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The Great Tambora Eruption in 1815 and Its Aftermath

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The largest and deadliest volcanic eruption in recorded history was the explosion of Mount Tambora (8°S, 118°E) on the island of Sumbawa, Indonesia, on 10 and 11 April 1815. More than 88,000 people perished from direct and indirect effects on Sumbawa and neighboring Lombok alone (*1, 2*). Yet little scientific work has been done on this catastrophic eruption, largely because of the paucity of contemporary documents, all of which were written by a handful of British resident agents, sea captains, and army officers, who were scattered among the tiny European enclaves that dotted the East Indian Archipelago. The available accounts, however, were immediately solicited and published by Raffles (*3*), the British lieutenant-governor of Java at that time, and by the London editors of *The Asiatic Journal* (*4*), some of these accounts being reprinted from the *Java Government Gazette*. Although there is a long list of additional sources, most of them duplications, all the scientifically useful information obtained from the eyewitness accounts is included in the two sources just mentioned and in four later reports made between 1820 and 1855 (under restored Dutch rule) by Zollinger (*1*), van den Broeck (*2*), Vetter (*5*), and Roorda van Eysinga (*6*).

Summary. Quantitative analytical methods are used to reconstruct the course of events during and after the cataclysmic eruption of Mount Tambora, Indonesia, on 10 and 11 April 1815. This was the world's greatest ash eruption (so far as is definitely known) since the end of the last Ice Age. This synthesis is based on data and methods from the fields of volcanology, oceanography, glaciology, meteorology, climatology, astronomy, and history.

In modern accounts of the eruption, the anecdotal material is usually paraphrased in some way, and the volume of ash fallout is computed from a subjective estimate of both the surface area covered and the average ash thickness. Understandably, the results for the volume vary widely: 300 km^3 (*7*), 1000 km^3 (*1*), 150 km^3 (*8*), and 100 km^3 (*9*). The value of 30 km^3 (*10, 11*) is merely an estimated volume of the missing upper part of the volcano.

To obtain more and better information about this important eruption and its aftermath, I adopted an approach used successfully by a committee that investigated the eruption of Krakatau, off the western end of Java, in 1883 (*12*). First, the original reports were compared, corrected where necessary, and synthesized to obtain a synoptic view of the eruption and an accurate chronology of events. Then the extracted data were analyzed, including data from later land and oceanographic field studies. Finally, information about the state of the atmosphere after the eruption was used to determine the eruption's global impact.

Chronology of the Eruption

Mount Tambora occupies most of the Sanggar Peninsula on Sumbawa Island (Fig. 1), although its central crater lies 20 km from the sea. Although it was thought to be extinct (or even nonvolcanic), the volcano began rumbling and generating a dark cloud around its summit about 3 years (*13*) before undergoing a moderate-sized eruption during the early evening of 5 April 1815 (local time). Thundering detonations, like the discharge of cannons, were heard as far away as Makassar on Celebes (380 km), Batavia (Jakarta) on Java (1260 km), and Ternate in the Molucca Islands (1400 km). On the following morning ash began to fall lightly on eastern Java, and went on falling, all the while accompanied by fainter and less frequent detonations, into the evening of 10 April.

At about 7 p.m. on 10 April the eruption intensified and attained its paroxysm. As viewed from Sanggar (about 30 km to the east), three columns of "flame" rose up from the crater and merged at a "very great" height. Soon the whole mountain (as reported also from the village of Tambora 20 km to the south) appeared like a flowing mass of "liquid fire." Pumice stones of diameter up to 20 cm began to rain on Sanggar at approximately 8 p.m.; ashes followed between 9 and 10 p.m.; and violent winds, which uprooted trees and other exposed objects, blew at Sanggar incessantly between 10 and 11 p.m. It is likely that the volcano's massive eruption column collapsed under its own weight shortly before 10 p.m. Possibly the caldera formed by collapse at the same time. Hot pyroclastic flows cascaded down the mountain, wiped out the village of Tambora, and probably created the powerful air currents that were responsible for the "whirlwind" felt at Sanggar, unless these currents were caused by violent convective downdrafts around the plume. The winds, however, did not reach Bima, 60 km farther east. Very loud explosions were heard all night throughout Java as far west as Cirebon (1050 km); in many places the sound waves produced concussions that

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resembled mild earthquakes (perhaps some were true earthquakes).

Noisy explosions continued into the evening of the next day, 11 April. The sound was picked up on that day as far west as Fort Marlborough at Benkulen (1800 km), Mukomuko (2000 km), and probably Trumon (2600 km) on the island of Sumatra, as well as in the east at Ternate (1400 km) in the Moluccas, and also on Java, Bangka, Borneo, Celebes, and Flores. On the same day, Tambora was still seen to be "flaming" on its lower slopes and covered with "clouds" on top. The original ash veil was in the meantime spreading out over a vast area extending as far as western Java and southern Celebes. Although in some areas the air was reported as being still, a light monsoon was blowing from either the east or the southeast according to other contemporary reports. The presence of the monsoon can account for the greater fall of ash to the west of Tambora. In many spots within 600 km of the volcano, the sky remained pitch dark for 1 or 2 days, and the air at first became very hot and then cold. A "nitrous" odor was noticeable as far west as Batavia (Jakarta), although not in Celebes. After 12 April, further accumulation of ash amounted to only about 20 percent of what had already fallen, at least at Banjuwangi in eastern Java, with a similar increase reported in the Makassar area of Celebes.

The shower of ash finally ended in Java between 14 and 17 April, as a result of heavy rainfalls, and in Celebes during 15 April. Enormous rafts of pumice mixed with ashes and uprooted trees (many of the trees appearing burnt and shivered) floated in the sea to the west, north, and east of Tambora; some of the pumice islands measured several kilometers across and close to a meter thick, and a number of them were transported by east-flowing currents far along the coast of Flores. Clouds of "smoke" and ashes still covered Tambora's summit on 23 April. Although the explosions ceased on 15 July, "smoke" emission was observed as late as 23 August, and "flame" and rumblings were reported in August of 1819. Tambora's profile had radically altered: its former double peak with eastern and western summits had become a "table land" of less than two-thirds its original height, the greater part of its top having fallen in. Today the caldera measures 6 km across and 600 to 700 m deep; its rim lies 2850 m above sea level (*9*). The original height of the mountain must have been over 4300 m, the highest point in the East Indies, as is suggested also by an old report that, before the eruption and from the direction of Bali, Tambora appeared as prominent as the closer volcano Rinjani (elevation 3726 m) on the island of Lombok.

Tsunami

A tsunami of relatively modest height struck the shores of the Indonesian islands on 10 April. The wave rose to a maximum height of 4 m at Sanggar for a short time around 10 p.m. and reached Besuki in eastern Java (500 km away), with a height of 1 to 2 m, before midnight; therefore its average velocity must have been of order 70 m/sec. The predicted velocity of a low-amplitude surface wave in a body of water of depth d is $v = (gd)^{1/2}$, where g is the earth's surface gravity (*12*). From a depth chart for the Bali Sea (*14*), the expected integrated travel time for a wave crossing between Tambora and Besuki can be estimated to

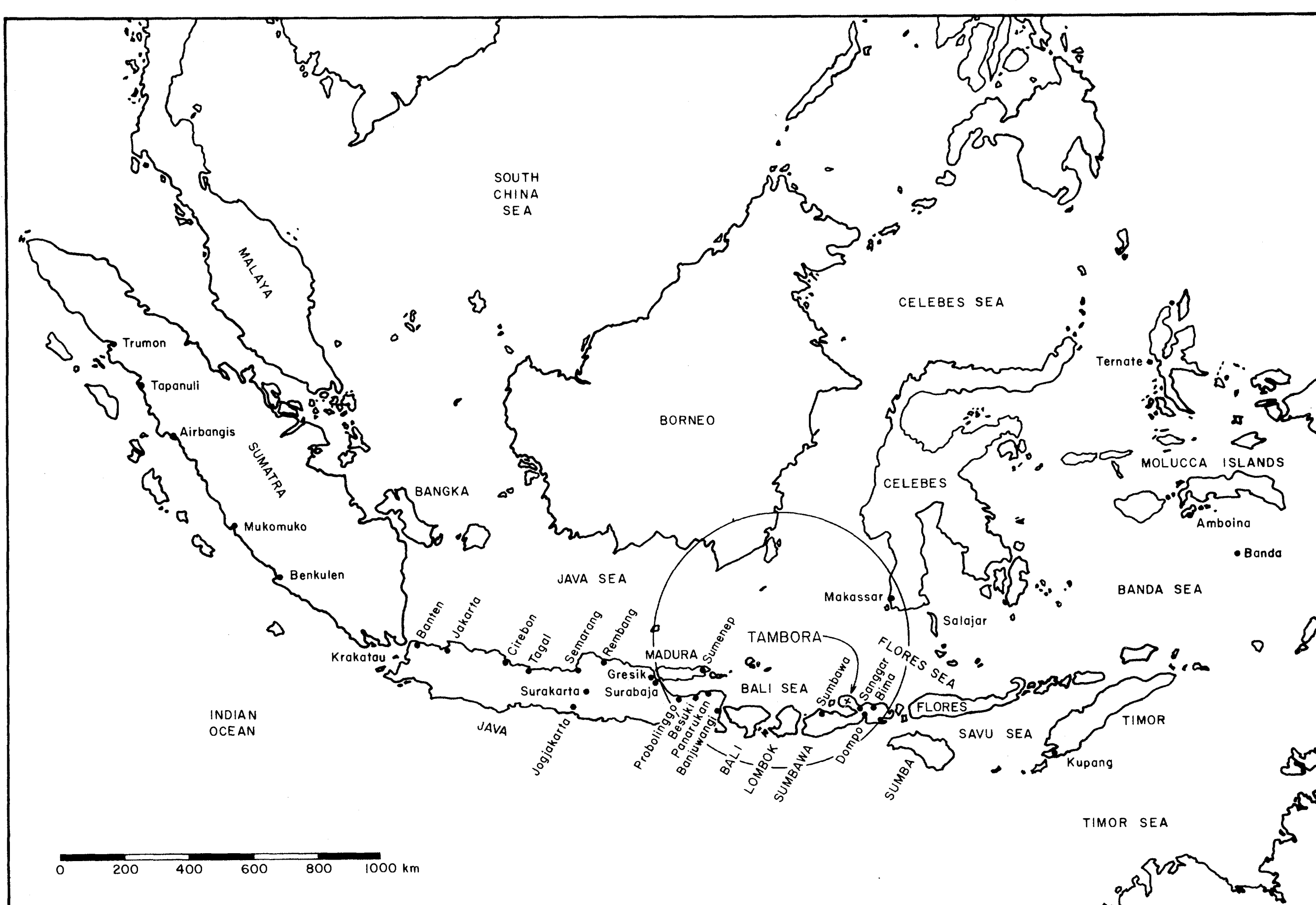

Fig. 1. Map of Indonesia and its environs. The circle surrounds the area of greatest ash fall after the eruption of Tambora on 10 and 11 April 1815. All localities mentioned in the text are shown.

be about 2 hours, which seems to confirm that the wave seen at Besuki originated from the Tambora eruption. The tsunami was also observed in the Molucca Islands, at an undocumented time, but with a wave height of over 2 m.

Since the tsunami and the "whirlwind" arrived at Sanggar at about the same time, the physical cause of the wave was probably the sudden entry of pyroclastic flows into the sea rather than a subsidence of land that was reported to have taken place in the three coastal towns—Tambora, Sanggar, and Bima. Contemporary observations on 10 and 23 April as well as modern field observations (*15*) confirm that the pyroclastic flows did run into the sea.

Unless the reported arrival time is wrong, another tsunami reached Sumenep on Madura (just north of Java) at 7 p.m. on 11 April, with a height of about 1 m.

Ash Fallout

Contemporary records of the total ash deposits are summarized in Table 1, where the various times of the beginning of the heavy ash fall in different localities are quoted, if known. From these times, which for a number of reasons are somewhat uncertain, and the known distances of the observing sites from Tambora, the vector components of the velocities of ash dispersal can be computed. They turn out to be, very consistently, 2, 6, and 6 m/sec to the east, west, and north, respectively. By assuming a model in which the tropospheric winds are composed of a random drift component $\mathbf{u}$ (due to changing wind directions) and a steady component $\mathbf{v}$, we can use an application of vector analysis to find $\mathbf{u} \approx 4$ m/sec isotropically away from Tambora and $\mathbf{v} \approx 3$ m/sec directed toward the northwest. This result for $\mathbf{v}$ agrees with contemporary reports that mention a prevailing light southeasterly monsoon. On the other hand, since the total average wind speed $|\mathbf{u} + \mathbf{v}|$ ranges only between 1 and 7 m/sec, it is easy to understand why the air was reported in many places as being still. In addition, since $|\mathbf{u}|$ is greater than $|\mathbf{v}|$, it is also possible to understand why, at Kupang on Timor, the wind was recorded at different times as coming from different directions (*16*).

Another way of estimating the direction of the steady component of air flow is to compute the major axis of the fallen ash distribution. The numerical data of Table 1 for the ash depths are plotted separately in Fig. 2 for the three cardinal directions for which data on depth are available. I have excluded Zollinger's (*1*) figures, because he did not give his sources, and the data seem in fact to be mainly guessed values. In any case, by the date of his East Indies visit in 1847, most, if not all, of the distal ash would have been washed away. Also omitted are Neeb's (*16*) sea-floor measurements of the Tambora ash thicknesses, which prove to be nonmonotonic with distance in many directions and are generally much too large to the east toward Flores and much too small to the west in comparison with the land measurements made right after the eruption. Sea currents have evidently been of great importance in redistribution of the ash, as was suggested by Neeb and indicated also by the original sightings of pumice islands floating along the Flores coast to the east.

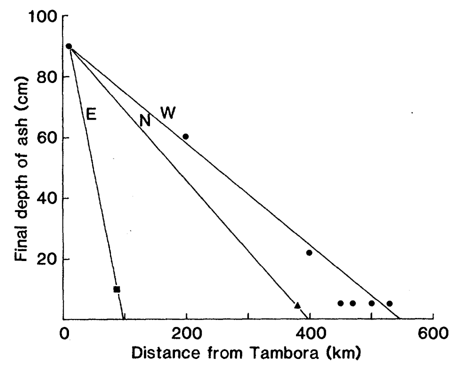

Fig. 2. Thickness of final ash fall deposits as a function of distance in the west, north, and east directions from Tambora.

If only the land measurements are used, a nearly linear relation emerges between ash depth and distance toward the west (Fig. 2). It is not unreasonable to assume, therefore, that linear relations hold also toward the east and north, in the absence of any good evidence for secondary thickness maxima. All three relations can be extrapolated to the distances at which the ash layer becomes formally negligible: 550 km in the west, 100 km in the east, and 400 km in the north. Although it is known that ash fell farther away than this, the small contribution of more distant ash to the total ash volume can be estimated from the data in Table 1 (with an assumed linear falloff beyond the 5 cm-isopach) to be no more than about 10 percent. Although the true relation between ash thickness and distance is possibly more nearly an exponential, its approximation by connected straight-line segments is justified here.

Two reasons may now be adduced for assuming that the isopachs of measurable ash fallout were approximately circles. First, Neeb's distribution of Tambora sea-floor ash is roughly circular (except for the Flores lobe discussed above). Second, a distribution that is roughly an ellipse with very small eccentricity is theoretically predicted from the calculated wind velocities together with the assumption that the atmospheric res-

Table 1. Distal ash fallout from Tambora.

Location	Distance from Tambora caldera (km)	Start of heavy ash fall	Travel time from Tambora (hours)	Average velocity (m/sec)	Final depth of ash (cm)*
		10 April			
Tambora	< 20	7 p.m.	0		90
Sanggar	30 east	10 p.m.	3	2.8 east	Thick
		11 April			
Bima	90 east	7 a.m.	12	2.1 east	10
Makassar	380 north	11 a.m.	16	6.5 north	4
Sumbawa (town)	60 west				Thick
Lombok	200 west				60
Bali	300 west	Morning			Thick
Banjuwangi	400 west	1 p.m.	18	6.2 west	22
Panarukan	450 west				5
Sumenep	470 west	4 p.m.	21	6.2 west	5
Besuki	500 west	4 p.m.	21	6.6 west	5
Probolinggo	530 west				5
Surabaja	590 west	10 p.m.	27	6.1 west	Some
Gresik	600 west	Night			Some
Rembang	740 west				Some
Surakarta (Solo)	790 west				Some
Jogjakarta	830 west				Some
Semarang	840 west				Some
Tagal	990 west				Slight
Jakarta (Batavia)	1260 west				Slight
Banten	1330 west				Slight

*Zollinger (*1*), without giving his sources, lists final ash depths: Sanggar, 90 cm; Bima, 45 cm; Sumbawa, 60 cm; West Lombok, 45 cm; Bali, 30 cm; and Banjuwangi, 22 cm.

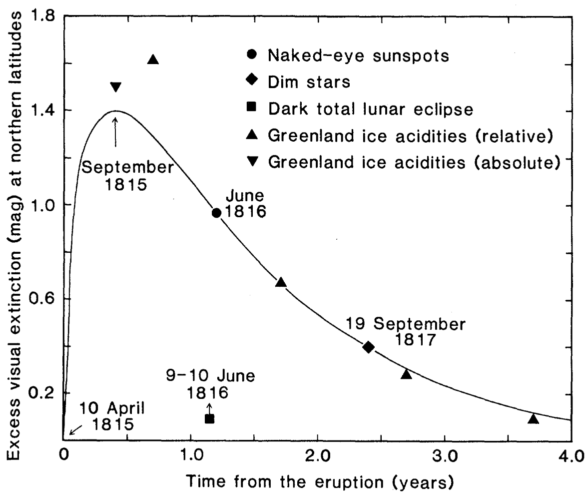

Fig. 3. Excess zenithal visual extinction $(\Delta m)_0{}^D$ in astronomical magnitudes (mag) at northern latitudes (41° to 71°N) as a function of time, reckoned from the date of Tambora's eruption. The plotted point for 9–10 June 1816 is only the lower limit to the true value. The optical depth is $\tau_D = 0.921\ (\Delta m)_0{}^D$.

idence time of the tropospheric ash burden for a given particle size was essentially the same everywhere. For these two reasons, it seems justifiable to draw a circle through the triangular points of formal zero ash depth derived above. The diameter of the circle turns out to be 760 km; its center lies approximately 300 km northwest of Tambora, and its southernmost point lies less than 100 km from the south coast of Lombok. This result agrees well with Neeb's finding of no significant Tambora ash in the Indian Ocean and Savu Sea. Notice that the main axis of ash dispersal is found again to run to the northwest. The consistency of all these results seems to rule out the possibility of any significant ash contribution coming from other East Indian volcanoes that might have been erupting at the same time (*3, 4*).

Most of the ash fallout was distributed approximately in an asymmetric cone of base area 4.5×10^5 km^2 and height 90 cm. The volume of the cone was, therefore, about 135 km^3. With an increment of 10 percent to include more distant ash, a total ash volume of roughly 150 km^3 is obtained (30 to 75 km^3 of dense rock equivalent). Since the missing upper part of the volcano occupied only ~ 30 km^3, there may be a volume excess of erupted material that could be made up by regional subsidence.

Deposits that were formed from the pyroclastic flows (now identified as ash-flow tuff or ignimbrite) (*15*) cover much of Sanggar Peninsula (*1, 9*). Most of the flow lobes actually extend all the way to the sea, especially in the north, north-northwest, west, and south directions, although not down the peninsula toward the southeast (*3, 6*). Along one stretch of coast, cliffs of pyroclastic ejecta were found to be 20 m in height (*5*). The underlying pumice and ash layers (at least near Sanggar) are, in comparison, very thin (*1*). If what went into the sea is ignored, and an average thickness of 20 m and a circular base area with a 20-km radius are assumed, a conservative estimate of the volume of pyroclastic near-source ejecta is 25 km^3 (about 12 km^3 of dense rock equivalent) (*17*).

The combined volumes of near-source and distal ejecta add up to 40 to 90 km^3 (dense rock equivalent). Since most of the material was probably ejected in a 3- to 24-hour interval, the average mass flux rate must have been 5×10^5 to 8×10^6 m^3/sec. Compositionally, the distal ash at Semarang on Java (*18*) and the near-source tephra on Sumbawa (*15, 17, 19*) are similar (within the uncertainties of the early ash analysis), being approximately 49 and 55 percent silica by weight, respectively.

Optical Phenomena

There is much evidence to indicate that Tambora's eruption column penetrated the stratosphere (altitude of more than 17 km at the equator). The direct observations of the column's "very great height" and of a widely dispersed pumice and ash fall hint at such a possibility but are not conclusive. Theory and analogy with other volcanic eruptions suggest that a mass flux rate of over 10^6 m^3/sec can thrust material up to 50 km (*20*). But the clearest evidence comes from subsequent observations of the globally dispersed dust in the atmosphere. As mentioned, the coarser ash particles fell out within a week or two of the eruption as a result of rapid tropospheric mixing and washout. If finer ash particles, aerosols, and gas molecules reached the stratosphere, where some of them might reside for months to a few years at altitudes of 10 to 30 km, they would eventually be carried by winds longitudinally around the globe and, at the same time, transported to all latitudes by meridional currents (*21*). Within several weeks of the eruption, numerous secondary aerosols would also have formed by photochemical reactions between the directly injected sulfur gases and the stratospheric ozone and water vapor (*22*).

Between 28 June and 2 July, and later between 3 September and 7 October 1815, prolonged and brilliantly colored sunsets and twilights were frequently seen near London, England (*23*). These displays were explicitly differentiated by the observers from the more familiar effects of London smog. Typically, the twilight glows appeared orange or red near the horizon, purple or pink above, and were occasionally streaked with diverging dark bands resembling cirrostratus clouds. The banded twilight glows were noticed first on 9 September, 5 months after the eruption. On 27 September, some high nimbus cloud tops continued to reflect colored light for 30 minutes after sunset. From this information, a lower limit to the altitude of the dust stratum can be computed, because the illumination of the cloud tops came either from direct sunlight or from reflection of sunlight by the dust; in either case, the dust stratum must have been situated higher up than the cloud tops. On the assumption that the nimbus clouds, because of the visibility of their tops, sat away from the zenith, they must have reached to

$$h = R \tan \alpha \tan (\alpha/2)$$

where $\delta/2 < \alpha < \delta$ (depending on zenith distance), R is the earth's radius, and δ is the angular depression of the sun below the horizon. The 30-minute duration of the glow formally implies $\delta = 4.5°$, which should be decreased by approximately 1° to correct for atmospheric refraction and screening near the horizon (*12*). It then follows that h is 3 to 12 km (the altitude of the tropopause in middle latitudes is about 10 km). The dust must have been higher than this.

The following year, 1816, during the spring and summer, a persistent "dry fog" was seen and reported in the northeastern part of the United States (*24, 25*). Since neither surface winds nor rain dispersed it, the haze must have been located above the troposphere. Its optical extinction properties, needed for climate model studies, can be estimated in several ways.

According to a New York report, the dry fog reddened and dimmed the sun to such an extent that sunspots became visible to the naked eye (*25*). This apparently took place over a "long" period in the day both before sunset and after sunrise. Sunspots can normally be seen with the naked eye only if the sun lies less than about 2.5° in apparent altitude above the horizon (*26*). Since the visual extinction of clear air (including the normal complement of solid particles, aerosols, water vapor, and so on) is 0.20 mag (astronomical magnitudes) per unit air mass and the air mass at an apparent zenith angle (z) of 87.5° is 17 (*27*), the visual extinction at this angle is normally 3.4 mag. In clear air, the sun's color begins to turn from yellow to red at an altitude of about 5°. In 1817, however, the thick volcanic haze at middle latitudes in the Northern Hemisphere extended effectively up to an altitude of 15° to 20° (*28*), and because of constant gravitational settling of the volcanic particles it is not likely that in 1816 the edge of the haze layer was lower than that. If the sun grew sufficiently red and dim so that sunspots became visible to the naked eye at an apparent zenith angle of 70° (refraction can here be ignored), then the total visual extinction at such an angle would have been given by Bouguer's law (*29*), which is here

$$[(\Delta m)_0^{\mathrm{D}} + 0.20] \sec z = 3.4$$

where $(\Delta m)_0^{\mathrm{D}}$ is the amount of visual extinction at the zenith due to the volcanic dust. It immediately follows that $(\Delta m)_0^{\mathrm{D}} = 1.0$ mag, which probably has an uncertainty of about a factor of 2.

Another approach to the determination of the extinction makes use of the darkening of the moon during a total lunar eclipse. In a normal total eclipse of the moon, the earth's atmosphere refracts and scatters sunlight into the shadow cone, so that the eclipsed moon appears faintly luminous and reddish. If clouds or other forms of haze significantly obscure the earth's terminator, the eclipse will appear dark. During the eclipse of 9 and 10 June 1816, the moon was seen to vanish entirely, under clear observing conditions, by Lofft at Ipswich, Lee at London, and Eule at Dresden (*30*). From modern lunar eclipse observations and calculations made after the 17 March 1963 eruption of Agung on Bali (*31*), it is possible to infer that the excess visual extinction in June 1816 must have been, at the very least, 0.1 mag. It could have been much greater. In any case, the result can be taken as an approximate global mean value, because the stratospheric dust cloud should have been well spread out more than a year after the eruption. Whether the moon appeared abnormally dark during other total lunar eclipses in the years immediately following Tambora's eruption is not known (*32*).

Stars, too, are dimmed by volcanic dust in the atmosphere. Before the middle of the 19th century, however, stellar magnitudes were still being measured by eye and estimated only to the nearest integer (occasionally with a plus or minus, or as two consecutive integers). Pond's (*33*) journal of nightly Greenwich observations of star positions for 1815 through 1818 contains occasional remarks that individual stars appeared "faint," but this was almost certainly a consequence of patchy cloud cover, as Pond sometimes mentioned actual cloudiness but never any persistent and uniform dimming of all the stars. In any case, stellar positions and magnitudes were regularly measured on the meridian where troublesome obscuration was generally least. Yet it is still true that magnitude estimates at that time being both uncalibrated and subjective, a systematic magnitude change of as much as 1 mag at the zenith could easily have gone undetected.

On the other hand, Pond's journal contains an exceptionally large number of entries for the period 6 through 20 September 1815 with the remark that the telescopic star images appeared "tremulous." This striking evidence for anomalous atmospheric turbidity (*34*) agrees in date with the peak period of brilliant twilights that were seen from the same part of England (3 through 14 September 1815).

Two years later, on 19 September 1817, while observing an aurora at the Glasgow Observatory 3 hours after sunset, the visiting French astronomer Dupin (*28*) noticed that the sky from the horizon up to 15° to 20° was unaccountably obscured, showing much atmospheric dispersion despite cloudless conditions, and that stars usually visible to the naked eye could be seen there "only with difficulty" and the aurora not at all. In the absence of atmospheric extinction a few first-magnitude stars would occupy a band of that size, covering a seventh of the whole sky. Although on a very clear and dark night an observer can ordinarily see down to sixth magnitude with the naked eye, an aurora was present on the night of Dupin's observation; nevertheless, the auroral light did not make naked-eye stars at altitudes above 15° to 20° particularly difficult for him to observe. If it is assumed that Dupin saw first-magnitude stars dimmed to fourth or fifth magnitude by the combined air mass and volcanic dust stratum at an average zenith angle of 80°, the dust contribution to the zenithal extinction must have been $(\Delta m)_0^{\mathrm{D}} \simeq 0.4$ mag. The uncertainty of this number, though large, is probably less than a factor of 2.

In summary, it would appear that the stratospheric dust veil produced by Tambora's eruption in April 1815 spread to England in about 3 months (with a large enhancement of stratospheric turbidity occurring about 2 months later) and created unusual twilights in England for 4 months. The temporary halt in the flow of dust north probably occurred at the summer meridional wind barrier, caused by the Hadley circulation, near 30°N. By the middle of 1816, the excess extinction at Northern Hemisphere mid-latitudes is estimated to have been ~ 1.0 mag at the zenith. Two and a half years after the eruption, some haze still remained, causing ~ 0.4 mag extinction.

These data can be represented accurately by a time development of the form $(\Delta m)_0^{\mathrm{D}} = c\ t^m \exp(-t/t_0)$, which has a peak at $t_{\max} = mt_0$. Substitution of $t_{\max} = 0.4$ year and $(\Delta m)_0^{\mathrm{D}} = 0$, 1.0, and 0.4 mag at $t = 0$, 1.2, and 2.4 years, respectively, gives

$$(\Delta m)_0^{\mathrm{D}} = 3.0\ t^{0.4}\ e^{-t/1.0}\ \mathrm{mag}$$

This formula predicts a maximum value for $(\Delta m)_0^{\mathrm{D}}$ of 1.4 mag (Fig. 3). The true time development would have been considerably less regular because of the highly variable rates of particle formation, growth, and sedimentation, as well as the slow drifting and patchiness of the dust veil.

Greenland Acid Precipitation

The rate of decline of the extinction curve can be checked with modern measurements of the record of acid fallout over the Greenland ice cap. Before Tambora's dust cloud reached Greenland, most of the fine silicate ash must have dropped out, leaving behind more slowly settling aerosols, principally sulfuric acid. A strong 4-year long (1815–1818) acidity enhancement in an ice core from Crête, Greenland (71°N), consists of the following annual acidities: 1.8, 4.9, 2.5, and 1.6 microequivalents of H^+ per kilogram of ice (*35*). The annual acidities for 1814 and 1819 amount to 1.0 and 0.9 μeq, respectively, which can be taken as the background acidity level for this period. After formal subtraction of a 0.9-μeq annual background, the integrated acidity signal due to Tambora is found to be 7.7 μeq, including an estimated 0.5 μeq that fell after 1818 as part of the background. The fraction of this total that was actually in the dust cloud at the end of each of the years from 1815 through 1818 is easily computed to be $f = 0.88$, 0.36, 0.16, and 0.06, respectively. On the assumption that the chemical properties of the dust cloud varied relatively little after the first few months (*36*), the cloud's visual extinction would have

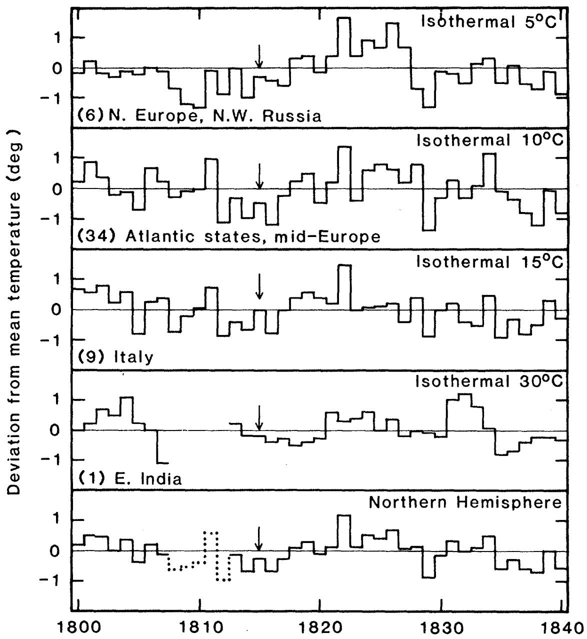

Fig. 4. Annual mean temperature deviations for four Northern Hemisphere isothermals as well as for the Northern Hemisphere as a whole. The minimum number of stations used and the areas in which they are situated are indicated. Arrows point to 1815, the year of Tambora's eruption.

been simply proportional to its column mass density and therefore to f. The unknown constant of proportionality can be derived from Fig. 3 by reading the curve at $t = 1.7$ years (the end of the year 1816); thus, $(\Delta m)_0{}^D/f = 1.9$. The corresponding scaled values of $(\Delta m)_0{}^D$ implied by the ice acidities are plotted in Fig. 3 (*37*). Agreement with the extinction curve is very good.

On the other hand, since the absolute calibration of the curve is rather uncertain, some independent calculation for at least one point is desirable. This can be done for the curve's maximum point in two ways. First, the total global acid fallout from Tambora, estimated by Hammer *et al.* (*35*) as $M_D = 1.5 \times 10^8$ tons (which will be increased here by a factor 1.3 to allow for the lower annual background acidity used in the preceding calculations), would, if placed in the stratosphere evenly over the globe, produce an optical depth perturbation of $\tau_D = \sigma\ n_D l$, where n_D is the number density of particles (of mean radius r, mass m, and density ρ), σ is their mean scattering coefficient, and l is the vertical path length through the scattering layer. With $\sigma = \pi r^2 Q$, $m = (4\pi r^3/3)\rho$, and $M_D = (4\pi R^2 l)(m n_D)$, the excess optical depth becomes

$$\tau_D = \frac{3Q\ M_D}{16\pi R^2\ r\rho}$$

This refers, in effect, to the middle latitudes of the Northern Hemisphere and Southern Hemisphere, since, in reality, the tropics would have been more heavily obscured than the poles. Adoption of typical modal values of $r = 0.3$ μm, $Q = 2$, and $\rho = 1.5$ g/cm^3 (*36, 38*) leads to $\tau_D = 1.3$, or $(\Delta m)_0{}^D = 1.086\ \tau_D = 1.4$ mag. Since M_D possesses an uncertainty of a factor of 2 (*35*), the derived value of $(\Delta m)_0{}^D$ cannot have better accuracy than this. Nonetheless, the result does agree very well with the curve in Fig. 3.

A more accurate way to estimate $(\Delta m)_0{}^D$ at the maximum point is to use a tie-in to the absolute calibration of the extinction produced after Krakatau's eruption of 26 and 27 August 1883. From reports of unusual atmospheric optical phenomena in late 1883, Deirmendjian (*39*) estimated that the peak excess visual extinction at tropical and Northern Hemisphere middle latitudes amounted to about 0.60 mag ($\tau_D = 0.55$). This is consistent with the 42 percent drop in direct noontime solar transmission measured with a pyrheliometer at Montpellier, France, between late November and early December 1883 (*40*); with corrections for solar zenith angle, forward scattering by the aerosols, and spectral response of the pyrheliometer (*31*), this drop corresponds to a visual extinction of 0.4 to 0.6 mag. Since Krakatau's integrated acidity signal at Crête, Greenland, is found to be 3.2 μeq (after subtraction of a 0.9-μeq annual background), the conversion to extinction magnitudes is 0.60/3.2 = 0.19 mag/μeq. Straight application of the derived calibration for Krakatau to Tambora can be justified by appealing to the similar injection latitude and patterns of growth and decay of their global dust clouds. Thus the peak excess visual extinction in 1815 would have been $(\Delta m)_0{}^D = 0.19 \times 7.7 = 1.5$ mag, which strongly supports the curve shown in Fig. 3.

Weather

To Europeans and North Americans, 1816 became known as "the year without a summer" (*41*). Daily temperatures (especially the daily minimums) were in many cases abnormally low from late spring through early fall; frequent northwest winds brought snow and frost to northern New England and Canada, and heavy rains fell in western Europe. Many crops failed to ripen, and the poor harvests led to famine, disease, and social distress, compounded by the aftermath of the Napoleonic wars. Tambora's dust veil is often blamed by modern researchers for the cold summer of 1816. The argument given is that the stratospheric dust veil would have absorbed or reflected solar radiation that could otherwise have reached the ground (*42*). Not all regions, however, experienced abnormally low temperatures, and the preceding winter had generally been mild. Therefore, a few researchers deny that there was any (or at least a strong) connection with the volcano (*39, 43*).

One simple measure of the overall meteorological conditions in any year is the annual deviation of the worldwide mean temperature. In other studies of this period, deviations of the various station temperatures from the station means were averaged, with weighting factors assigned either equally for all stations or else according to the station record length or reliability, or sometimes by geographical latitude, since the station coverage in 1816 was spotty and confined mostly, if not exclusively, to a few continental land areas of the Northern Hemisphere. An alternative procedure is followed here of first grouping the stations according to their annual mean temperatures. Köppen's (*44*) extensive compilation of annual deviations of the thermometric mean surface air temperatures was used in preference to the National Center for Atmospheric Research's smaller compilation adopted by other researchers (*45*). To reduce the statistical noise, Köppen's nine geographical areas, with all areas equally weighted, were combined into four larger areas in such a way that each area follows a broad temperature band centered on the following isothermals: 5°C, northern Europe, northwestern Russia (6 stations); 10°C, U.S. Atlantic states, British Isles, northern Germany and the Netherlands, western and middle Europe, Austria (34 stations); 15°C, Italy (9 stations); and 30°C, east coast of India (1 station). Since very short-term (year-to-year) changes are of interest, no secular smoothing of Köppen's temperature data was performed. The results are presented in Fig. 4, where the Northern Hemisphere average was formed from the four isothermals, all assigned equal weights in order to obtain as much effective area coverage as possible.

In 1816 the average deviation in the Northern Hemisphere was −0.7 degree. Is this significant in comparison with the interannual background fluctuations? In 1814 the average deviation was also −0.7 degree, and in 1812 it was −1.0 degree, all the contributing isothermals having temperature departures that were as low as, or lower than, those in 1816. Moreover, the standard deviation over the period from 1800 to 1840 was almost as large, ±0.5 degree. On the other hand, the data for all the isothermals except the hottest one suggest that between 1814 and 1819 there was a warming trend that was interrupted sharply in 1816. Adoption of a straight-line relation over these 6 years gives a "corrected" temperature depression in 1816 of −0.4 degree, about twice the standard deviation of the scatter around the relation. Discovery of additional station records elsewhere in the world could help to resolve this difficult question of statistical significance (*46*).

Summary and Conclusions

To appreciate the magnitude of Tambora's spectacular eruption in 1815, an inventory of the range of its primary phenomena is now drawn up in brief form: a sound range of 2600 km; an ash range of at least 1300 km; pitch darkness (up to 2 days) over a distance of 600 km; pyroclastic flows at least as far as 20 km from the mountain's summit; and a tsunami (of 1 to 4 m, shore height) over a range of at least 1200 km. Within 3 to 24 hours, the volcano succeeded in discharging ~ 150 km^3 of ash and ~ 25 km^3 of ignimbrite, with a lesser quantity of pumice falling out in the initial plinian phase (~ 3 hours long). The mass flux rate therefore averaged 5×10^5 to 8×10^6 m^3/sec (dense rock equivalent), the ratio of ash to ignimbrite lying between 2 and 6. The climax was preceded and then followed by subplinian phases marked by intermittent ash explosions.

This eruption stands out as being an order of magnitude bigger in volume of discharged pyroclastics than the Krakatau eruption in 1883, and two orders of magnitude bigger than Agung, on nearby Bali, in 1963 (*47*). In fact, it exceeds any other known eruption, historical or otherwise, during the past 10,000 years (*48*). Its dust veil increased the visual extinction in the stratosphere by 1.4 ± 0.2 mag at northern middle latitudes (41° to 71°N), which should be compared with ~ 0.60 mag for Krakatau and ~ 0.02 mag for Agung (*49*). Such a large atmospheric turbidity implies a worldwide stratospheric aerosol load (presumably mostly sulfuric acid) of ~ 2.0×10^{14} g, in near agreement with the value ~ 1.5×10^{14} g estimated by Hammer *et al.* (*35*) from Greenland ice acidities. The true perturbation to the stratospheric aerosol layer may have been even larger if the volcanic particles were more highly concentrated in the Southern Hemisphere, as was the case after Agung (*50*). Certainly, all three eruptions produced dust veils that exhibited rather similar temporal patterns, despite their very different mass loadings.

Not surprisingly, the months and years following Tambora's eruption have been remembered in popular writings for the remarkable meteorological and optical phenomena that the spreading dust veil produced. Although some serious questions remain, the mean temperature in the Northern Hemisphere apparently dropped by 0.4 to 0.7 degree in 1816, "the year without a summer." Tambora can rightly be regarded, in its global impact, as the most important of the historic Indonesian volcanoes. Its worldwide signal looms so large that, despite the measurement uncertainties of data acquired so early in the instrumental era, the extracted results have an unexpected high accuracy. It therefore appears feasible to attempt using Tambora as a calibrating standard in the investigation of earlier as well as smaller explosive volcanic eruptions at similar latitudes.

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46. Daily temperatures in the tropics following the eruption are also informative; for example, Madras, India, experienced a remarkable cooling during the last week of April 1815; the morning temperature stood at 11°C on Monday and dropped to −3°C by Friday [*Asiatic Journal* **1**, 274 (1816)]. But the decline was not universal: for example, Canton, China, did not show a drop [*Asiatic Journal* **4**, 300 and 393 (1817)]. Yet it appears that other large volcanic eruptions have produced statistically significant local and hemispheric temperature drops within 1 to 2 months of the eruption dates [C. B. Sear and P. M. Kelly, *Clim. Monit.* **11**, 134 (1982)]. Evidently, the atmosphere responds very promptly to the massive injection of the primary ash and aerosols but more slowly to the buildup of the secondary aerosols.
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51. The resources of the Columbia University Libraries and New York Public Library were indispensable aids in this study. I thank J. E. Hansen for suggesting the study; C. U. Hammer for supplying details of his ice acidity records; M. R. Rampino, S. Self, and L. D. Travis for discussions and advice; and T. Simkin and T. M. L. Wigley for substantial improvements to the text.

T and Tn, General Carcinoma Autoantigens

Georg F. Springer

Carcinomas originate from internal and external body surfaces, including ducts and glandular structures. Hence, they arise in epithelial tissue, where rapid cell loss and regeneration are physiological and defects in cell proliferation, differentiation, and proper integration would seem to be more likely than in tissues with slow turnover. Epithelia constitute only a small fraction of total body weight, yet carcinomas comprise more than 70 percent of all clinically manifest cancers. In addition, in the United States the frequency of lung carcinomas is doubling every 15 years (*1*). In the past, carcinomas were generally considered autonomous structures that invaded surrounding tissues and spread the seeds of trouble randomly at distant parts of the afflicted patient. However, Paul Ehrlich observed in 1909: "Borrel stated some years ago that the understanding of natural immunity [of the patient] is altogether the key to the carcinoma problem. This is also my belief" (*2*). Bertrand recognized in 1910 that in experimental animals ". . . une inoculation cancéreuse suivie d'un résultat négatif confère . . . à l'animal une immunité durable . . . l'explication de cette immunité nous échappe encore" (*3*). Comprehension of the basis of this general immunity toward any foreign tissue had to await the recent advances in our understanding of histocompatibility and blood group antigens.

Current efforts to characterize cancer-associated antigens and to use them clinically are built upon early work on human "cancer lipids and globulins" (*4*), and on the demonstration in animals of tumor-associated antigens (*5*). That at least some human carcinomas possess characteristic structures capable of eliciting autoimmune responses was first shown about 25 years ago in this country and in England (*6*). This discovery prompted the probing of patient-tumor interactions. Such studies were limited in scope because the antigenic material from cancers permitted testing only in carcinoma patients. In the clinical setting today, however, antisera or monoclonal antibodies raised in animals against non-autoantigenic human carcinoma markers are used. Most prominent are the oncofetal carcinoembryonic antigen and α-fetoprotein. The xenoantibodies against these markers are useful in monitoring, and sometimes diagnosing, carcinoma (*7*). Yet, early carcinoma detection is a major goal, as the following data show.

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