Burden of Volcanic Dust and Nuclear Debris After Injection Into the Stratosphere at 40°–58°N

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Meridional profiles of turbidity at some periods after the explosion of Katmai volcano in June 1912 at 58°N are compared with debris burden from Chinese nuclear tests. Katmai turbidity was previously obtained from solar radiation data, and debris burden was calculated from published mixing ratio data. Turbidity and burden generally peak strongly in arctic latitudes. Only two tests show indications of a bulge at 30°–45°N which probably existed for Katmai dust in spring 1913. The residence time of Katmai dust was found to have been about 1 year, whereas fallout of nuclear debris seems not to have started before the winter following the tests. For September 1912 the total amount of Katmai aerosol is estimated to have been 13 million metric tons. Analogies to predicted meridional distribution of SST pollutants are being mentioned.

INTRODUCTION

Features of transport of stratospheric tracers are still not well understood. The first insights were provided by the spread of dust over the globe from the explosion of Krakatoa volcano in 1883, but more recent data from numerous nuclear tests and studies of other tracers could not yet be integrated into a consistent picture and a full understanding of the general transport processes [*Reiter*, 1971] as far as these apply to individual situations. Very promising are calculations by global circulation models [e.g., *Mahlman*, 1973]. Recent concern about the effect of certain stratospheric tracers, partly known or expected to increase due to man's activities, on global climate add to the importance of the problem. Therefore we present new data from a big volcanic explosion of 1912 and compare them with appropriately matched results of nuclear tests, both of which emphasize the stratosphere of mid-latitudes and north latitudes as compared with preference of tropical sources in related studies of natural and artificial tracers.

DATA

In a companion paper [*Volz*, 1975*b*] we investigated the spread and abatement of the aerosol injected into the arctic stratosphere by the explosion of Katmai volcano in Alaska (58°N) on June 6, 1912. Reduction of the intensity of direct solar radiation as measured at about 16 stations in the United States and Europe was large enough to permit the study of volcanic turbidity for a period of 2.5 years.

In central and northern Europe, volcanic turbidity was very large but highly variable during the summer of 1912 and rather low in February of 1913, when it was still higher than that in Europe, over the most southern U.S. stations, and in northern India. From the summer of 1913 to late 1914, volcanic turbidity at $\lambda 0.50$ μm was still of the order of Rayleigh extinction but virtually absent afterwards. Small amounts of Katmai dust may have been over Mexico City (19°N), but increased turbidity at Arequipa, Peru (10°S), during 1913 may have had other causes.

Although there were no direct observations, the quantity of dust injected into the atmosphere and its persistence as well as the twilight phenomena reported in late 1912 and 1913 [see *Volz*, 1975*b*] make it very likely that the persisting fraction of dust was at 15- to 20-km altitude, although substantial amounts could initially have been at lower levels. This also is consistent with comparable explosions by Krakatoa [*Symons*, 1888] and of Agung, 12 years ago. Even the very recent eruption of apparently lesser explosive force by Fuego in Guatemala (mid-October 1974) spread dust up to a height of 20 km [*Volz*, 1975*a*].

The main Katmai results may now be compared with the stratospheric burden of radioactive debris from 5 high yield nuclear test series in the northern hemisphere. Concentration of specific fission products was derived from filter collections of high-altitude aircraft and balloons over the western part of the American continent during discrete periods after the nuclear events. Meridional profiles of mixing ratios (volume concentration at STP) have been presented and discussed by *Machta et al.* [1970] (test 1 and 2, see Figure 1 (*b* and *c*) for dates), *Telegadas* [1971] (test 3), and *Machta and Telegadas* [1973] (test 4). *Telegadas* [1974] recently published the results of the Chinese test (40°N) of October 14, 1970 (test 5) and included data of Tests 2–4 with additional meteorological detail.

Of the nuclear tests the first Russian series (test 1) was at 75°N. The debris of the Chinese tests (2–5) at Lop Nor (40°N, 90°E) had initial peak mixing ratios at a 16- to 19-km altitude, where most of the Katmai dust may have existed too. The distribution shortly after the tests depends largely on the particular circulation features with regard to the narrow sampling corridor. For example, 0.5 month after test 5, debris was only found in the northernmost part (Alaska) of this corridor, but a strong core existed at about 50°N about 1.3 months after test 3. However, about 2 months after test 3, debris was distributed more evenly over the corridor with the average mixing ratios peaking at 15 km in the arctic region and over the equator at 20 km [*Telegadas*, 1974]. *Telegadas* [1974] pointed out that it takes about 7 months until the distribution becomes fairly smooth.

After converting the mixing ratios to actual volume concentrations by multiplying with PT_0/P_0T (T = 220°K assumed), some data of tests 1–5 have been integrated vertically to obtain stratospheric burden which is a column density, as is turbidity. A graphical method based on isolines of the original cross sections of mixing ratios was used for the integration.

In Figure 1 (*b* and *c*) the meridional profiles at mainly 7 months after some tests will be compared with the equivalent smoothed profiles of Katmai turbidity (Figure 1*a*). To show

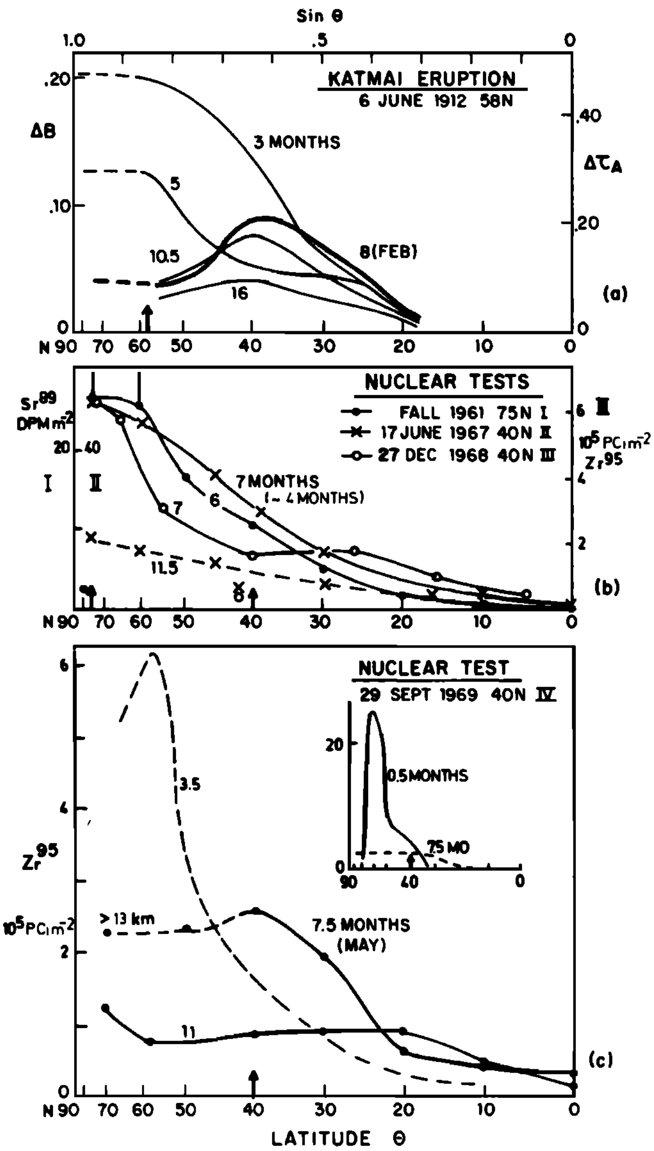

Fig. 1. Meridional profiles of (*a*) Katmai turbidity and (*b* and *c*) debris burden after nuclear high yield tests at specific periods after the events. Katmai data are averaged. Columnar integrals of nuclear debris are decay-corrected to time of event. Inset of *c* is burden profile 0.5 month (solid line) and 7.5 months (dashed line) after test 4.

the debris and turbidity distribution in relation to the surface area of the hemisphere, the abscissa is linear in the sine of the latitude θ.

TURBIDITY AND BURDEN PROFILES

The Katmai turbidity profiles (Figure 1*a*) show the rapid depletion of volcanic dust at >30°N in the first 5 months after the main eruption and continuing decrease at >50°N, while relatively high turbidity is found at 30°–40°N from about 8 to 10 months after the eruption. A few months after the nuclear tests, debris burden generally peaks strongly over the Arctic (Figure 1 (*b* and *c*) and also in test 5 for which profiles are not shown). This shows that the bulk of stratospheric debris even of mid-latitude origin had been transported to the Arctic—at least for these stratospheric injections, all of which occurred in the second half of the year. A slight secondary maximum of burden at 25°N is indicated 7 months after test 3. Even closer to the meridional distribution of Katmai turbidity during February 1913 seems to come the burden profile 7.5 months after test 4 (Figure 1*c*), although burden over the Arctic was very much higher 4 months earlier. However, substantial amounts of debris at >40°N could in this case (and to a smaller degree in other tests, too) have been below the lowest measuring altitude (≈13 km), forbidding a closer comparison.

This abnormal situation has been illustrated in Figure 2*a* by vertical profiles of debris concentration at different latitudes for the similar case 7.5 months after test 5. As is shown graphically in Figure 2*b* for 45°N, debris concentration peaks in most other test data at 15- to 18-km altitude, as did the dustsonde profiles from Minnesota reported by *Rosen* [1967] of the volcanic period August 1963 to December 1965. (The two dust profiles of late spring of 1966 have no discerned concentration peak between 5 and 18 km, but this will not be discussed further.) However, for the period shown in Figure 2*a*, the concentrations at 45°N were highest at the lowest measuring altitude of about 13 km. Concentrations are expected to fall off very rapidly across the tropopause. This indeed is confirmed for 45°N for the period in question. The results [*Moore et al.*, 1973] of two aircraft samplings of ^{90}Sr at about 41°N have been fitted in Figure 2*a* to the ^{95}Zr data with regard to tropopause height and concentrations at about 13 km. In the debris data taken 2–3 months later (not shown) the vertical profiles at 45°N and 60°N have become normal and peak near 17 km, but the profile at 75°N still peaks at 13 km. This indicates that debris which before was in the mid-latitude stratosphere near and below 13 km vanished by removal to lower levels and probably to more southern latitudes. However, it is questionable whether such processes would cause a temporary reversal of the meridional turbidity or burden profile as may have existed in the Katmai case for a few months.

Turning to the tropical stratosphere, it seems that the poorly established effect of Katmai turbidity at Mexico City is in agreement with the nuclear test data. Again, test 4 was different: by May 1970 a strong tongue of debris rose, as was suspected by *Machta and Telegadas* [1973] for meteorological reasons instead of by turbulent mixing, to 22 km over the equator, causing a higher burden at low latitudes than in the other tests.

Of the debris data extending to about 1 year, test 2 again shows a gradual decrease of burden with latitude, but the

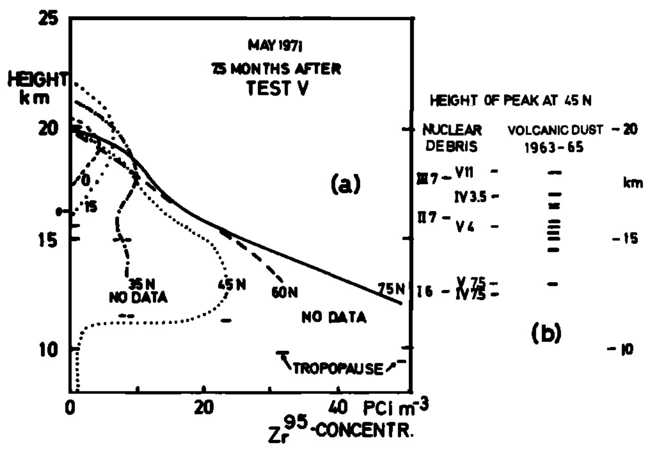

Fig. 2. (*a*) Vertical profile of debris volume concentration for different latitudes in May 1971, 7.5 months after the Chinese test of October 14, 1970. Short horizontal lines indicate tropopause heights. Extension of profile at 45°N to ground is after *Moore et al.* [1973]. (*b*) Heights of peak concentration at 45°N for volcanic dust (right) from *Rosen* [1967] and nuclear debris (left).

burden of test 4 (Figure 1*c*) is nearly constant (between the arctic region and 20°N) and still noticeable over the equator. However, Katmai dust still seems to peak at about 40°N (Figure 1*a*).

Total burden of Katmai dust, $\int_0^{\pi/2} \Delta B d \sin \theta$, from Figure 1*a* (assuming ΔB to be constant at >60°N) is presented in Figure 3. The mean residence time τ of the dust is of the order of 9–12 months and essentially the same as that deduced by *Telegadas* [1974] between the January following each test and 6–10 months later. However, on the basis of estimated bomb yields, there was no loss of nuclear debris between the time of the explosions and the first winter. The different behavior of Katmai dust and bomb debris in the first few months after the events probably indicates considerable fallout of large volcanic particles and removal of the tropospheric component of volcanic dust during this time period but generally only in the European data [see *Volz*, 1975*b*, Figure 3].

One may also ask what fraction of the debris has been transported northward and southward of the latitude of the explosions. According to Figure 1*a*, about 29% of Katmai dust probably present 5 months after the event was north of the latitude of the volcano (58°N), and 17% 3 months later. Of the debris of Chinese tests 2–5 (Figure 1 (*a* and *b*)), 53 to 75% was north of 40°N some 4–8.5 months after the detonations, and 73% of Katmai dust was in that latitude range.

The turbidity integral of Katmai dust (Figure 3) may be converted approximately to hemispherical aerosol mass loading M assuming that the relation $M = 55B$ (μg cm^{-2}), which is well-proven for surface aerosol, holds true. For September 1912 we obtained $B = 0.09$ and $M \approx 12.7 \cdot 10^6$ metric tons, and a year later, $M \approx 2.8 \cdot 10^6$ tons for $B = 0.02$. For comparison, the load of the northern hemispheric stratosphere by Agung dust 1 year after the explosion was of the order of $2 \cdot 10^6$ tons and about 8 times more over the southern hemisphere (F. E. Volz, unpublished manuscript, 1972). Estimates for Katmai dust by *Mitchell* [1973] and *Deirmendjian* [1973] were $8 \cdot 10^6$ tons and $13 \cdot 10^6$ tons, respectively.

Conclusions and Summary

Latitude profiles of Katmai turbidity generally agree with those of the debris burden of northern hemispheric nuclear tests in high values in high latitudes, although only two tests show indications of a bulge at 35°–40°N which probably existed for Katmai dust 8–10 months after the eruption. For brief periods only, small amounts of volcanic dust may have reached the tropical stratosphere, again in agreement with most of the nuclear test data. Vertical concentration profiles of some of the spring data of debris are found to be strongly peaked at north of 40°N near the lower limit ($\approx$13 km) of measurements. This lends support to speculation of imminent transfer of large quantities of debris to lower altitudes.

Comparison of the residence time of volcanic dust and nuclear debris seems to indicate considerable fallout of large volcanic particles and washout of the tropospheric component in the first few months after the eruption. Four months after the eruption, Katmai dust may have totaled 13 million metric tons as compared with perhaps 2 million tons of Agung dust in the more southern parts of the northern hemisphere 1 year after the explosion. How much and at what time scale the transfer of volcanic sulfuric gases to sulfur particles or coating of volcanic dust by sulfur compounds as observed by *Mossop* [1964] after the Agung eruption could have contributed to the volcanic turbidity is impossible to deduce from the data.

The data presented here make it likely that the minor dust amounts injected into the lower stratosphere by Shiveluch (57°N, 161°E) in November 1964 [see *Volz*, 1974] and possibly by Surtsey (63°N, 20°W) in November 1963 have been concentrated over the arctic region and hardly could have competed in middle latitudes with Agung dust, as was suggested by *Cronin* [1971]. However, the question remains whether the overall meridional transport and distribution of tracers would be different if injection into the lower stratosphere of mid-latitudes occurred during late winter to early spring rather than in the second half of the year as in all the data discussed here. But there still would be the problem of whether such results of mid-latitude injections are directly related to the seasonal variation of the northward flux of tracers from a quasi-persistent tropical stratospheric source. Such variations seem to have existed in the case of Agung [*Dyer and Hicks*, 1968].

The results presented on turbidity and debris burden are also of interest in problems pertaining to pollutants produced by supersonic transport aircraft, especially since the latitude range of heaviest traffic (40°–55°N) invites a comparison with them. Indeed, simple models show that the concentration in this zone would be 70% higher and in the polar region 50% higher than the world average [*Berman and Goldberg*, 1972]. Since the height change with latitude of the mixing vector apparently was not considered, the burden profile might peak in the polar zone, too. However, our results relate to generally lower altitudes than those of SST flights.

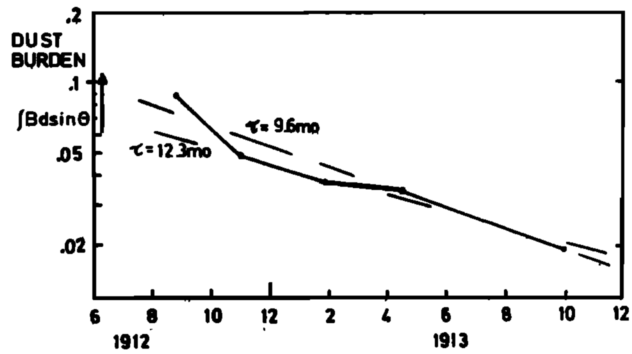

Fig. 3. Decrease of hemispherical aerosol burden after the Katmai explosion. Residence half time is equal to 0.693τ.

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