Recent Volcanism and the Stratosphere

Abstract. *In the quiet years after the 1956 eruption of the Bezymianny volcano in central Kamchatka, it is doubtful that any volcano vented into the stratosphere until the 1963 eruptions of Agung (Bali), Trident (Alaska), and Surtsey (Iceland). From 1963 to the Hekla (Iceland) event in May 1970, two latitudinal belts of volcanoes have ejected ash and gases into the stratosphere. One belt is equatorial and the other is just below the Arctic Circle. The latter, where the tropopause is considerably lower, may have been the principal source of replenishment of volcanic dust and gases to the stratosphere. Submarine and phreatic volcanic eruptions may have been the sources of reported increase of water vapor in the stratosphere.*

It has long been recognized that clusters of volcanic eruptions occur periodically. The pattern is evidently continuing. During the past two decades there have been two periods of strongly explosive eruption—1950 to 1956 and 1963 to 1970—separated by 7 years of relative quiet. As in the past, renewed volcanism has revived efforts to correlate volcanic activity with variations in such optical characteristics of the atmosphere as atmospheric turbidity, dust levels, dust distribution, aerosol content, and solar radiation intensity (*1–4*).These recent studies have had mixed results, among other reasons because most observers have attributed anomalous changes in the stratosphere solely or primarily to a single eruption, that of Mount Agung on Bali in 1963 (*4, 5*), and others may not have recognized the varied character of these explosive eruptions and their effluent.

From 1950 to 1956 seven major eruptions occurred, culminating in perhaps the most violent volcanic event of the century, that of Bezymianny in central Kamchatka (56°N, 160.5°E). Its paroxysmal explosion of 30 March 1956 expelled ash clouds to an altitude of 40 to 45 km, or more than 30 km above the regional tropopause (*6, 7*). Three years earlier an eruption of Mount Spurr in Alaska (*8*) ejected a dust cloud 22 km high. The optical effects of both these eruptions were observed over North America and Europe (*9*). For the next 7 years, April 1956 to March 1963, there is no indication that any eruption cloud penetrated the tropopause.

F. E. Volz has been compiling a considerable body of atmospheric data since 1959, including optical dust thickness, twilight sky radiance, and atmospheric turbidity profiles (*2, 3, 10, 11*). He has shown that the minimum values in several categories of measurment were those for the period September 1959 to March 1963. His data support the view that little or no eruption material entered the stratosphere for several years prior to March 1963. Mastenbrook (*12*) has also stated that there was less water vapor in the stratosphere during 1961 and 1962 than there has been at any time since.

During 1963 three eruptions to the stratosphere occurred. In March of that year the volcano Agung on the island of Bali ejected apparently great quantities of material into the stratosphere (*1, 13*). Although reliable elevations of the dust clouds are unavailable, there is little doubt, on the basis of indirect observations, that the eruption was the most significant explosive volcanic event since Bezymianny in 1956. A month after the Agung explosion, the volcano Trident in Alaska erupted gas and ash clouds, which rose to 15 km (*14*). In November of the same year the volcanic island Surtsey started to form off Iceland. The resultant increase and subsequent variations in stratospheric turbidity are represented in Fig. 1.

The absolute measurements of twilight sky radiance obtained by Volz in Massachusetts from 1959 to 1961 and in southern Germany from 1962 to 1967 are presented in Fig. 1 (inset) as the amplitude of the $\lambda\,659/\lambda\,516$ (Massachusetts) or $\lambda\,715/\lambda\,477$ (Germany) (*15*) ratio of red to green (R/G) of the sky radiance at 20° elevation in the solar vertical. The R/G ratio at 1° solar depression (sd) was established as a standard; the 4.5° sd R/G ratio is the maximum. The amplitude of this color ratio course is closely related to the peak mixing ratio of stratospheric dust (*11*). In May 1963, after the eruptions of Agung and Trident, there was a pronounced increase in the amplitude of R/G (see Fig. 1); the highest value in more than 3 years of measurement was reached. In January 1964, after the explosive eruptions of Surtsey the previous November, Volz obtained the highest values in this 8-year span of measurement or, indeed, during this last decade (*16*). It is suggested that this peak amplitude in January 1964 represents the replenishment by Surtsey of the volcanic dust and gases ejected into the stratosphere by Trident and Agung 9 and 10 months earlier.

There are several points of particular interest in the eruption of Surtsey, such as the height of the eruption cloud and the character of the ash and gases during the most explosive phases. In its earliest stages of submarine eruption, after a rather quiet start, the eruptions gradually increased

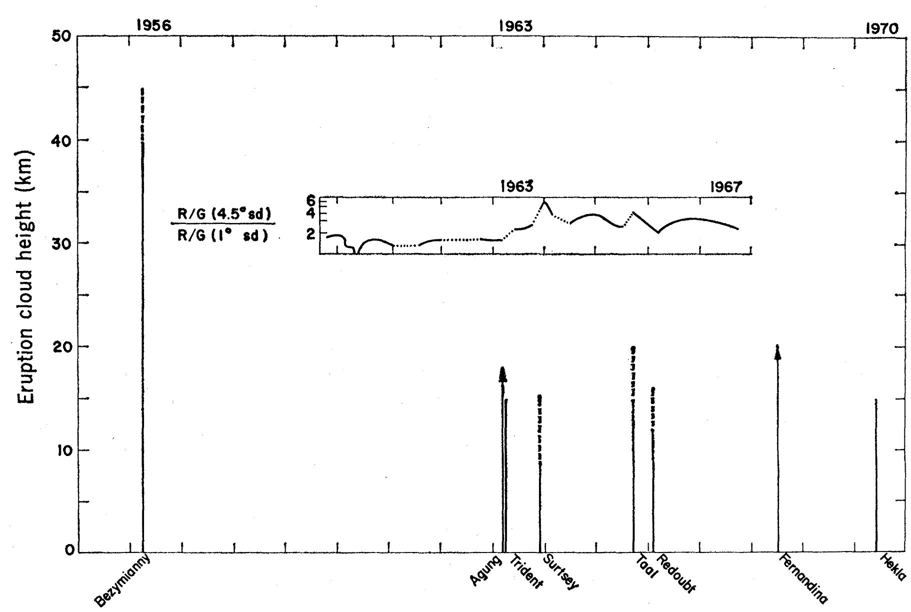

Fig. 1. Correlation of atmospheric turbidity and recent volcanic eruptions that vented to the stratosphere. Dashed lines indicate the reported range of maximum altitude of the eruption cloud. Arrows indicate the maximum height to be an altitude greater than was reported. The inset shows red to green twilight sky radiance measurements at 1° and 4.5° solar depression [from F. E. Volz (*3*)].

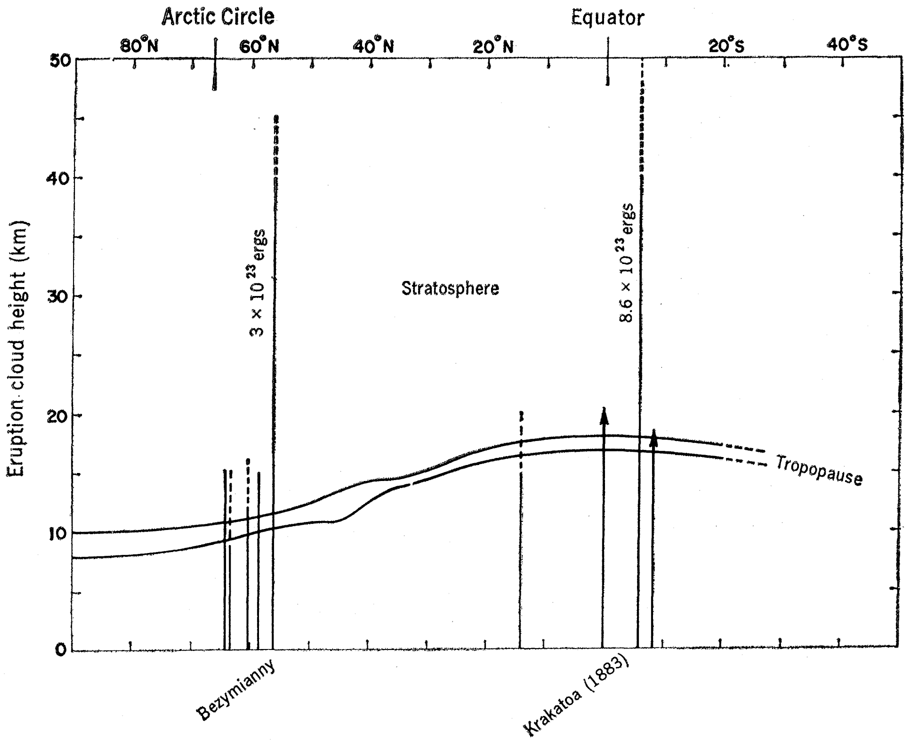

Fig. 2. Latitudinal distribution of the volcanic eruptions shown in Fig. 1, plus that of Krakatoa, and the mean seasonal height of the tropopause. The energy released by the climactic eruption of Bezmianny is compared with that of Krakatoa (*7*).

in intensity. They were of two kinds, as described by Thorarinsson (*17*): explosive eruptions and uprush eruptions. Surtsey was particularly explosive when the crater vent was open to the sea, but the eruption cloud rose to its highest altitude during the so-called uprush phases, when the crater rim of ash and cinder ejecta temporarily blocked out the sea. Several writers have stated that the maximum cloud height of Surtsey's eruption cloud was no higher than the tropopause (*18*). I believe that there has been an undue reliance on the intermittent photography of the clouds. One could justifiably question whether conventional photography or even a visual estimate could truly discern the top of the "cloud." Generally the dark lower portion of a volcanic cloud is considered to be composed of lithic particulate matter, and the higher, lighter-colored regions to be primarily steam. However, it should be obvious that gaseous clouds of SO_2, SO_3, the halogens, and even water could rise through ballistic and convective processes to much greater heights completely undetected, if the only means of detection were visual or photographic. In any case, Thorarinsson states (*19*) that Surtsey's clouds indeed rose to 50,000 feet, or some 4.5 km above the tropopause at 10.5 km, and that this happened more than once.

It is of interest to note that Mastenbrook (*12*) has measured an increasing amount of water vapor in the stratosphere since 1963. Surtsey may well have vented considerable quantities of water vapor to and above the tropopause during its first 3 months, when seawater had access to the vents or seeped through the tephra walls.

Another characteristic of a shallow submarine eruption such as that of Surtsey, which might contribute to the optical turbidity of the upper atmosphere, is the vesiculation and fragmentation by steam explosion of magma, and the consequent expulsion of unusually fine-grained lithic materials during the earlier, more intense explosive phase (*20*). Such fine lithic fragments may be the nuclei of an appreciable amount of stratospheric and tropospheric aerosols.

With the end of Surtsey's explosive phase in February 1964, no other volcanic eruption reached the stratosphere until that of the Taal volcano in the Philippines (14°N, 121°E) in September 1965. This was a phreatic volcanic event, the volcano being a breached crater on an island within Lake Taal. The major explosive phase was short-lived, but the eruption clouds reportedly rose to elevations of 15 to 20 km (*21*). As in so many phreatic volcanic eruptions, the initial ashfall is described as one of sand-sized particles. The water and fine ash of Taal's eruption may well have reinforced the turbidity of the stratosphere.

Four months later, from 25 January to 9 February 1966, Mount Redoubt (60.5°N, 153°W) in the Kenai region of Alaska ejected clouds to heights of 12 to 13.7 km. These clouds were monitored by U.S. Air Force jet aircraft and ground-based radar. Infrasonic wave interpretation indicates that these eruptions were not explosive but were probably sudden ejection of gas (*22*). Wilson and Nichporenko (*22*) estimated that the volume of gas ejected during the climactic eruption of 25 January was 9 km^3. The R/G ratios of Volz again appear to substantiate this infusion of Redoubt eruptives into the stratosphere.

A little more than 2 years later Fernandina volcano, which is located on the equator in the Galápagos Islands, 1000 km or so west of Ecuador, erupted to a height of 24 km. This was several kilometers higher than the highest cloud elevation reported for the 1963 Agung eruption on Bali. Fernandina volcano is a caldera, usually with a small lake within its crestal depression. Simkin and Howard (*23*) believe that the violence of the eruption suggests that water gained access to the vents in its early stage. The climactic eruption of 11 June 1968 was undoubtedly a phreatic eruption, as was that of Taal. Like Taal, it was also a short-lived event

And finally in May 1970, the tropopause was again penetrated by the eruption of Hekla volcano in Iceland. Within an hour of its start the eruption clouds, as monitored by radar from the naval air base at Keflavik, had reached an elevation of 16 km (*24*). Its explosive phase was short-lived.

To recapitulate, we see that in this current cycle of explosive volcanism there have been seven eruptions to the stratosphere in the past 7 years. Three of these, the eruptions of Surtsey in 1963, Taal in 1964, and Fernandina in 1968, may have been significant sources for the intromission of water to the stratosphere. Although all volcanic eruptions emit considerable amounts of water to the atmosphere, phreatic and submarine explosions that reach to and above the tropopause could effect, and sustain, a very specific change in stratospheric aerosol content. The eruption of Agung on the equator was undoubtedly the greatest single source of stratospheric ash in the past decade. The Alaskan eruptions of Trident and Redoubt may have been primarily gas eruptions.

A survey of explosive volcanism during the past two centuries (*25*) indicates there have been two primary latitudinal source belts of volcanic ejecta and gaseous effluent to the stratosphere. One rather narrow latitudinal belt is just below the Arctic Circle, 56°N to 65°N, and includes the volcanoes of Kamchatka, the Aleutian Islands, Alaska, and Iceland. The other is a broad belt centered about the equator, 8°S to 15°N, and includes the volcanoes of Indonesia, the Philippines, Central America, Ecuador, the Galápagos, and the Caribbean. Each of the two belts includes one of each of the two most explosive eruptions of the past century, that of Krakatoa (6°S) between Java and Sumatra in 1883 (*26*), and the other of Bezymianny (56°N) on the Kamchatka peninsula in 1956. In each of these belts have also occurred the two most violent eruptions in the Western Hemisphere during the last two centuries. Again, one was in the Arctic Circle belt—in the Katmai region of Alaska (58°N) during 1912 (*27*)— and the other was in the equatorial belt—Cosegüina volcano in Nicaragua (13°N) during 1835 (*28*). There has been an occasional explosive eruption in Japan (Bandai San in 1888 and Asama in 1783), New Zealand (Tarawera in 1886), the Kuriles, Antarctica, Chile, the Mediterranean, or along the Mid-Atlantic Ridge (other than Iceland); it is doubtful, however, that any eruption in any region outside the Arctic Circle and the equatorial belts during the last 200 years, with the exception of Asama and Tarawera, matched in volume of explosion effluent or intensity such eruptions within these belts as:

Indonesia	Iceland
Agung (1963)	Askja (1875)
Krakatoa (1883)	Hekla (1845)
Tambora (1815)	Laki (1783)
	Katla (1775)
Philippines	Alaska
Mayon (1776)	Katmai (1912)
Central America	Kamchatka
Consegüina (1835)	Bezymianny (1956)

It has also become evident in this survey that since the mid-18th century the frequency of explosive eruptions that probably reached the upper troposphere, or higher, is three to four times as great within these two latitudinal bands as the total of all other areas of the earth's surface.

During the past decade, four of the seven eruptions to the stratosphere were in the Arctic Circle belt (Trident, Surtsey, Redoubt, and Hekla), and the other three eruptions (Agung, Taal, and Fernandina) were in the equatorial belt (Fig. 2). Since there is no known instance of volcanic dust from an eruption in the Arctic Circle belt reaching the Southern Hemisphere, it can be assumed that dust and gases from this belt tend to be concentrated in the Northern Hemisphere. On the other hand, products of explosive volcanism from the equatorial belt are observed invariably in both the Northern and Southern hemispheres. One might conclude, therefore, that during any period, such as the last decade, when both belts of explosive volcanism are active, the stratosphere over the Northern Hemisphere would be more turbid than that over the Southern Hemisphere. Indeed, it has been reported variously (*11, 29*) that there has been an unusually protracted abatement of dust over the Northern Hemisphere after the 1963 eruption of Agung. One objective of this report was to emphasize the contribution of subsequent eruptions to the turbidity of the stratosphere.

The eruptions of the Arctic Circle belt, where the height of the tropopause is only two-thirds of the height over the equator (Fig. 2), may be of particular significance in this sustained turbidity of the stratosphere. A less explosive event in the northern latitudes could contribute as much or more to the northern stratosphere as an eruption on the equator of the magnitude of Agung. Historically, volcanic activity in any densely populated region such as Japan, Indonesia, and the Mediterranean is well documented. But to this day most observations of volcanic eruptions in such places as the Aleutian Islands are the chance sightings made by aircraft pilots.

For some time now man has sought to increase his activity in the stratosphere, particularly over the Northern Hemisphere where most traffic will continue to occur. Yet we still have so little knowledge about the volume, the distribution, and the chemical and optical properties of materials emanating from those volcanic eruptions that reach the stratosphere that we must continue to ask, What is the standard stratosphere?

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References and Notes

1. A. R. Hogg, *Aust. J. Sci.* **26**, 119 (1963).
2. F. E. Volz, *Tellus* **17**, 513 (1965).
3. ———, *Appl. Opt.* **8**, 2505 (1969).
4. A. J. Dyer and B. B. Hicks, *Quart. J. Roy. Meteorol. Soc.* **94**, 545 (1968); G. Grams and G. Fiocco, *J. Geophys. Res.* **72**, 3523 (1967).
5. L. Elterman, R. Wexler, D. T. Chang, *Appl. Opt.* **8**, 893 (1969); H. H. Lamb, *Weather* **21**, 50 (1966).
6. I. P. Passechnik, *Bull. Acad. Sci. USSR Geophys. Ser.* **9**, 1121 (1958).
7. A. Rittmann, *Les Volcans et Leur Activité* (Masson, Paris, 1963), p. 431.
8. R. E. Wilcox, *U.S. Geol. Surv. Bull. No. 1028* (1959).
9. F. E. Volz, *Meteorol. Rundsch.* **7**, 185 (1954); L. Jacobs, *Meteorol. Mag.* **83**, 115 (1954); G. A. Bull and D. G. James, *ibid.* **85**, 293 (1956); S. Fritz, *ibid.*, p. 110.
10. F. E. Volz, *Science* **114**, 1121 (1964).
11. ———, *J. Geophys. Res.* **75**, 1641 (1970).
12. H. J. Mastenbrook, *New York Times*, 28 May 1970, p. 23; and personal communication.
13. M. P. Meinel and A. B. Meinel, *Science* **142**, 582 (1963); W. P. Booth and S. W. Matthews, *Nat. Geogr. Mag.* **124**, 436 (1963).
14. R. W. Decker, *Trans. Amer. Geophys. Union* **48**, 639 (1967).
15. Wavelength (λ) values are in nanometers.
16. F. E. Volz, personal communication.
17. S. Thorarinsson, *Polar Rec.* **13**, 571 (1967).
18. ———, Th. Einarsson, G. Sigvaldasor, G. Elisson, *Bull. Volcanol.* **27**, 435 (1964); Th. Einarsson, *The Surtsey Eruption* (Heimskringla, Reykjavik, Iceland, 1965); R. Anderson, S. Bjornsson, D. C. Blanchard, S. Gathma, J. Hughes, S. Jonasson, C. B. Moore, H. J. Survilas, B. Vonnegut, *Science* **148**, 1179 (1965).
19. S. Thorarinsson, *Nat. Geogr. Mag.* **127**, 713 (1965); personal communication.
20. A. R. McBirney, *Bull. Volcanol.* **26**, 455 (1963); H. Tazieff, *Geol. Rundsch.* **57**, 3 (1968); E. Bonatti and H. Tazieff, *Science* **168**, 1087 (1970).
21. J. G. Moore, K. Nakamura, A. Alcaraz, *Science* **151**, 955 (1966).
22. C. R. Wilson and S. Nichparenko, *Nature* **211**, 163 (1966).
23. T. Simkin and K. A. Howard, *Science* **169**, 429 (1970).
24. *Notice 940* (Smithsonian Center for Short-Lived Phenomena, Cambridge, Mass., 1970).
25. J. F. Cronin, in preparation.
26. G. J. Symons, Ed., *The Eruption of Krakatoa: Report of the Krakatoa Committee* (Royal Society, London, 1888).
27. R. F. Griggs, *The Valley of Ten Thousand Smokes* (National Geographic Society, Washington, D.C., 1922); G. H. Curtis, *Geol. Soc. Amer. Mem. 116* (1968), p. 153.
28. H. Williams, *Univ. Calif. Berkeley Publ. Geol. Sci.* **29**, 21 (1951–52).
29. A. B. Meinel and M. P. Meinel, *Science* **155**, 189 (1967).
30. Portions of this report were presented at the annual meeting of the Geological Society of America in Milwaukee, Wis., November 1970, and at the national fall meeting of the American Geophysical Union in San Francisco, Calif., December 1970. The most exhaustive report on the subject of volcanic dust in the atmosphere since the report of the Krakatoa Committee in 1888 (*26*) is the recent paper by H. H. Lamb [*Phil. Trans. Roy. Soc. London Ser. A* **266**, 425 (1970)].

5 January 1971; revised 18 March 1971