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Potential atmospheric impact of the Toba mega-eruption ~71,000 years ago

G.A. Zielinski, P.A. Mayewski, L.D. Meeker, S. Whitlow, and M.S. Twickler
Climate Change Research Center, University of New Hampshire, Durham

K. Taylor
Desert Research Institute, University of Nevada, Reno

Abstract. An ~6-year long period of volcanic sulfate recorded in the GISP2 ice core about 71,100 ± 5000 years ago may provide detailed information on the atmospheric and climatic impact of the Toba mega-eruption. Deposition of these aerosols occur at the beginning of an ~1000-year long stadial event, but not immediately before the longer glacial period beginning ~67,500 years ago. Total stratospheric loading estimates over this ~6-year period range from 2200 to 4400 Mt of H_2SO_4 aerosols. The range in values is given to compensate for uncertainties in aerosol transport. Magnitude and longevity of the atmospheric loading may have led directly to enhanced cooling during the initial two centuries of this ~1000-year cooling event.

Introduction

The late Quaternary eruption of Toba, Sumatra, about 74,000 years ago produced 2500-3000 km^3 of magma (dense rock equivalent), almost two orders of magnitude greater than that produced by the largest known recent historical eruption (Tambora, A.D. 1815) [*Rose and Chesner*, 1987; *Rose and Chesner*, 1990; *Chesner et al.*, 1991]. Thus, the environmental and climatic effects of a mega-eruption like Toba have not been felt by society as we know it today. Previous assessments of the atmospheric impact of the Toba eruption have relied on estimates of the amount of sulfur emitted as approximated by mineralogical studies of the eruptive products [*Rose and Chesner*, 1990] and by an upward extrapolation based on the ratio (gas emitted/volume of erupted magma) for several historical eruptions [*Rampino et al.*, 1988; *Rampino and Self*, 1992]. These data have been compared to nuclear winter scenarios to postulate that the global climatic impact of the Toba eruption would have been severe (i.e., volcanic winter) [*Rampino and Self*, 1992]. We now present a more detailed assessment of the atmospheric impact of the Toba eruption through high-resolution glaciochemical and electrical (ECM) records in the GISP2 ice core, Summit, Greenland.

Interest in the atmospheric and climatic impact of the Toba eruption has stemmed from the possible coincident timing of the eruption with the initial phases of the last glaciation around 72,000 years ago [*Rampino and Self*, 1992; 1993]. The 3.5 x 10^{15} g H_2S thought to be emitted during the eruption would result in an atmospheric loading of 1 x 10^{16} g H_2SO_4 [*Rose and Chesner*, 1990], although more conservative estimates, taking into account possible self-limiting factors governing the mass of H_2SO_4 formed are on the order of 1 x 10^{15} g H_2SO_4 [*Rampino and Self*, 1992]. The resulting global optical depth (τ) based on 10^{15} g H_2SO_4 is 10 [*Rampino et al.*, 1988], compared to a maximum τ value (at 41-71°N) of 1.3 for the Tambora eruption 0.5 year after the eruption [*Stothers*, 1984]. The optical depth for the Tambora eruption may be less because the 1.3 value was derived from the acidity record of the Crête ice core [*Stothers*, 1984] and *Zielinski* [1995] found that optical depths based on ice core loading estimates may be 2-5x too high. An e-folding time for the Toba aerosols of about one year would result in several years with $\tau \geq 0.1$, values that would have produced a maximum northern hemispheric cooling of 3-5°C for several years following the Toba eruption [*Rampino and Self*, 1992; 1993].

Continuous measurements of the complete suite of major ions, solid ice electrical conductivity (ECM), and oxygen isotopes over the entire length of the GISP2 core enabled us to evaluate the timing of the eruption relative to changing climatic conditions during the last interglacial/glacial transition (80,000-60,000 years ago). Peaks in SO_4^{2-} [*Zielinski et al.*, 1994] and electrical conductivity [*Hammer et al.*, 1980] reflect deposition of volcanically-derived aerosols (i.e., H_2SO_4), whereas the time series of oxygen isotopes [*Dansgaard et al.*, 1993] and specific glaciochemical parameters like Ca^{2+} [*Mayewski et al.*, 1994] provide proxy records of climatic change. The coincident measurement of all of these parameters provide unprecedented information useful in evaluating the climatic impact of the Toba eruption. The ability to detect a distinct signal from the Toba eruption in the continuous sampling (about 30 years/sample at that depth) led us to perform a very detailed analysis of ice chemistry across that section of the core containing Toba debris (1 cm/sample resulting in ~1.5 years/cm at that depth; *D. Meese*, personal communication, 1995). The results from this sampling enable us to quantify the duration and magnitude of the atmospheric loading of the climate-forcing aerosols (H_2SO_4) likely to have been produced from the H_2S or SO_2 released by Toba.

The chronology of the GISP2 core was developed by multiparameter counting of annual layers to a depth corresponding to about 50,000 years ago [*Meese et al.*, 1994] with the remainder of the depth-age scale based on correlation with the $\delta^{18}O$ of atmospheric O_2 records from the GISP2 and Vostok (Antarctica) ice cores [*Sowers et al.*, 1993]. Conservative cumulative age error for the 60,000-80,000 year time period is about 5000 years based on the original SPECMAP timescale and global O_2 turnover rate [*Sowers et al.*, 1993].

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Volcanic Signal and Climatic Impact

Evidence of deposition of volcanic aerosols from a major explosive eruption during the period 60,000-80,000 years ago is suggested by the distinct SO_4^{2-} and ECM spikes at 71,100 ± 5000 years ago (Figure 1A, B). A complete ionic balance over the section of core containing that spike indicates that only a small fraction of the SO_4^{2-} is balanced by the cations measured including Ca^{2+}. Thus, this peak is volcanically-derived and not related to continental salt deposition ($CaSO_4$) so prevalent during the glacial period [*Mayewski et al.*, 1994], nor is it due to sea salt aerosol deposition. The presence of the large ECM spike also indicates a volcanic source, because high concentrations of $CaSO_4$ would decrease, not increase, the acidity of the ice [*Taylor et al.*, 1992].

There are several reasons why we believe that the volcanic signal at 71,100 ± 5000 years ago represents aerosol deposition from the Toba eruption. First, the age falls within the range of radiometric ages from Toba deposits [*Rose and Chesner*, 1987; *Rose and Chesner*, 1990; *Chesner et al.*, 1991]. These ages range from an isothermal plateau, fission track age of 68 ± 7 ka on glass from a deposit in Malaysia [*Chesner et al.*, 1991] to K-Ar ages of 75 ± 12 and 74 ± 3 ka on tuff deposits [*Ninkovitch et al.*, 1978a] and an Ar-Ar age of 73 ± 4 ka also on sanidine from the tuff [*Chesner et al.*, 1991]. Secondly, the magnitude of the SO_4^{2-} signal is the largest of the entire 110,000 years of record which would be appropriate for the great size of the eruption and the estimated large amount of atmospheric loading associated with it. Finally, this large peak is found close to the beginning of the last glacial as has been indicated by others [*Rose and Chesner*, 1990; *Rampino and Self*, 1992; 1993]. The two SO_4^{2-} peaks between 64,600 and 65,200 years ago fall well within the glacial period that begins about 67,500 years ago as indicated by the more negative values of $\delta^{18}O$ [*Grootes et al.*, 1993] (Figure 1C), high Ca^{2+} concentrations [*Mayewski et al.*, 1994] (Figure 1A), and low ECM signal [*Taylor et al.*, 1993] (Fig. 1B). The latter two parameters reflect the greater atmospheric loading of alkaline dust during glacial periods. We filtered meltwater samples that spanned the entire section containing the SO_4^{2-} signal at 71,100 years ago and several sections on each side in an attempt to locate and identify volcanic glass that matched Toba glass. None was found that would verify Toba as the source of this volcanic signal.

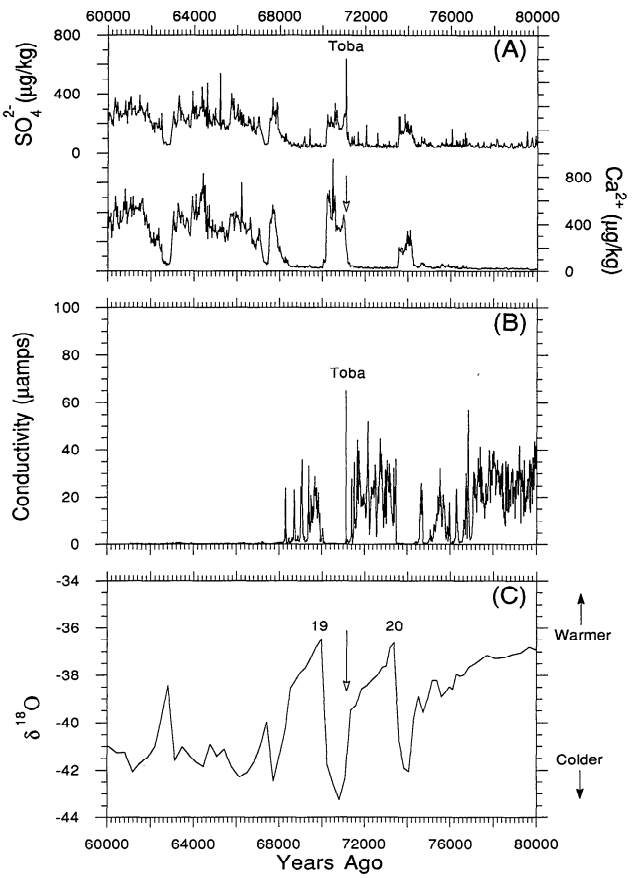

Figure 1. Time series of (A) SO_4^{2-} and Ca^{2+} concentrations, (B) electrical conductivity (ECM), and (C) $\delta^{18}O$ from the GISP2 ice core for the period between 60,000 and 80,000 years ago. Arrows show timing of Toba aerosols as related to non-volcanic Ca^{2+} and $\delta^{18}O$ records. Interstadial events 19 and 20 in (C) from *Dansgaard et al.* [1993].

Other small volcanic-SO_4^{2-} peaks are observed between 68,000 and 76,000 years ago (Figure 1A) that possibly could be linked to the Toba eruption. However, these are not of the magnitude expected from such a large eruption. Concentrations of the volcanic-SO_4^{2-} (based on the ionic balance) in the peaks around 69,400, 72,000 and 73,600 and 76,000 years ago are 3-5x less than that for the peak at 71,000. The low concentrations of these other peaks do not preclude the possibility that one of them is from Toba, but at this stage we feel this is unlikely.

The climatic significance of the Toba eruption comes from the timing of the SO_4^{2-} signal in relationship to periods of colder or glacial conditions. If the SO_4^{2-} peak at 71,000 years ago is due to Toba aerosols, then they are clearly prevalent at the beginning of the 1000-year cooling event between interstadials #19 and #20, but not immediately before the major ~9000-year long glacial period beginning about 67,500 years ago (Figure 1). In fact, an ~2000-year warm event (interstadial #19) clearly separates any climatic cooling resulting from the Toba eruption from the inception of the major cooling at 67,500 years ago (Figure 1). Our record indicates that despite the high amount of SO_4^{2-} deposition related to the Toba eruption, it was not enough to have initiated or contributed to a major glacial period. Other climate-forcing factors led to the major cooling beginning 67,500 years ago.

We can further place the paleoclimatic significance of the Toba eruption into perspective by placing it in the context of the marine isotope succession. Toba aerosol deposition apparently still occured during the transition from Stage 5a to Stage 4, as verified by the excellent correlation between the GRIP (Summit, Greenland) ice core $\delta^{18}O$ record (which has been matched to the GISP2 $\delta^{18}O$ record; *Grootes et al.*, 1993) and North Atlantic deep sea cores [*Bond et al.*, 1993]. However, this transition is marked by abrupt shifts in climate as evidenced by the presence of interstadials 19 and 20 beginning about 71,000 and 73,000 years ago, respectively. The $\delta^{18}O$ record in sediment cores from the Indian Ocean that contain Toba tephra [*Ninkovich et al.*, 1978b] is not of sufficient temporal resolution to place the Toba eruption in proper perspective. The ice core data indicate that the timing of the Toba eruption occurred during a period of even greater climatic change than previously thought [*Rampino and Self*, 1993].

To evaluate whether or not the Toba eruption could have contributed to the initiation of the stadial event 71,000 years ago, we sampled, in detail, the 30-cm section of the GISP2 core containing the Toba signal (Figure 2). High SO_4^{2-} concentrations are observed in five consecutive samples indicat-

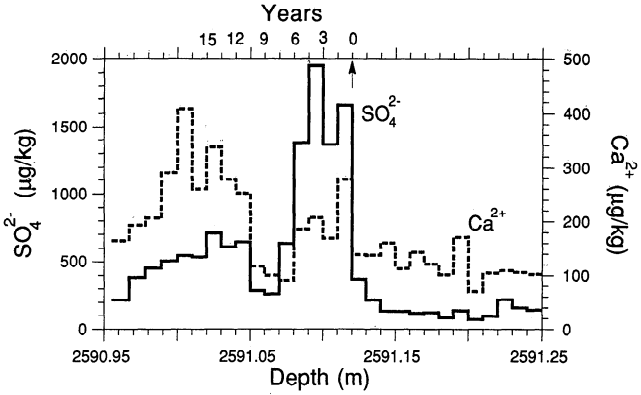

Figure 2. Detailed time series of SO_4^{2-} and Ca^{2+} concentrations for the 30-cm section of the GISP2 core containing the Toba signal. Number of years following initial deposition of volcanic SO_4^{2-}, as indicated by arrow, based on average of 1.5 yrs/cm/sample at this depth.

ing significant SO_4^{2-} aerosol deposition for a period between ~6 and 7.5 years depending on the actual length of signal within the 1.5-year samples (Figure 2). To be conservative we suggest that deposition of H_2SO_4 from the Toba eruption lasted for six years. There is no evidence of folding or shearing in this immediate section of core nor is there a repeat in concentrations that could imply some sort of post-depositional modification of the signal. We also do not see a symmetry to the signal suggesting diffusion of the acid. The duration of the GISP2 Toba signal thus appears to be accurate and of a length that would have had a significant climatic impact.

Another key factor in determining the role Toba played in initiating or modifying this cooling event is determining if the quantity and longevity of the Toba aerosols in the stratosphere were of sufficient magnitude to lead to cooling of ocean surface temperatures that would then lead to a complex response from the linked ocean-atmosphere system. *Pollack et al.* [1976] suggested that a volcanic pertubation has to be sustained for 4 years for the ocean-atmosphere system to achieve a steady-state temperature decrease. The apparent ~6-year residence time of Toba aerosols would be appropriate for forcing a response in the ocean-atmosphere system probably through some feedback that may have amplified the volcanic perturbation and then created its own forcing component.

To quantify the atmospheric impact of the eruption, we calculated the flux of volcanic SO_4^{2-} at the GISP2 site to estimate the range of stratospheric loading values resulting from the stratospheric injection of Toba aerosols (Table 1). There are several sources of uncertainty in these calculations, thus we provide a range of possible loading values. Foremost may be the overestimation (2-5x) of stratospheric loading values using ice core records because of some tropospheric transport to the deposition site [*Zielinski*, 1995]. We provide intermediate and minimum estimates of the atmospheric loading, although tropospheric transport from Toba to Greenland may have been minimal considering the equatorial location of the volcano. Consequently the intermediate to maximum values given in Table 1 may be more appropriate. Additional uncertainty exists because we do not know how the hemispheric dispersion of the aerosol cloud was affected by the season of the eruption(s) or the quasi-biennial oscillation (QBO). Nevertheless, we find that loading estimates are 150 to 1000 Mt H_2SO_4 for individual samples that each span 1.5 years resulting in a total H_2SO_4 loading around 1750-3000 Mt over about a 6-year period. This results in total aerosol loadings around 2200-4400 Mt from the Toba eruption, values in excellent agreement with previous estimates [*Rose and Chesner* , 1990]. Optical depths from such loadings could have been as high as 10 [*Rampino and Self*, 1992; 1993], sufficient enough to have significantly perturbed climate.

Although we established that the magnitude of Toba aerosol deposition was sufficient enough to force climate, we must address the apparent longevity (~6 years) of the volcanic aerosol loading especially considering that the atmospheric effects of large eruptions may be reduced by self-limiting factors in the aerosol cloud [*Pinto et al.*, 1989]. The easiest explanation to account for the 6-year length of the volcanic signal is the continual replenishment of aerosols from several explosive eruptions including the possibility of several major eruptive phases from Toba. *Ninkovitch et al.* [1978a] used the graded bedding of Toba tephra in marine sediment cores to suggest that two phases of the eruption lasted less than two weeks, but it is possible that these tephra layers only represent one part of a more extensive period of activity. The dense welding in the lower units of the Younger Toba Tuff [*Chesner and Rose*, 1991] could mask any evidence of breaks in deposition that would indicate several extended phases of activity. Given the inconclusive field evidence, we suggest that the Toba eruption involved multiple phases over a period of several years.

To determine the extent of the forcing due to Toba aerosols it is important to note the roughly 800-year period of lower $\delta^{18}O$ values, elevated Ca^{2+} values and very low ECM signal centered around 74,000 years ago (Figure 1), prior to the Toba eruption. This period of cooling together with the ~1000-year stadial immediately following Toba, indicate that climatic conditions were changing prior to the main glacial period. In fact in the ice record, Ca^{2+} concentrations are just beginning to increase and the ECM signal is beginning to decrease immediately prior to deposition of the Toba aerosols (Figure 1). All of these factors imply that the 71,000 year ago stadial

Table 1. Estimates of the Stratospheric Mass Loading of Aerosols from the Toba Eruption

Sample Depth (m)	Volcanic SO_4^{2-} Flux (x10^3) (kg/km^2/1.5 yrs)*	H_2SO_4 Loading (Mt)&	Total Aerosol Loading (Mt)#
2591.11-.10	117	281-140-56	351-176-70
2591.10-.09	287	688-344-138	860-430-172
2591.09-.08	418	1004-502-201	1255-628-251
2591.08-.07	284	682-341-136	853-426-171
2591.07-.06	352	844-422-169	1055-528-211
Total		3500-1750-700	4375-2187-875

*Product of volcanic SO_4^{2-} (total SO_4^{2-} - average background SO_4^{2-}), length of ice, ice density and a multiplier to account for an annual layer thinning of ~16x at that depth. This multiplier, and all subsequent calculations, could be as much as 1.4x greater depending on former positions of the ice divide [*J. Bolzan*, personal communication, 1995].

&Product of volcanic SO_4^{2-} flux and a multiplier of 2.4 x 10^9 for a low-latitude eruption. Multiplier based on amount of nuclear bomb fallout on the Greenland Ice Sheet from low latitude testing [*Clausen and Hammer*, 1988]. The three values represent the maximum-intermediate-minimum possible loadings based on calibration of optical depth/stratospheric loading estimates for individual eruptions from the GISP2 core with other independent estimates [*Zielinski*, 1995].

#Because the composition, by weight, of H_2SO_4 aerosol particles is roughly 75% H_2SO_4 and 25% H_2O, *Self et al.* [in press] used 1.25 as an average multiplier to convert to total aerosol loading. The three values represent the maximum-intermediate-minimum estimates.

event in question would have occurred without the Toba eruption. We cannot dispute this possibility, but if the climate system was in fact in the process of shifting modes (i.e., a high sensitivity), the magnitude and longevity of the Toba aerosols would be more capable of forcing at least part of the stadial event than they would have been if the climate system was not in a state of flux [*Rampino and Self*, 1992].

Therefore, we suggest that the long residence time and magnitude of aerosols from Toba and resulting feedbacks may have been responsible for the ~200-year period of enhanced cooling at the beginning of the 71,000 year ago stadial event. This enhanced cooling is reflected in the distinct Ca^{2+} peak at the very beginning of the stadial (Figure 1A). Other stadials in the record fail to have such a period of enhanced Ca^{2+} deposition prior to the main peak of the event [*Mayewski et al.*, 1994]. The Ca^{2+} record for the stadial centered around 74,000 years ago (Figure 1A) is more representative of the form that these ~1000-year long events take in the GISP2 record.

Summary

Our assessment of the atmospheric impact of the Toba mega-eruption strongly suggests that eruptions of this magnitude can significantly modify atmospheric conditions to the point of playing a role in forcing climatic cooling on century time scales. A key point in allowing such drastic environmental changes to occur is the assumption that the magnitude of the stratospheric loading we calculated and the residence time of 6-7.5 years for Toba aerosols will lead to cooling of ocean surface temperatures and the initiation of a complex response from the linked ocean-atmosphere system. We encourage the use of these data in modeling studies to verify or dispute the conclusions we present here. If our conclusions are correct, an eruption of Toba's magnitude occurring today would have devastating repercussions (i.e., a true volcanic winter).

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P.A. Mayewski, L.D. Meeker, M.S. Twickler, S. Whitlow, G.A. Zielinski, Climate Change Research Center, University of New Hampshire, Durham, NH 03824. (email: gaz@unh.edu)

K. Taylor, Desert Research Institute, University of Nevada, Reno, Nevada 89506

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