, were registered.

In the spectral density of the power of registered IS the spectral peaks are distinguished in the following frequency ranges: $f = 0.08$–0.5 Hz and $f = 0.004$–0.012 Hz. First range is related to the process of magma fragmentation and nonstationary processes, arisen when ash-gas mixture outflowing from the crater. Second is conditioned by appearance of continuous heat source, that brings to jet convective flow and eruptive cloud forming.

On the base of the kinematic and dynamic parameters of infrasound signals of the first range, the detailed reconstruction of course of the considered event is given. The eruption has begun with the weak enough explosion in 21 June, 17:46:00, after that the intensity of explosions began to increase. By the acoustic data 11 separate episodes are distinguished, they are given in the table.

Based on the wave pattern of IS of the first range, we made the conclusion, that for 4 episodes (no. 1, 5, 6, 8) the explosions of "burst" type are typical, and in other cases the process is going by the "blow" type, i.e. high-speed ash and gaseous mixture outflow from the volcano's throat. The most durable "blow" (no. episode) lasted ~3.5 hr.

On the base of IS of the second range, which appearance relates to various processes, arising in the convective jet, we carried out a calculation of the minimal volume of the ash, ejected in the atmosphere, by the methodology, offered by Yu. A. Gostintcev and Yu.V. Shatskih. Calculated volume amounts a little bit more than 0.1 km^3, that allows to assign the explosive activity index VEI – 4 to this eruption.

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References

1. Degterev A.V., Chibisova M.V. **2019**. The eruption of Raikoke volcano in June of 2019 (Raikoke Island, Central Kuril Islands). *Geosistemy perekhodnykh zon = Geosystems of Transition Zones*, 3(3): 304–309. (In Russ.). doi.org/10.30730/2541-8912.2019.3.3.304-3

2. Fedotov S.A. **1982**. [Assessments of heat and pyroclastics outflow with the volcanic eruptions and fumaroles by the height of their jets and clouds]. *Vulkanologiia i seismologiia = Volcanology and Seismology*, (4): 4–28. (In Russ.).

3. Fee D., Matoza R.S. **2013**. An overview of volcano infrasound: From hawaiian to plinian, local to global. *J. of Volcanology and Geothermal Research*, 249: 123–139. http://dx.doi.org/10.1016/j.jvolgeores.2012.09.002

4. Fee D., Izbekov P., Kimc K., Yokoo A., Lopez T., Prata F., Kazahaya R., Nakamichig H., Iguchig M. **2017**. Eruption mass estimation using infrasound waveform inversion and ash and gas measurements: Evaluation at Sakurajima Volcano, Japan. *Earth and Planetary Science Letters*, 480: 42–52. doi.org/10.1016/j.epsl.2017.09.043

5. Firstov P.P. **1994**. Wave perturbation in the atmosphere as a method of remote monitoring of volcanic eruptions. In: *Intern. Volcanol. Congress. JAVEI*. Theme 7. Ankara.

6. Firstov P.P. **1997**. The November 12, 1964, catastrophic eruption of Shiveluch, Kamchatka: A dynamic reconstruction based on signals recorded from atmospheric pressure variation and volcanic tremor. *Volcanology and Seismology*, 18: 412–432.

7. Firstov P.P. **2003**. *Vulkanicheskie akusticheskie signaly diapazona 1.0–10 Hz i ikh sviaz's eksplozivnym protsessom* [*Volcanic acoustic signals in the range of 1.0–10 Hz and their association with the explosive process*]. Petropavlovsk-Kamchatsky: KamGPU = KamSPU = Kamchatka State Pedagogical University, 90 p. (In Russ.).

8. Girina O.A., E.A. Loupian E.A., Uvarov I.A., Kramareva L.S. **2019**. [Raikoke volcano eruption on 21 June 2019]. *Sovremennye problemy distantsionnogo zondirovaniia Zemli iz kosmosa* [*Modern problems of remote sensing of the Earth from Space*], 16(3): 303–307. (In Russ.). doi:10.21046/2070-7401-2019-16-3-303-307

9. Gordeev E.I., Firstov P.P., Kulichkov S.N., Makhmudov E.R. **2013**. Infrasonic waves from volcanic eruptions on the Kamchatka Peninsula. *Izvestiya, Atmospheric and Oceanic Physic*, 49(4): 420–431. doi:10.1134/S0001433813030080

10. Gostintsev Yu.A., Shatskih Yu.V. **1989**. *Generatsiia dlinnovolnovykh akusticheskikh vozmushchenii v atmosfere vsplyvaiushchimi produktami goreniia i vzryva* [*Generation of long-wave acoustic perturbations in the atmosphere by the combustion and explosion products*]: preprint. Chernogolovka: N.N. Semenov Inst. of Chemical Physics, RAS, 33 p. (In Russ.).

11. Gostintsev Yu.A., Ivanov E.A., Shatskih Yu.V. **1983a**. [Infrasound and internal gravity waves during heavy fires]. *Doklady AN SSSR = Doklady of the Academy of Sciences of the USSR. Earth Science Sections*, 271(2): 327–330. (In Russ.).

12. Gostintsev Yu.A., Ivanov E.A., Kopylov N.P., Shatskih Yu.V. **1983b**. [Wave perturbations of the atmosphere during heavy fires]. *Fizika goreniia i vzryva = Combustion, Explosion, and Shock Waves*, 19(4): 62–64. (In Russ.).

13. Gushchenko I.I. **1979**. *Izverzheniia vulkanov mira*: katalog [*Eruptions of the world volcanos:* Catalog]. Moscow: Nauka Publ., 475 p. (In Russ.).

14. Lamb O.D., Angelis S.D., Lavallée Y. **2015**. Using infrasound to constrain ash plume rise. *J. of Applied Volcanology*, 4 (20). https://doi.org/10.1186/s13617-015-0038-6

15. Matoza R.S., Le Pichon A., Herry P. **2010**. Infrasonic observations of the June 2009 Sarychev Peak eruption, Kuril Islands: Implications for infrasonic monitoring of remote explosive volcanism. *J. of Volcanology and Geothermal Research*, 200(1–2): 35–47. https://doi.org/10.1016/j.jvolgeores.2010.11.022

16. Newhall C.G., Self S. *1982*. The Volcanic Explosivity Index (VEI): an estimate of explosive magnitude for historical volcanism. *J. of Geophysical Research*, 87(C2): 1231–1238. https://doi.org/10.1029/jc087ic02p01231

17. Pichon Le A., Blanc E., Hauchecorne A. (eds) **2019**. *Infrasound monitoring for atmospheric studies. Challenges in middle atmosphere dynamics and societal benefits*. 2nd ed. Springer, 1160 p. https://doi.org/10.1007/978-3-319-75140-5

18. Pushcharovskii Yu.M. (ed.) **1992**. *Podvodnyi vulkanizm i zonal'nost' Kuril'skoi ostrovnoi dugi* [*Submarine volcanism and zonality of Kuril Island Arc*]. Moscow: Nauka Publ., 528 p. (In Russ.).

19. Rashidov V.A., Girina O.A., Ozerov A.Yu., Pavlov N.N. **2019**. The June 2019. Eruption of Raikoke volcano (the Kurile Islands). *Vestnik KRAUNTs. Nauki o Zemle = Bull. of Kamchatka Regional Association "Educational-Scientific Center". Earth Sciences*, 42(2): 5–8. (In Russ.). doi:10.31431/1816-5524-2019-2-42-5-8

20. Tanakadate H. **1925**. The volcanic activity in Japan during 1914–1924. *Bulletin Volcanologique*, 1(3): 3–19. https://doi.org/10.1007/bf02719558

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