Aerosol Injections Into the Stratosphere by Volcanic Eruptions Over 225 Years

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Abstract: In this work, we present a list of volcanic eruptions, which products probably injected into the stratosphere from 1800 to 2024. Tropopause height data were used to determine the penetration of volcanic products into the stratosphere from eruptions from 1979 that have a plume altitude characteristic. In compiling the list of eruptions from 1800 to 1978, we used eruptions with a volcanic explosivity index (VEI) ≥ 4, which are most likely to inject a plume into the stratosphere. We show that over the past 25 years the number of eruptions with VEI 4 has almost doubled, while the number of eruptions with VEI 5–6 has decreased. The probability of a plume entering the stratosphere for eruptions with VEI 3 increases in middle and high latitudes due to the lower tropopause height. The volcanic load on the stratosphere in the middle and high latitudes of the Northern Hemisphere exceeds that of the Southern Hemisphere. Large eruptions of tropical volcanoes make the greatest contribution to the total aerosol load of the stratosphere. We have provided a map of volcanic eruptions with the possible injection of aerosols into the stratosphere from 1800 to 2024. The highest frequency of eruptions with plumes entering the stratosphere is observed in the regions of Kamchatka, Indonesia and the Aleutian Islands; among the volcanoes, the most frequent are Bezymianny, Bogoslof and Sheveluch. Volcanoes with eruptions with VEI 6–7 (Tambora, Krakatau, Santa Maria, Novarupta, Pinatubo) had only one eruption reaching the stratosphere over the past 225 years.

Keywords: Large volcanic eruptions, stratosphere, volcanic explosivity index, maximum plume altitude, stratospheric aerosol layer

Citation: Zuev V. V. and Savelieva E. S. (2026), Aerosol Injections Into the Stratosphere by Volcanic Eruptions Over 225 Years, *Russian Journal of Earth Sciences*, 26, ES1018, EDN: KLLWEF, https://doi.org/10.2205/2026es001061

Research Article

Received: December 19, 2024
Accepted: September 9, 2025
Published: April 21, 2026

1. Introduction

Large volcanic eruptions can influence the dynamics and temperature regime of the stratosphere and troposphere by injecting gases and aerosol particles into the stratosphere [*Kroll et al.*, 2021; *Robock*, 2015]. In the stratosphere, under conditions of low humidity, the lifetime of aerosol particles increases and can reach from six months to 4–8 years, depending on the altitude and volume of the volcanic emission. Positive temperature and negative ozone anomalies are formed from the first months after the eruption and are caused by aerosol heating of the stratosphere and ozone depletion on the surfaces of aerosol particles [*Angell*, 1997; *Glasow et al.*, 2009; *Ming et al.*, 2020; *Randel et al.*, 1995]. A temperature increase of the tropical stratosphere, especially in the autumn-winter period, can lead to an increase in the stratospheric meridional temperature gradient, subsequent strengthening of the stratospheric polar vortex and the polar ozone depletion in the period from late winter to spring [*Driscoll et al.*, 2012; *Stenchikov et al.*, 2006; *Zuev et al.*, 2017b].

Plinian eruptions, characterized by the formation of an eruptive column, at the top of which an eruptive cloud is formed, can have a significant impact on the stratosphere [*Sioris et al.*, 2016; *Stocker et al.*, 2019; *Vernier et al.*, 2011; *Wrana et al.*, 2023]. To quantitatively describe the strength of an eruption and its impact on the Earth's atmosphere, volcanologists K. Newhall and S. Self in 1982 proposed a scale of volcanic eruptions based on the volcanic explosivity index (VEI), which takes into account the volume of ejected products and the height of the eruptive column [*Newhall and Self*, 1982]. VEI is measured from 0 for non-explosive eruptions, with a tephra volume of about 10^4 m^3, to 8, when more than 10^{12} m^3 of ash enters the stratosphere at an altitude of more than 25 km. Eruptions with VEI ≥ 4, especially tropical volcanoes, can have a significant impact on the stratosphere [*Löffler et al.*, 2016; *Otterå*, 2008; *Robock et al.*, 2007]. Stratospheric ozone depletion is possible as a result of eruptions with VEI = 3 when the plume height exceeds the tropopause height [*Mehta et al.*, 2015]. This occurs more often during volcanic eruptions in Iceland, Kamchatka and Alaska, where the height of the tropopause, depending on the season, ranges from 8 to 12 km, compared to the tropical tropopause, which reaches 15–18 km.

Large tropical volcanic eruptions typically cause global aerosol enrichment observed in the Northern Hemisphere (NH) and Southern Hemisphere (SH) stratosphere [*Bebbington*, 2014]. Volcanic eruptions of middle and high latitudes are mainly recorded only in the middle and high latitudes of the corresponding hemisphere [*Zuev et al.*, 2017a]. For example, the eruptions of the volcanoes Askja (Iceland), Ksudach (Kamchatka Peninsula) and Novarupta (Alaska), which occurred in March 1875, 1907 and June 1912, were observed only in the NH, and the eruption of the volcano Calbuco (Southern Chile) in January 1893 was recorded only in the SH. Moreover, the eruptions of the Askja and Ksudach volcanoes, characterized by VEI = 5, were observed both in the high and middle latitudes of the NH, and the eruption of the Novarupta volcano with VEI = 6 was recorded even in the tropical latitudes of the NH, while eruptions of high-latitude volcanoes with VEI = 3–4 are observed mainly in the polar region [*LeGrande et al.*, 2016; *Robock and Oppenheimer*, 2003]. This work aims to examine the volcanic aerosol load on the stratosphere over the past 225 years. The major volcanic eruptions of the last 250 years were presented by Robock [*Robock*, 2015]. Volcanic eruptions of the late 20th century and in the 21st century that affected the aerosol load of the stratosphere are presented in particular in [*Andersson et al.*, 2015; *Gerasimov et al.*, 2024; *Mills et al.*, 2016; *Thomason et al.*, 2021; *Trickl et al.*, 2024].

2. Data and Methods

To compile the list of volcanic eruptions, the products of which probably injected into the stratosphere from 1800 to 2024, we used the data from the book of Siebert et al. [*Siebert et al.*, 2010] and the data of the Global Volcanism Program (GVP) of the Smithsonian Institution (http://www.volcano.si.edu). To analyze volcanic perturbations in the stratospheric aerosol layer, we used data on stratospheric aerosol optical thickness of the Goddard Institute for Space Studies NASA (http://data.giss.nasa.gov/modelforce/strataer). Tropopause height data were used to determine the stratospheric injection of volcanic products from eruptions between 1979 and 2024 that have a plume altitude characteristic. In compiling the list of eruptions from 1800 to 1978, we used eruptions with VEI ≥ 4, which are most likely to inject a plume into the stratosphere [*Newhall and Self*, 1982], and data on recorded cases of volcanic aerosol injection into the stratosphere (in particular, the list contains 9 eruptions with VEI = 3 for the period before 1979 that were recorded in the stratosphere). Tropopause heights for eruptions since 1979 were determined from data of the University of Wyoming Department of Atmospheric Science (https://weather.uwyo.edu/upperair/sounding.html). To determine the plume altitude of some eruptions, we used works devoted to them. In cases where the plume altitude according to GVP and according to the publication did not match, we in most cases used data from the publications (Table 1).

Table 1. List of volcanic eruptions for which the plume altitude was used according to the references

No.	Date of eruption	Volcano	VEI	Maximum plume altitude, km		References
				according to the GVP	according to the Ref.	
1	13.06.2011	Nabro	4	13.7	18	[*Fromm et al.*, 2014]
2	07.03.2017	Bogoslof	3	10.7	13.4	[*Coombs et al.*, 2019]
3	23.06.2017	Bogoslof	3	11.0	11.9	[*Coombs et al.*, 2019]
4	07.08.2017	Bogoslof	3	12.2	12.7	[*Coombs et al.*, 2019]
5	26.07.2018	Ambae	3	13.5	18	[*Kloss et al.*, 2020]

3. Results and Discussion

Table 2 shows the list of volcanic eruptions whose products probably entered the stratosphere (for eruptions below 20 km since 1979 the tropopause height is given). During eruptions with VEI ≥ 4, the plume altitude typically exceeds the tropopause height and volcanic ash and gases penetrate into the stratosphere. VEI is more of a measure of tephra volume and therefore sometimes does not reflect the maximum plume altitude well. For example, the April–May 2010 eruption of the Eyjafjallajökull volcano with a plume altitude of 9.3 km was assigned a VEI of 4, while the November 1985 eruption of the Nevado del Ruiz volcano with a plume altitude of 31 km was assigned a VEI of 3 (GVP). Despite the fact that during the eruption of the Eyjafjallajökull volcano the maximum plume altitude was below the tropopause, volcanic aerosol was recorded in the stratosphere over Germany (Garmisch-Partenkirchen) at an altitude of up to 14.3 km and over Russia (Tomsk) at an altitude of up to 15 km [*Trickl et al.*, 2013; *Zuev et al.*, 2017a]. During the eruption of the Puyehue volcano (Southern Chile) on 4 June 2011, characterized by VEI = 5, the maximum plume altitude was only 12.2 km (GVP). Thus, in rare cases during eruptions with VEI = 4 (and once even with VEI = 5) the volcanic emission can be below the tropopause height and a small part of the eruptions listed in Table 2 before the 1970s have a probabilistic nature of the penetration of volcanic products into the stratosphere. Figure 1 shows the time series of the stratospheric aerosol optical thickness (at an altitude of 15–35 km), reflecting the main volcanic perturbations of the stratospheric aerosol layer separately for the NH and SH from 1850 to 2012. As seen from Figure 1 , most of the eruptions before 1979 are reflected in the aerosol optical thickness by an increase in aerosol content, despite the fact that Figure 1 shows the average stratospheric aerosol optical thickness for each hemisphere and there must be a significant release of aerosol into the stratosphere to increase the average value for the entire hemisphere (as seen from the period after 1979, not many eruptions recorded in the stratosphere are so large-scale).

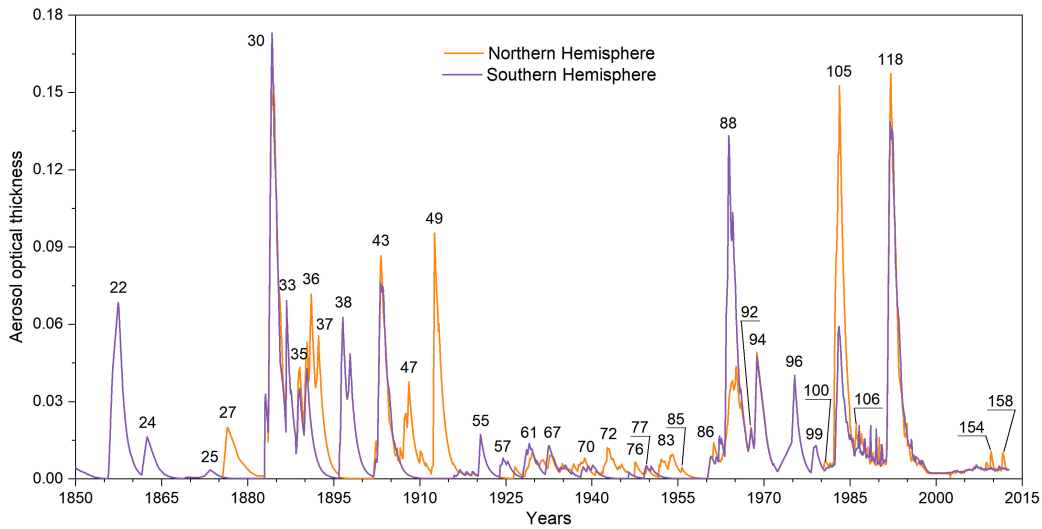

Figure 1. Time series of stratospheric aerosol optical thickness at a wavelength of 0.55 µm at an altitude of 15–35 km on average for the NH and SH (the numbers indicate volcanic eruptions according to Table 1).

The volume of volcanic ash injected into the stratosphere depends not only on the height of the emission, but also on the nature of the eruption. For example, with the same plume altitude of 31 km, the eruptions of El Chichon and Nevado del Ruiz volcanoes in April 1982 and November 1985 had tephra volumes of 2.3×10^9 and 4.8×10^7 m^3, respectively, and were thus characterized by VEI values of 5 and 3 (GVP). Another example is the eruptions of Fuego (plume altitude 24 km, tephra volume 4.0×10^8 m^3) and St. Helens (plume altitude 23 km, tephra volume > 10^9 m^3) volcanoes, which occurred in October 1974 and May 1980 and were characterized by VEI = 4 and VEI = 5, respectively. Although the Fuego eruption was assigned a VEI of 4 and the St. Helens eruption a VEI of 5, the first, being a tropical eruption, disturbed the stratospheric aerosol layer more significantly.

Table 2. List of large volcanic eruptions with the possible injection of aerosols into the stratosphere from 1800 to 2024

No.	Date of eruption	Volcano	Location	VEI	Maximum plume altitude, km	Tropopause altitude, km
1	15.01.1800	St. Helens	Washington, USA (46.20° N, 122.18° W)	5		
2	27.04.1812	Soufriere St. Vincent	Saint Vincent and the Grenadines (13.33° N, 61.18° W)	4		
3	06.08.1812	Awu	Indonesia (3.67° N, 125.50° E)	4		
4	01.02.1814	Mayon	Philippines (13.26° N, 123.69° E)	4		
5	10.04.1815	Tambora	Indonesia (8.25° S, 118.00° E)	7	40	
6	16.01.1817	Raung	Indonesia (8.13° S, 114.04° E)	4		
7	15.02.1818	Colima	Mexico (19.51° N, 103.62° W)	4		
8	12.03.1822	Toya Usu	Japan (42.54° N, 140.84° E)	4		
9	08.10.1822	Galunggung	Indonesia (7.25° S, 108.06° E)	5		
10	10.03.1825	Isanotski	Aleutian Islands (54.76° N, 163.72° W)	4		
11	11.10.1826	Kelut	Indonesia (7.93° S, 112.31° E)	4		
12	27.06.1827	Avachinsky	Kamchatka Peninsula (53.26° N, 158.83° E)	4		
13	09.09.1829	Klyuchevskoy	Kamchatka Peninsula (56.06° N, 160.64° E)	4		
14	??.??.1831	Babuyan Claro	Philippines (19.52° N, 121.94° E)	4		
15	20.01.1835	Cosigüina	Nicaragua (12.98° N, 87.57° W)	5		
16	02.09.1845	Hekla	Iceland (63.98° N, 19.70° W)	4		
17	11.06.1846	Fonualei	Tonga (18.02° S, 174.33° W)	4		
18	22.04.1853	Toya Usu	Japan (42.54° N, 140.84° E)	4		
19	15.12.1853	Chikurachki	Kuril Islands (50.33° N, 155.46° E)	3	13	
20	18.02.1854	Sheveluch	Kamchatka Peninsula (56.65° N, 161.36° E)	5		
21	25.09.1856	Komaga-take	Japan (42.06° N, 140.68° E)	4		
22	15.01.1857	Fuego	Guatemala (14.47° N, 90.88° W)	4		
23	08.05.1860	Katla	Iceland (63.63° N, 19.05° W)	4		
24	28.12.1861	Makian	Indonesia (0.32° N, 127.40° E)	4		
25	15.04.1872	Merapi	Indonesia (7.54° S, 110.44° E)	4		
26	08.01.1873	Grimsvötn	Iceland (64.42° N, 17.33° W)	4		
27	29.03.1875	Askja	Iceland (65.03° N, 16.75° W)	5		
28	26.06.1877	Cotopaxi	Ecuador (0.68° S, 78.44° W)	4		
29	28.06.1880	Fuego	Guatemala (14.47° N, 90.88° W)	4		
30	27.08.1883	Krakatau	Indonesia (6.10° S, 105.42° E)	6		
31	06.10.1883	Augustine	Alaska (59.36° N, 153.43° W)	4		
32	11.01.1886	Tungurahua	Ecuador (1.47° S, 78.44° W)	4		
33	10.06.1886	Okataina	New Zealand (38.12° S, 176.50° E)	5		
34	31.08.1886	Niuafo'ou	Tonga (15.60° S, 175.63° W)	4		
35	15.07.1888	Bandai	Japan (37.60° N, 140.07° E)	4		
36	16.02.1890	Colima	Mexico (19.51° N, 103.62° W)	4		
37	10.01.1893	Calbuco	Chile (41.33° S, 72.61° W)	4		
38	25.06.1897	Mayon	Philippines (13.26° N, 123.69° E)	4		
39	13.11.1899	Doña Juana	Colombia (1.47° N, 76.92° W)	4		
40	02.05.1902	Pelee	Saint Vincent and the Grenadines (14.81° N, 61.17° W)	4		
41	06.05.1902	Soufriere St. Vincent	Saint Vincent and the Grenadines (13.33° N, 61.18° W)	4		
42	08.05.1902	Pelee	Saint Vincent and the Grenadines (14.81° N, 61.17° W)	4		
43	24.10.1902	Santa Maria	Guatemala (14.76° N, 91.55° W)	6		
44	28.05.1903	Grimsvötn	Iceland (64.42° N, 17.33° W)	4		
45	??.01.1905	Lolobau	Papua New Guinea (4.92° S, 151.16° E)	4		
46	08.04.1906	Vesuvius	Italy (40.82° N, 14.43° E)	4		
47	28.03.1907	Ksudach	Kamchatka Peninsula (51.80° N, 157.53° E)	5		

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Table 2. List of large volcanic eruptions with the possible injection of aerosols into the stratosphere from 1800 to 2024(Continued)

No.	Date of eruption	Volcano	Location	VEI	Maximum plume altitude, km	Tropopause altitude, km
48	??.02.1911	Lolobau	Papua New Guinea (4.92° S, 151.16° E)	4		
49	06.06.1912	Novarupta	Alaska (58.27° N, 155.16° W)	6		
50	20.01.1913	Colima	Mexico (19.51° N, 103.62° W)	5		
51	12.01.1914	Sakura-jima	Japan (31.58° N, 130.66° E)	4		
52	09.04.1917	Agrigan	Mariana Islands (18.77° N, 145.67° E)	4		
53	05.04.1918	Tungurahua	Ecuador (1.47° S, 78.44° W)	4	25	
54	12.10.1918	Katla	Iceland (63.63° N, 19.05° W)	4		
55	19.05.1919	Kelut	Indonesia (7.93° S, 112.31° E)	4		
56	11.08.1919	Manam	Papua New Guinea (4.08° S, 145.04° E)	4		
57	23.10.1923	Cerro Negro	Nicaragua (12.51° N, 86.70° W)	3		
58	15.02.1924	Raikoke	Kuril Islands (48.29° N, 153.25° E)	4		
59	31.10.1924	Iriomote-jima	Japan (24.56° N, 124.00° E)	4		
60	05.04.1926	Avachinsky	Kamchatka Peninsula (53.26° N, 158.83° E)	4		
61	06.01.1929	Calbuco	Chile (41.33° S, 72.61° W)	3		
62	17.06.1929	Komaga-take	Japan (42.06° N, 140.68° E)	4		
63	25.03.1931	Klyuchevskoy	Kamchatka Peninsula (56.06° N, 160.64° E)	4		
64	01.05.1931	Aniakchak	Alaska (56.88° N, 158.17° W)	4		
65	11.05.1931	Aniakchak	Alaska (56.88° N, 158.17° W)	4		
66	21.01.1932	Fuego	Guatemala (14.47° N, 90.88° W)	4		
67	10.04.1932	Cerro Azul	Chile (35.65° S, 70.76° W)	5	30	
68	08.01.1933	Kharimkotan	Kuril Islands (49.12° N, 154.51° E)	5		
69	10.07.1933	Suoh	Indonesia (5.25° S, 104.27° E)	4		
70	03.04.1937	Klyuchevskoy	Kamchatka Peninsula (56.06° N, 160.64° E)	3		
71	29.05.1937	Rabaul	Papua New Guinea (4.27° S, 152.20° E)	4		
72	07.05.1941	Tolbachik	Kamchatka Peninsula (55.83° N, 160.33° E)	3		
73	20.02.1943	Michoacán-Guanajuato	Mexico (19.85° N, 101.75° W)	4		
74	25.02.1945	Avachinsky	Kamchatka Peninsula (53.26° N, 158.83° E)	4		
75	09.11.1946	Sarychev Peak	Kuril Islands (48.09° N, 153.20° E)	4		
76	29.03.1947	Hekla	Iceland (63.98° N, 19.70° W)	4		
77	??.??.1949	Michoacán-Guanajuato	Mexico (19.85° N, 101.75° W)	3		
78	??.??.1950	Michoacán-Guanajuato	Mexico (19.85° N, 101.75° W)	3		
79	??.??.1951	Ambrym	Vanuatu (16.25° S, 168.12° E)	4		
80	21.01.1951	Lamington	Papua New Guinea (8.95° S, 148.15° E)	4		
81	31.08.1951	Kelut	Indonesia (7.93° S, 112.31° E)	4		
82	29.02.1952	Bagana	Papua New Guinea (6.14° S, 155.20° E)	4		
83	09.07.1953	Spurr	Alaska (61.30° N, 152.25° W)	4		
84	27.07.1955	Carran-Los Venados	Chile (40.35° S, 72.07° W)	4		
85	30.03.1956	Bezymianny	Kamchatka Peninsula (55.98° N, 160.59° E)	5	30	
86	28.09.1960	Cerro Negro	Nicaragua (12.51° N, 86.70° W)	3		
87	15.10.1960	Okmok	Aleutian Islands (53.43° N, 168.13° W)	3		
88	17.03.1963	Agung	Indonesia (8.34° S, 115.51° E)	5	25	
89	16.05.1963	Agung	Indonesia (8.34° S, 115.51° E)	4		
90	12.11.1964	Sheveluch	Kamchatka Peninsula (56.65° N, 161.36° E)	4		
91	28.09.1965	Taal	Philippines (14.00° N, 120.99° E)	4		
92	26.04.1966	Kelut	Indonesia (7.93° S, 112.31° E)	4		
93	12.08.1966	Awu	Indonesia (3.67° N, 125.50° E)	4		
94	11.06.1968	Fernandina	Ecuador (0.37° S, 91.55° W)	4		
95	14.07.1973	Chachadake [Tiatia]	Kuril Islands (44.35° N, 146.25° E)	4		
96	17.10.1974	Fuego	Guatemala (14.47° N, 90.88° W)	4	24	
97	06.07.1975	Tolbachik	Kamchatka Peninsula (55.83° N, 160.33° E)	4		
98	22.01.1976	Augustine	Alaska (59.36° N, 153.43° W)	4		

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Table 2. List of large volcanic eruptions with the possible injection of aerosols into the stratosphere from 1800 to 2024(Continued)

No.	Date of eruption	Volcano	Location	VEI	Maximum plume altitude, km	Tropopause altitude, km
99	17.04.1979	Soufriere St. Vincent	Saint Vincent and the Grenadines (13.33° N, 61.18° W)	3	18.7	16.9
100	18.05.1980	St. Helens	Washington, USA (46.20° N, 122.18° W)	5	23	
101	17.08.1980	Hekla	Iceland (63.98° N, 19.70° W)	3	15	9.8
102	30.04.1981	Alaid	Kuril Islands (50.86° N, 155.55° E)	4	15	12.0
103	15.05.1981	Pagan	Mariana Islands (18.13° N, 145.8° E)	4	20	
104	28.03.1982	El Chichon	Mexico (17.36° N, 93.23° W)	4	24	
105	03.04.1982	El Chichon	Mexico (17.36° N, 93.23° W)	5	31	
106	13.11.1985	Nevado del Ruiz	Colombia (4.90° N, 75.32° W)	3	31	
107	27.03.1986	Augustine	Alaska (59.36° N, 153.43° W)	4	21	
108	18.04.1986	Pavlof	Aleutian Islands (55.42° N, 161.89° W)	3	15.2	11.1
109	16.09.1986	Lascar	Chile (23.37° S, 67.73° W)	3	16	14.2
110	20.11.1986	Chikurachki	Kuril Islands (50.33° N, 155.46° E)	4	14	9.5
111	23.02.1987	Klyuchevskoy	Kamchatka Peninsula (56.06° N, 160.64° E)	4	13.7	8.4
112	28.08.1987	Cleveland	Aleutian Islands (52.83° N, 169.94° W)	3	10.6	–
113	09.05.1988	Banda Api	Indonesia (4.53° S, 129.87° E)	3	17.7	15.2
114	14.12.1989	Redoubt	Alaska (60.49° N, 152.74° W)	3	12	9.6
115	02.01.1990	Redoubt	Alaska (60.49° N, 152.74° W)	3	13.5	10.5
116	10.02.1990	Kelut	Indonesia (7.93° S, 112.31° E)	4	20	
117	17.01.1991	Hekla	Iceland (63.98° N, 19.70° W)	3	11.5	8.3
118	15.06.1991	Pinatubo	Philippines (15.13° N, 120.35° E)	6	40	
119	12.08.1991	Cerro Hudson	Chile (45.90° S, 72.97° W)	5	18	10.7
120	27.06.1992	Spurr	Alaska (61.30° N, 152.25° W)	4	18	11.7
121	17.08.1992	Spurr	Alaska (61.30° N, 152.25° W)	3	15	9.6
122	19.04.1993	Lascar	Chile (23.37° S, 67.73° W)	4	25	
123	22.04.1993	Sheveluch	Kamchatka Peninsula (56.65° N, 161.36° E)	3	20	
124	21.10.1993	Bezymianny	Kamchatka Peninsula (55.98° N, 160.59° E)	3	15	8.3
125	25.05.1994	Cleveland	Aleutian Islands (52.83° N, 169.94° W)	3	10.5	10
126	19.09.1994	Rabaul	Papua New Guinea (4.27° S, 152.20° E)	4	21	
127	01.10.1994	Klyuchevskoy	Kamchatka Peninsula (56.06° N, 160.64° E)	3	18	9.9
128	05.12.1997	Bezymianny	Kamchatka Peninsula (55.98° N, 160.59° E)	3	13	11.8
129	18.12.1998	Grimsvötn	Iceland (64.42° N, 17.33° W)	3	10	8.7
130	19.04.1999	Shishaldin	Aleutian Islands (54.76° N, 163.97° W)	3	14	10.1
131	05.10.1999	Guagua Pichincha	Ecuador (0.17° S, 78.60° W)	3	20	
132	26.02.2000	Hekla	Iceland (63.98° N, 19.70° W)	3	15	–
133	18.08.2000	Miyakejima	Japan (34.09° N, 139.53° E)	3	17.5	–
134	29.09.2000	Ulawun	Papua New Guinea (5.05° S, 151.33° E)	4	17.3	16.3
135	22.05.2001	Sheveluch	Kamchatka Peninsula (56.65° N, 161.36° E)	4	20	
136	25.09.2002	Ruang	Indonesia (2.30° N, 125.37° E)	4	17	16.5
137	03.11.2002	Reventador	Ecuador (0.08° S, 77.66° W)	4	20.5	
138	26.07.2003	Bezymianny	Kamchatka Peninsula (55.98° N, 160.59° E)	3	11	–
139	10.05.2004	Sheveluch	Kamchatka Peninsula (56.65° N, 161.36° E)	3	11	10.0
140	01.11.2004	Grimsvötn	Iceland (64.42° N, 17.33° W)	3	14	10.3
141	24.11.2004	Manam	Papua New Guinea (4.08° S, 145.04° E)	4	18	17.6
142	27.01.2005	Manam	Papua New Guinea (4.08° S, 145.04° E)	4	24	
143	27.01.2006	Augustine	Alaska (59.36° N, 153.43° W)	3	12.2	8.5
144	27.02.2006	Manam	Papua New Guinea (4.08° S, 145.04° E)	4	19	16.0
145	09.05.2006	Bezymianny	Kamchatka Peninsula (55.98° N, 160.59° E)	3	15	10.5
146	20.05.2006	Soufriere Hills	Saint Vincent and the Grenadines (16.72° N, 62.18° W)	4	17	16.2
147	07.10.2006	Rabaul	Papua New Guinea (4.27° S, 152.20° E)	4	18	16.3
148	24.12.2006	Bezymianny	Kamchatka Peninsula (55.98° N, 160.59° E)	3	13	8.9
149	24.12.2007	Bezymianny	Kamchatka Peninsula (55.98° N, 160.59° E)	3	13	9.6

Continued on next page

Table 2. List of large volcanic eruptions with the possible injection of aerosols into the stratosphere from 1800 to 2024(Continued)

No.	Date of eruption	Volcano	Location	VEI	Maximum plume altitude, km	Tropopause altitude, km
150	02.05.2008	Chaiten	Chile (42.83° S, 72.65° W)	4	30	
151	12.07.2008	Okmok	Aleutian Islands (53.43° N, 168.13° W)	4	15	12.3
152	07.08.2008	Kasatochi	Aleutian Islands (52.18° N, 175.51° W)	4	14	12.1
153	22.03.2009	Redoubt	Alaska (60.49° N, 152.74° W)	3	18.2	9.3
154	26.03.2009	Redoubt	Alaska (60.49° N, 152.74° W)	3	20	
155	04.04.2009	Redoubt	Alaska (60.49° N, 152.74° W)	3	15.2	9.4
156	16.06.2009	Sarychev Peak	Kuril Islands (48.09° N, 153.20° E)	4	21	
157	17.12.2009	Bezymianny	Kamchatka Peninsula (55.98° N, 160.59° E)	3	15	6.9
158	04.11.2010	Merapi	Indonesia (7.54° S, 110.44° E)	4	18.3	16.3
159	18.04.2011	Karymsky	Kamchatka Peninsula (54.05° N, 159.44° E)	3	11.9	9.6
160	21.05.2011	Grimsvötn	Iceland (64.42° N, 17.33° W)	4	20	
161	13.06.2011	Nabro	Eritrea (13.37° N, 41.70° E)	4	18	16.7
162	13.02.2014	Kelut	Indonesia (7.93° S, 112.31° E)	4	17	16.5
163	29.08.2014	Rabaul	Papua New Guinea (4.27° S, 152.20° E)	3	18.3	17.0
164	22.04.2015	Calbuco	Chile (41.33° S, 72.61° W)	4	17	12.3
165	21.12.2016	Bogoslof	Aleutian Islands (53.93° N, 168.03° W)	3	10.7	10.0
166	20.01.2017	Bogoslof	Aleutian Islands (53.93° N, 168.03° W)	3	11	7.8
167	24.01.2017	Bogoslof	Aleutian Islands (53.93° N, 168.03° W)	3	10.7	7.6
168	17.02.2017	Bogoslof	Aleutian Islands (53.93° N, 168.03° W)	3	11.6	8.2
169	07.03.2017	Bogoslof	Aleutian Islands (53.93° N, 168.03° W)	3	13.4	12.3
170	28.05.2017	Bogoslof	Aleutian Islands (53.93° N, 168.03° W)	3	13.7	9.6
171	14.06.2017	Sheveluch	Kamchatka Peninsula (56.65° N, 161.36° E)	3	12	10.7
172	23.06.2017	Bogoslof	Aleutian Islands (53.93° N, 168.03° W)	3	11.9	11.5
173	23.07.2017	Sheveluch	Kamchatka Peninsula (56.65° N, 161.36° E)	3	12	8.8
174	07.08.2017	Bogoslof	Aleutian Islands (53.93° N, 168.03° W)	3	12.7	9.5
175	26.07.2018	Ambae	Vanuatu (15.39° S, 167.83° E)	3	18	16.3
176	22.06.2019	Raikoke	Kuril Islands (48.29° N, 153.25° E)	3	13	10.9
177	26.06.2019	Ulawun	Papua New Guinea (5.05° S, 151.33° E)	4	19.2	17.0
178	20.01.2020	Shishaldin	Aleutian Islands (54.76° N, 163.97° W)	3	9.1	7.3
179	09.04.2021	Soufriere St. Vincent	Saint Vincent and the Grenadines (13.33° N, 61.18° W)	4	16	15.5
180	13.08.2021	Fukutoku-Oka-no-Ba	Japan (24.28° N, 141.48° E)	4	16	15.7
181	14.01.2022	Hunga Tonga-Hunga Ha'apai	Tonga (20.54° S, 175.38° W)	4	20	
182	15.01.2022	Hunga Tonga-Hunga Ha'apai	Tonga (20.54° S, 175.38° W)	5	30	
183	07.04.2023	Bezymianny	Kamchatka Peninsula (55.98° N, 160.59° E)	3	12	9.7
184	11.04.2023	Sheveluch	Kamchatka Peninsula (56.65° N, 161.36° E)	4	20	

Figure 2 shows a diagram of the distribution of volcanic eruptions with probable emission into the stratosphere by VEI and the latitudinal location of the volcano for 1800–2024, obtained from the data of Table 2. From 1800 to 2024, 184 eruptions with probable stratospheric emissions were recorded. Among them there is 1 eruption with VEI = 7 (Tambora, April 1815), 4 eruptions with VEI = 6 (Krakatau, August 1883; Santa Maria, October 1902; Novarupta, June 1912; Pinatubo, June 1991), 16 eruptions with VEI = 5 (St. Helens, January 1800; Galunggung, October 1822; Cosigüina, January 1835; Sheveluch, February 1854; Askja, March 1875; Okataina, June 1886; Ksudach, March 1907; Colima, January 1913; Cerro Azul, April 1932; Kharimkotan, January 1933; Bezymianny, March 1956; Agung, March 1963; St. Helens, May 1980; El Chichon, April 1982; Hunga Tonga, January 2022), as well as 106 eruptions with VEI = 4 and 57 eruptions with VEI = 3. In the high and mid-latitudes of the NH, 95 eruptions with probable stratospheric emissions were recorded, in the tropical latitudes 79 were recorded, and in the high and mid-latitudes of the SH, 10 were recorded. In extratropical latitudes, the probability of ejection of products into the stratosphere increases in eruptions with VEI = 3 due to the lower tropopause height, which is especially evident in the NH. The VEI classification of eruptions proposed by Newhall and Self [*Newhall and Self*, 1982] defines ranges of volume of tephra: for eruptions with VEI = 3 it is 10^7–10^8 m^3, for eruptions with VEI = 4 it is 10^8–10^9 m^3, for eruptions with VEI = 5 it is 10^9–10^{10} m^3, for eruptions with VEI = 6 it is 10^{10}–10^{11} m^3, for eruptions with VEI = 7 it is 10^{11}–10^{12} m^3. If we ignore the differences in the nature of eruptions within the same VEI, then the approximate ratio in the contribution of the NH eruptions, tropical eruptions, and the SH eruptions to the increase in the aerosol load on the stratosphere is 6:40:1, respectively.

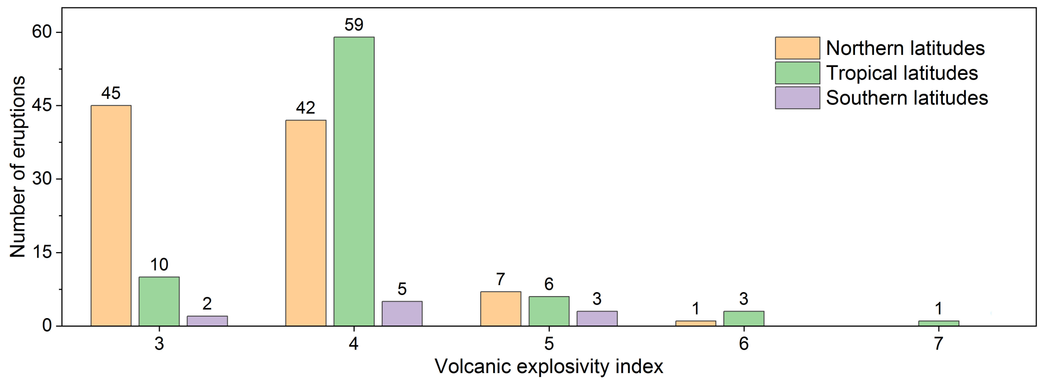

Figure 2. Number of volcanic eruptions with probable stratospheric emissions in northern, tropical and southern latitudes for 1800–2024.

Figure 3 shows a time series of volcanic eruptions with VEI ≥ 4 with probable penetration of products into the stratosphere from 1800 to 2024, ranked by VEI and latitudinal location of the volcano (for eruptions with VEI ≥ 5, the names of the volcanoes are given), according to Table 2. Figure 3 also illustrates the number of eruptions with VEI = 4 for every 25 years. We show that over the past 25 years, there has been an almost two-fold increase in the frequency of eruptions with VEI = 4, with a decrease in the number of eruptions with VEI ≥ 5 compared to previous periods. Figure 4 shows a time series of volcanic eruptions with the ejection of products into the stratosphere from 1980 to 2024 with distribution by maximum plume altitude, VEI and latitudinal location of the volcano (for eruptions with VEI ≥ 5, the names of the volcanoes are given), according to Table 2. The average altitude of eruptions with product injection into the stratosphere in the high and middle latitudes of the NH for 1980–2024 was 14.4 km (range 9.1–23.0 km; 54 eruptions), in the tropical latitudes was 21.2 km (range 16.0–40.0 km; 26 eruptions), and in the high and middle latitudes of the SH was also 21.2 km (range 16.0–30.0 km; 5 eruptions).

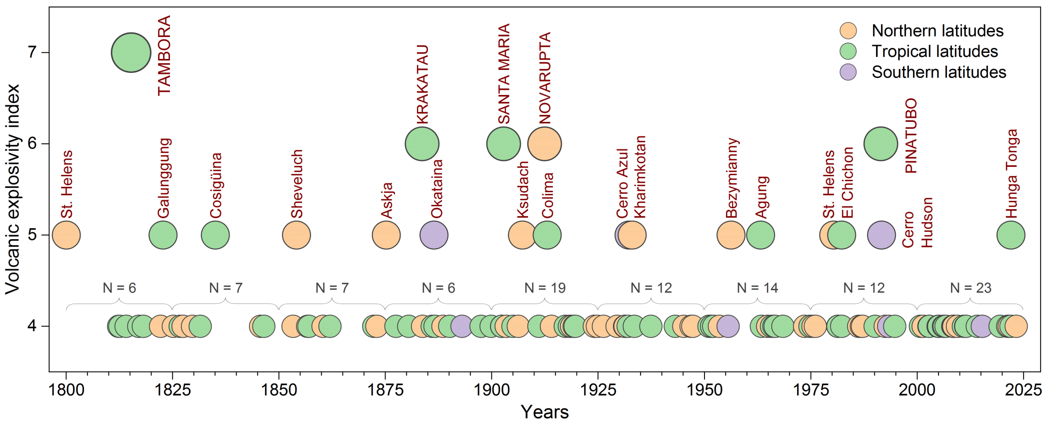

Figure 3. Distribution of volcanic eruptions with probable stratospheric emissions by VEI and latitudes from 1800 to 2024.

Figure 5 shows a map of volcanic eruptions with probable stratospheric emissions from 1800 to 2024, distributed by VEI, and Figure 6 shows the top 10 volcanoes and regions with the highest frequency of eruptions with probable stratospheric emissions

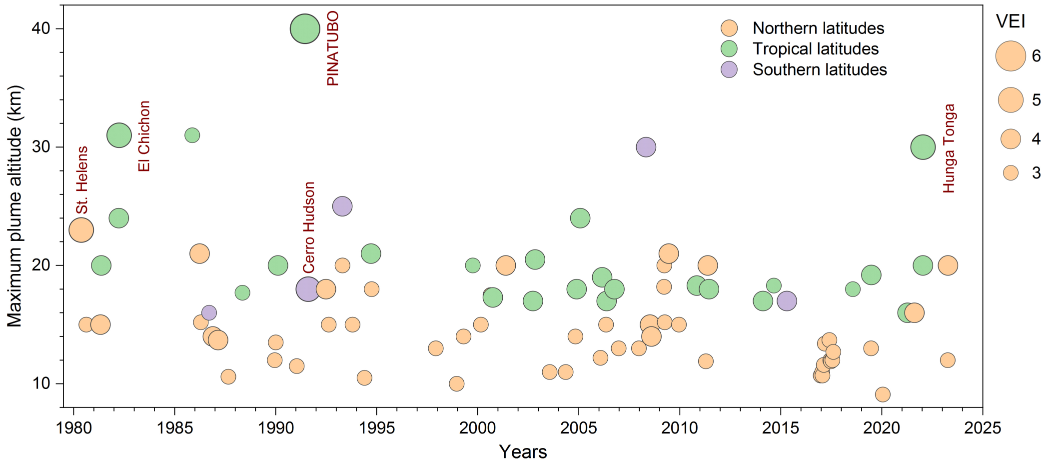

Figure 4. Distribution of volcanic eruptions with emissions into the stratosphere by maximum plume altitude, latitudes and VEI from 1980 to 2024.

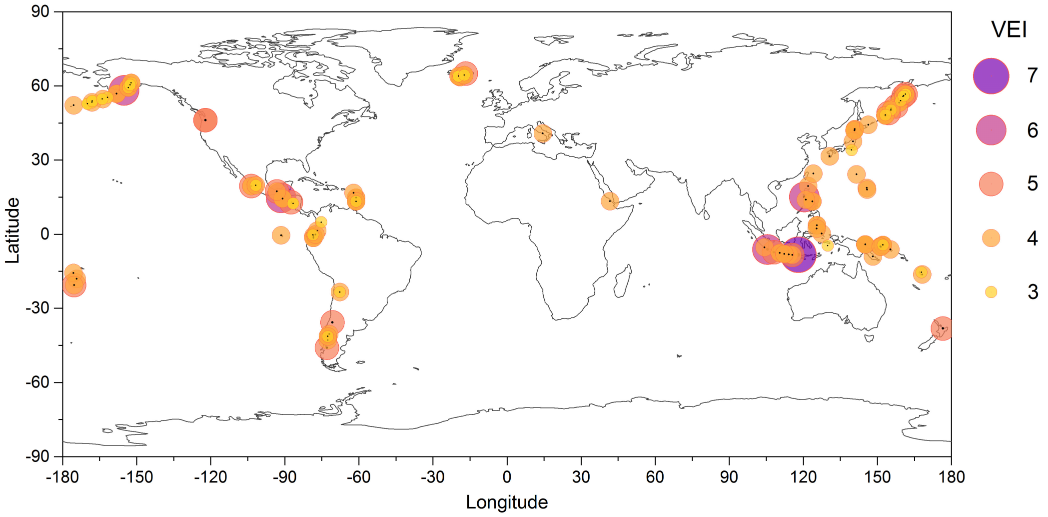

Figure 5. Map of volcanic eruptions with probable stratospheric emissions from 1800 to 2024.

from 1800 to 2024, distributed by VEI, according to Table 2. During this period, the largest number of eruptions with probable ejection of products into the stratosphere were observed in Kamchatka – 29 eruptions, of which 16 with VEI = 3, 10 with VEI = 4 and 3 with VEI = 5. In second place is Indonesia, where 20 eruptions were observed, including 1 with VEI = 3, 15 with VEI = 4, 2 with VEI = 5, and 1 each with VEI = 6 and VEI = 7. The top 3 volcanoes with the highest frequency of eruptions with emissions into the stratosphere were Bezymianny (8 eruptions with VEI = 3 and 1 with VEI = 5; Kamchatka Peninsula), Sheveluch (4 eruptions with VEI = 3, 3 with VEI = 4 and 1 with VEI = 5; Kamchatka Peninsula) and Bogoslof (8 eruptions with VEI = 3; Aleutian Islands), and in 4th place was the Indonesian volcano Kelut (6 eruptions with VEI = 4). Volcanoes with the highest frequency of eruptions with injection of products into the stratosphere are in most cases defined by eruptions with VEI ≤ 5, exceptions: Bezymianny (9 eruptions, 1 with VEI = 5), Sheveluch (8 eruptions, 1 with VEI = 5), Colima (3 eruptions, 1 with VEI = 5), as well as El Chichon, Agung, Hunga Tonga had 2 eruptions, 1 of which with VEI = 5, and St. Helens had 2 eruptions, both with VEI = 5. At the same time, the volcanoes Askja, Cerro Azul, Cerro Hudson, Cosigüina, Galunggung, Kharimkotan, Ksudach, Okataina had only one eruption each with penetration into the stratosphere, characterized by VEI = 5, and volcanoes with eruptions with VEI = 6–7 in all cases (Tambora, Krakatau, Santa Maria, Novarupta, Pinatubo) also had only one eruption each with injection of products into the stratosphere in 225 years.

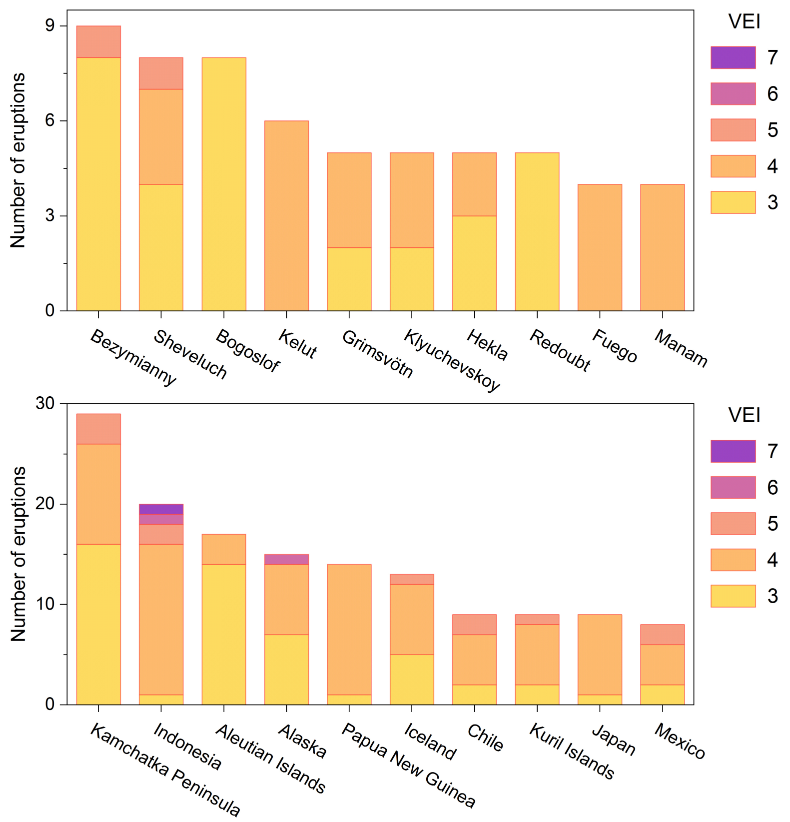

Figure 6. Top 10 volcanoes and regions with high frequency of eruptions with probable stratospheric emissions from 1800 to 2024.

4. Conclusion

In this work, using global data on volcanic eruptions from the book of Siebert et al. [*Siebert et al.*, 2010] and the Global Volcanism Program of the Smithsonian Institution, we examined the volcanic loading on the stratosphere over the past 225 years, based on the compiled list of volcanic eruptions whose products probably injected into the stratosphere for the period from 1800 to 2024. In compiling the list of eruptions that most likely ejected products into the stratosphere, we used VEI data, plume altitude data (if available; plume altitude was compared with tropopause height) and data on recorded eruptions with volcanic aerosol penetration into the stratosphere. Over the past 225 years (1800–2024), 184 eruptions with probable stratospheric emissions have been recorded, including 1 eruption with VEI = 7 (Tambora, April 1815), 4 eruptions with VEI = 6 (Krakatau, August 1883; Santa Maria, October 1902; Novarupta, June 1912; Pinatubo, June 1991), and 16, 106 and 57 eruptions with VEI = 5, VEI = 4 and VEI = 3, respectively. The probability of volcanic products entering the stratosphere during eruptions with VEI = 3 increases in middle and high latitudes due to the lower tropopause height, which is consistent with the results of Vernier et al. [*Vernier et al.*, 2011]. The volcanic loading on the stratosphere at mid- and high latitudes in the NH exceeds that of the SH, with large tropical volcanic eruptions making the largest contribution to the total aerosol loading of the stratosphere, as was also previously shown in Robock [*Robock*, 2015]. According to our estimates, the approximate ratio of the contribution of eruptions to the increase in the aerosol load on the stratosphere (without taking into account differences in the nature of eruptions within one VEI) in total over the last 225 years was 6:40:1, respectively, for eruptions in high and mid-latitudes of the NH, eruptions at tropical latitudes, and eruptions in high and mid-latitudes of the SH. The average plume altitude of eruptions with product injection into the stratosphere in the high and middle latitudes of the NH for 1980–2024 was about 14 km, and in the tropical latitudes and in the high and middle latitudes of the SH was about 21 km. We found that the number of eruptions with VEI = 4 has almost doubled over the past 25 years, while the number of eruptions with VEI = 5–6 has decreased. A map of volcanic eruptions with probable injection into the stratosphere is provided. We have traced that the highest frequency of eruptions (with volcanic products injection into the stratosphere) is observed in the regions of Kamchatka, Indonesia and the Aleutian Islands; among the volcanoes, the most frequent are Bezymianny, Bogoslof and Sheveluch. Moreover, volcanoes with eruptions with VEI ≥ 6 (Tambora, Krakatau, Santa Maria, Novarupta, Pinatubo) had only one eruption with the injection of volcanic aerosol into the stratosphere over the past 225 years.

Acknowledgments. This work was supported by the Ministry of Science and Higher Education of the Russian Federation (Institute of Monitoring of Climatic and Ecological Systems of the Siberian Branch of the Russian Academy of Sciences).

References

Andersson S., Martinsson B., Vernier J.-P., et al. Significant radiative impact of volcanic aerosol in the lowermost stratosphere // Nature Communications. — 2015. — Vol. 6, no. 1. — https://doi.org/10.1038/ncomms8692.

Angell J. K. Stratospheric warming due to Agung, El Chichón, and Pinatubo taking into account the quasi-biennial oscillation // Journal of Geophysical Research: Atmospheres. — 1997. — Vol. 102, no. D8. — P. 9479–9485. — https://doi.org/10.1029/96jd03588.

Bebbington M. S. Long-term forecasting of volcanic explosivity // Geophysical Journal International. — 2014. — Vol. 197, no. 3. — P. 1500–1515. — https://doi.org/10.1093/gji/ggu078.

Coombs M., Wallace K., Cameron C., et al. Overview, chronology, and impacts of the 2016-2017 eruption of Bogoslof volcano, Alaska // Bulletin of Volcanology. — 2019. — Vol. 81, no. 11. — https://doi.org/10.1007/s00445-019-1322-9.

Driscoll S., Bozzo A., Gray L. J., et al. Coupled Model Intercomparison Project 5 (CMIP5) simulations of climate following volcanic eruptions // Journal of Geophysical Research: Atmospheres. — 2012. — Vol. 117, no. D17. — P. D17105. — https://doi.org/10.1029/2012jd017607.

Fromm M., III G. Kablick, Nedoluha G., et al. Correcting the record of volcanic stratospheric aerosol impact: Nabro and Sarychev Peak // Journal of Geophysical Research: Atmospheres. — 2014. — Vol. 119, no. 17. — P. 10343–10364. — https://doi.org/10.1002/2014jd021507.

Gerasimov V. V., Zuev V. V., Savelieva E. S., et al. The impact of volcanic eruptions, pyrocumulonimbus plumes, and the Arctic polar vortex intrusions on aerosol loading over Tomsk (Western Siberia, Russia) as observed by lidar from 2018 to 2022 // International Journal of Remote Sensing. — 2024. — Vol. 45, no. 16. — P. 5464–5505. — https://doi.org/10.1080/01431161.2024.2377833.

Glasow R. von, Bobrowski N. and Kern C. The effects of volcanic eruptions on atmospheric chemistry // Chemical Geology. — 2009. — Vol. 263, no. 1–4. — P. 131–142. — https://doi.org/10.1016/j.chemgeo.2008.08.020.

Kloss C., Sellitto P., Legras B., et al. Impact of the 2018 Ambae Eruption on the Global Stratospheric Aerosol Layer and Climate // Journal of Geophysical Research: Atmospheres. — 2020. — Vol. 125, no. 14. — e2020JD032410. — https://doi.org/10.1029/2020jd032410.

Kroll C. A., Dacie S., Azoulay A., et al. The impact of volcanic eruptions of different magnitude on stratospheric water vapor in the tropics // Atmospheric Chemistry and Physics. — 2021. — Vol. 21, no. 8. — P. 6565–6591. — https://doi.org/10.5194/acp-21-6565-2021.

LeGrande A. N., Tsigaridis K. and Bauer S. E. Role of atmospheric chemistry in the climate impacts of stratospheric volcanic injections // Nature Geoscience. — 2016. — Vol. 9, no. 9. — P. 652–655. — https://doi.org/10.1038/ngeo2771.

Löffler M., Brinkop S. and Jöckel P. Impact of major volcanic eruptions on stratospheric water vapour // Atmospheric Chemistry and Physics. — 2016. — Vol. 16, no. 10. — P. 6547–6562. — https://doi.org/10.5194/acp-16-6547-2016.

Mehta S. K., Fujiwara M., Tsuda T., et al. Effect of recent minor volcanic eruptions on temperatures in the upper troposphere and lower stratosphere // Journal of Atmospheric and Solar-Terrestrial Physics. — 2015. — Vol. 129. — P. 99–110. — https://doi.org/10.1016/j.jastp.2015.04.009.

Mills M. J., Schmidt A., Easter R., et al. Global volcanic aerosol properties derived from emissions, 1990-2014, using CESM1(WACCM) // Journal of Geophysical Research: Atmospheres. — 2016. — Vol. 121, no. 5. — P. 2332–2348. — https://doi.org/10.1002/2015jd024290.

Ming A., Winton V. H. L., Keeble J., et al. Stratospheric ozone changes from explosive tropical volcanoes: Modeling and ice core constraints // Journal of Geophysical Research: Atmospheres. — 2020. — Vol. 125, no. 11. — https://doi.org/10.1029/2019jd032290.

Newhall C. G. and Self S. The volcanic explosivity index (VEI) an estimate of explosive magnitude for historical volcanism // Journal of Geophysical Research: Oceans. — 1982. — Vol. 87, no. C2. — P. 1231–1238. — https://doi.org/10.1029/jc087ic02p01231.

Otterå O. H. Simulating the effects of the 1991 Mount Pinatubo volcanic eruption using the ARPEGE atmosphere general circulation model // Advances in Atmospheric Sciences. — 2008. — Vol. 25, no. 2. — P. 213–226. — https://doi.org/10.1007/s00376-008-0213-3.

Randel W. J., Wu F., Russell J. M., et al. Ozone and temperature changes in the stratosphere following the eruption of Mount Pinatubo // Journal of Geophysical Research: Atmospheres. — 1995. — Vol. 100, no. D8. — P. 16753–16764. — https://doi.org/10.1029/95jd01001.

Robock A. Climatic Impacts of Volcanic Eruptions // The Encyclopedia of Volcanoes. — Massachusetts (USA) : Elsevier, 2015. — P. 935–942. — https://doi.org/10.1016/b978-0-12-385938-9.00053-5.

Robock A., Adams T., Moore M., et al. Southern Hemisphere atmospheric circulation effects of the 1991 Mount Pinatubo eruption // Geophysical Research Letters. — 2007. — Vol. 34, no. 23. — https://doi.org/10.1029/2007gl031403.

Robock A. and Oppenheimer C. Volcanism and the Earth's Atmosphere. — Washington (USA) : American Geophysical Union, 2003. — 360 p. — (Geophysical Monograph Series). — https://doi.org/10.1029/gm139.

Siebert L., Simkin T. and Kimberly P. Volcanoes of the World. — 3rd. — Berkeley (USA) : University of California Press, 2010. — 551 p.

Sioris C. E., Malo A., McLinden C. A., et al. Direct injection of water vapor into the stratosphere by volcanic eruptions // Geophysical Research Letters. — 2016. — Vol. 43, no. 14. — P. 7694–7700. — https://doi.org/10.1002/2016gl069918.

Stenchikov G., Hamilton K., Stouffer R. J., et al. Arctic Oscillation response to volcanic eruptions in the IPCC AR4 climate models // Journal of Geophysical Research: Atmospheres. — 2006. — Vol. 111, no. D7. — P. D07107. — https://doi.org/10.1029/2005jd006286.

Stocker M., Ladstädter F., Wilhelmsen H., et al. Quantifying stratospheric temperature signals and climate imprints from post-2000 volcanic eruptions // Geophysical Research Letters. — 2019. — Vol. 46, no. 21. — P. 12486–12494. — https://doi.org/10.1029/2019gl084396.

Thomason L. W., Kovilakam M., Schmidt A., et al. Evidence for the predictability of changes in the stratospheric aerosol size following volcanic eruptions of diverse magnitudes using space-based instruments // Atmospheric Chemistry and Physics. — 2021. — Vol. 21, no. 2. — P. 1143–1158. — https://doi.org/10.5194/acp-21-1143-2021.

Trickl T., Giehl H., Jäger H., et al. 35 yr of stratospheric aerosol measurements at Garmisch-Partenkirchen: from Fuego to Eyjafjallajökull, and beyond // Atmospheric Chemistry and Physics. — 2013. — Vol. 13, no. 10. — P. 5205–5225. — https://doi.org/10.5194/acp-13-5205-2013.

Trickl T., Vogelmann H., Fromm M. D., et al. Measurement report: Violent biomass burning and volcanic eruptions - a new period of elevated stratospheric aerosol over central Europe (2017 to 2023) in a long series of observations // Atmospheric Chemistry and Physics. — 2024. — Vol. 24, no. 3. — P. 1997–2021. — https://doi.org/10.5194/acp-24-1997-2024.

Vernier J.-P., Thomason L. W., Pommereau J. P., et al. Major influence of tropical volcanic eruptions on the stratospheric aerosol layer during the last decade // Geophysical Research Letters. — 2011. — Vol. 38, no. 12. — P. L12807. — https://doi.org/10.1029/2011gl047563.

Wrana F., Niemeier U., Thomason L. W., et al. Stratospheric aerosol size reduction after volcanic eruptions // Atmospheric Chemistry and Physics. — 2023. — Vol. 23, no. 17. — P. 9725–9743. — https://doi.org/10.5194/acp-23-9725-2023.

Zuev V. V., Burlakov V. D., Nevzorov A. V., et al. 30-year lidar observations of the stratospheric aerosol layer state over Tomsk (Western Siberia, Russia) // Atmospheric Chemistry and Physics. — 2017a. — Vol. 17, no. 4. — P. 3067–3081. — https://doi.org/10.5194/acp-17-3067-2017.

Zuev V. V., Zueva N. E. and Savelieva E. S. The role of the Mt. Merapi eruption in the 2011 Arctic ozone depletion // Atmospheric Environment. — 2017b. — Vol. 166. — P. 327–333. — https://doi.org/10.1016/j.atmosenv.2017.07.040.