We are very grateful to Anonymous Referee #2 for his specific and valuable suggestions on our manuscript. The manuscript has been modified. In the following, the comments from Referee #2 are in black, and our responses are in blue.

RC2: 'Comment on egusphere-2026-769', Anonymous Referee #2, 14 May 2026
Summary:

In their manuscript An et al. present a sulfate record for the last ~4000 from Dome A ice core DA2009, Antarctica. They present their methods for discrete sampling and analysis of major ions and volcanic signal detection, identifying 95 volcanic sulfate peaks above the nssS baseline, and use key volcanic markers as tie points to construct the age model for DA2009. The authors then go on to evaluate the volcanic record, classifying detected eruptions as Large, Moderate and Small events based on their flux magnitudes, and comparing the sulfate flux at DA2009 to other ice core volcanic sulfate records across this period from EDC, WDC and SP. From this evaluation they show the majority of Large and Moderate eruptions are tropical, stratospheric eruptions, and therefore likely to have global climate impact.

The record volcanic sulfate events are then used to make inferences about how the frequency and sulfate flux have changed over the last 4000 years, and how this compares at DA2009 to the other considered records. The authors conclude from this that volcanic activity has increased in the last millennia, compared to the previous 3000 years, accompanied by a reduction in snow accumulation rate since 1258 CE, attributed to shifts in regional climate and the onset of the Little Ice Age.

This study provides a very useful additional record of volcanic sulfur flux to Antarctica which is valuable to the community, and fits well with the journal scope. Comparison to other ice core records across the period is a useful addition to the discussion and demonstrates how variable volcanic ice core records of volcanism can be.

I believe that the manuscript would be suitable for publication after some revisions and elaboration of discussion points.

Thank you very much for the comments. We have revised the manuscript based on your suggestions.

General Comments:

I'd like to understand why the selected cores were chosen for comparison, as there are more cores which extend beyond the last 2000 years. The paper presenting the previous DA2005 core, which mentioned in the text (Jiang et al., 2012), compares to 6 other Antarctic cores including DML. There are others that extend beyond the CE too - Vostok, Dome Fuji, B53/B54.
Thanks for the comment. In the revised manuscript, we have selected 8 additional Antarctic ice core records for comparison, including the suggested DML, Vostok, Dome Fuji, and B53/B54 records. These results are presented in Table S3 below.

Table S3: Comparisons of the DA2009 volcanic records with other Antarctic ice core records.

Event Number[a]	Start Date in the DA2009 ice core (CE)	Other cores where the events detected[b]
1 Pinatubo	1991	WDC, EDC96, DSS, DML05
2 Agung	1964	WDC, SPC14, EDC96, DA2005, DSS, SDMA, DT-401, DML05
3 Krakatau	1885	WDC, SPC14, EDC96, DA2005, DSS, SDMA, DML05, DF01
4 Cosigtauu	1834	WDC, SPC14, DA2005, DSS, SDMA, DML05, DF01
5 Tambora	1815	WDC, SPC14, EDC96, DA2005, DSS, DT-401, VK16, DML05, DF01
6 UE 1809	1809	WDC, SPC14, EDC96, DA2005, DSS, SDMA, VK16, DML05, DF01
7	1763	WDC, EDC96, DA2005, VK16, DML05
8	1699	WDC, SPC14, EDC96, DA2005, DSS, VK16, DML05, DF01
9	1677	WDC, EDC96, DA2005, DSS, DML05, DF01
10	1644	WDC, SPC14, DA2005, DSS, VK16, DML05, DF01
11 Huainaputina	1603	WDC, SPC14, EDC96, DA2005, DSS, SDMA, DT-401, VK16, DML05, DF01
12	1600	WDC, SPC14, DA2005, VK16, DML05, DF01
13 Kuwae	1459	WDC, SPC14, EDC96, DA2005, DSS, SDMA, DT-401, VK16, DML05, DF01
14	1380	WDC, DA2005, SDMA, DT-401, DML05
15	1347	WDC, SPC14, EDC96, DA2005, DSS, SDMA, DT-401, VK16, DML05, DF01
16	1289	WDC, SPC14, EDC96, DA2005, DSS, DT-401, VK16, DML05, DF01
17 Samalas	1258	WDC, SPC14, EDC96, DA2005, DSS, SDMA, DT-401, VK16, DML05, DF01
18	1231	WDC, SPC14, EDC96, DSS, SDMA, VK16, DML05, DF01
19	1192	WDC, SPC14, EDC96, DA2005, B53/54, SDMA, VK16, DML05, DF01
20	968	WDC, SPC14, DA2005, DSS, DML05
21	750	SPC14, DA2005, DT-401, VK16
22	682	WDC, SPC14, DA2005, DSS, VK16, DML05, DF01
23	575	WDC, SPC14, DA2005, DSS, VK16, DML05, DF01
24	538	WDC, SPC14, DA2005, DSS, VK16, DML05, DF01
25	434	WDC, SPC14, DA2005, DSS, VK16, DML05, DF01
26	306	WDC, SPC14, EDC96, DA2005, DSS, SDMA, VK16, DML05, DF01
27	209	WDC, SPC14, EDC96, DA2005, DSS, DT-401, VK16, DML05, DF01
28	173	WDC, SPC14, EDC96, DA2005, DSS, B53/54, SDMA, DT-401, VK16, DML05, DF01
29	-4	WDC, EDC96, DA2005, DSS
30	-166	WDC, SPC14, SDMA, VK16
31	-204	WDC, SPC14, EDC96, DA2005
32	-243	WDC, SPC14, DA2005
33	-392	WDC, SPC14, EDC96, DA2005, B53/54
34	-427	WDC, SPC14, DA2005, SDMA
35	-518	WDC, DA2005, B53/54
36	-582	WDC, SPC14, DA2005
37	-647	DA2005
38	-723	WDC, SPC14, DA2005, SDMA
39	-1173	WDC, SPC14

40	-1255	WDC, SPC14
41	-1366	WDC, SPC14, EDC96, B53/54
42	-1408	WDC, SPC14
43	-1533	WDC
44	-1657	WDC, SPC14, EDC96
45	-1719	WDC, SPC14
46	-1880	WDC, SPC14, EDC96
47	-1923	WDC, SPC14

[a] Only events with volcanic flux ≥ 5 kg km^{-2} are listed in the table.

[b] Antarctic ice core volcanic records: WDC (WAIS Divide; Cole-Dai et al., 2021), SPC14 (South Pole; Brandis, 2022), EDC96 (Dome C; Castellano et al., 2005), DA2005 (Dome A; Jiang et al., 2012), DSS (Law Dome; Plummer et al., 2012), B53/54 (East Antarctic Plateau; Abbott et al., 2024), SDMA (Siple Dome; Kurbatov et al., 2006), DT-401 (East Antarctic Plateau; Ren et al., 2010), VK16 (Vostok; Veres et al., 2023), DML05 (Dronning Maud Land; Traufetter et al., 2004), DF01 (Dome F; Motizuki et al., 2014).

There could be more discussion on the possible differences in signals between the cores. I've added suggestions below, but how susceptible to scouring/erosion the site is, and some thought to how this might affect the confidence of volcanic tie-points for age models as well if the ties are made using the size of individual events.

Thanks for the comments. Dome A is characterized by low mean-annual wind speed, indicating relatively weak erosion. Its flat surface implies uniform deposition and limited post-depositional disturbance. The low mean-annual temperature favors the preservation of primary environmental signals. Taken together, these factors suggest that post-depositional processes exert relatively minor impacts in this region.

To improve the robustness of our dating results, we have incorporated pattern-matching of volcanic events from sulfate records. The overall volcanic-event pattern derived from sulfate records is shown in Figure S1, whereas detailed features of the tie-point events are presented in Figures S2–S7.

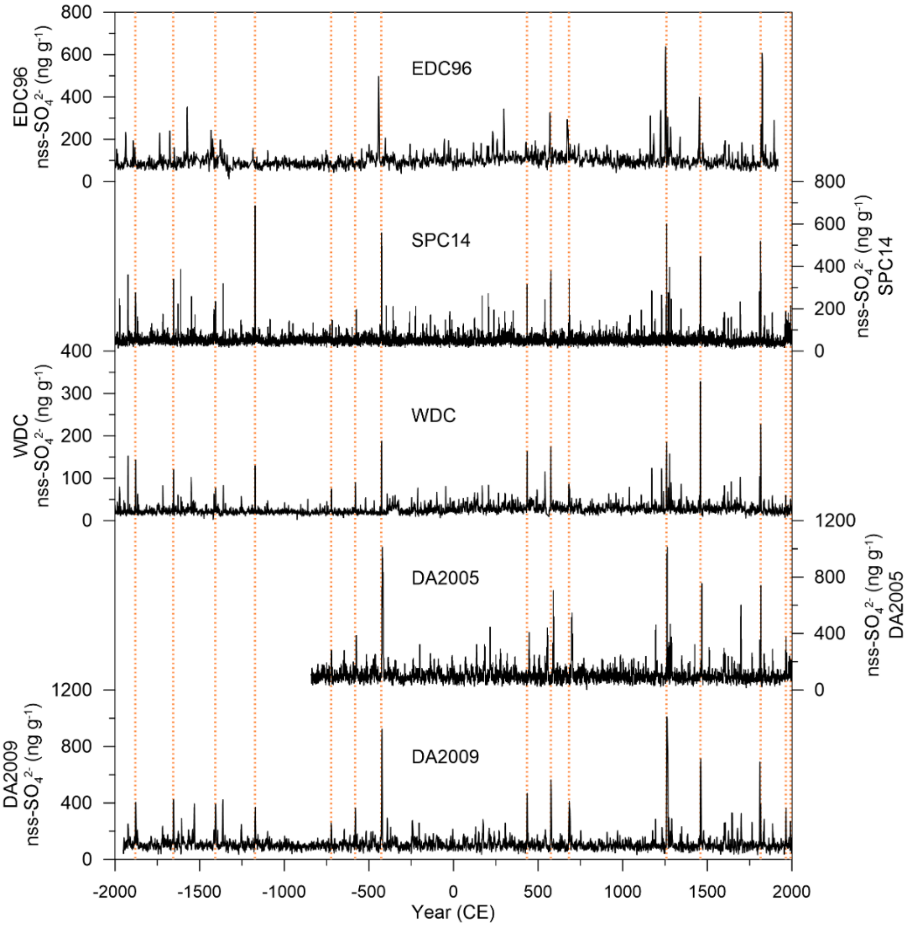

Figure S1: Non-sea-salt sulfate ($nssSO_4^{2-}$) concentration records from five Antarctic ice cores between 2000 BCE and 2000 CE. The records (line in black) are from: DA2009 (Dome A; this study), DA2005 (Dome A; Jiang et al., 2012), WDC (WAIS Divide; Cole-Dai et al., 2021), SPC14 (South Pole; Brandis, 2022), and EDC96 (Dome C; Castellano et al., 2005; Severi et al., 2020). The orange dashed lines indicate the 15 tie-points of volcanic matching between the DA2009 and WDC records.

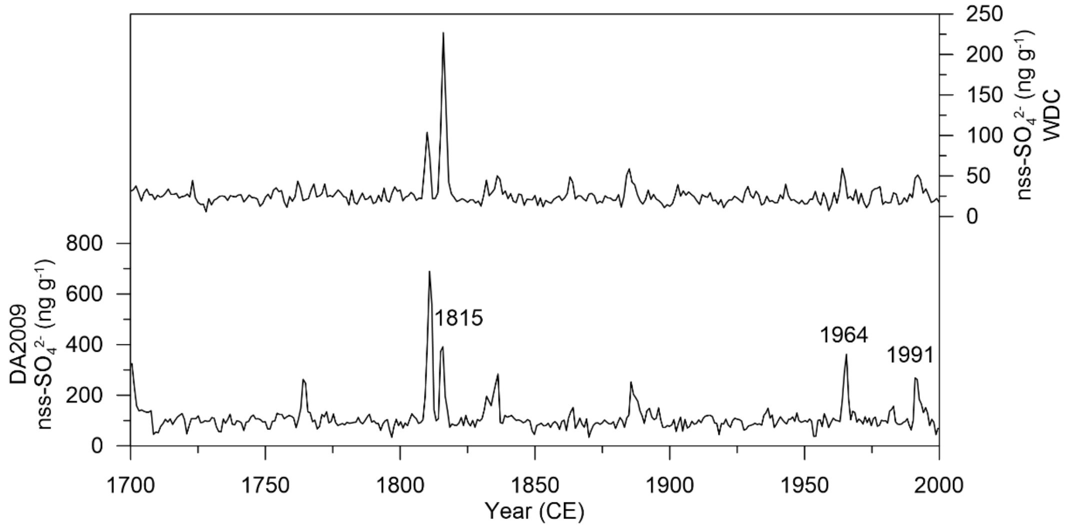

Figure S2: Non-sea-salt sulfate ($nssSO_4^{2-}$) concentration records from DA2009 (bottom) and WDC (top) ice cores between 1700 and 2000 CE showing the year of volcanic tie-points.

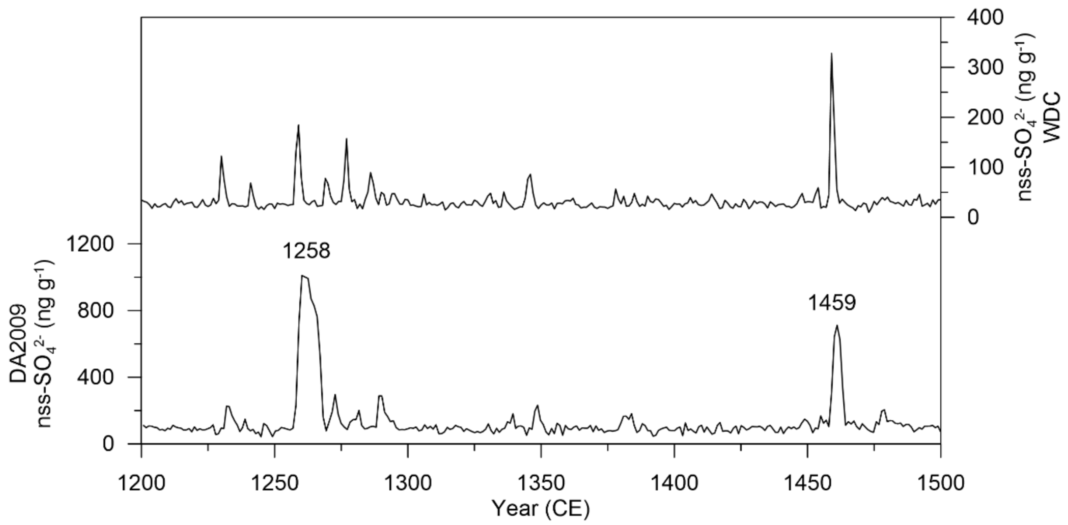

Figure S3: Non-sea-salt sulfate (nssSO$_4^{2-}$) concentration records from DA2009 (bottom) and WDC (top) ice cores between 1200 and 1500 CE showing the year of volcanic tie-points.

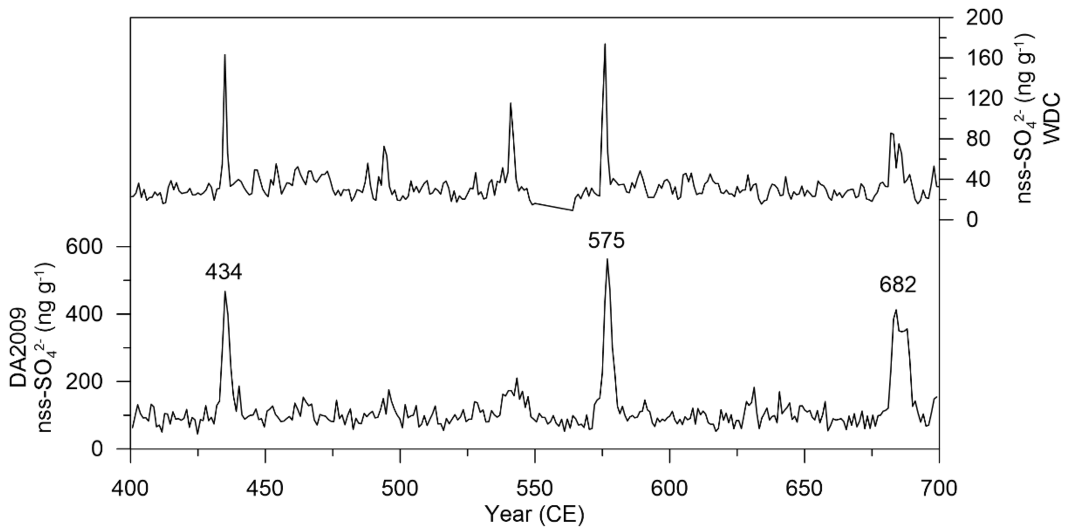

Figure S4: Non-sea-salt sulfate (nssSO$_4^{2-}$) concentration records from DA2009 (bottom) and WDC (top) ice cores between 400 and 700 CE showing the year of volcanic tie-points.

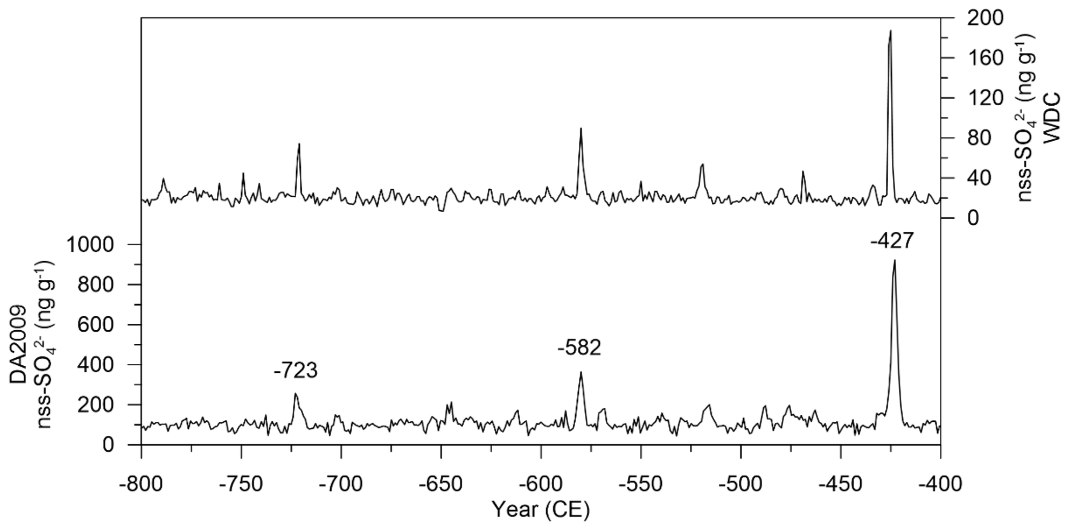

Figure S5: Non-sea-salt sulfate ($nssSO_4^{2-}$) concentration records from DA2009 (bottom) and WDC (top) ice cores between 800 and 400 BCE showing the year of volcanic tie-points.

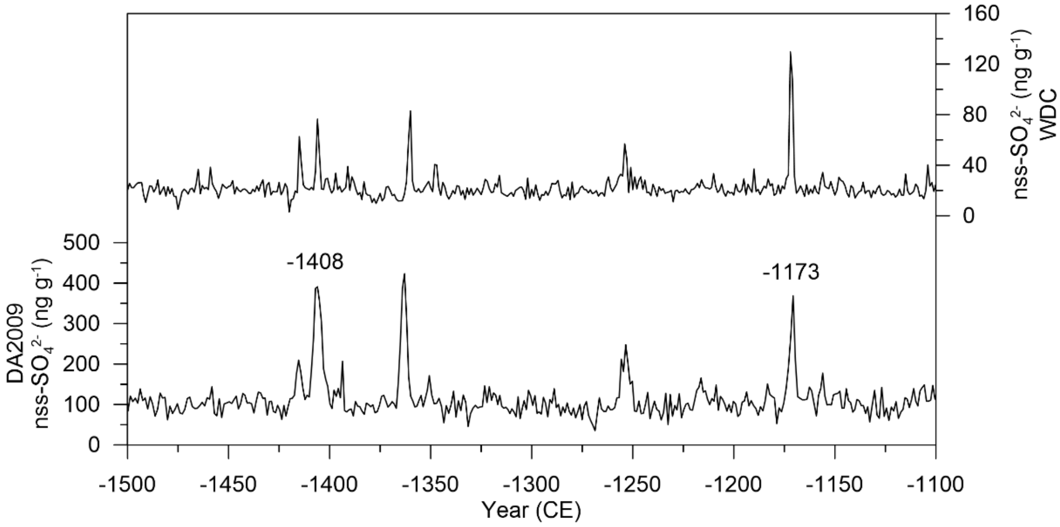

Figure S6: Non-sea-salt sulfate ($nssSO_4^{2-}$) concentration records from DA2009 (bottom) and WDC (top) ice cores between 1500 and 1100 BCE showing the year of volcanic tie-points.

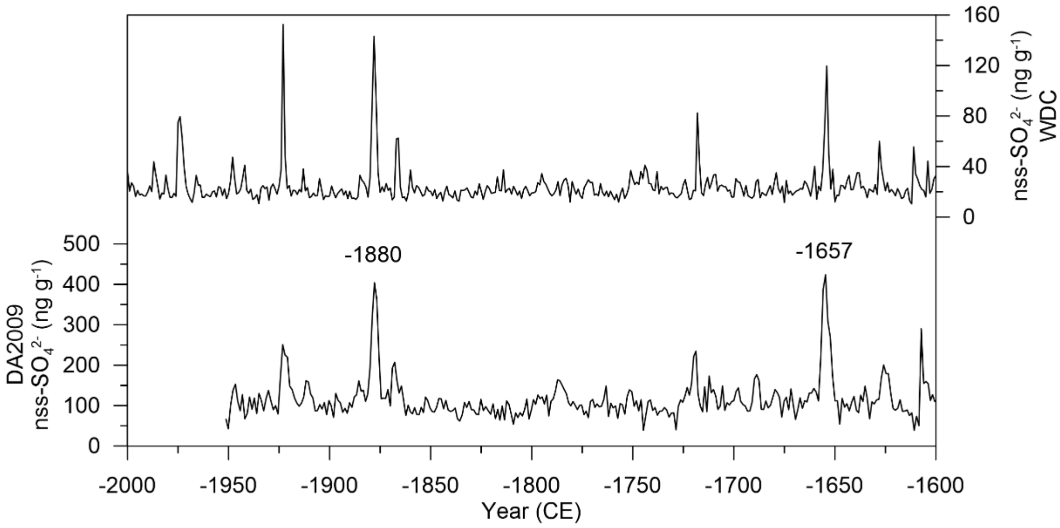

Figure S7: Non-sea-salt sulfate ($nssSO_4^{2-}$) concentration records from DA2009 (bottom) and WDC (top) ice cores between 2000 and 1600 BCE showing the year of volcanic tie-points.

In terms of the signal attenuation being lower at DA2009 than other cores, how much could the background nssS threshold contribute to the estimated flux of volcanic sulfate to Antarctica? Could the sampling resolution of 3-4 cm give an elevated S "background" concentration, especially if samples are ~1 year? Could the method in which you calculate this be contributing to the overall lower fluxes compared to other cores, as your threshold for detection could be higher?

Thanks for the comments. Indeed, detecting criteria may exert potential impacts on volcanic event identification. While a high threshold could miss small volcanic events, large eruptions remain well-captured. To facilitate comparisons with previous work, we adopted a method nearly identical to those used in the WDC ice core volcanic record (Cole-Dai et al., 2021). In terms of resolution, Cole-Dai et al. (2021) applied annual-resolution data for volcanic event detection, including background estimation and flux calculation. Given that our study features a comparable resolution, the above-mentioned factors are largely negligible, at least for comparisons against the WDC dataset reported by Cole-Dai et al. (2021).

Line by line comments:

Line 40-41: the authors say an ideal site with "exceptionally flat surface" and "extremely low ice-flow velocity" but then in a later section (line 101) say the "extremely low snow accumulation rate" prevents annual layer counting. Can it be an ideal paleoclimate site if annual layer counting isn' t possible? Does the very low accumulation rate affect the quality potential of paleoclimate record? Perhaps the language is quite superlative in this case.

Thanks for the comments. First, we have revised the language to adopt more objective and moderate statements, replacing the previously somewhat extreme wording. Second, low accumulation rates do impose limitations on certain aspects of paleoclimate reconstruction, particularly for investigations requiring high-resolution constraints such as seasonal-scale studies. Nevertheless, this region features flat terrain, low annual wind speeds, and low mean annual temperatures. These conditions favour the preservation of primary paleoclimate signals, making the site suitable for paleoclimate reconstructions at interannual and longer timescales. Many seminal climate records have likewise been retrieved from other low-accumulation sectors of the Antarctic Ice Sheet, such as Dome C, Vostok, and Dome F.

Line 143: a little elaboration on why the impacts of stratospheric eruptions greater would be useful (i.e. longer residence time)

Thanks for the suggestion. We have added the corresponding elaborations in the revised manuscript as follows.

"Volcanic eruptions that inject substantial sulfur into the stratosphere are far more likely to exert significant climatic impacts than those confined to the troposphere, for three key reasons: first, such events typically release massive quantities of sulfur dioxide; second, stratospheric aerosols remain suspended far longer than those confined within the troposphere; and third, stratospheric circulation spread these volcanic particles across entire hemispheres or even the whole planet (Cole-Dai, 2010; Robock, 2000)."

Line 147: Again a short elaboration on why tropical stratospheric eruptions have global impact rather than impact being concentrated in one hemisphere may be relevant here.

Thanks for the suggestion. Relevant elaboration has been supplemented, as shown below.

"If a stratospheric eruption is located in the tropics, it tends to have a global impact, as fast zonal wind flows and bidirectional poleward movement within the atmosphere can spread their aerosol particles across the entire planet (Cole-Dai, 2010; Robock, 2000)."

Line 150-151: These are assumed tropical and southern hemisphere based on their appearance as peaks in both Greenland and Antarctica. Aside from the events you attribute to known eruptions (e.g. 1258 = Samalas is known tropical) we cannot rule out large NH and SH eruptions happening within uncertainty of each other and appearing as tropical signals.

Thanks for the comments. We have supplemented the relevant discussion, as shown below.
"It should be noted that, the simultaneous eruption of at least one volcano at high latitudes in the northern and southern hemispheres, although in rare cases, may also generate bipolar signals in the ice core. Analyses of volcanic signal magnitude, signal duration, and inter site consistency of ice core signals may provide additional information for constraining the sources and impacts of volcanic eruptions."

Line 155: is there a need for decimal in 1533.6 BCE?
Decimals represent fractional time rather than months within a calendar year. Ages of volcanic chronological tie-points are sourced from the WAIS Divide chronology, in which fractional-year values were not used (Cole-Dai et al., 2021). The remaining ages are obtained through linear interpolation or extrapolation. If fractional-year values were not adopted for our DA2009 record, some adjacent samples would be assigned identical ages. Fractional-year ages are therefore applied to all samples to facilitate discrimination between neighbouring samples. Given that this notation is prone to ambiguity and that none of the identified volcanic events are coeval, we have revised the ages of all volcanic layers to integer-year values.

Line 159: What effect does diffusion of the sulfate in ice have in this core/at this depth? Could this make shorter deposition from a local, tropospheric volcano appear to last 2 years?
Thanks for the comments. We have added supplementary discussion concerning the potential impacts of diffusion within Section 3.4, as follows.
"Diffusion reduces the amplitude and broadens the width of sulfate peaks in older ice layers, which may result in the underdetection of volcanic events or underestimation of volcanic flux. If diffusion were the primary controlling factor, a progressive declining trend would be expected, yet no such trend is observed in Figure 5. Furthermore, previous research has demonstrated that the effective diffusivity of sulfuric acid in Antarctic ice cores is sufficiently low that Holocene volcanic events are not significantly impacted by diffusion (Fudge et al., 2024)."

Line 170: The authors use the "relative flux metric" to compare the flux of each eruption to Tambora (f/fTambora), as has been performed in previous publications (Cole-Dai et al., 2021). However, in lines 195-200 the authors discuss how Tambora 1815 sulfate in particular greatly varies between ice cores in Antarctica, and how at DA2009 it appears very modest. It doesn't feature in the top 10 ranked volcanic events at DA2009 but does in all other ice cores compared to, so is comparing each eruption to Tambora and using the relative flux metric appropriate?
Thanks for the comments. Considering possible fluctuations in the 1815 Tambora signal among various ice-core archives, its adoption as an analytical reference is not well-justified. Accordingly, we have deleted the associated text from this paragraph.

Line 196-197: The variability of the Tambora signal at Dome C is discussed in Gautier et al., (2016) Clim. Past., https://doi.org/10.5194/cp-12-103-2016, where it is sometimes entirely missing from records. It would be good to bring these results into discussion here as well if focussing on 1815/1816 signal variability. In this paper there is also discussion of post-depositional processes that may remove the signal, such as erosion and snow drifting. It would be good to see these post-depositional processes acknowledged in the manuscript too when considering the possibly lower fluxes at DA2009. Comparing the signals at DA2005 and DA2009 may aid this as they are closer in location.

Thanks for the comments. We have supplemented the following discussion content as suggested.

"A comparison of Tambora's approximate ranking between the DA2009 (10th among 55 events) and DA2005 (11th among 57 events) 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. This phenomenon is also observed in volcanic records from the VK16 ice core at Vostok in inland East Antarctica, where the sulfate flux of the Tambora event ranks 9th among the 59 volcanic events recorded in the past 2000 years (Veres et al., 2023). A study from Dome C has demonstrated that (Gautier et al., 2016), within low-accumulation zones across the interior Antarctic Plateau, volcanic signals preserved in ice cores retrieved from adjacent sites (spaced 1 m apart) can diverge, with signals of major volcanic eruptions such as Tambora potentially being absent entirely. This phenomenon has been attributed to snow drift and surface roughness at Dome C, whose impacts are stochastic and lack discernible pattern. Considering the low accumulation rate at Dome A, the relatively weak Tambora signals observed in the DA2009 and DA2005 ice cores might also be related to this process. Nevertheless, Dome A features a markedly higher elevation relative to other ice core drilling sites; whether additional drivers including elevation-modulated atmospheric circulation are also at play remains to be further explored."

Line 230: Query that you state a mean of 2.37 cm w.e. yr-1but in previous sections you use 2.3. Should this be rounded to 2.4?

The annual accumulation rate of 2.3 cm w. e. yr^{-1} originates from other investigations conducted in this region, which we mainly used for age estimation in the preliminary dating step. The value of 2.37 cm w. e. yr^{-1} is our own result based on DA2009 ice core; discrepancies relative to prior studies arise from differences in sampling locations and study intervals.

Figure 3:

It would be useful to point out the individual volcanic peaks used to tie the DA2009 core the WDC age model. Also showing the S records from other ice cores compared in the study would be a useful addition to robustly demonstrate the age model holds across other sites as well. It would be interesting to see the overlapping period between DA2009, DA2005 (also DA2005 in Fig 2.?) and EDC especially due to similarities in low accumulation rate and the number of signals preserved.

Thanks for the comments. The Figure 3 has been revised based on the comments as follows. The non-sea-salt sulfate (nssSO_4^{2-}) concentration records from DA2005 have been shown in Figure S1.

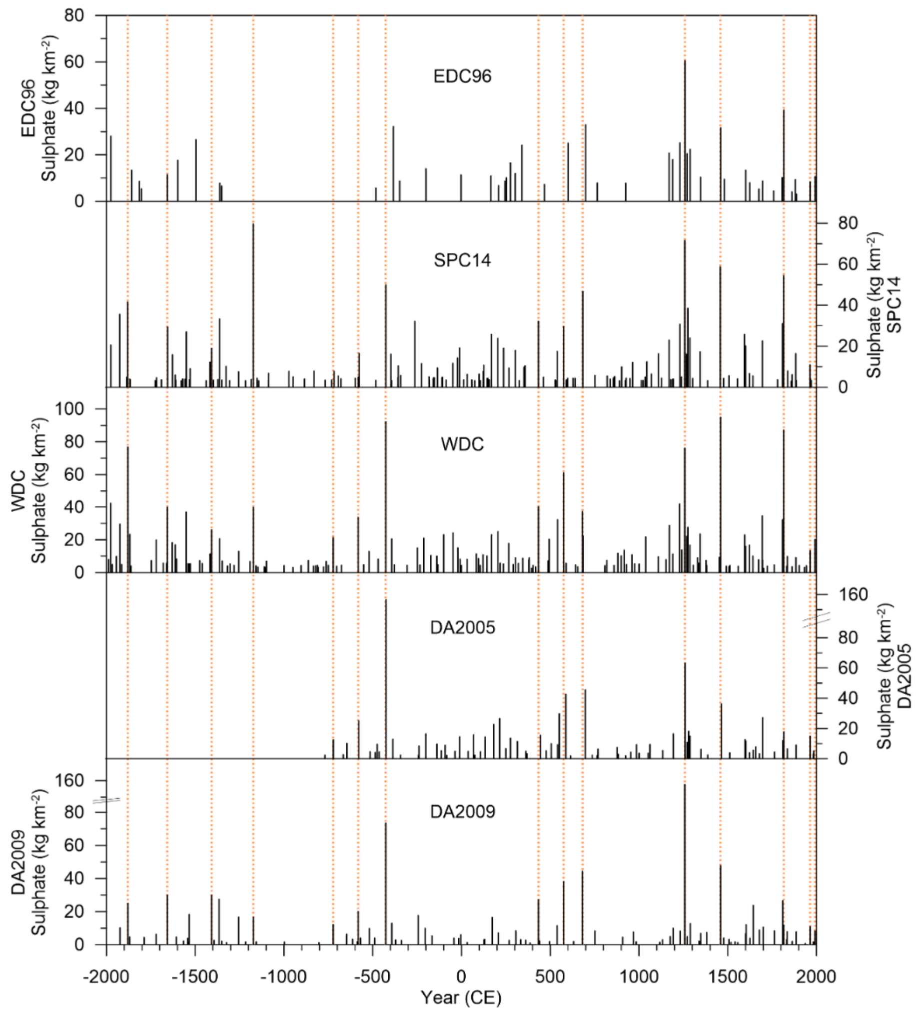

Figure 3: Comparison of volcanic sulfate fluxes over the past 4000 years among ice core records of DA2009 (Dome A; this study), DA2005 (Dome A; Jiang et al., 2012), WDC (WAIS Divide; Cole-Dai et al., 2021), SPC14 (South Pole; Brandis, 2022), and EDC96 (Dome C; Castellano et al., 2005). The orange dashed lines indicate the 15 tie-points of volcanic matching between the DA2009 and WDC records.

Figure 4:

From visuals of Fig 4., it seems the frequency of eruptions is only significantly higher for 2000-1000 CE in the DA and EDC records. Is there a reason this might be the case? Could it be related to their geographical position and deposition conditions being more similar at EDC and Dome A? Are there uncertainties to include?

Thanks for the comment. We have analyzed more records and discussed possible influencing factors. The revised text is as follows.

"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. 5a). 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.

5b). These findings seem to 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.

To investigate whether the above phenomenon is widespread, we compiled ice core volcanic records from five additional Antarctic sites: DSS (Law Dome; Plummer et al., 2012), SDMA (Siple Dome; Kurbatov et al., 2006), DT-401 (East Antarctic Plateau; Ren et al., 2010), VK16 (Vostok; Veres et al., 2023), and DML05 (Dronning Maud Land, Traufetter et al., 2004). Owing to the limited temporal coverage of these records, a full analysis spanning the entire past 4000 years was not feasible. However, evidence from DA2009, WDC, and EDC records indicates that volcanic intensity during the 1–1000 CE period was comparable to or higher than that of the preceding two millennia (Fig. 5). Accordingly, characterizing the variation patterns over the past two millennia can largely validate the aforementioned hypothesis. We then compared the frequency and flux of volcanic events between the 1000–2000 CE and 1–1000 CE intervals across these records. Our results show that for the five sites (Law Dome, Siple Dome, DT-401, Vostok and DML05), the ratios of volcanic event count in the 1000–2000 CE interval to those in the 1–1000 CE interval are 1.31, 1.22, 1.90, 1.11 and 1.72, respectively. The corresponding ratios of volcanic sulfate flux are 1.80, 1.63, 1.88, 2.22, and 1.86, respectively. This finding provides robust evidence that, within the context of the past 4000 years, the peak volcanic intensity recorded in Antarctic ice cores during the 1000–2000 CE interval is a widespread phenomenon.

To determine whether this phenomenon reflects genuine volcanic activity, we must further account for the influences of other factors such as accumulation rate and diffusion. High accumulation rates enhance wet deposition, which in turn elevates the flux of volcanogenic sulfate. However, at least in the DA2009 record, the 1000–2000 CE interval is characterized by relatively low accumulation rates (see next section for detailed discussion). Diffusion reduces the amplitude and broadens the width of sulfate peaks in older ice layers, which may result in the underdetection of volcanic events or underestimation of volcanic flux. If diffusion were the primary controlling factor, a progressive declining trend would be expected, yet no such trend is observed in Figure 5. Furthermore, previous research has demonstrated that the effective diffusivity of sulfuric acid in Antarctic ice cores is sufficiently low that Holocene volcanic events are not significantly impacted by diffusion (Fudge et al., 2024).

In summary, the 1000–2000 CE interval is the millennium with the highest volcanic intensity over the past 4000 years. This pattern is not only a widespread phenomenon across Antarctic ice core records, but also most likely represents genuine volcanic activity. 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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