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Annually resolved southern hemisphere volcanic history from two Antarctic ice cores

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Abstract. The continuous sulfate analysis of two Antarctic ice cores, one from the Antarctic Peninsula region and one from West Antarctica, provides an annually resolved proxy history of southern semisphere volcanism since early in the 15th century. The dating is accurate within ±3 years due to the high rate of snow accumulation at both core sites and the small sample sizes used for analysis. The two sulfate records are consistent with each other. A systematic and objective method of separating outstanding sulfate events from the background sulfate flux is proposed and used to identify all volcanic signals. The resulting volcanic chronology covering 1417-1989 A.D. resolves temporal ambiguities about several recently discovered events. A number of previously unknown, moderate eruptions during late 1600s are uncovered in this chronology. The eruption of Tambora (1815) and the recently discovered eruption of Kuwae (1453) in the tropical South Pacific injected the greatest amount of sulfur dioxide into the southern hemisphere stratosphere during the last half millennium. A technique for comparing the magnitude of volcanic events preserved within different ice cores is developed using normalized sulfate flux. For the same eruptions the variability of the volcanic sulfate flux between the cores is within ± 20% of the sulfate flux from the Tambora eruption.

Introduction

Explosive volcanic eruptions introduce large amounts of dust and gaseous materials into the atmosphere and often directly into the stratosphere. The main component of acidic volcanic gases, sulfur dioxide (SO_2), is oxidized in the atmosphere to form sulfuric acid and water (H_2SO_4/H_2O) aerosol particles. In the stratosphere these aerosol particles are spread globally via atmospheric circulation and often reside there for several years during which they may alter significantly the radiative balance and albedo of the Earth-atmosphere system. Satellite and ground-based measurements of the June 1991 eruption of the Mount Pinatubo volcano (15°N, 121°E) in the Philippines clearly show a rapid zonal dispersion of sulfurous aerosols [*Bluth et al.*, 1992] and then a gradual poleward transport [*Trepte et al.*, 1993].

Explosive volcanism has long been recognized as one of the three most important factors affecting the decadal to millennial scale climate variability (the other two are solar variability and internal interactions of the ocean-atmosphere system). The short-term climatic impact of explosive volcanic eruptions has been well documented [*Rampino and Self*, 1982; *Robock*, 1991]. For example, following the Pinatubo eruption, a decrease of 0.2-0.7°C was observed in global tropospheric and near-surface temperatures [*McCormick et al.*, 1995; *Robock and Mao*, 1995] with a corresponding increase in stratospheric temperatures [*Randel et al.*, 1995]. In general, the temperature responses to explosive eruptions last several years [*Robock*, 1991; *Robock and Mao*, 1995].

Evaluating the climatic (e.g., temperature) effects of volcanism requires comprehensive and accurate climatic and volcanic histories. While historical temperature records are fairly extensive [e.g., *Jones*, 1994], the history of global volcanism is, in most cases, sparse and only qualitative or semiquantitative. Existing volcanic chronologies include the dust veil index (DVI) of *Lamb* [1970] and the volcanic explositivity index (VEI) by *Newall and Self* [1982] and *Simkin et al.* [1981]. These indices rely on historical and geological compilations and therefore suffer from incomplete early records and historical inaccuracies [*Robock and Free*, 1995]. An ideal volcanic history for the purpose of evaluating the volcanic impact on the climate should (1) provide a quantitative proxy of the atmospheric effects caused by volcanic eruptions, (2) include a comprehensive and accurate chronology of the most explosive eruptions, and (3) contain high temporal resolution for accurate dating of the eruptions.

Recently polar ice cores, along with tree-ring data [e.g., *Jones et al.*, 1995, and references therein], have provided most of the newly acquired information on volcanic history. The concentrations of sulfuric acid (H_2SO_4), sulfate (SO_4^{2-}), and acidic conductivity of Antarctic ice cores have been shown to be directly related to aerosol concentrations of H_2SO_4 in the atmosphere [e.g., *Wagenbach et al.*, 1988]. Large amounts of SO_2 from volcanic eruptions enhance

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atmospheric sulfur concentrations from months to a few years. *Hammer* [1977] and *Hammer et al.* [1980] first used the electrical conductivity method (ECM) to measure the acidity of Greenland ice cores as a proxy for volcanic history. *Legrand and Delmas* [1987] proposed a glaciological volcanic index (GVI) based on H_2SO_4 concentrations in ice cores as a way to estimate the global impact of explosive eruptions. *Robock and Free* [1995] evaluated the strengths and limitations of combining various ice core records to create an ice core-volcano index (IVI). *Zielinski et al.* [1994] recently published SO_4^{2-} measurements from the central Greenland GISP2 ice core, which have provided the longest continuous (biyearly resolution) volcanic record from an ice core.

For the southern hemisphere (SH), *Delmas et al.* [1992] constructed a 1000-year volcanic record based on ECM and H_2SO_4 measurements on a number of south pole ice cores. *Moore et al.* [1991] measured continuously the dielectrical conductivity of an ice core from East Dronning Maud Land (site G15) in East Antarctica and presented the results as a 770-year volcanic record. *Langway et al.* [1994, 1995] reported a 1300-year record from a recent core from Byrd Station in West Antarctica.

All of the volcanic horizons in these previous Antarctic ice cores were detected by an initial survey of the cores using ECM or the dielectric profiling (DEP) method. Ice layers containing suspected "volcanic events" were subsequently analyzed for H_2SO_4 or SO_4^{2-} concentrations. Although major eruptions are detected in a quick scan of ice cores using the ECM and DEP methods, small and moderate volcanic signals may be overlooked due to the background variability of the signals which these methods measure. The ECM method detects the ice acidity which may have significant contributions from acids other than H_2SO_4 (e.g., HNO_3 and carboxylic acids). The DEP method is an indirect measurement of total salt content of the ice [*Moore et al.*, 1992]. Nonvolcanic ice layers containing unusuably large amounts of snow impurities other than H_2SO_4 and SO_4^{2-} may exhibit high ECM and DEP signals and may thus be erroneously identified as volcanic. Furthermore, most of these volcanic chronologies rely on mathematical modeling to establish the depth-age relationship. In general, the modeling approach assumes a constant snow accumulation rate and establishes the depth-age relationship based on the physics of ice flow and densification. This relationship may be refined further using known volcanic time-stratigraphic horizons, such as Tambora (1815) and the 1259 unknown eruption first identified by *Langway et al.* [1988]. As accumulation rates may vary substantially over a few decades or longer and identification of the exact eruption producing the volcanic SO_4^{2-} signal is difficult, the timescales based on this method may contain considerable errors and uncertainties.

We present SO_4^{2-} records from two ice cores: one from Siple Station (75°55'S; 84°15'W) located at the base of the Antarctic Peninsula, the other from the Dyer Plateau (70°40'S; 64°52'W), about halfway between the northern tip and the southern base of the peninsula (Figure 1). These two SO_4^{2-} records are used to construct an annually resolved, continuous volcanic chronology for the SH. This chronology offers improvements upon some of the previously published ice core-derived volcanic records: (1) the parameter or proxy for volcanic signals is the quantity of SO_4^{2-}, which is related directly to SO_2, the major chemical component emitted by volcanic eruptions, whereas the acidity in Antarctic snow/ice may be affected by the presence of nonvolcanic acids; (2) both records are dated entirely by layer counting, so the dating accuracy of identified volcanic events is significantly higher than in the previous records based on modeled depth-age relationships; and (3) the ice core records from two different sites are combined which helps eliminate spurious signals arising from postdepositional effects, poor ice core quality, and other experimental errors. In addition, these records are from the West Antarctica and Antarctic Peninsula region where few long, high-resolution volcanic records are currently available.

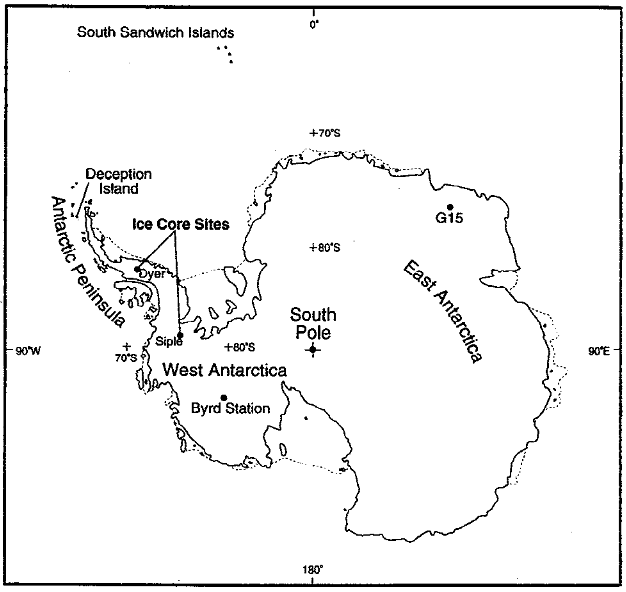

Figure 1. Location of Siple Station and the Dyer Plateau in the Antarctic Peninsula region and other Antarctic ice core sites.

Analysis and Dating of Cores

The Siple core (302 m) was drilled in the 1985-1986 austral summer, while the two 235-m Dyer cores (cores 1 and 2) were drilled, 1 meter apart, in 1989-1990. The Siple core was analyzed continuously for concentrations of major anions (Cl^-, NO_3^- and SO_4^{2-}), oxygen isotopic ratios ($\delta^{18}O$) and microparticle concentrations. The top 181 m (0-112 m of core 1 and 107-181 m of core 2) of the Dyer cores were similarly sampled and analyzed. Procedures of sample preparation and ion chromatographic measurements are presented elsewhere [*Dai et al.*, 1995]. Concentrations of major cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}) and aluminum (Al) were measured on selected core sections using a Varian SpectrAA-20 atomic absorption spectrophotometer with a GTA-96 graphite furnace atomizer (GFAA).

To resolve an annual layer, five to eight measurements are required for a seasonally varying parameter (e.g., $\delta^{18}O$ or SO_4^{2-}). Because of the relatively high annual snow accumulation at Siple (~550 mm of water equivalent (w.e.)) and Dyer (~450 mm w.e.), it was possible to cut an average of

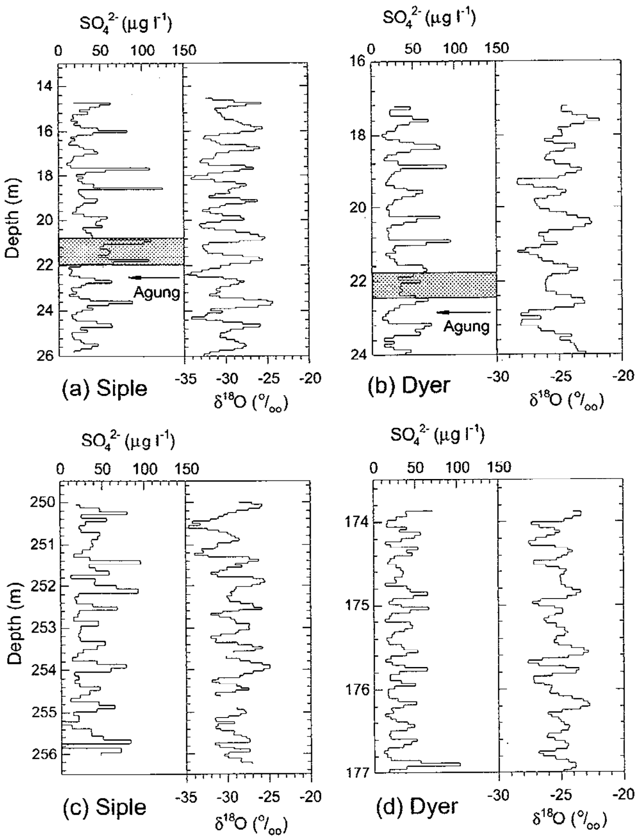

Figure 2. Annual (seasonal) variations of SO_4^{2-} concentrations in microgram per liter (μg L^{-1}) and $\delta^{18}O$ in parts per thousand (‰) are shown at the top of the Siple (a) and the Dyer (b) cores and near the bottom of the Siple (c) and the Dyer (d) cores. The arrows in Figures 2a and 2b point to the probable time of the Agung eruption (1963), and the shaded area indicates the time period when volcanic SO_4^{2-} deposition from Agung eruption likely occurred.

seven to eight samples (approximately fifteen samples at the top and five samples at the bottom) for each annual layer in both cores. This high sampling frequency (resolution) easily resolved the well-preserved $\delta^{18}O$ and SO_4^{2-} seasonal cycles (Figure 2) which were counted to establish the depth-age relationship with excellent accuracy (e.g., the 1815 Tambora eruption was dated both in the Siple and in the Dyer cores at 1816 and 1817, as expected). The accumulated errors, attributable to a few ambiguous seasonal cycles, are estimated to be only ±3 years at the end of each record. The 302-m Siple core contains 568 years (1417-1985 A.D.), while the Dyer cores yield a 485-year (1504 to 1989) continuous chronology [*Dai et al.*, 1995]. Here all dates relating to ice cores are considered "ice core years," such that 1988 represents the snow layer accumulated from the austral winter (most negative $\delta^{18}O$ during that seasonal cycle) of 1987 to the austral winter of 1988.

Data Presentation

Non-Sea-Salt SO_4^{2-}

The extremely low concentrations of Al and microparticles in both Siple and Dyer samples indicate that there is little continental aerosol dust in the snow [*Mosley-Thompson et al.*, 1991; *Thompson et al.*, 1994]. Therefore sea-salt aerosols are assumed to be the only important source of Na^+ in the snow. The ratios of Na^+ to Cl^- concentrations in Siple and Dyer snow are similar to that of bulk seawater [*Dai et al.*, 1995], suggesting that like Na^+, essentially all Cl^- is also derived from sea-salt aerosols. Therefore non-sea-salt (nss) SO_4^{2-} concentrations are calculated using the SO_4^{2-}/Cl^- concentration ratio in bulk sea water. Because nss SO_4^{2-} constitutes the overwhelming majority of total SO_4^{2-} (≥95%) at these two locations, no distinction is made between total SO_4^{2-} and nss SO_4^{2-} in subsequent discussion, although the volcanic SO_4^{2-} flux calculations are all based on nss SO_4^{2-}.

Calculation of Annual SO_4^{2-} Flux

With a subannual sampling frequency, it was possible to calculate the annual SO_4^{2-} flux for the Dyer cores [*Dai et al.*, 1995] and the Siple core. Because of ice flow and densification, annual layers become progressively thinner with depth. Because flux calculations depend on sample or layer thickness, it is necessary to adjust the measured layer thicknesses to account for layer thinning. In the Dyer cores the original annual layer thicknesses were reconstructed by ice flow modeling using ice depth and strain rates measured in the field [*Weertman*, 1993]. No ice flow and strain rate measurements are available for Siple Station and the depth of the ice sheet can only be estimated from airborne radio echo soundings by Scott Polar Research Institute [see *Drewry*, 1983, Figure 2c]. Using a simple flow model and assuming a constant accumulation rate (550 mm w.e.) and an ice depth of 1800 m, *Mosley-Thompson et al.* [1993] reconstructed the original thicknesses of individual annual layers in the Siple core. The annual SO_4^{2-} fluxes in the Siple and Dyer cores were subsequently calculated using these reconstructed annual layer thicknesses. The unsmoothed data, shown in Figure 3, form the basis of the ice-core-derived volcanic chronology presented below.

No continuous ice core SO_4^{2-} flux records have been reported previously, although several recent ice core studies [*Delmas et al.*, 1992; *Zielinski et al.*, 1994] have calculated the H_2SO_4 or SO_4^{2-} fluxes for specific volcanic events. Our results presented below indicate that using the annual SO_4^{2-} flux and its background variability facilitates the detection of small and moderate volcanic signals. Therefore our data are presented as annual SO_4^{2-} fluxes rather than concentrations. However, as the relationship between the concentrations and fluxes of snow impurities and their abundance in the atmospheric reservoir remains poorly understood at this time, it is unclear whether concentrations or fluxes provide a better proxy for the atmospheric abundance.

Results and Discussion

Volcanic aerosols are transported and distributed by the atmosphere prior to deposition in snow. Atmospheric phenomena such as the Quasi-Biennial Oscillation can strongly influence the direction and speed of the global spread of aerosols from low-latitude eruptions, as occurred with Pinatubo [*Trepte et al.*, 1993]. Therefore the temporal variation of volcanic signals in ice cores may reflect variations in the atmospheric circulation. However, the role of the atmospheric processes in the transport of volcanic aerosols to the polar ice sheets is beyond the scope of this study, which focuses on the glaciological variability of volcanic signals.

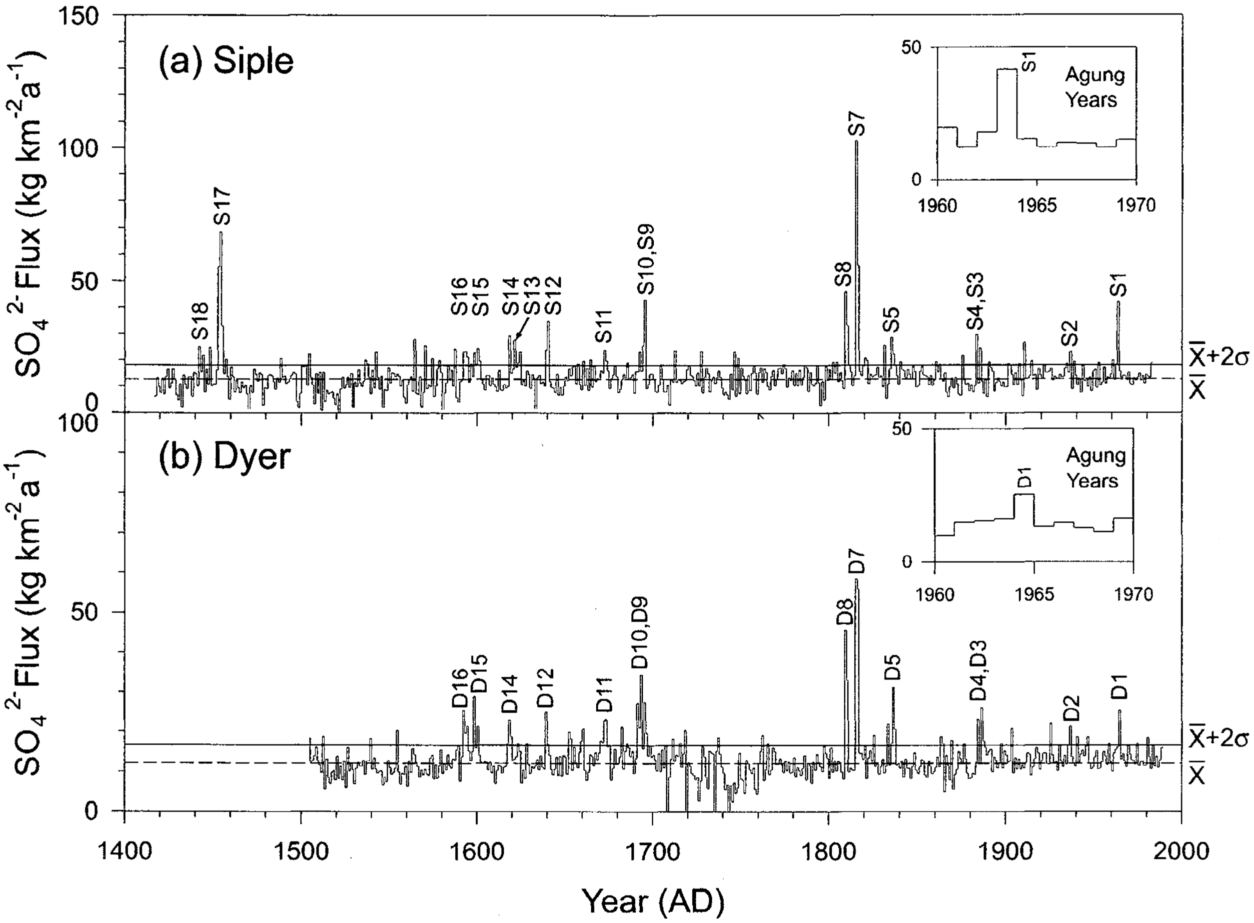

Figure 3. Annual nss SO_4^{2-} fluxes are shown for the Siple (a) and Dyer (b) cores. Data are unsmoothed. Dashed straight lines represent average nonvolcanic flux and the solid lines represent the upper limit of nonvolcanic flux ($\bar{x}+2\sigma$). The inserts show years in which the Agung eruption appears. A section in the Dyer core (112-130 m) suffered loss of ice during core drilling, resulting in low fluxes from 1706 to 1763 A.D. in Figure 3b. See *Dai et al.* [1995] for details.

Background Versus Volcanic SO_4^{2-}

Organic sulfur compounds (e.g., dimethyl sulfide or DMS) from marine biogenic emissions permeate the SH marine atmosphere. The final oxidation product of these compounds is primarily SO_4^{2-} [*Saltzman*, 1995], which forms the background SO_4^{2-} in Antarctic snowfall. Volcanic SO_4^{2-} is superimposed on this variable background and a useful ice core volcanic chronology must separate volcanic SO_4^{2-} from the background SO_4^{2-} in the snow.

The detection of volcanic signals in ice cores, especially those corresponding to the small and moderate events, depends on how the nonvolcanic background is estimated. *Crowley et al.* [1993] used the signal from the 1883 Krakatoa eruption as a minimum reference to exclude the varying background in the acidity record from the Crête (Greenland) ice core by *Hammer et al.* [1980]. A number of quantitative strategies have also been used to separate volcanic signals from the background. *Delmas et al.* [1992] defined a volcanic signal as a SO_4^{2-} concentration spike larger than the "normal" background (average plus standard deviation). *Zielinski et al.* [1994] approximated the background SO_4^{2-} concentrations in the GISP2 core using a spline-fitted curve and then considered events to be volcanic when SO_4^{2-} concentrations exceed the value of the fitted background plus a standard deviation of the residuals.

The "normal" background approach of estimating nonvolcanic SO_4^{2-} and its variability is based on the assumption that in the absence of significant inputs from volcanic and anthropogenic SO_4^{2-} the SO_4^{2-} flux and concentration in snow are not controlled by any dominant sources or transport and deposition processes. *Legrand and Feniet-Saigne* [1991] found a significant correlation between the concentrations of methanesulfonic acid (MSA) in a south pole ice core and the El Niño Southern Oscillation (ENSO) events. As MSA and nonvolcanic SO_4^{2-} share the same source (DMS), it was suggested that nonvolcanic SO_4^{2-} in Antarctic snow may be related to ENSO variations. However, in the same south pole core, no similar relationship was found between SO_4^{2-} concentration and ENSO, indicating that background SO_4^{2-} is not affected by the phrases of ENSO, a coupled atmosphere-ocean phenomenon that may influence the transport of ocean-emitted sulfur species to the Antarctic troposphere. *Pasteur et al.* [1995] reported no significant link between either MSA or nss SO_4^{2-} and ENSO events in an ice core from Dolleman Island on the Weddell Sea side of the Antarctic Peninsula. The background SO_4^{2-} at Siple and Dyer, which are in the same region as Dolleman Island, is likely to be similar to that of Dolleman Island in terms of potential oceanic influence, and therefore is not likely affected by ENSO events.

Flux Versus Concentration as a Tool to Facilitate the Detection of Volcanic Signals

To assess the nonvolcanic annual SO_4^{2-} flux background and the range of its variations, the following procedure is devised. The annual flux data are first smoothed with a three-sample running mean to remove noise originating from the division of samples into annual layers. Next, those years associated with either a known or probable large volcanic eruption (marked with an asterisk in Table 1) are removed from the annual flux time series. The identification of these volcanic events relied on the accurate dating of the Siple and Dyer cores and was made using the VEI list of volcanic records [*Newall and Self*, 1982] and with reference to results from previous Antarctic ice cores. Finally, the average ($\bar{x}$) and standard deviation (σ) of the remaining smoothed annual fluxes are computed to represent the background and its variability, respectively. Subsequently, volcanic years are identified as those having a SO_4^{2-} flux that exceeds the background ($\bar{x}$) by 2σ, an approach similar to that used by *Delmas et al.* [1992]. Fortunately, the anthropogenic SO_4^{2-} influence in the SH is minimal, making it unnecessary to detrend the Siple and Dyer data for the last 100 years, as is necessary for Greenland ice cores [*Robock and Free*, 1995].

An alternative to the flux procedure is using the SO_4^{2-} concentration data to detect volcanic signals. However, the variability of the background SO_4^{2-} concentrations at Dyer and Siple is considerably higher than that for the SO_4^{2-} annual fluxes: the relative standard deviation (RSD=%(standard deviation/mean), which allows comparison of variability between different data sets) is ≈70% for the overall nonvolcanic SO_4^{2-} concentrations in both the Dyer and the Siple cores, compared with ≈30% for the annual fluxes. This higher variability of sample concentrations makes it more difficult to detect small and moderate volcanic events, even though a similar approach used by *Delmas et al.* [1992] appears to have been effective for south pole ice cores. To compare this concentration approach with the flux procedure described above, the average of the annual nonvolcanic SO_4^{2-} maxima and its standard deviation in each of the Dyer and Siple data sets were used to identify potential volcanic signals (concentrations are considered volcanic only when they exceed the nonvolcanic annual maxima). Only the largest eruptions (Tambora, the 1809 Unknown, Huaynaputina, and Kuwae in Table 1) were identified. In contrast, the flux procedure produced a more extensive list of volcanic events (Table 1), including all those found in the south pole cores by *Delmas et al.* [1992] and four previously unreported events (see discussion on individual events).

The effect of the flux approach is further illustrated by the identification of the Agung eruption (1963). As shown in Figures 2a and 2b, the summer SO_4^{2-} concentrations associated with the 1963 Agung eruption (shaded) do not exceed the normal annual summer SO_4^{2-} maxima. Only the winter SO_4^{2-} concentrations, which are lower than the summer maxima, in 1964-1965 are above the average winter concentrations for nonvolcanic years. Thus the Agung signal could not be identified using only high SO_4^{2-} concentrations. As illustrated in the inserts in Figure 3, the Agung signal is easily recognizable in the flux profiles. For Dyer and Siple, small and moderate volcanic signals can be detected only by a close examination of the detailed seasonal SO_4^{2-} concentrations or the calculation of annual flux. In both cases a subannual sampling frequency is required.

Table 1. Volcanic Events Found in Siple and Dyer Ice Cores

Siple Event	Event Date	Dyer Event	Event Date	Probable Eruption and Year
S1	1964-1965	D1	1965	*Agung 1963
S2	1937	D2	1937	? (Darney Island 1936)
S3	1886	D3	1887	*Tarawera 1886
S4	1884	D4	1885	*Krakatoa 1883
S5	1836-1837	D5	1836-1838	*Cosiguina 1835
S6	1832	D6	1834	
S7	1816-1817	D7	1816-1817	*Tambora 1815
S8	1810-1811	D8	1810-1811	*Unknown 1809
S9	1695-1696	D9	1696-1697	? (East Indies 1693-1694)
S10	1693	D10	1692	? (Reventador 1691)
S11	1673-1674	D11	1673-1674	? (San Salvador 1671 or Gamkonora 1673)
S12	1640-1641	D12	1640-1641	Awu 1640 and others
S13	1622	--		
S14	1619	D14	1619-1620	? sub-Antarctic 1618
S15	1599-1602	D15	1599-1601	Huaynaputina 1600
S16	1593-1595	D16	1593-1595	? (Raung 1592)
S17	1454-1457			*Kuwae 1453
S18	1443			?

See text for selection method. Event dates are ice core years in which volcanic SO_4^{2-} deposit is found. Volcanoes are identified according to VEI and previously published records and unknown eruptions are represented by a question mark with the suspected eruptions in parentheses. Eruptions marked with an asterisk were removed from flux data sets to calculate nonvolcanic background. Dashes indicate that no contemporaneous event is found at Dyer.

Identification of Volcanic Years and Events

The flux procedure described above was used to produce a list of potential volcanic years from the Siple and Dyer SO_4^{2-} flux data sets. Since smoothing "spreads" an original volcanic year into the adjacent years, the smoothed data sets were examined against the unsmoothed data sets to remove false-positive years from the list. The remaining years were considered volcanic in origin. Consecutive volcanic years may result from either a large eruption producing multiple-year SO_4^{2-} deposition or two or more eruptions occurring within a short (1 or 2 years) time interval. It is probable that a careful examination of the SO_4^{2-} concentrations of the individual samples in the volcanic years may be the only reliable way to distinguish between these two scenarios. Fortunately, the high sampling frequency and dating accuracy of the Siple and Dyer cores allow the resolution of closely spaced events that were difficult to resolve in previous ice core records [*Delmas et al.*, 1992; *Langway et al.*, 1995; *Legrand and Delmas*, 1987; *Moore et al.*, 1991].

Table 1 lists all potential volcanic events, selected using the procedure described above, for the past 570 years as recorded in these two Antarctic ice cores. In Table 1 and Figure 3 the events are numbered and denoted by "S" for

Siple and "D" for Dyer. The event dates are years when the volcanic signals are found, not necessarily the eruption years. It may take 1 or 2 years for stratospheric SO_4^{2-} to be transported from lower latitudes to Antarctica. This lag is well documented for the Tambora eruption and is also evident for the June 1991 Pinatubo eruption (the Philippines), which first appears in south pole snow in late 1992 (J. Cole-Dai and E. Mosley-Thompson, unpublished data, 1995). A short lag (i.e., less than 1 year) indicates either a middle or high southern latitude location, while a long lag may indicate either a low-latitude location and hence a long transport time or a middle- to high-latitude eruption late in the austral summer or fall so that the volcanic aerosols will not penetrate the Antarctica troposphere until the breakup of the polar vortex the next spring. The individual events, along with the years of their appearance in the cores, are discussed in the following section. Contemporaneous events (within the range of dating error and uncertainty due to division of discrete years) in Siple and Dyer are presumed to have originated from the same eruption and therefore designated the same number.

Previously published records seem to indicate that the volcanic acid or SO_4^{2-} signals are more prominent in ice cores recovered from low snow accumulation areas. For example, the above mentioned Agung eruption appears prominently in Dome C and south pole cores [*Legrand and Delmas*, 1987], both located in the East Antarctica region where annual accumulation (≤ 100 mm w.e.) is considerably lower than at Siple and Dyer. Sulfate deposition consists of wet (snow and fog) and dry deposition [*Davidson et al.*, 1996]. In areas of relatively high snow accumulation the SO_4^{2-} contribution by dry deposition is small [*Dai et al.*, 1995] and its concentration is probably diluted by high precipitation. Such a dilution effect may explain the reduced prominence of the Agung and other signals in cores from higher accumulation areas. However, the relationship between accumulation rate and the proportion of dry deposition is poorly understood and needs to be addressed in future research.

Individual Events

S1 (1964-65) and D1 (1965). This event lasts nearly 2 years in both cores and is consistent with the 1963 Agung eruption (8°S, 115°E). Since this eruption has been identified in many previous Antarctic ice cores [*Delmas et al.*, 1985, and 1992; *Langway et al.*, 1995; *Legrand and Delmas*, 1987; *Moore et al.*, 1991], its signal may serve as a time-stratigraphic marker for future cores, although flux calculation may be necessary for its identification, as demonstrated previously (Figures 2 and 3). Despite the fact that Agung is located in the tropics and its SO_4^{2-} aerosols were expected to spread to both hemispheres, it has not been unambiguously identified in Greenland snow [*Mosley-Thompson et al.*, 1993; *Zielinski et al.*, 1994]. Two possible explanations are uneven interhemispheric distribution of the aerosols with the bulk going to the SH or that the SO_4^{2-} signal in Greenland is embedded in the high background concentrations due to the deposition of the NH anthropogenic SO_4^{2-}. Moderate NH eruptions in the same time period may also have obscured the Agung signal in Greenland [*Zielinski et al.*, 1994]

S2 (1937) and D2 (1937). These are small signals (about 30% that of Agung and 8-10% of Tambora) and appear to represent a single-year event. The VEI does not contain a significant eruption in the Southern Hemisphere in this time period, although the signal could have been left by a modest Antarctic or sub-Antarctic eruption, such as the VEI 2 eruption on Darney Island in the South Sandwich Islands (59°S, 26°W) late in 1936, as recorded by *Simkin et al.* [1981]. At Siple this is a "one-sample" event (i.e., due to only one sample with high SO_4^{2-} concentration), while at Dyer, the SO_4^{2-} background is slightly elevated over a large part of the annual layer. This difference between Siple and Dyer may reflect the effect of postdepositional processes (e.g., snow drifting). If this signal is indeed produced by the Darney Island eruption, there may be another explanation for the difference: the strong and frequent storms at Dyer can prolong the SO_4^{2-} deposition process, whereas Siple lies more within the polar vortex, so the influx of the tropospheric volcanic SO_4^{2-} aerosols may be more sporadic.

S3 (1886), D3 (1887) and S4 (1884), D4 (1885). The elevated SO_4^{2-} flux and concentrations in 1884-1887 in both Siple and Dyer apparently are the result of two separate volcanic events. A similar volcanic doublet was found in an East Dronning Maud Land (G15) core [*Moore et al.*, 1991] and in south pole cores [*Delmas et al.*, 1992]. As Krakatoa (6°S, 105°E) erupted in August 1883, it is likely that its SO_4^{2-} deposition in Antarctica would begin a year later (middle to late 1884). Indeed, SO_4^{2-} concentrations begin to rise above the seasonal background in the latter half of 1884 or early 1885, suggesting that the Krakatoa eruption is the likely source of S4 and D4. The SO_4^{2-} flux increase in late 1886 and 1887 (S3 and D3) is unlikely to be from Krakatoa, 3.5 years prior. Both *Delmas et al.* [1992] and *Moore et al.* [1991] suggested the June 1886 eruption of Tarawera (38°S, 176°E) in New Zealand as the source of the second event in the doublet. Our precisely dated records support their conclusions. The short interval (less than 1 year) between the eruption and the bulk SO_4^{2-} deposition probably reflects the closer proximity of Tarawera to Antarctica. The assignment of the later event in the doublet to Tarawera is further supported by the lack of a contemporaneous event in Greenland.

S5 (1836-37) and D5 (1836-38). S5 and D5 SO_4^{2-} deposit begins in 1836 and the small magnitudes are consistent with the January 1835 eruption of Cosiguina in Nicaragua (13°N, 87°W; VEI=5), which may not have been a sulfur-rich eruption [*Self et al.*, 1989]. The flux calculation shows that SO_4^{2-} deposition from Cosiguina lasted 3 years (1836-1838) at Dyer but only 2 years at Siple. Considering that Tambora lasted only 2 years, the 3-year deposition is unusual for Cosiguina. The third year (1838) at Dyer may reflect a higher-than-normal SO_4^{2-} background, leading to a possible overestimation of the net D5 volcanic SO_4^{2-} flux for Cosiguina.

S6 (1832) and D6 (1834). S6 and D6 are separated by 2 years. Given the high dating accuracy (±0 year) at this depth in the cores, it is impossible that these reflect the same event. D6 appears to result from high snow accumulation in 1834 (600 mm w.e.; the average for Dyer is 450 mm). *Delmas et al.* [1992] and *Langway et al.* [1995] reported a weak volcanic signal just a few years prior to Cosiguina (1836) in their respective cores, which they suspected to be the 1831 Babuyan (19.5°N, 122.0°E) eruption in the Philippines.

Although possible, the absence of a corresponding signal in Dyer casts doubt on the Babuyan eruption as the source for S6. It is probable that both S6 and D6 reflect high SO_4^{2-} flux from nonvolcanic sources.

S7 (1816-17), D7 (1816-17) and S8 (1810-11), D8 (1810-11). This well-known doublet has been found in all previous Antarctic ice cores. The younger event, dated at 1816 and 1817 in both cores, reflects the 1815 Tambora eruption. The 1-year lag between the eruption and the initial SO_4^{2-} deposition is consistent with the transport time of volcanic aerosols from the tropics.

With regard to event 8, no significant eruptions are found in the VEI records in the years immediately prior to Tambora. Comparison with the contemporaneous SO_4^{2-} doublet in Greenland cores led *Dai et al.* [1991] to attribute the older event to an unknown eruption in 1809 in the tropics. It is possible that a high-latitude SH eruption produced the 1810-1811 Antarctic signal [*Moore et al.*, 1991], and a coincidental eruption in the NH produced the 1810-1811 signal in Greenland. However, the close match between the timing of the 1809 event in Antarctic and Greenland cores and the similarity of the relative signal amplitudes in both polar regions support our original conclusion that a single, low-latitude eruption is the most likely source of the bipolar volcanic signals.

S9 (1695-96), D9 (1696-97) and S10 (1693), D10 (1692). The period from 1691 to 1697 contains elevated SO_4^{2-} concentrations and fluxes in both Dyer and Siple (Figure 4). Two events (eruptions) are identified using our selection method, and the possibility of more eruptions occurring within a 2 to3-year period cannot be excluded. No volcanic eruptions have been identified in previous Antarctic ice cores during this period. In the GISP2 core, *Zielinski et al.* [1994] found volcanic signals in 1693 and 1695 and attributed them to NH eruptions (in Iceland and Japan). It is highly unlikely that those eruptions also produced the Antarctic signals of events 9 and 10 at Siple and Dyer. According to *Simkin et al.* [1981] a series of moderate (VEI=3) eruptions occurred in the Banda Sea area of Indonesia (~7°S) during 1693 and 1694 and another moderate (VEI=3+) eruption of Reventador in Ecuador (8°S, 78°W) in 1691. If they injected sulfur-rich aerosols directly into the stratosphere, these eruptions could have caused elevated SO_4^{2-} concentrations in the snow in both polar areas. However, the possibility cannot be discounted that moderate or large sub-Antarctic eruptions are responsible for events 9 and 10, since the historical records for these areas are rather poor [*Newall and Self*, 1982; *Simkin et al.*, 1981]. In any case, the accurately dated Siple and Dyer cores contain elevated SO_4^{2-} flux due to two or more volcanic eruptions in the period of 1690 to 1697.

S11 (1673-74) and D11 (1673-74). The years of 1673 and 1674 (dating uncertainty at this age: ±2 years) is characterized by elevated SO_4^{2-} concentrations and fluxes at both Siple and Dyer (Figure 4). There are no previous ice core records of volcanic signals during this period. Such moderate events may have been easily missed in previous Antarctic ice cores, which were not analyzed for SO_4^{2-} continuously and with high sampling frequency. *Newall and Self* [1982] and *Simkin et al.* [1981] reported a moderately large (VEI=4?) eruption of San Salvador in El Salvador (14°N, 89°W) in 1671 and a VEI 4 eruption in Indonesia (Gamkonora, 1°N, 127°E) in May 1673. Either the San Salvador or both of these eruptions may have produced or contributed to event 11, although this cannot yet be confirmed.

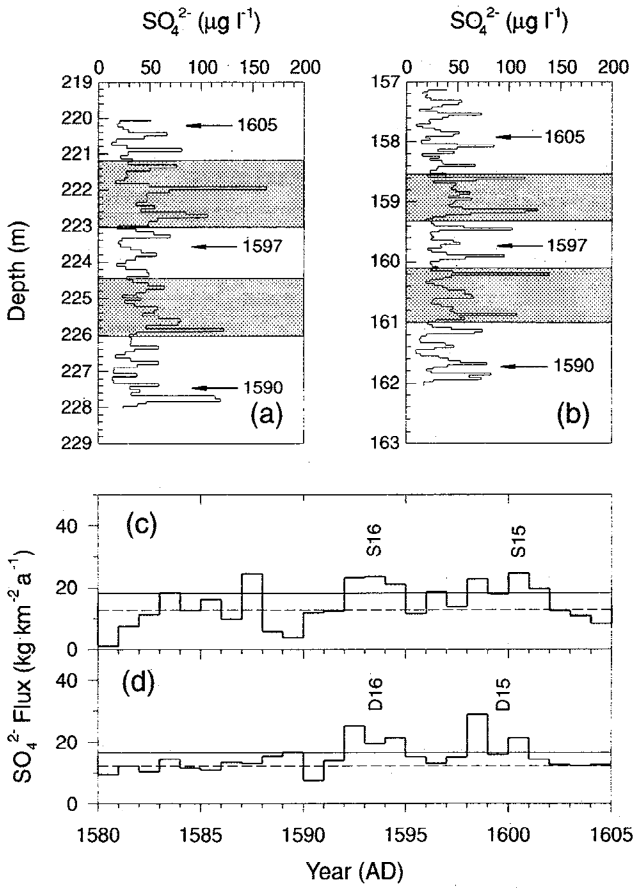

Figure 4. Sulfate concentrations (μg L^{-1}) are shown on a depth scale for the Siple (a) and Dyer (b) cores for the period from 1670 to 1700. The shaded areas indicate volcanic SO_4^{2-} deposit. (c and d) Annual SO_4^{2-} fluxes for Siple and Dyer, respectively, for the same time period.

S12 (1640-41) and D12 (1640-41). This event appears to be a moderately strong eruption with a 2-year deposition pattern (Figure 3). *Delmas et al.* [1992] found a modest signal in the 1641 ice layer in a south pole core and suspected an Antarctic (Deception Island) eruption. There is a rather strong (VEI=5) eruption of Awu (4°S, 125°E) in Indonesia in January 1641 [*Simkin et al.*, 1981], and a signal (1640) in the GISP2 core was attributed to this eruption [*Zielinski et al.*, 1994]. Such a strong tropical eruption should also leave a detectable signal in Antarctica. The probable years of SO_4^{2-} deposition from Awu (1641-1642) are within the time interval (1638-1643, dating uncertainty at this depth: ±2 years) of event 12 in our records. The first year of deposition (1640) in the annual flux records appears to suggest that the Awu eruption may have occurred one or two years before the date reported by *Simkin et al.* [1981], given the same date (1640) of this event in the Siple and Dyer cores and in the GISP2 core. On the other hand, it is possible that we have overcounted the number of annual layers by 1 or 2 years. Our date of 1599 for the probable Huaynaputina eruption (1600) in these cores (discussed below) seems to verify the overcounting.

S13 (1622). No matching signal for S13 is found in Dyer and no records, including ice core records, of any significant volcanic eruptions exist. Although the high SO_4^{2-} flux results from the high summer SO_4^{2-} concentrations, rather than from a year of exceptionally high accumulation rate, it is unlikely that S13 reflects a volcanic event, given the lack of a corresponding signal in Dyer.

S14 (1619) and D14 (1619-20). This event is more prominent in Dyer than in Siple (Figure 3). The volcanic SO_4^{2-} deposition began in early 1619. *Delmas et al.* [1992] dated a moderate south pole signal at 1621 and attributed it to a sub-Antarctic eruption, based on the composition of particles found in ice. Our data and the lack of a corresponding signal in Greenland supports their suggestion of an eruption source somewhere in the middle to high southern latitudes. Although not identified as volcanic, a DEP/acidity signal also appears around 1620 in an East Antarctic core [see *Moore et al.*, 1991, Figure 3].

S15 (1599-1602), D15 (1599-1601) and S16 (1593-95), D16 (1593-95). Another pair of events is shown in Figure 5. Event 16 lasts 3 years (1593-1595) both at Siple and at Dyer, followed by event 15 starting in 1599. *Delmas et al.* [1992] and *Kirchner and Delmas* [1988] found a similar doublet in south pole cores during this decade, but the precise age difference between the two events could not be determined.

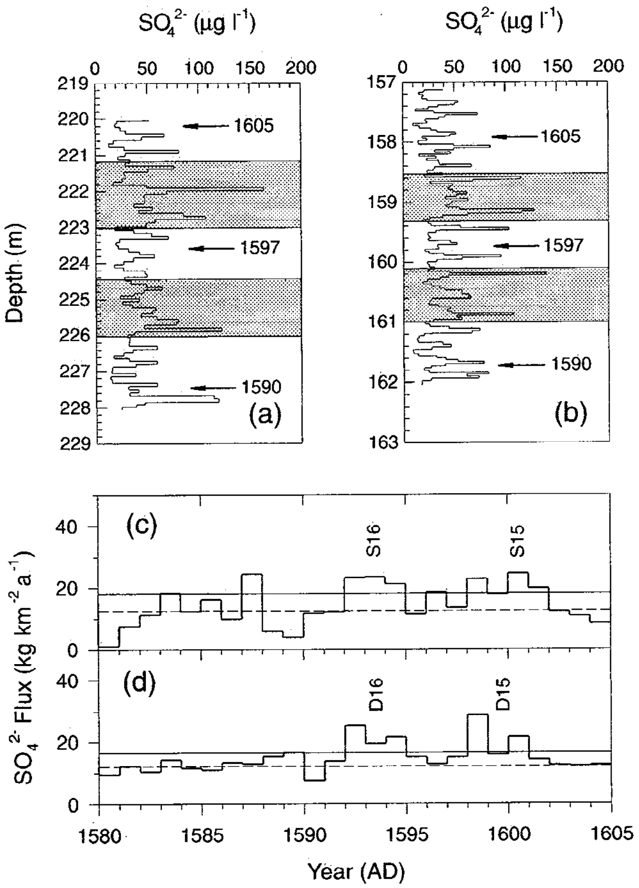

Figure 5. Sulfate concentrations (μg L^{-1}) are shown on a depth scale for the Siple (a) and Dyer (b) cores for the period from 1590 to 1602. The shaded areas indicate volcanic SO_4^{2-} deposit. (c and d) Annual SO_4^{2-} fluxes for Siple and Dyer, respectively, for the same time period.

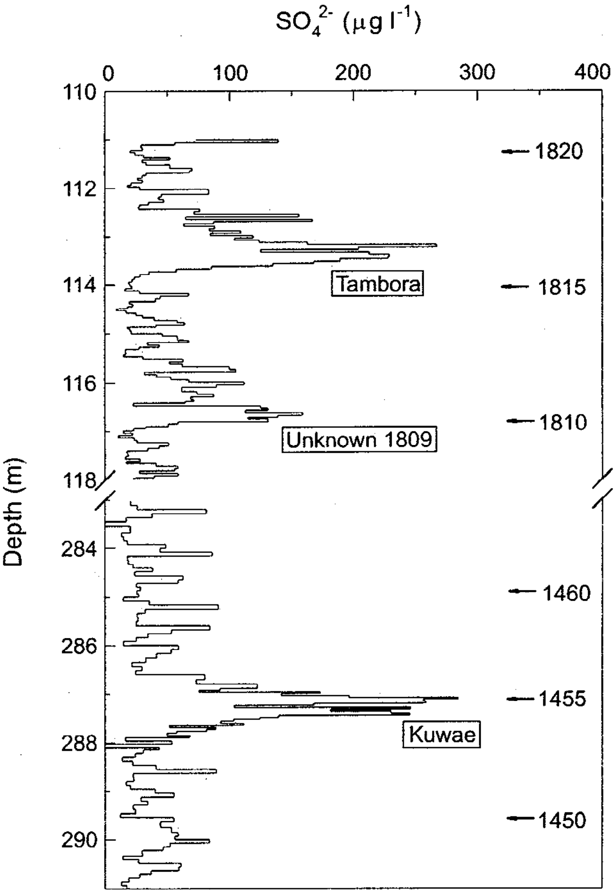

Figure 6. Highly elevated SO_4^{2-} concentrations caused by the Tambora (1815), the Unknown (1809), and the Kuwae (1453) eruptions are shown on a depth scale. The explosive character of the Kuwae eruption is similar to that of Tambora, considered the largest volcanic eruption in the last half millennium.

On the basis of elemental analyses of volcanic particles (tephra) found in the same cores, *Palais et al.* [1990] concluded that the younger event is from the 1600 eruption of Huaynaputina (17°S, 71°W) in Peru. The age of event 15 suggests that it is from the Huaynaputina eruption. If so, our dating (1599) of this event is off by 1 or 2 years (the earliest possible deposition is late 1600), which is consistent with the overestimation of event 12 (Awu, 1640) but still within the dating range indicated by the counting errors (±2 years). *Palais et al.* [1990] also suggested that the older event in the south pole doublet may be from the 1595 eruption of Ruiz in Colombia (5°S, 75°W), implying an age difference of 5 years between the two events (both eruptions occurred in the same season, March and February, of their respective years). However, the Siple and Dyer data clearly show that the age difference is 6 years between the initial SO_4^{2-} deposition of both events. As the confidence is high on the Huaynaputina identification [*Palais et al.*, 1990], the 6-year age difference casts doubt on Ruiz as the source for the older event, although the Ruiz eruption could be responsible for the volcanic deposit in the last 2 years of the 3-year event. If the younger event is indeed Huaynaputina, we suggest that the source of the volcanic SO_4^{2-} arriving in 1593 may be another eruption 1 or 2 years before Ruiz. A moderate (VEI=4) eruption (Raung, Indonesia, 8°S, 114°E) is documented by *Newall and Self* [1982] and *Simkin et al.* [1981].

S17 (1454-57). One of the most interesting features in the Siple core is the section containing extremely high SO_4^{2-} concentrations. This feature begins in 1454 and lasts 4 full years (Figure 6, bottom portion), representing a sustained and/or tremendously explosive eruption. Given the total ±3-year dating uncertainty at this depth, the data strongly suggest an eruption date between 1451 and 1456. *Pang* [1993] examined historic records from Europe and Asia and concluded that a very explosive eruption of Kuwae (17°S, 168°E) in the South Pacific occurred in early 1453, and its global scale atmospheric effects lasted at least through 1456. This conclusion is consistent with event S17 in the Siple record and the eruption date is verified by our accurately dated ice core records. A large volcanic event has been dated between 1450 and 1464 in various Antarctic ice cores [*Delmas et al.*, 1992; *Langway et al.*, 1995; *Moore et al.*, 1991]. *Zielinski et al.* [1994] reported a large eruption at 1459-1460 in GISP2 which was attributed to the Kuwae eruption. It is likely that all of these ice core volcanic signals originate from the explosive Kuwae eruption of 1453.

S18 (1443). Unfortunately, the Dyer SO_4^{2-} record does not extend this far back in time. It is difficult to evaluate this moderate signal using only the Siple core. It is worth noting that no volcanic signal has been reported in any previous ice core records. S18 may be similar to S13, a year with exceptionally high SO_4^{2-} background, due to unusually high accumulation for that year (650 mm w.e.; core average=550 mm w.e.). However, it is also possible that S18 is from a moderate eruption somewhere in the middle or high southern latitudes.

Table 2. Volcanic SO_4^{2-} Fluxes (f, in kilogram per square kilometer) for All Events in Siple and Dyer

Eruption	Siple Event	Siple f	Siple $f/f_{Tambora}$	Dyer Event	Dyer f	Dyer $f/f_{Tambora}$	R_S-R_D*
Agung 1963	S1	33	0.25	D1	13	0.15	+0.10
? (1937)	S2	11	0.08	D2	9	0.10	−0.02
Tarawera 1886	S3	12	0.09	D3	20	0.22	−0.13
Krakatoa 1883	S4	17	0.13	D4	11	0.12	+0.01
Cosiguina 1835	S5	26	0.19	D5	33	0.36	−0.17
Tambora 1815	S7	133	**1.00**	D7	90	**1.00**	**0.00**
Unknown 1809	S8	54	0.40	D8	54	0.60	−0.20
? (1695-1697)	S9	43	0.33	D9	24	0.27	+0.06
? (1692-1693)	S10	11	0.08	D10	16	0.17	−0.09
? (1673-1674)	S11	19	0.14	D11	22	0.25	−0.11
Awu 1641 and others	S12	34	0.25	D12	13	0.14	+0.11
? (1619-1620)	S14	16	0.12	D14	18	0.19	−0.07
Huaynaputina 1600	S15	34	0.26	D15	30	0.33	−0.07
? (1593-1595)	S16	30	0.22	D16	30	0.33	−0.11
Kuwae 1453	S17	122	0.92	--			
? (1443)	S18	13	0.10	--			

The year of eruption follows an identified event. Unknown eruptions are marked with a question mark, and their event dates are given in parentheses.

* $R_S = f/f_{Tambora}$ for Siple, $R_D = f/f_{Tambora}$ for Dyer.

Comparison of Volcanic Events

The net volcanic SO_4^{2-} flux for each event (Table 2) is calculated as the difference between the sum of SO_4^{2-} flux of the volcanic years and the average background SO_4^{2-} flux. The volcanic SO_4^{2-} flux, similar to volcanic acidity and the volcanic SO_4^{2-} concentration, can be used to compare the magnitude of eruptions and to evaluate quantitatively the climatic impact of specific eruptions [*Robock and Free*, 1995; *Zielinski*, 1995]. However, it is not yet well understood how various air-to-snow mass transfer mechanisms (wet and dry deposition, riming, and vapor transfer) of atmospheric species such as SO_4^{2-} affect the flux of volcanic SO_4^{2-}. Therefore by using only the volcanic SO_4^{2-} flux, it is difficult to compare volcanic events in ice cores obtained from various locations, as different mass transfer mechanisms may be dominant at different ice core locations. For example, the spatial variability for the Tambora H_2SO_4 fluxes is quite large among the various ice cores from Greenland [*Clausen and Hammer*, 1988]. It is probably better to compare different events in the same ice core, as the depositional mechanisms are likely to be more consistent at the same location. One approach to comparing volcanic SO_4^{2-} events among different ice cores is to first calculate the SO_4^{2-} flux ratio of a specific event to that of a well-documented one in each ice core. The normalized values of that event can then be compared among the cores. For example, *Dai et al.* [1991] estimated the total SO_2 emission from the Unknown 1809 eruption using the ratios of the volcanic SO_4^{2-} flux of two events in several Greenland and Antarctic cores. Here the volcanic SO_4^{2-} flux for each of the identified events is normalized against that of Tambora in their respective cores (Table 2). Data in Table 2 show that events 1 (Agung), 8 (Unknown 1809), 9 (1695), 12 (Awu?), 15 (Huaynaputina), and 16 (1593) are all moderately large eruptions producing volcanic SO_4^{2-} flux of 25% to 50% that of Tambora. The Dyer results support our previous conclusion [*Dai et al.*, 1991] that the Unknown Eruption of 1809 eruption emitted approximately half the amount of SO_2 as Tambora.

The differences between the normalized flux of any specific event for Siple and Dyer (Table 2) are all within −0.20 to +0.20. This suggests that the core-to-core variability is within ±20% of the Tambora flux, when using such an approach to evaluate a specific event in Antarctic cores. However, this approach needs to be verified with additional ice core data sets.

Previous ice core volcanic chronologies show that Tambora is the most explosive eruption (in terms of volcanic SO_4^{2-} aerosols produced) in the past 500-700 years. In Greenland, the Kuwae SO_4^{2-} concentrations are lower than those from Tambora [*Zielinski et al.*, 1994], while in a Byrd Station (Antarctica) core, the Kuwae SO_4^{2-} concentrations are higher than those from Tambora [*Langway et al.*, 1995]. In the Siple core, some individual samples associated with the Kuwae eruption contain SO_4^{2-} concentrations higher than individual samples associated with the Tambora eruption

(Figure 6). In addition, the SO_4^{2-} deposition from Kuwae lasted longer (4 years) than that from Tambora (2 years). Nonetheless, net volcanic SO_4^{2-} flux from Kuwae (122 kg km^{-2}) is very similar to that for Tambora (133 kg km^{-2}). This is consistent with the estimate of magma volume (Dense Rock Equivalent (DRE)) erupted by Kuwae which is slightly less than that erupted by Tambora [*Monzier et al.*, 1994]. The Siple results show that the amount of SO_4^{2-} aerosols produced by the Kuwae eruption is comparable with that produced by Tambora. No records of any significant eruptions can be found during this time period (1450-1460) in either VEI or DVI. Since Kuwae is a low-latitude volcano and the signal of this eruption is found in Greenland ice cores, its atmospheric impact must have been global, and given its estimated DRE and SO_2 emission, it clearly warrants a 6 or 7 designation on the VEI scale.

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References

Bluth, G.J.S., S.D. Doiron, C.C. Schnetzler, A.J. Krueger, and L.S. Walter, Global tracking of the SO_2 clouds from the June, 1991 Pinatubo eruptions, *Geophys. Res. Lett.*, *19*, 151-154, 1992.

Clausen, H.B., and C.U. Hammer, The Laki and Tambora eruptions as revealed in Greenland ice cores from 11 locations, *Ann. Glaciol.*, *10*, 16-22, 1988.

Crowley, T.J, T.A. Criste, and N.R. Smith, Reassessment of the Crete (Greenland) ice core acidity/volcanism link to climate change, *Geophys. Res. Lett.*, 20, 209-212, 1993.

Dai, J., E. Mosley-Thompson, and L.G. Thompson, Ice core evidence for an explosive tropical volcanic eruption 6 years preceding Tambora, *J. Geophys. Res.*, *96*, 17,361-17,366, 1991.

Dai, J., L.G. Thompson, and E. Mosley-Thompson, A 485 year record of atmospheric chloride, nitrate and sulfate: Results of chemical analysis of ice cores from Dyer Plateau, Antarctic Peninsula, *Ann. Glaciol.*, *21*, 182-188, 1995.

Davidson, C.I., M.H. Bergin, and H.D. Kuhns, The deposition of particles and gases to ice sheets, in *Chemical Exchange Between the Atmosphere and Polar Snow, NATO ASI Ser.*, vol. 43, edited by E.W. Wolff and R.C. Bales, pp. 275-306, Springer-Verlag, New York, 1996.

Delmas, R.J., M. Legrand, A.J. Aristarain, and F. Zanolini, Volcanic deposits in Antarctic snow and ice, *J. Geophys. Res.*, *90*, 12,901-12,920, 1985.

Delmas, R.J., S. Kirchner, J.M. Palais, and J.R. Petit, 1000 years of explosive volcanism recorded at the South pole, *Tellus*, *44B*, 335-350, 1992.

Drewry, D.J., *Antarctica: Glaciological and Geophysical Folio*, Scott Polar Res. Cent., University of Cambridge, London, 1983.

Hammer, C.U., Past volcanism revealed by Greenland ice sheet impurities, *Nature*, *270*, 482-486, 1977.

Hammer, C.U., H.B. Clausen, and W. Dansgaard, Greenland ice sheet evidence of post-glacial volcanism and its climatic impact, *Nature*, *288*, 230-235, 1980.

Jones, P.D., Hemispheric surface air temperature variations: A reanalysis and an update to 1993, *J. Clim.*, *7*, 1794-1802, 1994.

Jones, P.D., K.R. Briffa, and F.H. Schweingruber, Tree-ring evidence of the widespread effects of explosive volcanic eruptions, *Geophys. Res. Lett.*, *22*, 1333-1336, 1995.

Kirchner, S., and R.J. Delmas, A 1000 year glaciochemical study at the South pole, *Ann. Glaciol.*, *10*, 80-84, 1988.

Lamb, H.H., Volcanic dust in the atmosphere with a chronology and assessment of its meteorological significance, *Phil. Trans. R. Soc. London*, *266*, 425-533, 1970.

Langway, C.C., Jr., H.B. Clausen, and C.U. Hammer, An inter-hemisphere volcanic time-marker in ice cores from Greenland and Antarctica, *Ann. Glaciol.*, *10*, 102-108, 1988.

Langway, C.C., Jr., K. Osada, H.B. Clausen, C.U. Hammer, H. Shoji, and A. Mitani, New chemical stratigraphy over the last millennium for Byrd Station, Antarctica, *Tellus*, *46B*, 40-51, 1994.

Langway, C.C., Jr., K. Osada, H.B. Clausen, C.U. Hammer, and H. Shoji, A 10-century comparison of prominent volcanic events in ice cores, *J. Geophys. Res.*, *100*, 16,241-16,247, 1995.

Legrand, M., and R.J. Delmas, A 220-year continuous record of volcanic H_2SO_4 in the Antarctic Ice Sheet, *Nature*, *327*, 671-676, 1987.

Legrand, M., and C. Feniet-Saigne, Methanesulfonic acid in south polar snow layers: A record of strong El Niño?, *Geophys. Res. Lett.*, *18*, 187-190, 1991.

McCormick, M.P., L.W. Thomason, and C.R. Trepte, Atmospheric effects of the Mt. Pinatubo eruption, *Nature*, *373*, 399-403, 1995.

Monzier, M., C. Robin, and J.-P. Eissen, Kuwae (≈1425 A.D.): The forgotten caldera, *J. Volcanol. Geotherm. Res.*, *59*, 207-218, 1994.

Moore, J.C., H. Narita, and N. Maeno, A continuous 770-year record of volcanic activity from East Antarctica, *J. Geophys. Res.*, *96*, 17,353-17,359, 1991.

Moore, J.C., E.W. Wolff, H.B. Clausen, and C.U. Hammer, The chemical basis for the electrical stratigraphy of ice, *J. Geophys. Res.*, *97*, 1887-1896, 1992.

Mosley-Thompson, E., L.G. Thompson, J. Dai, M.E. Davis, and P.-N. Lin, Climate of the last 500 years: High resolution ice core records, *Quat. Sci. Rev.*, *12*, 419-430, 1993.

Mosley-Thompson, E., J. Dai, L.G. Thompson, P.M. Grootes, J.K., Arbogast, and J.F. Paskievitch, Glaciological studies at Siple Station (Antarctica): Potential ice core paleoclimatic record, *J. Glaciol.*, *37*, 11-22, 1991.

Newall, C.G., and S. Self, The volcanic explositivity index (VEI): An estimate of explosive magnitude for historical volcanism, *J. Geophys. Res.*, *87*, 1231-1238, 1982.

Palais, J.M., S. Kirchner, and R.J. Delmas, Identification of some global volcanic horizons by major elemental analysis of fine ash in Antarctic ice, *Ann. Glaciol.*, *14*, 216-220, 1990.

Pang, K.D., Climatic impact of the mid-fifteenth century Kuwae Caldera formation, as reconstructed from historic and proxy data (abstract), *Eos Trans, AGU*, *74*(43), Fall Meet. Suppl., 106, 1993.

Pasteur, E.C., R. Mulvaney, D.A. Peel, E.S. Saltzman, and P.-Y. Whung, A 340-year record of biogenic sulphur from the Weddell Sea area, Antarctica, *Ann. Glaciol.*, *21*, 169-174, 1995.

Randel, W.J., F. Wu, J.M. Russell III, J.W. Waters, and L. Froidevaux, Ozone and temperature changes in the stratosphere following the eruption of Mount Pinatubo, *J. Geophys. Res.*, *100*, 16,753-16,764, 1995.

Rampino, M.R., and S. Self, Historical eruptions of Tambora (1815), Krakatau (1883), and Agung (1963), their stratospheric aerosols and climatic impact, *Quat. Res.*, *18*, 127-143, 1982.

Robock, A., The volcanic contribution to climate change of the past 100 years, in *Greenhouse-Gas-Induced Climatic Change: A Critical Appraisal of Simulations and Observations*, edited by M.E. Schlesinger, pp. 429-444, Elsevier, New York, 1991.

Robock, A., and M.P. Free, Ice cores as an index of global volcanism form 1850 to the present, *J. Geophys. Res.*, *100*, 11,549-11,567, 1995.

Robock, A., and J. Mao, The volcanic signal in surface temperature observations, *J. Clim.*, *8*, 1086-1103, 1995.

Saltzman, E.S., Ocean/atmosphere cycling of dimethylsulfide, in *Ice Core Studies of Global Biogeochemical cycles, NATO ASI Ser.*, vol. 30, edited by R.J. Delmas, pp. 65-89, Springer-Verlag, New York, 1995.

Self, S., M.R. Rampino, and M.J. Carr, A reappraisal of the 1835 eruption of Cosiguina and its atmospheric impact, *Bull. Volcanol., 52*, 57-65, 1989.

Simkin, T., L. Siebert, L. McClelland, D. Bridge, C. Newall, and J.H. Latter, *Volcanoes of the World*, Hutchinson Ross, Stroudsburg, Pa., 1981.

Thompson, L.G., D.A. Peel, E. Mosley-Thompson, R. Mulvaney, J. Dai, P.N. Lin, M.E. Davis, and C.F. Raymond, Climate since AD 1510 on Dyer Plateau, Antarctic Peninsula: Evidence for recent climate change, *Ann. Glaciol., 20*, 420-426, 1994.

Trepte, C.R., R.E. Veiga, and M.P. McCormick, The poleward dispersal of Mt. Pinatubo volcanic aerosol, *J. Geophys. Res., 98*, 18,563-18,573, 1993.

Wagenbach, D., U. Gorlach, K. Moser, and K.O. Munnich, Coastal Antarctic aerosol: The seasonal pattern of its chemical composition and radionuclide content, *Tellus, 40B*, 426-436, 1988.

Weertman, B.R., A radio-echo sounding study of the Dyer Plateau, Antarctica, Ph.D. dissertation, Univ. of Wash., Seattle, 1993.

Zielinski, G.A., Stratospheric loading and optical depth estimates of explosive volcanism over the last 2100 years derived from the Greenland Ice Sheet Project 2 ice core, *J. Geophys. Res., 100*, 20,937-20955, 1995.

Zielinski, G.A., P.A. Mayewski, L.D. Meeker, S. Whitlow, M.S. Twickler, M. Morrison, D.A. Meese, A.J. Gow, and R.B. Alley, Record of volcanism since 7000 B.C. from the GISP2 Greenland ice core and implications for the volcano-climate system, *Science, 264*, 948-952, 1994.

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