JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 96, NO. D9, PAGES 17,361-17,366, SEPTEMBER 20, 1991

Ice Core Evidence for an Explosive Tropical Volcanic Eruption 6 Years Preceding Tambora

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High-resolution analyses of ice cores from Antarctica and Greenland reveal an explosive volcanic eruption in the tropics in A.D. 1809 which is not reflected in the historical record. A comparison in the same ice cores of the sulfate flux from the A.D. 1809 eruption to that from the Tambora eruption (A.D. 1815) indicates a near-equatorial location and a magnitude roughly half that of Tambora. Thus this event should be considered comparable to other eruptions producing large volumes of sulfur-rich gases such as Coseguina, Krakatau, Agung, and El Chichón. The increase in the atmospheric concentration of sulfuric acid may have contributed to the northern hemisphere cooling observed in the early nineteenth century and may account partially for the decline in surface temperatures which preceded the eruption of Tambora in A.D. 1815.

INTRODUCTION

Explosive volcanic eruptions often inject large amounts of ash and gaseous aerosols into the upper troposphere and stratosphere. The coarser fraction of the ash particles (tephra) generally settles out within a few months after the eruptions have ceased. On the other hand, volcanic gases, along with the finest ash, may persist 6 to 18 months in the stratosphere and be spread hemispherically or, in some cases, globally [*Cadle et al.*, 1976; *Cadle*, 1980].

In the atmosphere, sulfur dioxide (SO_2), the dominant chemical component of volcanic gases, is oxidized to sulfate (SO_4^{2-}) or sulfuric acid (H_2SO_4) by reactions with the hydroxyl radical and other oxidants [*Cadle*, 1980; *Hamill et al.*, 1977]. The sulfate aerosols concentrate in the stratospheric aerosol layer [*Junge et al.*, 1963], increasing the aerosol optical depth and reducing the radiation receipt at the Earth's surface. Ultimately, the largest eruptions may cause a temporary decrease in land and ocean surface temperatures [*Pollack et al.*, 1976; *Self et al.*, 1981; *Bradley*, 1988; *Mass and Portman*, 1989].

The climatic impact of explosive volcanic eruptions is still a matter of much debate [*Bradley*, 1988; *Mass and Portman*, 1989], and the lack of adequate volcanic and surface temperature data bases is a major hindrance to such assessments. A number of chronologies of explosive eruptions exist: the dust veil index (DVI) of *Lamb* [1970], the volcanic explosivity index (VEI) devised by *Simkin et al.* [1981] and *Newhall and Self* [1982], and the atmospheric optical depth estimates of *Pollack et al.* [1976]. Each of these chronologies have limitations [*Bradley*, 1988] and become increasingly deficient or inaccurate in the older part of the volcanic record [*Simkin et al.*, 1981].

Ice cores preserve a broad spectrum of environmental records often with very high time resolution [*Thompson*, 1991]. Using acidity measurements in Greenland ice cores, *Hammer* [1977] demonstrated that the concentrations of sulfuric acid in snow can be significantly elevated by the deposition of aerosols derived from volcanic eruptions. Initially, these volcanic signals preserved in Greenland were exploited as time stratigraphic markers for dating ice cores. Subsequently, ice cores have provided a means for augmenting and extending the historical record of globally significant volcanic events [*Hammer*, 1980; *Delmas et al.*, 1985]. For example, in Greenland and Antarctic cores, *Langway et al.* [1988] discovered that one of the largest volcanic eruptions since the end of the last glacial stage (Wisconsin) may have occurred around A.D. 1259. A glaciological volcanic index based upon polar ice core records has been proposed [*Legrand and Delmas*, 1987] and could prove more valuable for assessment of climatic impacts than previous indices. A glaciological volcanic index would be limited for some applications as it provides only estimates of the gaseous emissions from volcanic eruptions. In addition, the magnitude of deposition on a given ice cap or glacier depends upon variations in large-scale atmospheric circulation, season of the eruption, and local deposition processes.

In general, identification, accurate dating, and characterization of specific eruptions within ice cores have been limited by the lack of high-resolution records. Most ice core records are not analyzed continuously and in sufficient detail to detect each annual layer. Generally, only selected core sections are scrutinized in fine detail by multiple analytical procedures, which include $\delta^{18}O$, dust, soluble chemical species, and *p*H. These selected sections are generally (1) those identified by electrical conductivity measurements as potentially containing "unusual" chemical signals or (2) those suspected to contain specific "known events" such as the Tambora and Krakatau eruptions, which are useful for dating purposes [*Hammer*, 1980; *Zanolini et al.*, 1985].

Estimates of the magnitude of a specific volcanic eruption from measured ice core H_2SO_4 concentrations must be made cautiously. The total deposition of H_2SO_4 (kg km^{-2}) may not provide the best basis for comparing data among different sites as the amount deposited is dependent upon the net accumula-

Paper number 91JD1634.
0148-0227/91/91JD-01634$05.00

tion rate, among other factors. This is demonstrated by *Clausen and Hammer*'s [1988] extensive comparison of volcanic horizons associated with the Laki (A.D. 1783, Iceland) and Tambora eruptions in 11 Greenland ice cores which reveals large spatial differences in the preserved signals. For example, in Greenland, H_2SO_4 deposition from Laki ranges from 295 kg km^{-2} to 62 kg km^{-2} and from 129 kg km^{-2} to 13 kg km^{-2} for Tambora. The latter two estimates are from central Greenland sites only 140 km apart but which have substantially different net accumulation regimes. Their study highlights the important role of local surface processes, particularly net annual accumulation rate, in the deposition and preservation of these records within ice sheets.

This paper discusses our identification of a volcanic eruption preserved as elevated sulfate concentrations which first appear in the layers deposited in Antarctica and Greenland in A.D. 1810. Our results are based upon four ice core records, two from Antarctica and two from Greenland, which have been absolutely dated by counting each individual year preserved in multiple parameters as discussed below.

ANALYSES AND DATING OF THE ICE CORE RECORDS

The first set of cores (depths: 302 and 132 m) were recovered in 1985 at Siple Station (75°55'S; 84°15'W) in West Antarctica (Figure 1) as part of an extensive glaciological investigation [*Mosley-Thompson et al.*, 1990]. The second set of cores (depths: 200 and 84 m) were recovered in 1989 at a site (henceforth, site T) near the summit (72°35'N; 38°27'W) of the Greenland Ice Sheet (Figure 1) in close proximity to the Greenland Ice Sheet Deep Drilling Program (GISP 2) site. In addition, a 100-m core drilled in 1985 at site A (70°38'N; 35°49'W) in Greenland (Figure 1) was also analyzed in similar fashion to the other four cores. All of the Greenland cores and one of the Siple cores were analyzed along their entire length by ion chromatography for the seasonal variations in inorganic anions (Cl^-, NO_3^-, and SO_4^{2-}). In addition, the insoluble microparticle concentrations (dust) were measured continuously on all five cores, and oxygen isotope abundances ($\delta^{18}O$) were measured continuously for one Siple core. The analytical procedures for the particulate and chemical measurements are described elsewhere [*Thompson*, 1977; *Mosley-Thompson et al.*, 1991].

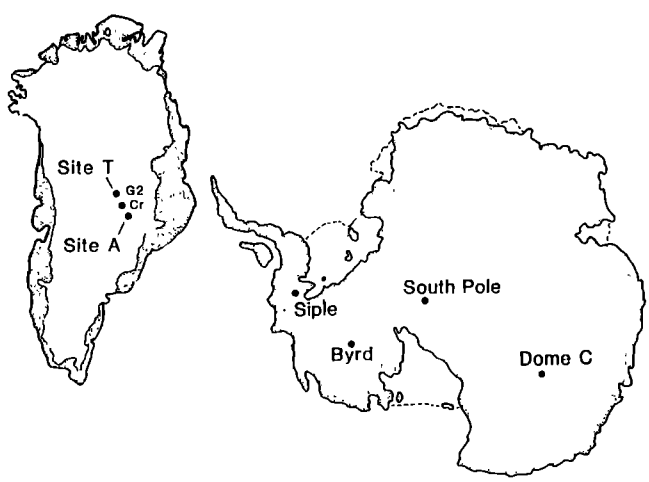

Fig. 1. Locations are shown for the sites in Antarctica and Greenland mentioned in the text. In Greenland, Gr indicates the GISP 2 Drilling Program, and Cr indicates Crête.

The analyses of multiple shallow cores for seasonally varying constituents (NO_3^-, SO_4^{2-}, $\delta^{18}O$, and dust) coupled with the identification of known time stratigraphic marker horizons in total beta radioactivity from thermonuclear testing [*Picciotto et al.*, 1963] provide an excellent estimate of average annual net accumulation for both sites: 0.23 m H_2O equivalent for site T, Greenland, and 0.56 m H_2O equivalent for Siple Station, Antarctica. These well-constrained average annual net accumulation rates, coupled with their respective continuous depth-density profiles, provide a first approximation of the time-depth relationship in each core. This estimated time scale is then refined by identification of annual variations in the constituents discussed below.

The Siple cores were dated with very high precision (±1 year at A.D. 1800) using excellently preserved seasonal variations (Figure 2) in $\delta^{18}O$ and SO_4^{2-} concentrations [*Mosley-Thompson et al.*, 1990]. The Greenland cores were dated with equal precision using annual variations (Figure 3) in insoluble microparticle (dust) and NO_3^- concentrations. *Hammer et al.* [1978] and *Herron* [1982] previously demonstrated the utility of particulates and NO_3^-, respectively, for dating Greenland ice cores. In addition, the identification of the A.D. 1783 Laki eruption, the primary time stratigraphic horizon in the Greenland Ice Sheet [*Hammer*, 1984], confirmed the dating of the Greenland cores.

RESULTS

The background concentrations of SO_4^{2-} at Siple Station vary seasonally in the range of 10-90 μg/kg [*Mosley-Thompson et al.*, 1991], consistent with previously reported concentrations. Two prominent SO_4^{2-} horizons were found at depths corresponding to the early nineteenth century (Figure 2). In the Greenland cores the ice corresponding to the same time period contains two similarly outstanding SO_4^{2-} signals (Figure 3). The more recent SO_4^{2-} horizon is dated at A.D. 1816-1817 in both cores, suggesting that the elevated SO_4^{2-} originated from the A.D. 1815 eruption of the Tambora Volcano (8°S; 118°E) in Indonesia. Similar acidity and SO_4^{2-} deposits from the Tambora eruption have been found in the A.D. 1816 horizon of many Greenland cores [*Clausen and Hammer*, 1988]. Elevated sulfate in several Antarctic cores has also been attributed to Tambora [*Legrand and Delmas*, 1987]. The concentrations of the SO_4^{2-} at site T associated with Tambora are in agreement with those reported from similar central Greenland cores [*Clausen and Hammer*, 1988].

Figures 2 and 3 illustrate that SO_4^{2-} is highly concentrated in the A.D. 1810-1811 horizons of the Siple Station and site T

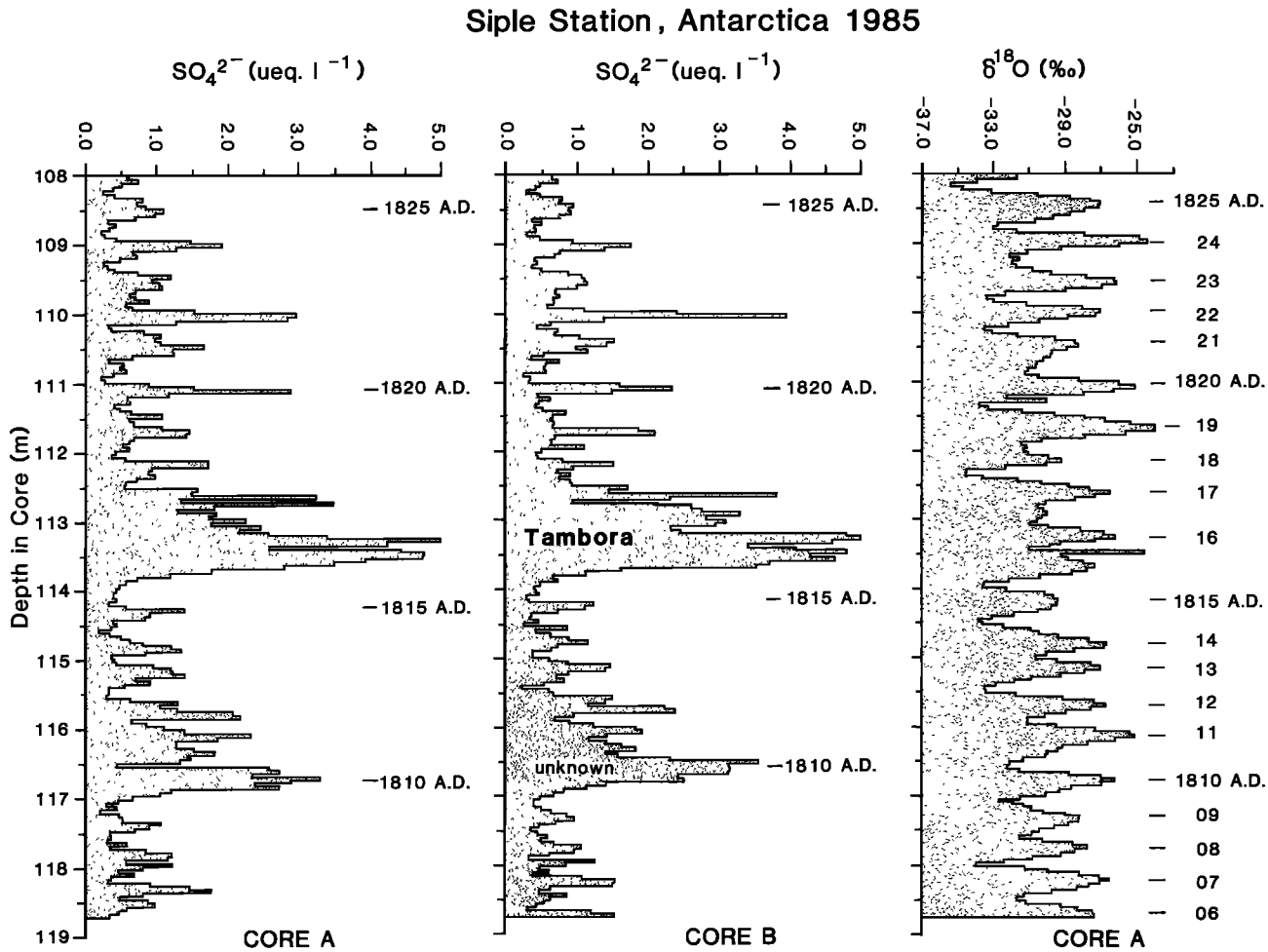

Fig. 2. Sulfate concentrations in two parallel cores (A and B) several meters apart at Siple Station, Antarctica, illustrate the excellent reproducibility in both cores of the elevated sulfate concentrations from Tambora and the A.D. 1809 event. The annual variations is $\delta^{18}O$ are shown on the right for core A and were used in conjunction the well-preserved annual SO_4^{2-} variations to accurately date both cores.

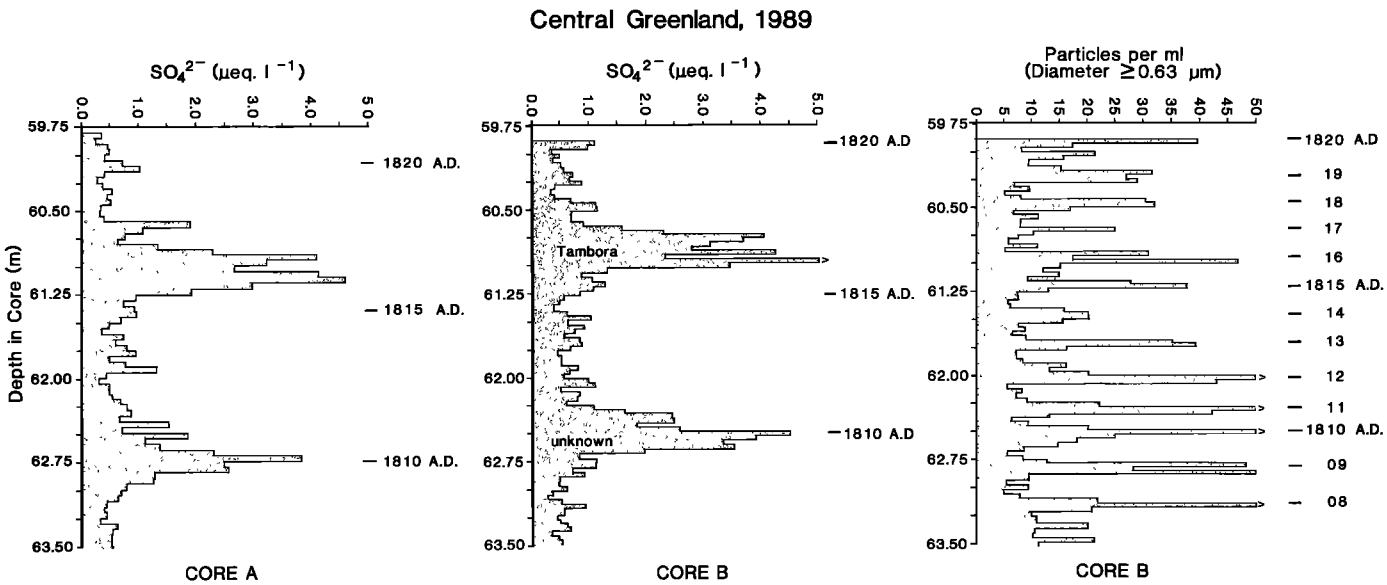

Fig. 3. Sulfate concentrations in two parallel cores (A and B) 4 km apart at site T in central Greenland illustrate the excellent reproducibility in both cores of the elevated sulfate concentrations from Tambora and the A.D. 1809 event. The annual variations in microparticle (dust) concentrations are shown on the right for core B and were used in conjunction with the annual NO_3^- variations to accurately date both cores.

cores. To facilitate comparison of these sulfate events, the annual SO_4^{2-} fluxes from A.D. 1800 to 1820 were calculated for each core (Figure 4) based on their independent time scales. The annual flux is the sum of the SO_4^{2-} concentration in each sample within the annual unit multiplied by the respective sample length. It is important to note that the amount of sulfate preserved within the snow at a site is partially dependent upon (1) the net annual accumulation, (2) the efficiency of atmospheric removal mechanisms, primarily precipitation, which may vary seasonally, and (3) the temporal relationship between maximum concentrations of SO_4^{2-} in the atmospheric reservoir and optimal atmospheric conditions for deposition at the surface. Further, the season of an eruption is a critical factor in determining how the gases are distributed between the hemispheres. Figure 4 demonstrates that the elevated sulfate in the Greenland and Antarctic cores in A.D. 1810-1811 share two similar features: (1) elevated sulfate first appears 6 years prior to the initial Tambora SO_4^{2-} horizon (A.D. 1816) and (2) SO_4^{2-} concentrations associated with the A.D. 1810-1811 horizons are elevated above background for ≈2 years with somewhat reduced deposition the second year, identical to Tambora (A.D. 1816-1817). These similarities lead us to suggest that the elevated sulfate originated from a volcanic event in A.D. 1809, henceforth referred to as the A.D. 1809 eruption.

For the period A.D. 1785 to 1808 an average unperturbed background sulfate flux was calculated to be 16.8 kg km^{-2} for Siple and 6.6 kg km^{-2} for site T. Errors in the flux data which might arise from dating inaccuracies are small as a result of the precise dating and high sampling resolution of ~10 and 6 samples per year for Siple and Greenland, respectively. Table 1 compares the cumulative fluxes (minus respective unperturbed background fluxes) associated with Tambora (A.D. 1815-1818) and the A.D. 1809 event (A.D. 1809-1812). At site T in central Greenland the A.D. 1809 eruption is associated with a sulfate flux 60% that of Tambora while at Siple Station it is roughly 40% of the Tambora flux (Table 1).

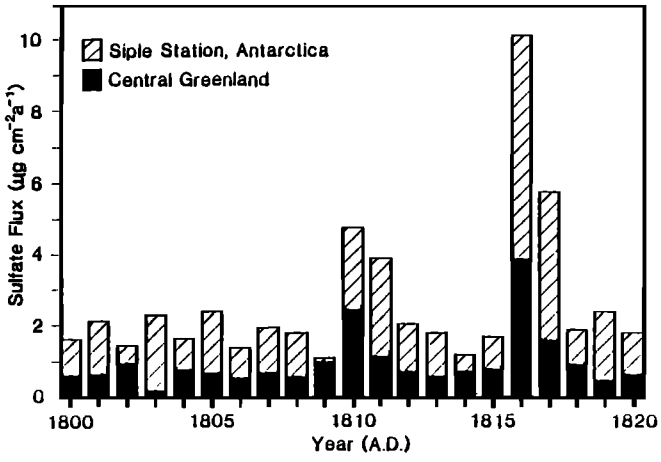

Fig. 4. Annual sulfate fluxes in ice cores from Siple Station, Antarctica, and site T in central Greenland were computed using measured sulfate concentrations and the thicknesses of individual annual accumulation layers.

TABLE 1. Total Cumulative Sulfate Fluxes (kg km^{-2}) From the 1815 Tambora Eruption and the A.D. 1809 Eruption Were Calculated From Sulfate Concentrations Measured in Ice Cores From Siple Station, Antarctica and Site T in Central Greenland

Ice Core Site	Tambora (1815)	Unidentified (1809)	Ratio (A.D. 1809/ Tambora)
Southern hemisphere			
Siple Station, Antarctica	129	53	0.41
Northern hemisphere			
Central Greenland	47	28	0.60

The average annual sulfate flux from A.D. 1785 to 1808 was assumed to represent the unperturbed SO_4^{2-} background flux for each core site. The total flux for each eruption was calculated from the total sulfate flux for 1809-1812 (A.D. 1809 eruption) and 1815-1818 (Tambora) minus their respective background fluxes, 16.8 kg km^{-2} and 6.6 kg km^{-2}.

DISCUSSION

Of the known sources of SO_4^{2-} in polar snow, only explosive volcanic eruptions produce a sudden elevation above the background level for a period of 1-2 years [*Herron*, 1982, *Legrand and Delmas*, 1984]. *Hammer* [1977] reported that signals of moderate and large eruptions in the low latitudes and northern hemisphere since A.D. 1770, including Tambora, were found in the acidity records of a core from Crête, Greenland. His Crête data also show elevated acidity around A.D. 1810, which Hammer suggested could be due to unnoticed eruptions. However, he did not investigate this further and later work [*Hammer et al.*, 1980; *Herron*, 1982] on volcanic records in Greenland ice cores did not address the possibility of a large magnitude eruption around A.D. 1810. *Legrand and Delmas* [1987] reported two closely spaced (6-8 years) H_2SO_4 peaks in the early 1800s within several Antarctic cores. Time scale uncertainties arising from low snow accumulation over East Antarctica made it impossible to determine with certainty which was associated with Tambora. Initially, the older event was attributed to Tambora and the younger event to Galunggung (A.D. 1822), but subsequent comparisons lead to the correct assignment of Tambora to the younger sulfate horizon. No further studies have investigated the A.D. 1809 eruption, and no interhemispheric connection has been explored.

The Tambora eruption has been well studied in ice cores [*Thompson et al.*, 1991]. *Clausen and Hammer* [1988] compared

Tambora at 11 locations in Greenland and noted that H_2SO_4 input from this tropical volcanic eruption is quite variable from site to site (129 to 13 kg km^{-2}). This reflects the dependence of deposition on both atmospheric and surface processes of which accumulation rate may be the most important. Our central Greenland SO_4^{2-} flux associated with Tambora is 47 kg km^{-2} (48 kg km^{-2} H_2SO_4), well within the range of Clausen and Hammer's results. The flux to site T, Greenland, from the A.D. 1809 event is roughly 60% that from Tambora (Table 1). The presence of the SO_4^{2-} signal in both Greenland and Antarctic cores strongly suggests that the volcano is located in low latitudes (≈20°N-20°S) as only large eruptions in low latitudes can perturb stratospheric sulfur levels in both hemispheres.

In Antarctica there have been several estimates of the flux from Tambora. *Legrand and Delmas* [1987] estimated the sulfate flux at Siple Station by extrapolating from the electrical conductivity measurements of *Schwander* [1984] using Hammer's calibration curve based upon the empirical relationship between Greenland acidity levels and direct current measurements for nine eruptions. Their SO_4^{2-} estimates (their Figure 5) were 47 kg km^{-2} (48 kg km^{-2} H_2SO_4) for peak 9 (now known to be the A.D. 1809 event) and 67 kg km^{-2} (68 kg km^{-2} H_2SO_4) for peak 8 which is now attributed to Tambora. *Langway et al.* [1988] used sulfate measurements at South Pole Station to estimate a SO_4^{2-} flux of 81 kg km^{-2} (83 kg km^{-2} H_2SO_4) associated with Tambora and noted that this is eight times that deposited by Krakatau (A.D. 1883). On the basis of our Siple measurements of SO_4^{2-} we estimate 129 and 53 kg km^{-2} (Table 1) for Tambora and A.D. 1809 eruption, respectively, suggesting that the A.D. 1809 event contributed roughly 40% as much H_2SO_4 to Siple Station as Tambora.

Legrand and Delmas [1987] used their Dome C, Antarctica data to estimate a global emission of 100 Tg SO_2 (150 Tg H_2SO_4) from Tambora, while *Langway et al.* [1988] estimated 240 Tg SO_2 (360 Tg H_2SO_4) based upon South Pole Station SO_4^{2-} measurements. From Greenland cores, *Clausen and Hammer* [1988] estimated a Tambora SO_2 emission of 120-179 Tg. These data illustrate the range of uncertainty in such estimates. Our flux data suggest that the A.D. 1809 eruption emitted approximately half (Table 1) the SO_2 of Tambora. If we accept the lower estimates of Tambora SO_2 emission, 100 Tg in Antarctica, and 120 Tg in Greenland, then on the basis of our analyses the SO_2 emission from the A.D. 1809 eruption was 50 to 60 Tg. For comparison, the 1883 Krakatau (6°S, 105°E) eruption is estimated to have emitted a global total of 10-25 Tg [*Legrand and Delmas*, 1987], 36 Tg [*Hammer et al.*, 1980], or 48 Tg [*Langway et al.*, 1988] of SO_2 to the atmosphere. These data suggest that Tambora produced at least 5 times more SO_2 than Krakatau and that the A.D. 1809 eruption produced 2 or 3 times as much SO_2 as Krakatau.

A number of papers have investigated the impact of major volcanic eruptions upon global climate. There is some consensus that surface temperatures may be depressed slightly after major eruptions [*Self et al.*, 1981; *Kelly and Sear*, 1984], but others do not concur [*Landsberg and Albert*, 1974; *Ellsaesser*, 1977]. *Mass and Portman* [1989] attempted a reevaluation of the meteorological effects of volcanic eruptions. They concluded that only the largest eruptions producing extensive stratospheric dust clouds and a great abundance of sulfuric acid were evident in the surface temperature records and produced only a modest cooling of 0.1 to 0.2°C. No response was found in either precipitation or pressure records. They also attempted to remove one source of interannual variability: the El Niño-Southern Oscillation (ENSO). Upon removing the ENSO signal from both the composite and individual eruption series they found an apparent enhancement of the cooling associated with the largest eruptions.

There has been a long debate about the climatic effects of Tambora to which the "year without a summer" (A.D. 1816) is attributed. In the northern hemisphere there is a decadal temperature minimum in A.D. 1815, but it is unlikely that Tambora could have affected the northern hemisphere temperature regime that quickly. Certainly, some regional temperature responses may have been more immediate and deviated substantially from the hemispheric mean. Investigations of surface temperature effects [*Angell and Korshover*, 1985] indicate that the prominent cooling during the decade, A.D. 1810-1820, began before Tambora erupted (see Figure 1 of *Angell and Korshover* [1985]). We suggest that the A.D. 1809 eruption may have contributed to the observed cooling early in the decade, and Tambora 6 years later may have sustained the cooling trend already underway.

The sulfate records from Greenland and Antarctic ice cores confirm (1) the timing of this event as A.D. 1809, (2) a tropical location for the volcano, (3) a major perturbation of the sulfate burden of both hemispheres for roughly 2 years, and (4) an SO_2 contribution to the atmosphere roughly half that of Tambora and 2 or 3 times that of Krakatau. We have been unable to find written documentation of any major volcanic eruption in A.D. 1809-1810 [*Lamb*, 1970], and no eruptions with VEI greater than 3 appear between A.D. 1800-1812 in the volcanic chronology by *Simkin et al.* [1981]. Recognition of this eruption via ice core records suggests that other unreported eruptions of potential climatic significance may be awaiting discovery. Certainly, a better volcanic chronology will contribute to the search for a link, if one exists, between volcanism and climate.

Acknowledgments. We thank K. Mountain, K. Najmulski, and J. Paskievitch for their participation in the Antarctic and Greenland field programs and the Polar Ice Coring Office of Fairbanks, Alaska (formerly of Lincoln, Nebraska) for conducting the drilling. M. Davis and L. Klein conducted the particulate analyses. Their contribution to this work is gratefully acknowledged. We are indebted to Claus Hammer for his review of the manuscript. The oxygen isotope measurements were made at the Quaternary Isotope Laboratory of the University of Washington by P. M. Grootes and at the Geophysical Institute of the University of Copenhagen by N. Gundestrup. The diagrams were produced by J. Nagy. This work was supported by NSF grants DPP-8410328 and DPP-8520885. This is contribution 737 of the Byrd Polar Research Center.

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(Received February 28, 1991;
revised June 18, 1991;
accepted June 18, 1991.)