The Number and Magnitude of Large Explosive Volcanic Eruptions Between 904 and 1865 A.D.: Quantitative Evidence From a New South Pole Ice Core

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A new volcanic record covering the period of 904 to 1865 A.D. was produced from continuous chemical analysis of a 2001 South Pole ice core. This new record is consistent with previous records in the number and dates of large volcanic events. The relative magnitudes of several prominent events in this new record were compared to the same events in previous records from South Pole and Plateau Remote (East Antarctica) ice cores. The comparison demonstrates that the discrepancies in reported magnitudes of these events are probably a result of the glaciological complications at Plateau Remote, and that volcanic deposit or flux measurements from South Pole ice cores are therefore more reliable parameters of the atmospheric mass loadings of volcanic aerosols. The new record also confirms the previous finding that five large or moderately large volcanic eruptions occurred in the 13th century. The total atmospheric aerosol mass loadings, inferred from volcanic sulfate flux in this new ice core, from these five eruptions appear to be 3 to 20 times those in other centuries during the last millennium, suggesting a significant role by explosive volcanism in the climatic transition from the Medieval Warm Period to the Little Ice Age.

1. INTRODUCTION

Explosive volcanic eruptions inject large amounts of dust and gaseous materials into the atmosphere. The major component of the injected gas is sulfur dioxide which is rapidly oxidized in the atmosphere to sulfuric acid. The resulting aerosol particles of sulfuric acid and water can reside for months to several years in the stratosphere where they are distributed throughout a hemisphere or globally by atmospheric circulation. Generally, aerosols from large explosive volcanic eruptions at the low latitudes (between 0° and 20°) of either hemisphere are capable of global distribution via the stratosphere. Elevated aerosol concentrations in the stratosphere increase the atmospheric aerosol optical depth, thereby altering the atmospheric albedo and reducing the radiation receipt at the Earth's surface. Therefore, atmospheric perturbation from large volcanic eruptions can have a significant impact on the climate and the magnitude of the impact is believed to be related to the volcanic aerosol mass loadings [*Robock*, 2000; *Zielinski*, 1995; 2000]. This climatic impact can be viewed within two timeframes: short term (up to five years after the initial perturbation) and long term. The short-term, immediate effects of explosive eruptions on climate have been well studied and well documented [*Rampino and Self*, 1982; *Robock*, 2000; *Robock and Mao*, 1995; *White et al.*, 1997]. The long term, cumulative impact of sustained explosive volcanic activities with frequent injections of large amounts of fresh sulfur aerosols during a period of a few decades has not been explored, although it has been speculated [*Briffa et al.*,

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1998; *Zielinski,* 2000]. Recent observations [*Barnes and Hoffmann*, 2001; *Hervig and Deshler*, 2002] show that global stratospheric aerosols have declined continuously since 1991 when the Pinatubo eruption introduced massive amounts of volcanic aerosols into the stratosphere, indicating that volcanic aerosols linger in the stratosphere long past the period of the short-term and apparent climatic impact. This suggests that stratospheric residence times of volcanic aerosols are probably longer than previously thought and frequent injection of volcanic aerosols within a few decades could have a greater impact on climate than the short-term effects of individual volcanic eruptions.

Sulfuric acid or sulfate aerosols of volcanic origin, along with other trace atmospheric species, are deposited in the Antarctic continent with snowfall. The continuous snow accumulation creates and preserves records of variations in atmospheric composition and sources of atmospheric components, including those from explosive volcanic eruptions [*Delmas et al.*, 1985; *Legrand et al.*, 1984]. Chemical analysis for acidity or sulfate concentration of ice cores drilled in Antarctica can therefore provide chronological and continuous records of explosive volcanic eruptions dating back thousands of years. Several volcanic records from Antarctic ice cores are available [*Cole-Dai et al.*, 2000; *Delmas et al.*, 1992; *Langway et al.*, 1995; *Legrand and Delmas*, 1987; *Palmer et al.,* 2001]. These records document in detail the chronological history of explosive volcanism over the last several millennia that may have had a significant impact on atmospheric chemical composition and the climatic system. Due to the atmospheric circulation patterns, the volcanic aerosols deposited in Antarctica originate either from high southern latitude (Antarctic continent and subantarctic islands) and mid southern latitude (South America and the South Pacific) eruptions or from large eruptions in low latitudes of either hemisphere. As a result, volcanic records from Antarctic ice cores in general cover volcanoes in the Southern Hemisphere and the low latitudes.

Antarctic ice core volcanic records may differ in a number of aspects: length of time covered, temporal resolution, method of analysis, definition of nonvolcanic background and volcanic detection threshold. Therefore, climatic interpretation of ice core volcanic records may depend on specific records used. In presenting a 4100 year ice core record (PR86) from a location (Plateau Remote, 84°S, 43°E) in East Antarctica, *Cole-Dai et al.* [2000] recently compared that record with several other existing records and summarized the similarities and differences among the records. In particular, the PR86 record was compared with the 1000 year record (SP84) compiled from two South Pole cores [*Delmas et al.*, 1992]. These two records have several similarities: (1) the cores are from locations in central East Antarctica where snow accumulation rates are low, (2) both are based on continuous examination of the core and detailed sulfate analysis, and (3) a similar definition of the volcanic threshold is used. *Cole-Dai et al.* [2000] concluded from the comparison that in terms of the number and dates of large eruptions in the last 1000 years, the two records are consistent with each other. However, significant discrepancies among the records were found in relative magnitudes of volcanic signals. For example, volcanic sulfate deposit of the 1259 A.D. Unknown eruption in SP84 is significantly larger than that of a large eruption in the 1450s (assumed to be a massive eruption of Kuwae in the South Pacific), whereas in the PR86 record the Kuwae eruption has the largest volcanic sulfate deposit and sulfate concentration during the last 1000 years. Another significant difference between SP84 and PR86 is the number of eruptions in the 13th century: *Delmas et al.* [1992] found only three volcanic eruptions, while *Cole-Dai et al.* [2000] reported five eruptions during the same time period.

Cole-Dai et al. [2000] speculated that the discrepancies between SP84 and PR86 may be due to the extremely low snow accumulation rate at Plateau Remote and significant surface snow redistribution after deposition may have affected the preservation of the volcanic chronology at that location. The mean annual accumulation at the Plateau Remote site is approximately 10 cm snow per year, while the average height of sastrugi (surface undulations) is up to 40 cm. Snow deposition at a given spot (e.g., at a sastrugi peak) could be lost to valleys on the snow surface for up to 4 or 5 years [*Cole-Dai et al.*, 2000]. The magnitude of surface snow redistribution at South Pole is considered much less, where the snow accumulation rate is higher (averaging 20 cm snow per year) [*van der Veen et al.*, 1999] and the snow surface is smoother. Another possible cause of the discrepancies may be the somewhat different analytical approaches used to reconstruct the SP84 and PR86 records. *Cole-Dai et al.* [2000] suggested that the discrepancies may be resolved by a study of additional ice cores from South Pole, using an approach similar to that used in the Plateau Remote study.

A pair of recent, intermediate-depth ice cores from South Pole offered an opportunity to produce a new volcanic record that can be compared with the previous volcanic records in an attempt to resolve these discrepancies. Using a methodology similar to those in our previous studies [*Cole-Dai et al.*, 1997a; 2000], we have constructed and hereby present a new ice core volcanic record covering the last 1000 years.

2. ICE CORE SAMPLING AND ANALYSIS

In the austral summer of 2000/2001 two ice cores were drilled to a depth of 123 m at the Amundsen-Scott South Pole Station, Antarctica. For this study one of the cores (Core 1) was sampled continuously from the depth of 25 m to the bottom. This portion of the core was chosen to focus on the older part of the ice cores, as there have been numerous studies [*Cole-Dai and Mosley-Thompson*, 1999; *Cole-Dai et al.*, 1997b; *Delmas et al.*, 1992; *Dibb and Whitlow*, 1996] from previous South Pole ice cores covering the most recent 200 years (to depth of approximately 40 m). Core sampling was performed at the US National Ice Core Laboratory in Denver, Colorado, using stringent contamination control procedures [*Cole-Dai et al.*, 1995]. A total of 3966 samples were produced for the 25–123 m part of Core 1, resulting in an average of 2.5 cm per sample. The samples were melted in sealed containers on a clean-air bench, and analyzed in the Ice Core and Environmental Chemistry Laboratory of South Dakota State University. Two Dionex DX600 ion chromatographs were used for anion and cation measurements. The cations (Na^+, NH_4^+, K^+, Mg^{2+}, and Ca^{2+}) were separated on a Dionex IonPac CS12A column with an isocratic 15 mM sulfuric acid eluent. The anions (F^-, CH_3COO^-, $HCOO^-$, MSA^-, Cl^-, NO_3^-, and SO_4^{2-}) were separated using a gradient elution of 0.75 mM to 9 mM NaOH on an IonPac AS11 column.

3. RESULTS

3.1. Sulfate Profile

Sulfate concentrations in the 3966 samples were plotted as a function of core depth in Figure 1. Although it was possible to calculate and remove non-sea-salt sulfate concentrations, we chose to make no distinction between total sulfate and non-sea-salt sulfate in this study, as previous work at South Pole has shown that greater than 95% of the sulfate in snow originates from sources other than sea salt [*Cole-Dai and Mosley-Thompson*, 1999; *Cole-Dai et al.*, 1997b]. Large concentration spikes in the depth profile were likely from volcanic eruptions and are therefore removed from the dataset when the average and standard deviation of the non-volcanic background (discussed later) sulfate concentration were calculated.

3.2. Core Dating and Error Estimates

Snow accumulation at South Pole is approximately 20 cm per year [*Cole-Dai and Mosley-Thomspon,* 1999; *van der Veen et al.,* 1999]. Annual layer thickness decreases with depth, as density increases, to around 10 cm at the bottom of the 123 m core. At 2.5 cm per sample, a temporal resolution of 8 (top of core) to 4 (bottom) samples per year was achieved for chemical analysis. No visible stratigraphy was observed or recorded in this study; however, the sampling resolution permits dating by annual layer counting using chemical species with seasonal variations. Detailed snow chemical analysis in previous work [*Cole-Dai and Mosley-Thompson*, 1999; *Dibb and Whitlow*, 1996; *Legrand et al.*, 1984] has shown that concentrations of several species exhibit annual or seasonal cycles. For example, Na^+, Cl^- and Mg^{2+} (all major components of sea salts) reach a maximum in winter snow at South Pole and a minimum in summer [*Cole-Dai and Mosley-Thompson*, 1999]. Aerosol studies at coastal Antarctic locations [*Wagenbach et al.*, 1998] also indicate that sea salts in air are most abundant during winter, rather than in the summer/fall season. Figure 2 demonstrates that Na^+ annual cycles are easily identified in this new South Pole core and these cycles are therefore used to date the core. An annual layer or a year is approximated as from Na^+ minimum to minimum (Figure 2), corresponding to a calendar year, for the Na^+ minimum occurs in summer (December–January).

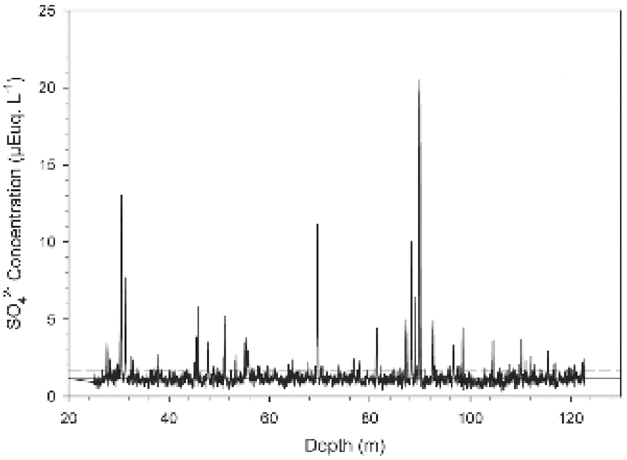

Figure 1. Continuous profile of sulfate concentration (μEqu. kg^{-1}) in the South Pole core (SP2001) as a function of depth. The solid line indicates the nonvolcanic background (1.13 μEqu. kg^{-1}) and the dashed line represents the volcanic detection threshold (1.67 μEqu. kg^{-1}).

Since the analysis did not begin at the top of the core, an alternative starting point with a known age was needed for counting annual layers. Two large volcanic signals in the sulfate record were found at 30.4 and 31.3 m (Figure 2) and were presumed to correspond to the Tambora eruption of

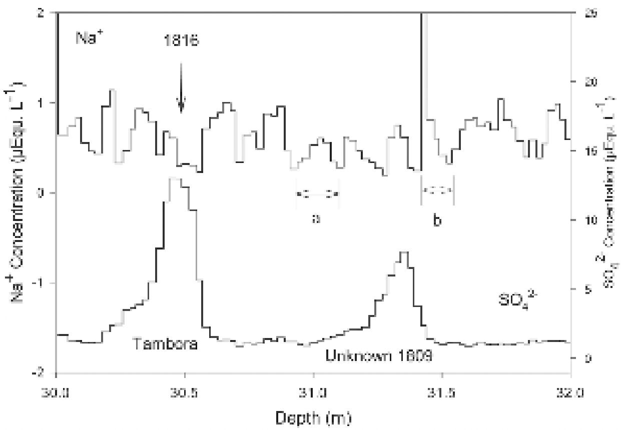

Figure 2. Sodium concentration (top profile) and sulfate concentration (bottom profile) as a function of depth for part of Core 1. The Na$^+$ profile was used to date the ice core. Ranges *a* and *b* are examples of single annual cycles. The peak of the 1816 Tambora sulfate at 30.44 m was used as the starting point of dating by layer counting.

1815 and the unknown eruption of 1809. This doublet has been well documented and dated in all previous ice cores from Antarctica [*Cole-Dai et al.*, 1997a; *Cole-Dai et al.*, 2000; *Cole-Dai et al.*, 1995; *Delmas et al.*, 1992; *Langway et al.*, 1995; *Legrand and Delmas*, 1987; *Palmer et al.*, 2001]. The peak deposition of the Tambora volcanic aerosols in Antarctic ice cores is most commonly dated at 1816. Therefore, the depth at the peak of the Tambora sulfate signal is assigned the year of 1816. The depth corresponding to this maximum is then the starting point for counting Na$^+$ annual cycles (Figure 2) in either direction. This dating was reinforced by a concurrent examination of the annual Mg^{2+} cycles (not shown) and by the dates of several well-known, and well-dated volcanic events (e.g., the 1600 Huaynaputina eruption, the Kuwae eruption in the 1450's and the 1259 Unknown eruption) in Antarctic ice cores. Through this portion of the core the dating error is ±4 years, which is attributed to the number of ambiguous annual cycles. The top of this portion (25 m) was dated at 1865 A.D. and the bottom of the core was dated at 904 A.D.

3.3. Criteria for Detection of Volcanic Signals

Volcanism is only one of several sources of sulfur species in Antarctic snow. Sulfate from non-volcanic sources constitutes background concentrations on which the sulfate from volcanic eruptions is superimposed. Therefore, to detect the presence of volcanic sulfate, the background must be quantified and a detection threshold for volcanic signals established. The background is usually established by computing the average sulfate concentration for long periods when no volcanic inputs are expected. Calculations using all available sulfate concentration data yielded an average nonvolcanic background of 1.13 µEqu. kg^{-1} (solid line in Figure 1) and a standard deviation of 0.27 µEqu. kg^{-1}. These values are consistent with previously reported average and variations of background sulfate in South Pole snow (e.g., 1.12±0.26 µEqu. kg^{-1} by *Cole-Dai and Mosley-Thompson* [1999]; 1.14±0.24 µEqu. kg^{-1} by *Delmas et al.* [1992]). For this work the volcanic threshold will be as defined by *Cole-Dai et al.* [2000], i.e., the average nonvolcanic sulfate concentration plus two standard deviations (dashed line in Figure 1). This definition, with the assumption of a Gaussian distribution of the variable nonvolcanic, background sulfate concentrations, still leaves a 4.5% probability that a spurious, high background concentration may be detected as a volcanic signal. To reduce this possibility of false positive detection from a single sample with high background sulfate concentration, a second criterion was used by *Cole-Dai et al.* [2000], namely that the sulfate concentration must be elevated above this threshold for at least two consecutive samples. This second criterion is also adopted in this work. Using these criteria, we found 33 events within this portion (25–123 m) of the core. A complete list of the events is shown in Table 1. The events are numbered in order of their appearance in the core and will be referred to by these numbers in the following discussions. The date and duration of each event in Table 1 have been determined following the procedures developed and discussed by *Cole-Dai et al.* [1997a; 2000].

3.4. Volcanic Flux

The volcanic sulfate flux is defined as the total amount (in mass unit per unit area) of volcanic sulfate from an eruption deposited in Antarctic snow. The length of time associated with the volcanic flux is the duration (in number of years) in which the deposition took place (Table 1). Following the procedures used by *Cole-Dai et al.* [1997a; 2000], the volcanic flux for each event detected in this new South Pole core has been calculated and is presented in Table 1.

In general, the ice core volcanic flux of an eruption reflects the magnitude or atmospheric aerosol (sulfur dioxide or sulfuric acid) mass loading by that eruption, i.e., the larger the volcanic flux, the greater the atmospheric mass loading [*Zielinski*, 1995]. However, it is important to recognize that the volcanic flux of an eruption in polar snow is also related to the latitude of the source volcano [*Dai et al.*, 1991; *Delmas et al.*, 1985; *Langway et al.*, 1995]. For exam-

Table 1. Volcanic events found between 25 m and 123 m of a 2001 ice core from South Pole, Antarctica. Identification of volcanic eruptions is based on dates of events in core and magnitude (volcanic flux) of the signals and on comparison with previous ice core records. Determination of date/year and duration follows procedures by *Cole-Dai et al.* [2000]. The f/f_T is defined as the flux of the event divided by the flux of the Tambora event.

Volcanic Eruption	Event	Year A.D.	Duration, years	Depth in core, m	Peak Sulfate, $\mu g\ kg^{-1}$	Volcanic Flux f, $kg\ km^{-2}$	f/f_T
Coseguina	SP2001-1	1842	2.8	27.61	164	9.72	0.15
	SP2001-2	1837	2.1	28.20	115	3.53	0.06
Tambora	SP2001-3	1816	3.8	30.44	626	64.01	1.00
Unknown 1809	SP2001-4	1809	2.4	31.37	371	28.04	0.44
	SP2001-5	1800	1.2	32.78	114	2.38	0.04
	SP2001-6	1759	2.6	37.65	130	5.89	0.09
	SP2001-7	1694	2.3	45.07	106	2.21	0.03
	SP2001-8	1691	3.6	45.45	293	22.17	0.35
	SP2001-9	1668	2.3	47.65	135	9.02	0.14
Parker & Deception Island	SP2001-10	1636	3.5	51.06	249	19.88	0.31
	SP2001-11	1618	2.3	53.27	130	6.54	0.10
Huaynaputina	SP2001-12	1600	3.5	55.28	185	22.98	0.36
	SP2001-13	1596	3.4	55.87	135	14.80	0.23
	SP2001-14	1508	1.6	64.67	115	0.85	0.01
Kuwae	SP2001-15	1458	4.5	69.58	537	65.55	1.02
	SP2001-16	1422	1.1	73.86	101	1.96	0.03
	SP2001-17	1396	2.3	76.70	119	5.80	0.09
	SP2001-18	1383	2.7	78.02	110	4.06	0.06
	SP2001-19	1347	3.1	81.37	214	25.46	0.40
	SP2001-20	1287	3.5	87.27	240	24.31	0.38
	SP2001-21	1276	3.3	88.23	481	45.37	0.71
	SP2001-22	1270	2.1	88.94	310	19.93	0.31
Unknown/ 1259	SP2001-23	1260	4.7	89.96	985	179.45	2.80
	SP2001-24	1236	2.8	92.66	236	26.60	0.420
	SP2001-25	1195	3.1	96.72	158	13.22	0.21
	SP2001-26	1174	1.8	98.48	215	15.69	0.25
	SP2001-27	1113	2.1	104.57	175	11.45	0.18
	SP2001-28	1094	1.0	110.21	178	8.94	0.14
	SP2001-29	1083	1.0	111.09	111	3.53	0.06
	SP2001-30	983	1.1	115.43	142	6.71	0.10
	SP2001-31	966	1.2	116.89	104	6.24	0.10
	SP2001-32	911	1.1	122.30	108	5.02	0.08
	SP2001-33	905	1.5	122.86	116	4.33	0.07

ple, an eruption in the Antarctic or subantarctic region will have a larger flux than an equivalent event originating from a low latitude location due to the loss of volcanic aerosols during transport from the low latitudes. Therefore, direct comparison and discussion of the magnitudes or mass loadings of explosive eruptions based on ice core data are only applicable to eruptions originating from the same latitude region (e.g., low latitude eruptions).

On the other hand, the volcanic flux of a particular eruption varies from location to location where the ice core is obtained, as the depositional flux is highly dependent on such parameters as scavenging efficiency and snow accumulation rates which have significant spatial variations across the Antarctic continent. In general, the unique high latitude circulation pattern (i.e., the polar vortex) helps distribute stratospheric volcanic aerosols all over Antarctica. As a result, a non-Antarctica eruption can be found in ice cores across the continent. For example, the Pinatubo signal has been found in snow and ice cores from more than 5 East Antarctica locations, although the signal is too weak, in comparison to fluctuations of the nonvolcanic background, to be detected at a few West Antarctica sites (*Cole-Dai*, unpublished data). To compare volcanic flux data between ice cores of different locations, *Cole-Dai et al.* [1997a] proposed a relative scale to measure the signal magnitude of volcanic eruptions in ice cores, based on the assumption that location-specific effects are minimized when the volcanic flux (f) of an event is normalized against that of a well-known event, i.e., the 1815 Tambora eruption (f_T). Consequently, the normalized volcanic flux (f/f_T) of all detected events in the new South Pole core has been calculated and is also included in Table 1.

In essence, Table 1 summarizes the volcanic record from this study, which will be henceforth referred to as the SP2001 record.

4. DISCUSSION

In addition to the mass loading of an eruption and the latitude location of the erupting volcano, several other factors also influence the magnitude (i.e., volcanic flux) of the volcanic signal in ice cores. An important atmospheric factor is the distribution and transport process that brings volcanic aerosols from the latitude of eruption to the Antarctic continent. Atmospheric observations of a number of recent volcanic eruptions (i.e., the 1963 Agung and 1982 El Chichon eruptions) demonstrate that distribution of volcanic aerosols between the two hemispheres can be highly variable and uneven, as it is subject to the inter-annual and intraannual variations of the atmospheric circulation patterns [*Hitchman et al.*, 1994; *Legrand and Wagenbach*, 1999; *McCormick et al.*, 1995; *Trepte and Hitchman*, 1992; *Trepte et al.*, 1993]. Our understanding of this variability in distribution is rather poor at the present and an examination of this variability is beyond the scope of this study. However, observations of the 1991 Pinatubo eruption [*Hitchman et al.*, 1994; *McCormick et al.*, 1995; *Trepte et al.*, 1993] indicate that for very large low latitude eruptions, the volcanic aerosol layers in the stratosphere eventually blanket the globe; and long residence times (more than 1 year) tend to favor equal hemispheric distribution. This suggests that exceptionally large low latitude eruptions that enhance the stratospheric sulfur reservoir for several years may have somewhat equal hemispheric distribution and similar transport efficiency to polar regions. For this study, the same atmospheric distribution and transport efficiency to Antarctica is assumed for all eruptions discussed herein. This assumption makes it possible to compare the normalized volcanic flux of volcanic events found in different ice cores.

4.1. Uncertainty of Normalized Volcanic Flux

Quantitative evaluation of eruption magnitude using the normalized volcanic flux requires the estimate of its uncertainty. Here we have elected to evaluate the uncertainty of the normalized volcanic flux by examining the uncertainty in the volcanic flux of individual events found in South Pole ice cores. The Tambora and the Unknown 1809 events have been extensively studied in numerous ice core records [*Clausen and Hammer*, 1988; *Cole-Dai et al.*, 2000; *Dai et al.*, 1991; *Delmas et al.*, 1992; *Langway et al.*, 1995; *Legrand and Delmas*, 1987], and volcanic flux data on these two events are available from several South Pole cores. The Unknown 1809 event is chosen to represent a typical low latitude event and the uncertainty of its normalized flux will be assumed to reflect the variability of normalized flux of low latitude events in South Pole ice cores. The uncertainty of the volcanic flux is assumed to be the standard deviation of these events reported from ice cores recovered near the South Pole. The values from the two 1984 South Pole ice cores by *Delmas et al.* [1992] (67.6 and 72.3 kg km^{-2} for Tambora, 32.0 and 29.8 kg km^{-2} for Unknown 1809) and the new SP2001 Core 1 (64.0 and 28.0 kg km^{-2}, respectively) are used to calculate the average and standard deviation of the total volcanic flux for each of these events. These values are then used to calculate the relative uncertainty of the normalized flux. The relative uncertainty of the normalized flux ($\%e_{f/fT}$) is propagated as the square root of the sum of the squared relative uncertainties for the two events:

$$\%e_{f/fT} = [(\%e_{\text{Unknown 1809}})^2 + (\%e_{\text{Tambora}})^2]^{1/2}$$

Calculations with this method result in an error of 9%. Consequently, the normalized flux values of events in the SP2001 and other South Pole cores will be considered significantly different if their differences are greater than 9%.

4.2. Comparison With Previous Records

4.2.1. Number of Volcanic Events. The SP2001 record is initially compared with SP84 and PR86, in an attempt to resolve discrepancies between these two previous records. All large and moderate events (normalized volcanic flux greater than 0.20 in SP2001) in these three records between 904 A.D. and 1865 A.D., the time period covered by the SP2001 record, are listed in Table 2. An event is assigned to the same volcanic eruption when its dates are within the reported dating uncertainties and its volcanic flux values are similar in the SP2001 and SP84 records. Similar assignments were made by *Cole-Dai et al.* [2000] when comparing the SP84 and PR86 records.

It appears that the three Antarctic records are consistent in terms of the number and dates of large and moderate volcanic events in the last millennium. The 1691 event (SP2001-8) does not have a corresponding event in SP84, but an event similar in date and signal magnitude has been

Table 2. Comparison of large and moderate ($f/f_T > 0.20$ in SP2001) volcanic events between 904 A.D. and 1865 A.D. in several Antarctic ice cores. Correlation between records is based on date and magnitude (volcanic flux).

Volcanic Eruption	South Pole, SP2001 This work			South Pole, SP84 *Delmas et al.* [1992]			Plateau Remote, PR86 *Cole-Dai et al.* [2000]		
	Event Number	Year A.D.	f/f_T	Event Number	Year A.D.	f/f_T	Event Number	Year A.D.	f/f_T
Tambora	SP2001-3	1816	1.00	SP84-7	1816	1.00	PR-4	1816	1.00
	SP2001-4	1809	0.44	SP84-8	1809	0.47	PR-5	1810	0.37
	SP2001-8	1691	0.35				PR-6	1694	0.48
Parker & Deception Island	SP2001-10	1636	0.31	SP84-10	1641	0.29	PR-9	1639	0.32
Huaynaputina	SP2001-12	1600	0.36	SP84-12	1601	0.33	PR-10	1600	0.22
	SP2001-13	1596	0.23	SP84-13	1596	0.32	PR-11	1595	0.33
Kuwae	SP2001-15	1458	1.02	SP84-14	1450	1.10	PR-12	1454	5.96
	SP2001-19	1347	0.40	SP84-15	1340	0.28	PR-13	1343	0.66
	SP2001-20	1287	0.38				PR-14	1285	0.94
	SP2001-21	1276	0.71	SP84-16	1279	1.29	PR-15	1277	2.47
	SP2001-22	1270	0.31	SP84-17	1269	0.16	PR-16	1269	0.53
	SP2001-23	1260	2.80	SP84-18	1259	2.01	PR-17	1260	2.07
	SP2001-24	1236	0.42				PR-18	1234	1.39
	SP2001-25	1195	0.21	SP84-19	1191	0.18	PR-19	1197	0.47
	SP2001-26	1174	0.25	SP84-20	1177	0.29			
	SP2001-27	1113	0.18	SP84-21	1118	0.15			

found in a number of other Antarctic ice core records [*Cole-Dai et al.*, 2000]. The absence of this event, and two events in the 13th century (SP2001-20 and SP2001-24), in SP84 could be due to a number of technical reasons. For example, the initial analysis of the 1984 South Pole ice core was performed using the ECM technique, rather than a continuous sulfate analysis [*Delmas et al.*, 1992]. Very small or moderate volcanic events may not have been detected by ECM and consequently samples containing these events would not have been analyzed for sulfate concentration. The absence of events in PR86 corresponding to SP84-20 (1177 A.D.) and SP84-21 (1118 A.D.) has been discussed by *Cole-Dai et al.* [2000]. The SP2001 record confirms the findings in SP84 by *Delmas et al.* [1992] that there are indeed two moderate volcanic eruptions events in the 12th century.

Of the 17 small SP2001 events, 3 (Events 2 (1837 A.D.), 7 (1694) and 9 (1668) were also seen in PR86 (PR Events 3, 6 and 7, respectively), and one (SP2001-3 (966 A.D.) is close in time to a small event in SP84 (Event 23 (970)). Thirteen SP2001 events are not seen in either PR86 or SP84; all are small events with a volcanic flux less than 9.0 kg km^{-2} (normalized flux < 0.15). As discussed previously, detection of small events in Antarctic ice cores is subject to a number of variables: surface glaciology at the core site, analytical methodology, definition of background and detection threshold and level of background noise in the data. The absence of the 1174 and 1113 A.D. events in PR86 is an example of failure to detect minor or moderate events in a core from a site of complicated local glaciology [*Cole-Dai et al.*, 2000]. The fact that these 13 minor SP2001 events were not found in either SP84 or PR86 may be due to any one or a combination of these variables. However, it is more likely that some or most of them are false positive detections, due to the somewhat noisier background in the SP2001 core sulfate concentrations. In any case, small eruptions contribute little volcanic aerosols to the atmosphere and therefore can have only minimal impact on the climate system.

4.2.2. Magnitude of Signals of Several Events.

As previously stated, significant differences exist between SP84 and PR86 in the signal magnitude (i.e., volcanic flux) of several large and well-known eruptions (Table 3): Huaynaputina (1600 A.D.), Kuwae (1450's), Unknown Eruption at 1347, and a number of eruptions in the 13th century. Even under the relative scale, i.e., the normalized flux, the differences persist (Table 3). *Cole-Dai et al.* [2000] suggested that the differences are likely caused by significant post-depositional processes (i.e., snow redistribution) at the Plateau Remote location and/or, to a lesser extent, by the different analytical methodologies used for the two previous studies. Below we discuss those differences in light of the uncertainty of the normalized volcanic flux and the new volcanic flux data in the SP2001 record produced with the same analytical methodology as that used by *Cole-Dai et al.* [2000]. Note that the Tambora flux in SP2001 (64.0 kg km^{-2}) is very close to that in SP84 (67.6 kg km^{-2}). Therefore, differences in nor-

Table 3. Total volcanic flux (f in kg km^{-2}) and normalized flux (f/f_T) values for events in the SP2001 that show discrepancies in the SP84, and the PR86 records. Uncertainties for normalized flux of SP2001 events are calculated for 9% relative error (see text). The events in the 13th century are numbered in order of occurrence. ND: not detected; N/A not available.

Event Number	Eruption/Year	South Pole, SP2001 this work		South Pole, SP84 [*Delmas et al.*, 1992]		Plateau Remote, PR86 [*Cole-Dai et al.*, 2000]	
		f	f/f_T	f	f/f_T	f	f/f_T
SP2001-3	Tambora/1815	64.01	1.00±0.09	67.6	1.00	22.39	1.00
SP2001-12	Huaynaputina/1600	22.98	0.36±0.03	22.5	0.33	4.91	0.22
SP2001-15	Kuwae/1454	65.55	1.02±0.09	74.4	1.10	133.37	5.96
SP2001-19	Unknown/1347	25.46	0.40±0.04	19.0	0.28	14.88	0.66
SP2001-20	Unknown/1287	24.31	0.38±0.03	ND	N/A	21.05	0.94
SP2001-21	Unknown/1276	45.37	0.71±0.06	87.3	1.29	55.39	2.47
SP2001-22	Unknown/1270	19.93	0.31±0.03	10.5	0.16	11.85	0.53
SP2001-23	Unknown/1260	179.45	2.80±0.25	135.7	2.01	46.30	2.07
SP2001-24	Unknown/1236	26.60	0.42±0.04	ND	N/A	31.21	1.39
SP2001-25	Unknown/1195	13.22	0.21±0.02	12.1	0.18	10.62	0.47

malized flux between SP2001 and SP84 are mainly due to the volcanic flux difference of the event of interest.

4*.2.2.1. Huaynaputina and Kuwae.* The normalized fluxes of Huaynaputina and Kuwae in PR86 are significantly different from those of the same events in SP84, given the estimated uncertainty (9%) of the normalized flux for South Pole ice cores. In fact, Kuwae is the largest event in the PR86 record [*Cole-Dai et al.*, 2000] with a very large normalized flux (5.96). The normalized flux for Kuwae in SP2001 is 1.02, about 20% of that in the PR86 record, but in agreement with that (1.10) in the SP84 record. Similarly, the SP2001 Huaynaputina normalized flux (0.36) is virtually the same as that (0.33) in SP84, and thus significantly larger than that (0.22) in PR86. These data suggest that South Pole records are more reliable in estimating volcanic flux and consequently in the normalized flux, while large variations and perhaps distortions in volcanic flux exist in the PR86 record, presumably due to the strong post-depositional snow redistribution effects at the Plateau Remote location [*Cole-Dai et al.*, 2000]. Further evidence of significant rearrangement of annual snow layers at Plateau Remote is suggested by the long duration of the Kuwae event in the PR86 record (7.2 years), almost twice as long as in either the SP84 (3.9 years) or SP2001 (4.5 years) records.

4.2.2.2. Unknown 1347. An unknown event in the mid-14th century (1347 in SP2001, 1340 in SP84 and 1343 in PR86) is considered the same event, as the age differences are within dating errors and no other volcanic events are found during this time period. The normalized flux from the three cores is significantly different from each other at 0.40, 0.28, and 0.66, respectively. The high value for PR86 could be the result of increased snow layer thickness from redistribution. The difference between SP2001 and SP84 is more difficult to explain. Possible causes may include minor loss of volcanic sulfate in the SP84 or enrichment in the SP2001 record due to slight redistribution of snow, or the differences in analytical methodology and in the calculation of volcanic flux.

4.2.2.3. Events in the 13th Century. Delmas et al. [1992] reported three large volcanic events in SP84 dated at 1279 A.D. (SP2001-21), 1269 A.D. (SP2001-22), and 1259 A.D. (SP2001-23). *Cole-Dai et al.* [2000] found corresponding events in PR86, but the 1279 A.D. and 1269 A.D. events had significantly different normalized fluxes when compared to SP84 (Table 3). Previous discussion on the Kuwae signal suggests that the SP84 results are more reliable. However, the SP2001 results do not seem to agree with SP84, although the differences between SP84 and SP2001, in the case of the 1279 and 1269 events, are smaller than those between South Pole cores and PR86 cores. For the 1259 event, possibly the largest low latitude eruption in the last 1000 years, the normalized flux differs slightly between SP2001-23 (2.80) and SP84 (2.01). This difference is larger than the estimated uncertainty (0.25=2.80×9%) and therefore suggests that the 9% relative uncertainty derived from the 1809 Unknown Eruption may underestimate the variability of normalized flux in South Pole cores.

4.2.2.4. Unknown 1195. An unknown event at the end of the 12th century is found in all 3 records: SP2001-25 (1195 A.D.), SP84-19 (1191) and PR86-19 (1197). This event has similar normalized flux in SP2001 (0.21) and SP84 (0.18), while its normalized flux in PR86 is significantly different (0.47). This again suggests that normalized volcanic flux for South Pole ice cores is more reproducible and therefore more reliable than that from Plateau Remote.

4.2.3. The 13th Century

4.2.3.1. Number of Events. In addition to the three events (1259, 1269 and 1279) discussed above, *Cole-Dai et al.* [2000] found in the Plateau Remote core two other moderate volcanic events (1234 and 1285, with a normalized flux of 0.21 and 0.38, respectively) in the 13th century (Figure 3a) and noted that five large and moderate volcanic events make this century an exceptional one during the last several millennia. These five events have also been reported in other Antarctic records [e.g., *Langway et al.*, 1995] that cover the last 1000 years, but the SP84 record is notably different in that the earliest (ca. 1234) and latest (ca. 1285) events are absent. The absence could be due to the fact that the initial ECM analysis may not have indicated possible volcanic events and, as a consequence, no detailed sulfate analysis was carried out at the appropriate depths.

The SP2001 results (Figure 3b) confirm the findings from other Antarctic ice cores that a total of five large and moderate volcanic eruptions occurred in the 13th century. All five eruptions (SP2001-20 to 24), produced significant amounts of volcanic aerosols, as indicated by the volcanic flux data in Table 3. Volcanic events have been found in Greenland ice cores [*Clausen et al.*, 1997; *Langway et al.*, 1995; *Zielinski.*, 1995] that are contemporaneous with three of the five events, Events 24 (ca. 1234), 23 (1259) and 20 (ca. 1285), while no events have been reported in Greenland cores corresponding to the other two events. Recent evidence [*Dunbar et al.*, 2003] from Siple Dome and Taylor Dome (Antarctica) ice core tephra analysis indicates that the source of the 1276/1279 volcanic sulfate may well be an Antarctic volcano. Therefore, of the five events, three are likely, and one is possible, low latitude eruptions capable of impacting the global climate.

4.2.3.2. Climatic Significance of the 13th Century Events. The climatic impact of explosive volcanism has been extensively studied and reviewed recently [*Robock,* 2000; *Zielinski,* 2000]. Reduced radiative forcing by stratospheric volcanic aerosols is the recognized mechanism of volcanic forcing on climate. Therefore, volcanic impact on climate is in general short-lived (up to 5 years after the introduction of volcanic aerosols), due to the relatively short (up to a few years) of stratospheric residence time of volcanic aerosols. Such short term climatic impact has been well documented. For example, *White et al.* [1997] found that cooling of the atmosphere, as represented by δD decreases in Greenland snow, lasts no more than 5 years after an eruption. Therefore, the atmospheric impact of explosive volcanic eruptions, including unusually large eruptions such as Tambora and Kuwae, is expected to disappear several years after an eruption.

There has been some speculation that there may be long term impact on the climate by volcanic eruptions: cumulative cooling by eruptions a number of years or a few

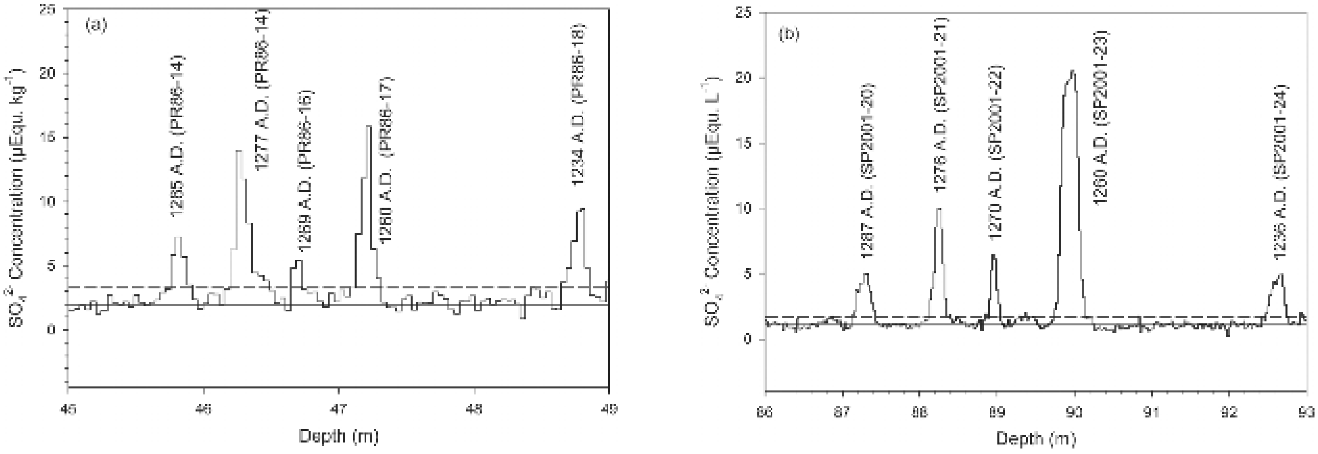

Figure 3. Five volcanic events in the 13th Century detected in the Plateau Remote core (a) and 2001 South Pole core (b). All dates indicated are the years of the event peak within the timescale of the core. Events are numbered in order of occurrence.

decades apart [*Briffa et al.*, 1998; *Zielinski,* 2000]; feedbacks via ice cover and oceanic circulation could transform short-term volcanic forcing into a longer-term effect [*Robock,* 2000]. Perhaps the strongest argument for a longer climatic impact is that stratospheric residence times of volcanic aerosols may be longer than previously thought, as indicated by the continued decline of stratospheric aerosols more than a decade after the 1991 Pinatubo eruption [*Barnes and Hoffman*, 2001; *Hervig and Deshler*, 2002]. This suggests that background stratospheric aerosol levels may have been overestimated.

The five large and moderate eruptions in the 13th century occurred within a 50 year span (Figure 3). Some cumulative climatic effect could be expected during this century and possibly in the early 14th century. Figure 4 illustrates that the 13th century has the largest total volcanic flux (larger by a factor of 3 to 20 than in other centuries), implying the highest atmospheric aerosol mass loading by volcanic eruptions during the last millennium. Even when the contribution of Event 21 (ca. 1276), a possible high latitude eruption that may not have impacted the climate system, is excluded, the cumulative volcanic sulfate flux (250 kg km^{-2}) for the 13th century is still 6 times the average century volcanic flux (~40 kg km^{-2}) for the rest of the 904–1865 A.D. period. This century of frequent large volcanic eruptions coincides with the period of transition from the Medieval Warm Period to the Little Ice Age. Model calculations [*Robock*, 2000] have shown that volcanic forcing, probably due to this series of eruptions in the 13th century, in conjunction with variations in solar and other forcings was an important cause for the onset of the Little Ice Age. It is possible and indeed probable that the cumulative effect of repeated injection of large amounts of volcanic aerosols into the stratosphere by frequent large eruptions within a few decades or a century can initiate, enhance or reverse a climatic trend. Furthermore, continuous volcanic forcing on a longer (decadal to century) timescale may be amplified by the combined ocean-atmosphere system. As already suggested by other researchers [*Robock,* 2000; *Zielinski,* 2000], these aspects of the volcano-climate system need to be further investigated in future research.

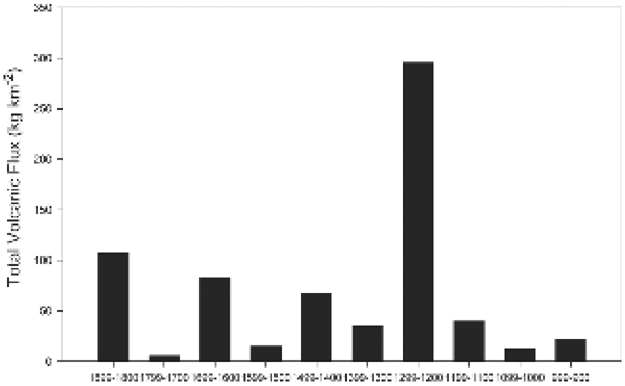

Figure 4. Total volcanic flux in a century interval. The period between 1299 and 1200 has the largest amount of volcanic activity in record. The last 1899-1800 period contains only 66 years (1866-1800) as the SP2001 record covers 904–1866 A.D.

5. CONCLUSIONS

Analysis of a new South Pole ice core has produced a continuous volcanic record covering the period of 904 to 1865 A.D. In terms of the number and dates of moderate and large volcanic eruptions in this period, the new record is consistent with records from previous Antarctic ice cores. About 13 additional events in the sulfate profile slightly exceed the volcanic detection threshold value and have not been previously reported. While these may represent small volcanic signals (small volcanic flux), they are more susceptible to variations in the detection threshold definition and in flux calculation and most are considered to be false positives from the noisier background of the SP2001. These possible small events are not considered important with respect to potential climatic impact of volcanic eruptions, due to their small amounts of volcanic aerosols.

Comparison with a previous South Pole ice core volcanic record by *Delmas et al.* [1992] and a recent record from a Plateau Remote ice core by *Cole-Dai et al*. [2000] indicates that discrepancies in volcanic flux between these two previous records are probably due to glaciological complications at Plateau Remote. We conclude that volcanic flux estimates using South Pole ice cores are more reproducible and therefore more reliable and representative of atmospheric volcanic aerosol mass loadings than those from an ice core location where snow accumulation rates are extremely low and post-depositional alterations of deposition records may be significant.

The new South Pole record supports the findings in previous Antarctic ice cores (except the SP84 record) that five large and moderately large volcanic eruptions occurred in the 13th century. At least three of the five are probably large, low-latitude eruptions capable of impacting the global climate. Total volcanic flux for this century is the largest in the last millennium. We suggest that the frequent injection of large amounts of volcanic aerosols into the atmosphere during the 13th century may have contributed to the climatic transition from the Medieval Warm Period to the Little Ice Age. This suggestion supports previous model results [*Robock*, 2000].

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