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Dirty thunderstorms caused by volcano explosive eruptions in Kamchatka by the data of electromagnetic radiation

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Abstract. During volcano eruptions, so called dirty thunderstorms are the sources of electromagnetic radiation. They are caused by ash-gas clouds formed during explosive eruptions. Thunderstorm activity in an ash-gas cloud during volcano eruption is monitored by radio equipment. The VLF direction finder, located at Paratunka, monitors thunderstorm activity in the region of Kamchatka Peninsula including dirty thunderstorms accompanying explosive eruptions of Shiveluch and Bezymyanniy volcanoes. In the paper, we analyze records of electromagnetic radiation associated with dirty thunderstorms occurring during volcano eruptions from 2017 to 2020. During that period 24 eruptions of Shiveluch volcano and 5 eruptions of Bezymyanniy volcano occurred. Seventeen and three of them, respectively, caused dirty thunderstorms. Two-stage scenario of development is typical for all the dirty thunderstorms. The first stage lasts for 5-7 minutes and accompanies eruptive column development. However, if the eruption begins according to a smooth scenario, the first stage may be weak. The second stage lasts for 20-80 minutes and is associated with eruptive cloud formation and propagation. The intensity of this dirty thunderstorm stage depends on eruption power as well as on the interaction of an eruptive cloud during its propagation with the clouds of meteorological origin. Based on the obtained data, that is indicated by the increase of cloudto-cloud stroke number.

1. Introduction

Volcano explosive eruptions are accompanied by complicated geophysical processes occurring during injection of a great amount of burning ash and volcanic gases composed of 90 % of water steam. The presence of dissolved water in the magma up to 7 % from its composition results in its fragmentation (destruction) under geostatic pressure release and formation of a large amount of dispersed material (pyroclastics) which forms eruptive clouds together with volcanic gases.

Volcanic ash creates danger for population and urban lands in the far-field zone. It is also dangerous for airplane engines. Eruptive cloud propagation monitoring by different methods allows one to notify about ash hazardous situation. That makes it possible to take preventive actions to decrease the consequences. One of the methods to trace eruptive cloud motion is observation of electromagnetic pulses (atmospherics) accompanying lightning strokes that was described in a number of papers [1-3].

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Figure 1. Location of Shiveluch and Bezymyanniy volcanoes and observation sites in the far-field zone on Kamchatka Peninsula (a); location of radiotelemetric seismic stations (RTSS) (BZW, BZP, BZG) near Bezymyanniy volcano and location of lightning strokes recorded by the WWLLN during the eruption on December 20, 2017 (b); location of RTSS (BDR, SMK) near Shiveluch volcano and location of lightning strokes recorded by the WWLLN during the eruption on March 9, 2019 (c) [15].

The Shiveluch volcano in Kamchatka is one of the most active. Its latest catastrophic eruption occurred on November 12, 1964. After a 16-year pause, the extrusive dome has been growing within a newly formed crater from August 1980 up to the present time with short pauses. That is accompanied by explosive eruptions [6]. During strong explosions, eruptive cloud rises up to the tropopause height (10–12 km) and propagates for hundreds of kilometers. In this case, significant lightning activity is observed [7]. In some cases, during the eruptions, pyroclastic flows were formed that is a mixture of hot gas (up to 800 °C), ash and stones moving with the velocity up to 700 km/h along the volcano slopes (figure 2).

Another the most active volcano of the world, Bezymyanniy volcano, is located in the central part of Kluchevskaya Group of Volcanoes on Kamchatka Peninsula (figure 1a). After the catastrophic eruption on March 30, 1956, an extrusive dome was constantly rising up in the newly formed crater (1.5×2.8 km, 700 m deep) [Gorshkov, Bogoyavlenskaya 1965] up to the end of 2012 with some periods of activation in the form of separate explosive eruptions and relatively calm periods. Manifestations of its volcanic activity are various: formation of extrusive domes and blocks; explosions of different intensity including directed ones; eruptions of pyroclastic flows and squeezing of small viscous lava flows. From the end of 2012 up to December 2016, the volcano was in relatively calm and in December 2016, the volcanic activity began to grow.

In the paper, we present observation results for the atmospherics accompanying separate volcano explosions for the period of 2017–2019.

2. Existing methods

A direction finder of very low frequencies (VLF) was developed at the Institute of Cosmophysical Research and Radio Wave Propagation (IKIR) FEB RAS to record electromagnetic radiation form lightning strokes. The software-hardware complex for recording atmospherics is described in the paper [4]. The VLF direction finder, located at Karymshina site, that is 390 km from Shiveluch

volcano, recorded 17 dirty thunderstorms accompanying separate explosions of Shiveluch volcano and 3 dirty thunderstorms accompanying Bezymyanniy volcano eruption.

The World Wide Lightning Location Network (WWLLN, http://wwlln.com) allows us to record atmospheric coordinates with the accuracy up to several microseconds [8]. WWLLN records atmospherics from volcanic lightning and gives good results for the monitoring of eruptive cloud propagation in case of optimal location of the network sites [10]. Unfortunately, due to the sparse network of the sites on Kamchatka Peninsula, WWLLN records only powerful lightning strokes which are not more than 10 % from the atmospherics recorded in the same region by the VLF direction finder [5]. Thus, in this paper we use the VLF direction finder as the main source of data.

Data on atmosphere stratification were taken from the open sources (https://ruc.noaa.gov).

3. Data and analysis

Based on the data of Kamchatka Branch of the Geophysical Survey RAS [14] a catalogue of the strongest events on Shiveluch (table 1) and Bezymyanniy (table 2) volcanoes was made for the period of 2017–2019. Then, eruptive cloud height was estimated for the same period. During the first stage, azimuthal distribution of atmospherics in the sector of 0° –80° was considered for the selected events (figure 2a). It is clear from the figure that during the Shiveluch volcano eruption on May 11, 2017, lightning activity was observed for half an hour from the azimuth of 25.6°±10°. During the second stage, graphs for atmospheric counting rate dynamics (ν) from the direction to the volcano were plotted (figure 2b).

		first	maximum		second			
		phase	counting rate	pulse	phase	maximum	pulse	
date	time	time		number	time	counting rate	number	WWLLN
11.05.17	18:24:00	4	16	47	28	14	183	4
23.07.17	17:43:00	4	3	10	26	18	205	0
09.03.19	05:49:00				24	12	107	8
26.09.19	20:57:00				9	5	24	0
01.10.19	23:38:00	4	11	21				0
21.10.19	12:17:00	5	18	45				0

Table 1. Parameters of six the most vivid events recorded during Shiveluch volcano explosions [8].

For a more detailed analysis we selected the events on May 11, 2017 (figure 2b), on July 23, 2017 and on October 21, 2019 (figure 3a, b) since they occurred under relatively similar height distribution of airflow velocities.

The eruption on May 11, 2017 is the most vivid event, since it began with an explosion followed by ash-gas mixture outflow. Eruptive cloud rose to the tropopause height (10 km). There are two phases in the counting rate dynamics (v) for this eruption. Phase I lasted for ~ 4 min and is characterized by a sudden increase followed by sudden decrease. More gradual increase of v and significant duration for ~ 30 min is characteristic for the next phase II (figure 2b).

Dynamics ν with two phases was observed for some explosions on Alaska volcanoes, Augustine in 2006 and Redoubt in 2009 [13]. Phase I takes place during the first stage of the eruption on the areas of thermal formation and rising (gas pressure and automodel) that determines its short duration. Phase II characterizes eruptive cloud electrification on the section of floating when it becomes blurred and carried by the wind. In this case, eruptive cloud contacts with the clouds of meteorological origin that causes water steam crystallization and additional electrification causing powerful lightning activity [3].

A similar picture was observed on October 21, 2019, except for the duration of the whole eruption process. In the first case, the duration of the explosive earthquake was ~ 46 min, whereas in the second case the duration of the process was about 10 min. An analogous situation with short

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time of eruption (~10 min) is observed in all the cases containing only the first stage of volcanic thunderstorm. Thus, we can make a conclusion that presence of phase II of the volcanic thunderstorm on May 11, 2017, and its absence in the eruption on October 21, 2019, is determined by the amount of the erupted material in the form of gas-ash cloud.



Figure 2. Azimuthal distribution of atmo-spherics in the sector of $0^{\circ}-80^{\circ}$ according to the color gradient from blue (min) to yellow (max) (a), the atmospheric counting rate from the direction to Shiveluch volcano (b) during the eruption on May 11, 2017.



Figure 3. Atmospheric counting rate during Shiveluch volcano eruptions on October 21, 2019 (a) and on July 23, 2017 (b).

The eruption on July 23, 2017, (figure 3b) is opposite in dynamics and is characterized by gradual increase within ~ 10 min and gradual decrease within ~ 47 min of explosive earthquake intensity. There is no phase I in the dynamics of volcanic thunderstorm in this case. That, in its turn, confirms the assumption on the dependence of charge separation intensity on the velocity of ash-gas stream outflowing from the vent.

					U	5 5 5	1	
		first	maximum		second			
		phase	counting rate	pulse	phase	maximum	pulse	
date	time	time		number	time	counting rate	number	WWLLN
20.12.17	18:24:00	3	4	9	38	54	790	4
20.01.19	17:43:00				28	6	63	0
15.03.19	17:11:00				58	83	1138	13

Table 2. Parameters of three events recorded during Bezymyanniy volcano explosions.

In December 2016, Bezymyanniy volcano became active again. On March 9 and June 16, 2017, two explosive eruptions occurred and the third, the most powerful one, began on December 20, 2017, at 03:39. Intensive flowing of pyroclastic streams began at 03:45. When the streams were in the stagnation area, secondary eruptive clouds were generated. This process promoted the formation of a multilayer eruptive cloud. The eruptive cloud height was 15 km, the area, above which it propagated, was \sim 78 000 km² (figure 2a). According to the satellite data, the pyroclastic flow drift length was 6 km and that of mud flows was up to 18 km. Based on the modeling estimates of

eruptive cloud motion, the erupted tephra mass on the land was ~ 3.107 t (~ 0.023 km³) [9]. Three eruptions of Bezymyanniy volcano described in table 2 were accompanied by dirty thunderstorms. Their peculiarity is the absence of phase I. That confirms the fact that all eruptions accompanied by volcanic thunderstorms began according to the "smooth" scenario (without explosion).

4. Conclusion

During the past years, great attention is paid to electromagnetic radiation from dirty thunderstorms accompanying explosive eruptions. That is associated with the increase of population density on the Earth and ash hazard for the population and for the aviation, in the first instance. In the paper, we compare lightning activity dynamics during explosions. We distinguished the features for the development of two stages of dirty thunderstorms. They are associated with eruptive column formation during the first stage and eruptive column development during the second one. Data analysis allowed us to understand clearly the mechanism of Bezymyanniy volcano eruption occurred on December 20, 2017, and that of Shiveluch volcano eruption occurred on May 11, 2017. Two phases are distinguished in the dynamics v depending on eruption character and intensity. Phase I reflects the character of the eruptions onset. For the eruptions, which begin with magma fragmentation according to the explosion scenario, peak phase I is observed. It lasts up to 6 minutes. For the explosions, which begin according to the "smooth" scenario, only phase II is observed. It characterizes lightning activity in a developed eruptive cloud. This phase intensity depends not only on eruption mechanisms but on meteorological conditions in the region as well. That explains the fact that, on the whole, there is no relation between the dynamics v, eruptive column height and the atmospherics number according to WWLLN data. Monitoring of electromagnetic pulses from dirty thunderstorm strokes expands the informative value of the eruption process and the characteristics of eruptive column propagation depending on meteorological state. Undoubtedly, during current development of technologies and computational methods, VLF radiation monitoring may be included into the system of notification on ash hazard for airplanes having multiple routes along the eastern coast of Kamchatka.

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