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An ice core record of volcanic eruptions for the past 4000 years from Dome A, Antarctica

Chunlei An[1], Su Jiang[1,2], Guitao Shi[3,4], Hongmei Ma[1], Chuanjin Li[1], Zhe Li[3], Xiaolong Li[3], Ye Hu[3], Yan Liu[3], Xiao Yan[3], Ningning Sun[3], Bo Zhang[3], Shugui Hou[2,5], Yuansheng Li[1]

[1]Key Laboratory for Polar Science (MNR), Polar Research Institute of China, Shanghai, 200136, China
[2]School of Oceanography, Shanghai Jiao Tong University, Shanghai, 200240, China
[3]Key Laboratory of Geographic Information Science (Ministry of Education), School of Geographic Sciences, East China Normal University, Shanghai, 200240, China
[4]State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai, 200241, China
[5]School of Geography and Ocean Science, Nanjing University, Nanjing 210023, China

Correspondence to: Su Jiang (jiangsu@pric.org.cn); Chunlei An (anchunlei@pric.org.cn)

Abstract. Improving the spatial and temporal coverage of volcanic records is essential to accurately quantify volcanic forcing and to provide reliable references for climate models validation. In this study, we present a new volcanic record derived from a 133 m ice core (DA2009) drilled at Dome A, Antarctica. Based on measurements of non-sea-salt sulfate concentrations, 95 volcanic events are identified. Using 15 volcanic age markers aligned with the West Antarctic Ice Sheet (WAIS) Divide ice core (WDC) record, the DA2009 core is dated to cover the past 3951 years, from 1951 BCE to 2000 CE. By comparing the DA2009 record with three Antarctic ice cores from WAIS Divide, Dome C and South Pole, 12 prominent volcanic events are recognized. The period between 1000 and 2000 CE exhibits the most intense volcanic activity of the past 4000 years. The mean snow accumulation rates calculated between adjacent age markers indicate a marked decline in accumulation at Dome A since the 13th century CE. This low-accumulation interval coincides with a pronounced cold phase on the East Antarctic Plateau, suggesting a potential connection between regional climate variability and local accumulation rates at Dome A.

1 Introduction

Volcanic eruption is an important forcing of climate change. Strong eruptions can inject large amounts of sulfur dioxide into the atmosphere, which is subsequently converted into sulphate aerosol. These aerosols increase the Earth's surface albedo, thereby influencing regional and even global climate (Cole-Dai, 2010; Robock, 2000). Because of the limited spatial and temporal coverage of the observation data, climate proxies are needed to provide more information of the volcanic forcing in the past. The reconstructions of volcanic forcing mainly rely on polar ice core records (Crowley & Unterman, 2013; Gao et al., 2008; Sigl et al., 2022; Sigl et al., 2015), however, only a few records could extend before the Common Era, calling a need for more long-term records to improve the accuracy of the reconstructions.

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Volcanic signals preserved in ice cores can also be used to establish ice-core chronologies and to reconstruct past snow accumulation rates (Jiang et al., 2012; Li et al., 2009). By identifying known volcanic age markers, the ages of the corresponding ice layers can be determined. The mean snow accumulation rate between volcanic markers can then be calculated, providing a basis for reconstructing historical variations in surface mass balance—a key parameter for evaluating the overall mass balance of the Antarctic ice sheet and its consequent contribution to sea level change (Rignot & Thomas, 2002). Given the vast extent of the East Antarctic Plateau, reconstructing its accumulation history is essential for assessing the mass balance of the Antarctica ice sheet. However, substantial uncertainty remains due to the limited number of available records (Thomas et al., 2017).

Dome Argus (Dome A, Fig. 1) is the highest dome on the Antarctic ice sheet. The unique natural conditions in this area make it an ideal site for paleoclimate reconstruction (Hou et al., 2007; Xiao et al., 2008). The combination of an exceptionally flat surface, extremely low ice-flow velocity (11.1 ± 2.4 cm yr^{-1}; Yang et al., 2014) and low wind speed (2.7 m s^{-1}, 2 m above the ground; Bian et al., 2016) minimizes post-depositional disturbance, thereby preserving past climate signals with remarkable fidelity. In addition, the site's high elevation (4093 m a.s.l.; Zhang et al., 2007) and inland location (~1200 km from the ocean) diminish oceanic influence relative to coastal regions and enhance sensitivity to global climate signals. Here, we present chemical analyses of a 133 m ice core drilled at Dome A, focusing on volcanic sulfate deposition, ice age-depth relationships, and local snow accumulation rate over the past 4000 years.

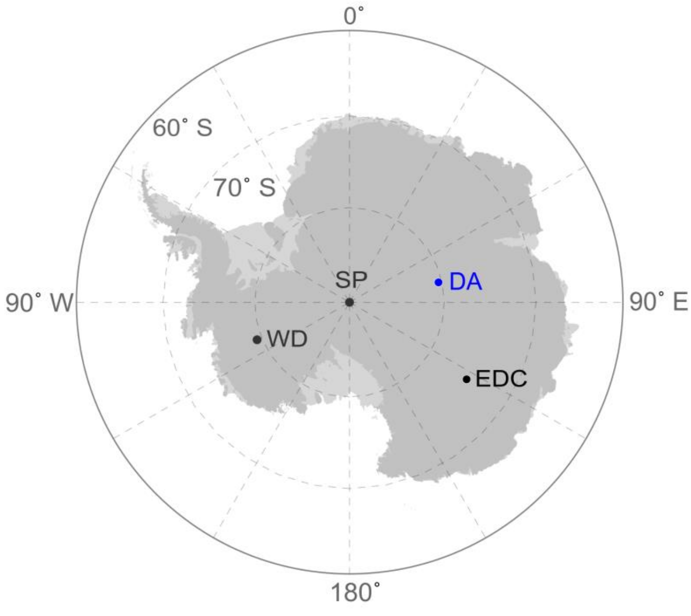

Figure 1: Map of Antarctica showing the locations of ice cores used in this study: DA (Dome A), EDC (EPICA Dome C), WD (WAIS Divide), and SP (South Pole).

2 Data and methods

2.1 DA2009 ice core recovery and analysis

During the 2009/2010 austral summer, an electromechanical drill was used to extract the DA2009 ice core at Kunlun Station (80°25′ S, 77°07′ E, 4087 m a.s.l.), located ~7 km from the summit of Dome A, Antarctica. The core sampling began at a depth of 0.57 m below the snow surface and extended down to 133.71 m. A total of 175 drilling runs were conducted to recover this core, averaging ~0.76 m per run. The length, diameter (95 mm) and weight of each core section, which were used to calculate its bulk density, was measured immediately after each drilling run. Then the core sections were sealed in clean plastic bags, enclosed in thermal insulation boxes and shipped frozen to the Polar Research Institute of China in Shanghai.

The DA2009 ice core was processed in a class 1000 clean laboratory maintained at −15 °C. Each core section was longitudinally divided, with one half designated for chemical analysis. Sampling employed a discrete methodology using a pre-cleaned band-saw, followed by meticulous surface decontamination: the outer 1-2 mm layer was systematically removed with a high-carbon steel scalpel to eliminate potential contamination introduced during transport and processing. The pristine inner ice was then aseptically sealed in pre-cleaned containers. All processing equipment underwent rigorous cleaning with Milli-Q water (18.2 MΩ·cm). Procedural blanks were prepared by processing frozen Milli-Q water in parallel with core samples using identical protocols, enabling systematic contamination monitoring. Personnel wore polyethylene gloves and face masks throughout all handling procedures to minimize exogenous contamination. The sampling depth resolution is 4 cm for the 0~40 m interval, 3.5 cm for 40~80 m, and 3 cm for 80~133 m. In total, 3910 samples were obtained from the 133 m ice core. Given the recent annual accumulation rate of 2.3 cm water equivalent (w.e.) / ~7 cm snow (snow density of about 0.33 g cm^{-3}) around Dome A (Hou et al., 2007), the average time resolution of each sample is expected to be ~1 year.

Concentrations of major ions in ice core samples (SO_4^{2-}, Cl^-, NO_3^-, Na^+, NH_4^+, K^+, Mg^{2+}, and Ca^{2+}) were measured with an Aquion RFIC ion chromatograph (IC, Thermo Scientific, USA) at East China Normal University Environmental Stable Isotope Laboratory (ECNU-ESIL). Separations of cations were performed using a CG12A guard column (2×50mm) coupled with a CS12A analytical column (2×250mm). A 20 mM methylsulfonic acid (MSA) eluent was delivered at a flow rate of 0.30 mL min^{-1}, with conductivity suppression performed by an CDRS 600 cation dynamically regenerated suppressor (2 mm) operating at 15 mA in the external water mode. Anion separations utilized an AG11-HC guard column (2×50 mm) in conjunction with an AS11-HC analytical column (2×250 mm). The 22 mM potassium hydroxide eluent was used at a flow rate of 0.25 mL min^{-1}. The eluent conductivity was suppressed by an ADRS 600 anion dynamically regenerated suppressor (2 mm) operated at 21 mA in the external water mode. Analytical precision was confirmed by replicate measurements (n=5), with standard deviations (1σ) consistently below 5% for all analyzed ions.

2.2. Volcanic signal detection and extraction

During volcanic eruptions, large quantities of sulfur, mainly in the form of SO_2, are injected into the atmosphere, where they undergo oxidation to form sulfuric acid (H_2SO_4), eventually leading to the formation of sulfate aerosols (Cole-Dai, 2010). These aerosols can be transported to Antarctica and deposit on the ice sheet, thus form sulfate-rich snow/ice layers. Besides volcanic eruptions, sea-salt aerosols also contribute to sulfate in Antarctic snow. In order to identify volcanic sulfate signal, the sea-salt sulfate ($ssSO_4^{2-}$) has to be removed from the total sulfate concentration. The non-sea-salt sulfate ($nssSO_4^{2-}$) is calculated as follows: $nssSO_4^{2-} = SO_4^{2-} - R \times Na^+$, where R is the ratio of the concentration (mass) of SO_4^{2-} and Na^+ in seawater, and the value used in this study is 0.253 (Kohno et al., 1996).

The analytical approach employed in this study follows methodologies similar to that originally proposed by Traufetter et al. (2004) and refined by Cole-Dai et al. (2021) for volcanic signal detection. In brief, the $nssSO_4^{2-}$ concentration series was smoothed using a 41-point window running median (RM) to characterize the natural background, and the median absolute deviation (MAD) from RM was subsequently calculated for each window. Volcanic signals were identified using a threshold of RM + 4 × MAD. Adjacent ice layers with $nssSO_4^{2-}$ concentrations exceeding RM + 3 × MAD were considered part of the same volcanic event. Then all data points attributed to volcanic eruptions were removed, and the reduced running median (RRM) was calculated for the remaining $nssSO_4^{2-}$ concentrations using the same window series as the RM, in order to estimate the non-volcanic background. The volcanic flux of an individual sample was calculated by subtracting the RRM from the sample $nssSO_4^{2-}$ concentration and multiplying by the sample length in water equivalent. The total flux for a volcanic event was obtained by summing the volcanic fluxes of all samples associated with that event. And the year assigned to a volcanic event corresponds to the earliest occurrence of its signal in the ice core record.

3. Results and discussion

3.1. Ice core dating

Due to the extremely low snow accumulation rate at Dome A and the limited sampling resolution (~1 sample per year) for ionic measurements, dating of the DA2009 core could not be achieved through annual layers counting. To establish a timescale for the core, stratigraphic horizons from volcanic eruptions are used as chronological markers. The $nssSO_4^{2-}$ concentration profile of the DA2009 ice core is shown in Fig. 2. Similar to other sulfate records from inland Antarctica, the profile exhibits no obvious long-term trend, with values ranging from 33.84 to 1010.05 ng g^{-1}. The non-volcanic background $nssSO_4^{2-}$ concentrations range from 79.40 to 126.26 ng g^{-1}, and the threshold for volcanic events lies between 122.82–295.17 ng g^{-1}. Following the procedure described in Sect. 2.2, a total of 95 volcanic events were identified in the DA2009 ice core. An annual accumulation rate of 2.3 cm w. e. yr^{-1}, derived from previous reconstructions and observations (Hou et al., 2007; Jiang et al., 2012; Wang et al., 2025), was then applied to estimate the preliminary ages of these volcanic events, providing a rough estimate of the core's time coverage of approximately 4000 years.

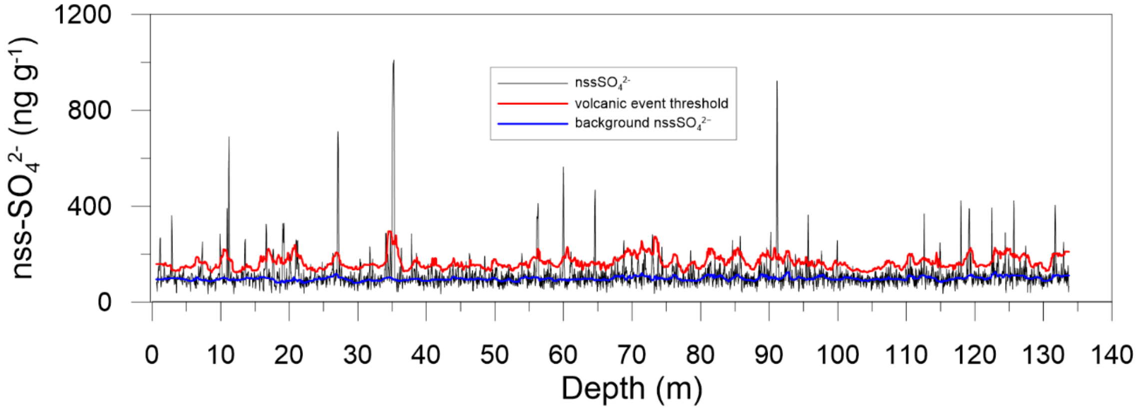

Figure 2: Non-sea-salt sulfate ($nssSO_4^{2-}$) concentrations in the DA2009 ice core (black line) as a function of snow/ice depth. The red line represents the volcanic event threshold \ (RM + 4 × MAD), and the blue line indicates the background $nssSO_4^{2-}$ concentrations (RRM).

To obtain more precise ages for the volcanic events recorded in the DA2009 ice core, volcanic matching was performed between the DA2009 ice core and the West Antarctic Ice Sheet (WAIS) Divide ice core (WDC) based on their volcanic flux time series (Cole-Dai et al., 2021). The WDC ice core is chosen for this comparison because its upper section (0-2815 m) has been dated by annual layer counting, providing a highly accurate chronology with an estimated uncertainty of less than ± 5 years for the most recent 2500 years, and less than 0.5% of the age for other periods of the Holocene (Sigl et al., 2016). Among the 95 volcanic events identified in the DA2009 ice core, 15 were selected as tie-points by matching with the WDC volcanic record (Fig. S1, Table S1). The preliminary ages of these tie-points in DA2009 were then revised according to the WDC chronology. Of these 15 tie-points, 12 have also been used in previous volcanic matching studies (Winski et al., 2019), including volcanic events in 1991 CE (Pinatubo), 1964 CE (Agung), 1815 CE (Tambora), 1459 CE (Kuwea), 1258 CE (Samalas), 682 CE, 575 CE, 434 CE, 427 BCE, 1173 BCE, 1657 BCE and 1880 BCE. Noted that, the date here is the age of an ice layer with detected volcanic signal, but not the time of a volcano eruption which occurred earlier. For example, the volcanic signal of event 1964 CE and 1258 CE comes from the 1963 Agung eruption and 1257 Samalas eruption, respectively.

Based on the ages of the volcanic tie-points, the ice ages between them were determined by linear interpolation, while those beyond the outermost tie-points were estimated by linear extrapolation. As a result, the DA2009 ice core is dated to cover a period of 3951 years, from 1951 BCE to 2000 CE. To evaluate the dating uncertainty of the DA2009 record, 30 volcanic events not used as tie-points, each with a flux ≥5 kg km^{-2}, are selected for comparison with their counterparts in the WDC record. Results show that the age differences for these 30 events range from 0.3 to 8.5 years, with a mean of 3.0 years and a standard deviation of 2.0 years.

3.2. DA2009 volcanic record

A total of 95 volcanic events are recorded in the DA2009 ice core. The volcanic sulfate flux of these events ranges from 0.82 to 157.65 kg km^{-2} (Fig. 3a, Table S2), with a mean of 11.06 kg km^{-2} and a median of 4.98 kg km^{-2}. Following the classification criteria proposed by Cole-Dai et al. (2021), these volcanic events are categorized according to their flux magnitudes: 27 events (28%) are classified as Large (flux > 10.0 kg km^{-2}), 20 events (21%) as Moderate (5.0 -10.0 kg km^{-2}), and the remaining 48 events (51%) as Small (<5.0 kg km^{-2}).

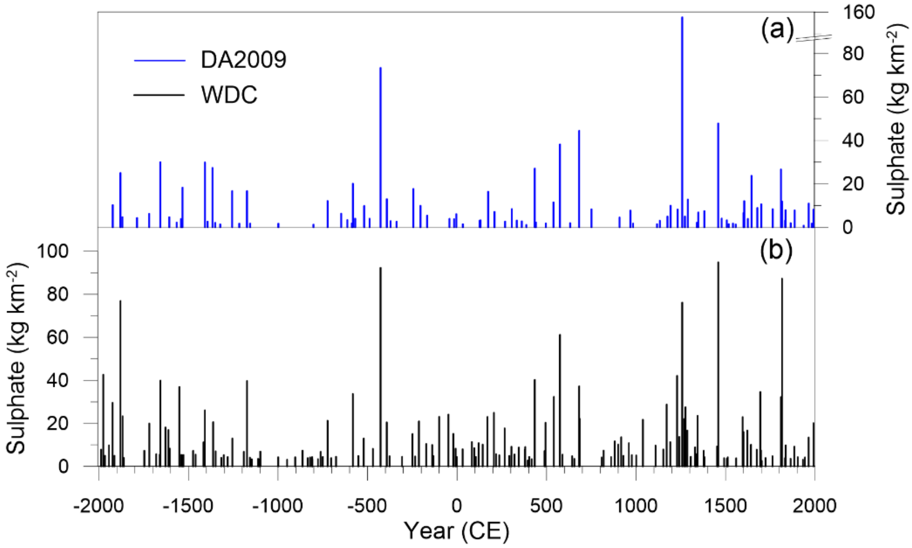

Figure 3: Comparison of volcanic sulfate fluxes over the past 4000 years between (a) the DA2009 record from Dome A and (b) the WDC record from WAIS Divide (Cole-Dai et al., 2021).

Volcanic eruptions that inject substantial sulfur into the stratosphere are far more likely to exert significant climatic impacts than those confined to the troposphere. Gautier et al. (2019) provided a 2600-year stratospheric volcanic record based on ^{33}S and ^{17}O isotopic signatures of ice core sulfate. According to their results, 16 of the 17 large volcanic events and 15 of the 17 moderate events recorded in the DA2009 ice core during 500 BCE–2000 CE (Table 1) are identified as stratospheric eruptions. If a stratospheric eruption is located in the tropics, it tends to have a global impact (Cole-Dai, 2010; Robock, 2000). Based on previous estimations of the location of Holocene eruptions (Sigl et al., 2015; Sigl et al., 2022), which are inferred by whether simultaneous signals appear in the Greenland and Antarctic ice cores, 30 of the 31 stratospheric volcanic events in our record over the past 2500 years are tropical eruptions (Table 1). For the past 4000 years, among the 47 Large and Moderate volcanic events in the DA2009 record, 41 are tropical eruptions, 6 originate from Southern Hemisphere extratropics (SHET) (Table 1) (Sigl et al., 2015; Sigl et al., 2022). Sigl et al. (2022) calculated the volcanic stratospheric sulfur injections based on a method assuming that the stratospheric sulfur emission is proportional to the ice-core sulfate deposition. Based on their reconstructions, the mean sulfur injections of the 6 SHET eruptions in DA2009 record is 2.31 teragram of sulfur (Tg S), substantially lower than the mean of tropical eruptions (19.6 Tg S). It is notable that two SHET

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events (1366 BCE and 1533.6 BCE, corresponding to 1363 BCE and 1530 BCE in Sigl et al. (2022), respectively) exhibit particularly high volcanic fluxes in the DA2009 record, 27.4 and 18.34 kg km^{-2} respectively, suggesting that their stratospheric sulfur injections might have been underestimated by previous studies. In addition, all Large and Moderate events in the DA2009 record exhibit multi-year durations, lasting more than one year and appearing in at least two samples (Table 1). Given the high proportion of stratospheric and tropical eruptions among these events, they are inferred to have had a substantial climate impact.

Table 1: Volcanic events recorded in the DA2009 ice core.

Event Number	Start Date (CE)	Duration (Year)	Event Flux (kg km^{-2})	Signal Strength[a]	Place of Eruption[b]	Type of Eruption[c]
1 Pinatubo	1991.0	3.10	8.23	M	T	S
2 Agung	1964.0	3.08	10.99	L	T	S
3 Krakatau	1885.7	3.27	7.85	M	T	S
4 Cosigtauu	1834.6	2.55	7.91	M	T	S
5 Tambora	1815.0	2.55	11.89	L	T	S
6 UE 1809	1809.3	3.28	26.71	L	T	S
7	1763.1	4.36	8.38	M	T	S
8	1699.6	2.68	10.67	L	T	S
9	1677.4	3.85	8.93	M	T	S
10	1644.7	5.48	23.79	L	T	S
11 Huainaputina	1603.8	3.61	12.12	L	T	S
12	1600.2	1.81	6.66	M	T	S
13 Kuwae	1459.0	5.25	47.87	L	T	S
14	1380.9	4.06	7.49	M	T	S
15	1347.6	3.14	6.90	M	T	S
16	1289.2	4.29	12.81	L	T	S
17 Samalas	1258.0	10.19	157.65	L	T	S
18	1231.9	3.00	8.26	M	T	S
19	1192.8	4.03	9.97	M	T	S
20	968.1	3.97	7.75	M	SHET	S
21	750.8	4.71	8.33	M	T	Tr
22	682.0	8.02	44.44	L	T	S
23	575.0	5.57	38.22	L	T	S
24	538.1	6.26	11.58	L	T	S

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25	434.0	5.21	27.10	L	T	S
26	306.0	2.98	8.45	M	T	S
27	209.0	3.06	7.18	M	SHET	Tr
28	173.8	4.30	16.46	L	T	S
29	-4.2	2.23	6.11	M	T	S
30	-166.8	3.02	5.42	M	T	S
31	-204.5	3.80	9.93	M	T	S
32	-243.8	5.11	17.71	L	T	S
33	-392.3	4.12	12.97	L	T	
34	-427.0	7.96	73.47	L	T	S
35	-518.7	5.01	9.87	M	SHET	
36	-582.0	4.97	20.12	L	T	
37	-647.0	3.23	6.35	M	T	
38	-723.0	4.05	12.16	L	T	
39	-1173.0	4.61	16.70	L	T	
40	-1255.7	6.53	16.73	L	T	
41	-1366.0	6.14	27.40	L	SHET	
42	-1408.0	6.03	29.95	L	T	
43	-1533.6	3.89	18.34	L	SHET	
44	-1657.0	7.06	30.05	L	T	
45	-1719.8	2.17	6.28	M	SHET	
46	-1880.0	5.54	25.05	L	T	
47	-1923.2	3.51	10.26	L	T	

[a] Volcanic events are classified based on the magnitude of the sulfate flux: L for Large event (flux$\geq$10 kg km^{-2}), and M for Moderate events (5 kg km$^{-2}\leq$flux$<$10 kg km^{-2}). Only Large and Moderate events are listed in the table.

[b] Place of eruption estimated by Sigl et al. (2015, 2022). T, tropical; SHET, Southern Hemisphere extratropics.

[c] Type of eruption estimated by Gautier et al. (2019). S, stratospheric volcanic eruptions; Tr, tropospheric volcanic eruptions.

Comparison between our record and another record from Dome A (DA2005 ice core, ~8 km from the DA2009 core site; Jiang et al., 2012) during 1-2000 CE show that, the number of volcanic events in the two records is very similar, with 55 events in DA2009 and 57 in DA2005. To assess the magnitudes of individual events, we employed the relative flux metric f/f_T, defined as the ratio of the volcanic flux of a given event (f) to that of the 1815 Tambora eruption (f_T). In the DA2009 record, the number of volcanic events with $f/f_T\geq1$, $0.5\leq f/f_T < 1$ and $f/f_T < 0.5$ is 11, 17 and 27, respectively, closely mirroring

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the distribution in DA2005 (10, 17, and 30 events). These findings demonstrate remarkable consistency between the two Dome A archives, suggesting a coherent volcanic signal over the past two millennia.

However, when compared with the WDC record (Cole-Dai et al., 2021), the DA2009 ice core contains substantially fewer volcanic events (95 vs. 154; Fig. 3b) and lower total volcanic flux (1051 vs. 2170 kg km^{-2}) over the same period. Given the similar detection methodologies used in both records, these differences may be primarily attributed to contrasting environmental conditions at the two sites: Dome A has a higher elevation (4087 m a.s.l.) and lower accumulation rate (2.3 cm w.e. yr^{-1}) compared with WAIS Divide (1766 m a.s.l., 20 cm w.e. yr^{-1}), which may result in thinner annual ice layers and less frequent deposition of volcanic sulfate, thereby reducing the number of detectable volcanic signals.

3.3. Prominent volcanic events over the past 4000 years

Strong volcanic eruptions can exert significant impacts on the climate and environment. Identifying prominent volcanic events in the past is essential for understanding climate variability. However, the signal strength of a given eruption can vary substantially among different ice cores due to differences in the atmospheric aerosol transport, regional deposition processes, and post-depositional preservation (Cole-Dai et al., 2021). Consequently, the investigation of prominent volcanic events cannot rely on a single ice core record. In this study, we examine the 10 volcanic events with the highest sulfate fluxes over the past 4,000 years using multiple Antarctic records, including DA2009, WDC (Cole-Dai et al., 2021), EPICA Dome C (EDC; Castellano et al., 2005), and South Pole (SP; Brandis, 2022). The results are summarized in Table 2. Overall, notable discrepancies exist in both the timing and relative ranking of major volcanic events across these ice cores. For instance, the largest volcanic signal in the DA2009 record appears in 1258 CE, corresponding to the Samalas eruption in Indonesia (Lavigne et al., 2013), with a remarkable sulfate flux of 157.65 kg km^{-2}. In contrast, the strongest events in the WDC and SP records occur in 1459 CE and 1174 BCE, respectively, with only the EDC record sharing the same top-ranked event as DA2009.

Further examination of this multi-core comparison reveals that 12 prominent eruptions are recorded in at least two ice cores (Table 3). Several of these events, such as those in 1815 CE (Tambora), 1459 CE (Kuwea), 1258 CE (Samalas), 682 CE, 575 CE, and 427 BCE, are well known and have been demonstrated to be major climate-forcing events (Sigl et al., 2015; Cole-Dai et al., 2009; Lavigne et al., 2013; Plummer et al., 2012). Among the 12 prominent events, the 1815 Tambora eruption stands out as a particularly illustrative example of how volcanic signals differ across Antarctic sites. The Tambora eruption is well known for its significant climatic impact (Cole-Dai et al., 2009). In the DA2009 ice core, this event is classified as a Large eruption with a sulfate flux of 11.89 kg km^{-2}, ranking only 23rd among the 95 detected events. This modest ranking contrasts sharply with its prominence in other Antarctic records, where Tambora appears as the 3rd largest event in WDC, 2nd in EDC, and 4th in SP. A comparison of Tambora's approximate ranking between the DA2009 and DA2005 records over the past two millennia further suggests that volcanic signals at Dome A tend to be relatively attenuated compared with those preserved at other Antarctic sites.

Table 2: The ten largest volcanic events by volcanic flux in DA2009, WDC, EDC, and SP ice cores.

rank	DA2009	WDC	EDC	SP
1	1258.0	1459	1259	-1174
2	-427.0	-427	1816	1258
3	1459.0	1815	699	1458
4	682.0	-1880	-384	1814
5	575.0	1258	1460	-426
6	-1657.0	575	-1975	683
7	-1408.0	-1976	-1496	-1881
8	-1366.0	1229	1230	1276
9	434.0	434	601	-1925
10	1809.3	-1657	340	-1362

Table 3: Volcanic events recorded in at least two ice core records from Table 2

Event year（CE）	Records
1815	WDC (1815)，EDC (1816)，SP(1814)
1459	DA (1459)，WDC (1459)，EDC (1460)，SP (1458)
1258	DA (1258)，WDC (1258)，EDC (1259)，SP (1258)
1229	WDC (1229)，EDC (1230)
682	DA (682)，SP (683)
575	DA (575)，WDC (575)
434	DA (434)，WDC (434)
-427	DA (-427)，WDC (-427)，SP (-426)
-1366	DA (-1366)，SP (-1362)
-1657	DA (-1657)，WDC (-1657)
-1880	WDC (-1880)，SP (-1881)
-1976	WDC (-1976)，EDC (-1975)

3.4. Changes in volcanic frequency and flux

Changes in long-term volcanic frequency and flux are concerned, because on the one hand, it may reflect the response of volcanic activity to the change of accumulated ice volume on the continents and sea level caused by climate change (Rampino et al., 1979; Zielinski, 2000; Castellano et al., 2004), on the other hand, its cumulative effect may affect the long-

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term climate change trend (McGregor et al., 2015). Here, we examine millennial-scale variations in volcanic frequency and flux in the DA2009 record. The average volcanic event frequency in DA2009 is 23.7 events per millennium, with the most recent millennium (1000-2000 CE) showing the highest frequency (34 events). Consistently, the volcanic sulfate flux during this period reaches 435.3 kg km^{-2}, exceeding the four-millennial average of 262.6 kg km^{-2}.

To facilitate comparison across different sites, millennial volcanic frequency and flux values from DA2009, WDC, EDC, and SP were normalized by the total for each record over the past 4000 years. The normalized frequency results indicate that 1000-2000 CE is the most volcanically active millennium in the DA2009, WDC, and EDC ice cores, with the strongest peaks observed in DA2009 and EDC (Fig. 4a). Although the SP core ranks this period as the second highest in frequency, its flux pattern is consistent with the other records. Similarly, normalized sulfate flux values show a clear millennial-scale maximum during 1000-2000 CE across all four cores (Fig. 4b). These findings indicate that the period 1000–2000 CE is characterized by the strongest volcanic activity of the past 4,000 years, both in terms of eruption frequency and sulfate deposition across Antarctica. Our results also support the previous findings that volcanic activity has increased in the past 2000 years compared with the previous 2000 years (Kurbatov et al., 2006; Castellano et al., 2005; Cole-Dai et al., 2000).

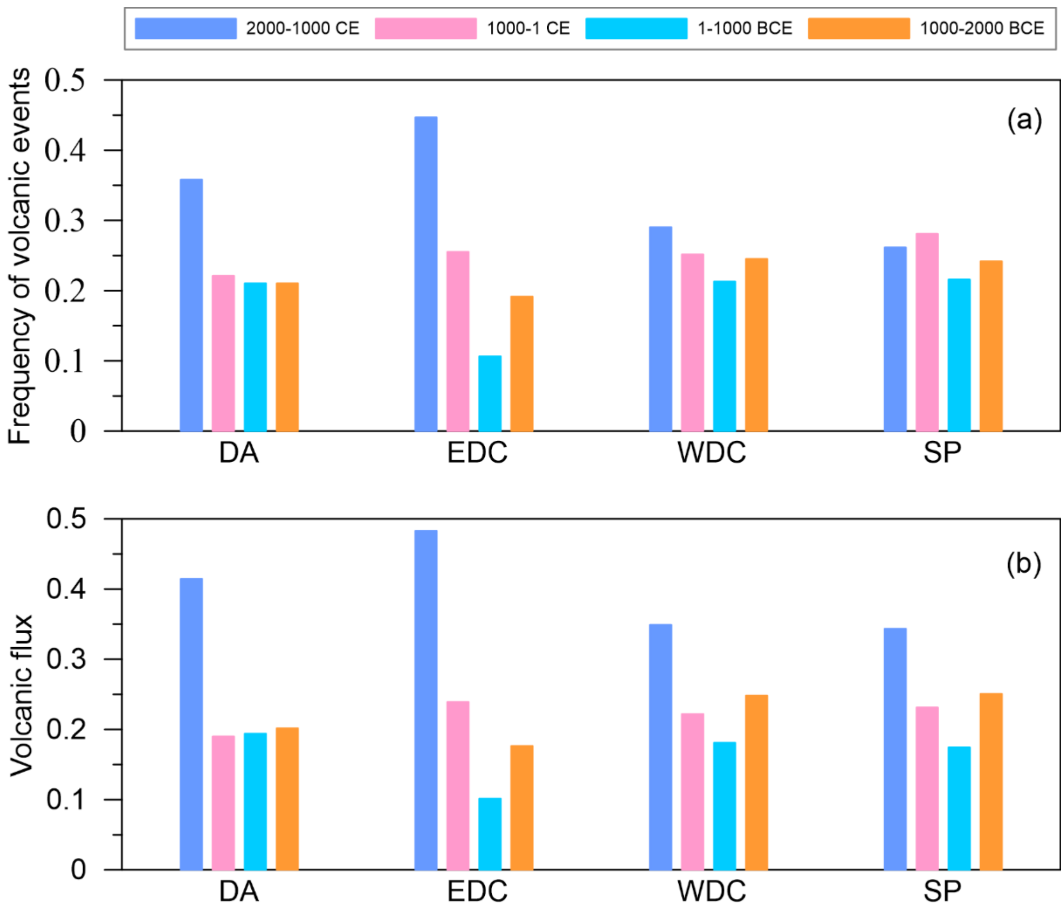

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Figure 4: The normalized number (a) and normalized flux (b) of volcanic events by millennium in the DA2009, WDC, EDC, and SP ice core records over the past 4000 years.

3.5. Snow accumulation rate variation

The history of snow accumulation rates at Dome A over the past 4000 years, calculated based on 15 volcanic tie-points in the DA2009 ice core, is shown in Fig. 5. Accumulation rates varied between 2.10 and 2.51 cm w.e. yr^{-1}, with a mean of 2.37 cm w.e. yr^{-1}. A notable feature of the record is the relatively stable accumulation prior to 1258 CE, followed by a marked decrease thereafter, with mean rates of 2.41 and 2.20 cm w.e. yr^{-1} before and after 1258 CE, respectively.

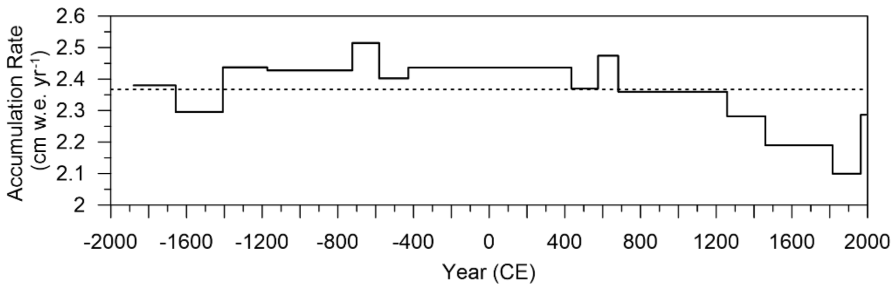

Figure 5: Snow accumulation rates (black solid line) at Dome A over the past 4000 years derived from the DA2009 ice core. Horizontal dashed lines indicate the mean value of the time series.

Although climate models generally predict increased Antarctic snow accumulation under warming scenarios due to enhanced precipitation from greater atmospheric moisture content (IPCC 2013), this relationship exhibits significant temporal and spatial variability. While robust at glacial-interglacial timescales (Frieler et al., 2015), the precipitation-temperature correlation shows substantial variation across shorter timescales (Fudge et al., 2016) and pronounced spatial heterogeneity (Man et al., 2025). For the East Antarctic Ice Sheet, the recent decadal change in snow accumulation is primarily influenced by atmospheric circulation patterns (Wang et al., 2025). If similar mechanisms operated over the past 4000 years, the observed reduction in snow accumulation at Dome A since the 13th century may reflect shifts in regional climate dynamics. Indeed, a recent ice core record suggests a weakening of meridional atmospheric transport towards the Antarctic ice sheet in the Southern Indian Ocean sector during the "Little Ice Age" period (~ 1400–1800 CE; Li et al., 2025). Notably, the period of reduced accumulation identified in our results coincides with centennial-scale cold events (1200–1300, 1400–1550, and 1600–1700 CE) recorded across the East Antarctic Plateau (An et al., 2021). This temporal correspondence suggests a potential link between local snow accumulation and regional temperature on centennial timescales. However, due to the low temporal resolution of accumulation rate data, this relationship remains uncertain and warrants further investigation.

4. Conclusion

A total of 95 volcanic eruptions are identified in the DA2009 ice core, which spans the period from 1951 BCE to 2000 CE. Among them, 47 are classified as large and moderate events with volcanic flux exceeding 5.0 kg km^{-2}. All large and moderate events in the DA2009 record persist for multiple years, with 91% attributed to stratospheric eruptions (500 BCE–2000 CE) and 87% identified as tropical events. Integrating volcanic records from the DA2009, WDC, EDC, and SP ice cores, we further identify 12 prominent volcanic events over the past 4000 years, occurring in 1815 CE, 1459 CE, 1258 CE, 1229 CE, 682 CE, 575 CE, 434 CE, 427 BCE, 1366 BCE, 1657 BCE, 1880 BCE, and 1976 BCE. These eruptions likely exerted strong impacts on the climate system. Analysis of the millennial-scale variations in volcanic frequency and sulfate flux across these 4 records shows that the period 1000–2000 CE experienced the strongest volcanic activity of the past four millennia. The snow accumulation record from Dome A reveals a pronounced decline in accumulation rates since the 13th century CE. The low-accumulation phase corresponds with documented cold intervals across the East Antarctic Plateau, implying a possible relationship between local snow accumulation patterns and regional climate variability at centennial timescales.

Data availability

The non-sea-salt sulfate ($nssSO_4^{2-}$) concentration data of DA2009 ice core used in this study are available at the National Tibetan Plateau Data Center, https://doi.org/10.11888/Cryos.tpdc.303318. (An, 2026)

Author contributions

CA, SJ and GS designed the experiments, and ZL, XL, YH, YL, XY, NS and BZ carried them out. CA, SJ and GS prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that there are no competing interests for this manuscript.

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