Quaternary Science Reviews 274 (2021) 107260

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Volcanic climate forcing preceding the inception of the Younger Dryas: Implications for tracing the Laacher See eruption

P.M. Abbott [a], [*], U. Niemeier [b], C. Timmreck [b], F. Riede [c], J.R. McConnell [d], M. Severi [e], H. Fischer [a], A. Svensson [f], M. Toohey [g], F. Reinig [h], M. Sigl [a]

[a] Climate and Environmental Physics, Physics Institute, and Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland
[b] The Atmosphere in the Earth System, Max Planck Institute for Meteorology, Hamburg, Germany
[c] Department of Archaeology and Heritage Studies, Aarhus University, Højbjerg, Denmark
[d] Desert Research Institute, Nevada System of Higher Education, Reno, NV, USA
[e] Department of Chemistry "Ugo Schiff", University of Florence, Florence, Italy
[f] Physics of Ice Climate and Earth, Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[g] Institute of Space and Atmospheric Studies, University of Saskatchewan, Saskatoon, Canada
[h] Department of Geography, Johannes Gutenberg University, Mainz, Germany

ARTICLE INFO

Article history:
Received 15 July 2021
Received in revised form
27 October 2021
Accepted 28 October 2021
Available online 6 November 2021

Handling Editor: Giovanni Zanchetta

Keywords:
Ice cores
Sulphate
Volcanic radiative forcing
Younger Dryas
Laacher See eruption

ABSTRACT

Climatic warming from the last glacial maximum to the current interglacial period was punctuated by a ~1300 years long cold period, commonly referred to as the Younger Dryas (YD). Several hypotheses have been proposed for the mechanism triggering the abrupt inception of the YD, including freshwater forcing, an extra-terrestrial impact, and aerosols from volcanic eruptions. Here, we use synchronised sulphate and sulphur records from both Greenland and Antarctic ice cores to reconstruct volcanic forcing between 13,200–12,800 a BP_{GICC05} (years before 1950 CE on the Greenland Ice Core Chronology 2005; GICC05). This continuous reconstruction of stratospheric sulphur injections highlights a ~110-year cluster of four major bipolar volcanic signals alongside several smaller events just prior to the YD inception. The cumulative Northern Hemisphere aerosol burden and radiative forcing from this cluster exceeds the most volcanically active periods during the Common Era, which experienced notable multidecadal scale cooling commonly attributed to volcanic effects. The Laacher See eruption (LSE), recently redated to 13,006 ± 9 cal a BP, falls within our time window of study and has been proposed as a trigger for the YD but a direct volcanic imprint for the LSE in the Greenland ice cores has thus far proved elusive. Comparison of simulated sulphate deposition for mid- and high-sulphur LSE-type emission scenarios to the ice-core estimated sulphate deposition and interhemispheric asymmetry ratios allows several signals between 13,025 and 12,975 a BP_{GICC05} to be proposed as plausible candidates for the LSE. The magnitude and persistence of volcanic forcing directly preceding the YD inception highlights the need to consider stratospheric sulphur injections and their radiative forcing in future analyses and climate model experiments used to explore the mechanisms that triggered this or similar abrupt cooling events.

1. Introduction

The last deglaciation was punctuated by the abrupt onset of a ~1300 years long millennial-scale cooling event, most commonly referred to as the Younger Dryas (YD) in European sequences (Mangerud, 2021) and Greenland Stadial (GS) 1 in the Greenland ice-core chronostratigraphy (Rasmussen et al., 2014). Differences in the timing of proxy responses and potential asynchronous responses, however, do not allow a chronozone to be defined for the event (Mangerud, 2021) and the YD and GS-1 may not necessarily have been contemporaneous. This "event" left an imprint in many global climate records, but most strongly in the northern mid- and high-latitudes (Broecker et al., 2010; Cheng et al., 2020). The mechanisms that contributed to the inception of the YD approximately 12,800 a BP and the environmental response are hotly debated (e.g. Renssen et al., 2015), with three external mechanisms most widely discussed in the literature: (1) freshwater forcing (e.g. Berger, 1990; Broecker et al., 2010), (2) an extra-terrestrial impact

---

[*] Corresponding author.
E-mail address: peter.abbott@climate.unibe.ch (P.M. Abbott).

https://doi.org/10.1016/j.quascirev.2021.107260

(e.g. Firestone et al., 2007; Kennett et al., 2009; Petaev et al., 2013; Sweatman, 2021) and (3) volcanic eruptions (e.g. Baldini et al., 2018). All of these mechanisms may have triggered the strong changes in Atlantic Meridional Overturning Circulation (AMOC; McManus et al., 2004) encountered at that time of an, in general, metastable AMOC state (Rahmstorf, 2002). The structure of the climatic changes related to the YD has strong similarities to the numerous millennial-scale climatic events characterising the last glacial period (Mangerud et al., 2010; Rasmussen et al., 2014; Nye and Condron, 2021). Therefore, improved understanding of the mechanisms that triggered the YD inception may also contribute to interpretation of similar large-scale climatic fluctuations in the past and help assess the potential for such events in the future.

Testing different mechanisms for the YD inception, in isolation or in combination, requires model simulations with boundary conditions closely reflecting the environmental setting prevailing at the time (Renssen et al., 2015). It has been shown that volcanic eruptions can significantly impact the climate, with the sulphur they emit converting into sulphate aerosols and causing short-term local to global scale cooling (Robock, 2000; Timmreck, 2012). Impacts may also be seen over longer decadal to centennial periods due to positive feedback effects from sea-ice, glacier growth and ocean–atmosphere heat exchanges (e.g. Church et al., 2005; Zhong et al., 2011; Miller et al., 2012; Schleussner and Feulner, 2013) or from potential impacts on AMOC. Coupling continuous analyses of sulphate concentrations measured in polar ice cores to high-precision chronologies for these archives permits the reconstruction of past stratospheric sulphur injections from volcanic eruptions that can be integrated in future model experiments (Sigl et al., 2015; Toohey and Sigl, 2017). Here, we use synchronised records of sulphate and sulphur from Greenland and Antarctic ice cores to provide a well-dated reconstruction of spatio-temporal changes of volcanic climate forcing for a critical time period during the Bølling-Allerød/Greenland Interstadial (GI) 1a and prior to the YD inception (13,200–12,800 a BP_{GICC05}).

Our volcanic reconstruction also is relevant for tracing any evidence of the Laacher See eruption (LSE) in the Greenland ice cores. This eruption from the East Eifel Volcanic Field (Germany), with a volcanic explosivity index (VEI; Newhall and Self, 1982) of 6, is one of the largest known volcanic eruptions from Central Europe during the Quaternary and has been proposed as a potential trigger for the YD inception (Baldini et al., 2018). This proposition relied on the widely accepted age for the eruption of ~12,880 ± 40 a BP, based on the position of the tephra in varved lake sequences (Brauer et al., 1999), which placed the eruption just prior to the GI-1a/GS-1 climatic transition, dated at 12,846 ± 138 a BP_{GICC05} in the Greenland records (Rasmussen et al., 2014; Baldini et al., 2018). However, Reinig et al. (2021) recently reported a new age for the LSE of 13,006 ± 9 cal a BP, based on radiocarbon dating of subfossil trees buried during the eruption. This redating places the eruption ~160 years prior to the climatic cooling in the Greenland records, which is consistent with European lake sequences (e.g. Lake Mondsee and Lake Ammersee; Fig. 1; Reinig et al., 2021). This would imply that there was no direct causal link between the LSE and the YD inception and cooling was synchronous over Greenland and Europe (Fig. 1; Reinig et al., 2021).

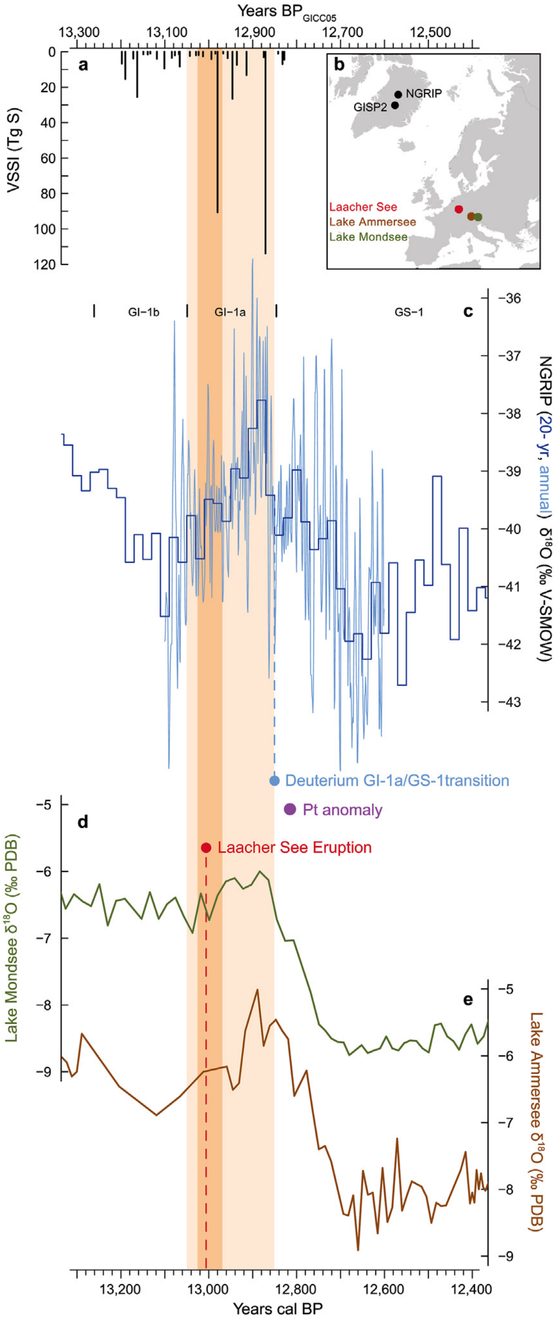

Fig. 1. (a) Reconstruction of the volcanic stratospheric sulphur injection (VSSI) from 13,200 to 12,800 a BP_{GICC05}. (b) Location map of the Greenland ice cores used in this study, the Laacher See volcano and two alpine lakes recording the LSE and YD inception. (c) 20-yr and annual resolution oxygen isotope ($\delta^{18}O$) records from NGRIP on the GICC05 timescale (Steffensen et al., 2008; Rasmussen et al., 2014). Stratigraphic position of the platinum anomaly in GISP2 from Petaev et al. (2013), who interpreted it as evidence for an extra-terrestrial impact trigger for the YD. (d and e) Late Glacial alpine $\delta^{18}O$ records from Lake Mondsee (Lauterbach et al., 2011) and Lake Ammersee (von Grafenstein et al., 1999) that both clearly record environmental changes related to the inception of the YD. The light orange bar denotes the time window focused on in Fig. 2a and the dark orange bar the LSE search window. (a and c) are plotted on the GICC05 timescale with respect to 1950 CE. (d and e) are plotted on the ^{14}C timescale cal BP relative to 1950 CE. Panels (c–e) adapted from Reinig et al. (2021).

A more direct synchronisation of European palaeoclimatic archives to the Greenland ice cores around the LSE would allow further exploration of large-scale synchroneity of the climate changes across the North Atlantic and the chronology of the Greenland cores. The most robust method for tracing specific eruptions in ice cores is the identification and geochemical characterisation of volcanic tephra (see Abbott and Davies, 2012). However, to date, no tephrochronological studies have identified LSE deposits in any Greenland ice cores (Mortensen et al., 2005; Cook, 2015). Candidate sulphate peaks also can be proposed based on age and sulphur emission estimates (e.g. Zielinski et al., 1996) and several peaks in the Greenland ice cores have previously been suggested for the LSE (e.g. Brauer et al., 1999; Mortensen et al., 2005; Baldini et al., 2018; Svensson et al., 2020). Linking a sulphate signal in ice to the LSE, however, is hindered by uncertainty regarding the expected sulphate concentration strength, as estimates of sulphur emitted during the eruption range between 3.5 and 150 Tg (Schminke et al., 1999; Textor et al., 2003). Moreover, the prior propositions should be revisited due to the new LSE age. Here we compare estimated sulphate deposition and interhemispheric asymmetry ratios from our volcanic reconstruction, which spans the new LSE age estimate, to simulated sulphate deposition for mid- and high-sulphur emission scenarios for a Northern Hemisphere (NH) mid-latitude LSE-type eruption to propose several signals as plausible candidates for the eruption.

2. Methods

We used sulphate or sulphur measurements from four ice cores – the Greenland Ice Sheet Project 2 (GISP2) and North Greenland Ice Core Project (NGRIP) cores from Greenland and the EPICA Dronning Maud Land (EDML) and West Antarctic Ice Sheet Divide project (WD) cores from Antarctica – to reconstruct polar volcanic sulphate deposition between 13,200–12,800 a BP$_{\text{GICC05}}$ (Table S1 and S2; Mayewski et al., 1997; Bigler et al., 2007, 2011; Severi et al., 2007, 2015; McConnell et al., 2017). The time resolution of the ice-core measurements range between multi-annual (~4 years) for GISP2 to sub-annual for NGRIP and WD. Since sulphate deposition onto the ice surface persists for 2–3 years following major climate impacting eruptions, these events are detectable and their sulphate loading quantifiable even at a 4-year resolution (e.g., Zielinski et al., 1997).

Common volcanic events were used to synchronise EDML and WD on the annual-layer dated WD2014 chronology (Sigl et al., 2016; Buizert et al., 2018) and GISP2 and NGRIP on the annual-layer counted GICC05 chronology (Rasmussen et al., 2006; Seierstad et al., 2014). Using linear interpolation between common chronological tie-points, GISP2 and EDML sulphate data were remapped onto GICC05 and WD2014 respectively. At ~13 ka BP, the absolute age difference between WD2014 and GICC05 is ~20–30 years, with WD2014 the “younger” chronology.

Annual mean sulphate concentrations were derived by interpolation for GISP2 and by averaging all values contained within a year for NGRIP, WD and EDML; using the discrete GISP2 data instead of annually resampled data would only marginally affect the results. At the ice-core sites, sporadic volcanic sulphate deposition is superimposed on background variability from other sources, such as mineral dust and marine biogenic emissions (Sigl et al., 2013). Therefore, to distinguish volcanic sulphate from non-volcanic sources we quantified the background signal and its variability using established methods (Fischer et al., 1998; Gao et al., 2007; Sigl et al., 2014).

Thinning-corrected accumulation rates were used to quantify sulphate mass deposition fluxes at the four ice-core sites (Table S1). Further, we stacked the time-integrated cumulative volcanic sulphate fluxes from the same events in both Greenland and Antarctica to derive Greenland and Antarctica composite records, using a flux of 0 kg km^{-2} in cases where sulphate was only detected in one ice core. For Antarctica, we applied a spatial weighting, 80% EDML and 20% WD, following Sigl et al. (2014), to account for the relative size of the vast East Antarctica plateau and that the EDML record is a better representation of the aerosol deposition regime for that region. Eruptions were defined as either “bipolar events”, if volcanic sulphate is co-registered within relative age errors in Antarctica and Greenland, or “unipolar events” if volcanic sulphate is only detected in one hemisphere. Plausible eruption latitudes were attributed to unipolar events (48°N or 37°S, the mean location of Holocene eruptions with VEI$\geq$4 in the Global Volcanism Project (2013) catalogue). Aerosol modelling (Marshall et al., 2019; Toohey et al., 2019) and ice-core studies (Toohey et al., 2016a; McConnell et al., 2020) have indicated the possibility of volcanic sulphate deposition following mid-latitude eruptions in polar regions of the opposing hemisphere. In contrast to previous work, we therefore assigned “bipolar events” with a strong hemispheric asymmetry in sulphate deposition (i.e. asymmetry ratio >0.75) to the NH (i.e. 48°N). All other “bipolar events” were attributed to the low-latitudes (i.e. 5°N). Then, using the methodology of Toohey and Sigl (2017), we estimated the ice-sheet wide fluxes of volcanic sulphate to Greenland and Antarctica and the volcanic stratospheric sulphur injection (VSSI in Tg of sulphur) with transfer functions accounting for the spatial distribution of sulphate deposition over each hemisphere (Gao et al., 2007). The VSSI values, the Easy Volcanic Aerosol (EVA) forcing generator (Toohey et al., 2016b; Toohey and Sigl, 2017) and the radiative forcing scaling factor from Hansen et al. (2005) were used to estimate the stratospheric aerosol optical depth (SAOD) and radiative forcing globally and between 30 and 90°N (Table S3). We compared our final estimates of ice-sheet wide sulphate flux, asymmetry of the sulphate burden and estimates of VSSI for eight events (labelled V1–V8) with the corresponding estimates derived for three historic explosive eruptions, two located in the tropics (Tambora, 1815 CE, 8°S, VEI 7; Krakatau 1883 CE, 6°S, VEI 6 both in Indonesia) and one in the NH mid-latitudes (Okmok, Alaska, 43 BCE, 53°N, VEI 6; McConnell et al., 2020, Table 1a). We note that eruptions with lesser sulphate deposition only slightly exceeding predefined detection thresholds in the ice core records have large uncertainties that remain difficult to quantify.

Global sulphate deposition values recently have been simulated for a NH mid-latitude Laacher See-type eruption (Niemeier et al., 2021). The simulations were performed with the middle atmosphere version of the general circulation model MAECHAM5 (Giorgetta et al., 2006). MAECHAM5 was interactively coupled to the prognostic modal aerosol microphysical model HAM (Stier et al., 2005), which calculates the sulphate aerosol formation including nucleation, accumulation, condensation and coagulation, as well as its removal processes by wet and dry deposition. This allows the model to simulate the evolution of a volcanic sulphate cloud (Niemeier et al., 2009). Background aerosols are simulated from sulphur sources relevant for stratospheric background concentration, i.e. dimethyl sulphide and carbonyl sulphide, but anthropogenic sources and wildfires are not included. A background simulation over 20 years was performed and subtracted from the simulations presented in Niemeier et al. (2021). Here we consider simulated sulphur deposition values from two emission scenarios (15 and 100 TgS) which represent medium and high scenarios for the wide range of petrologically-derived LSE sulphur yield estimates (3.5–150 TgS; Schminke et al., 1999; Textor et al., 2003).

3. Results and discussion

3.1. *Volcanic forcing prior to the YD inception*

Between 13,200–12,800 a BP$_{\text{GICC05}}$ our combined volcanic reconstruction comprises 30 volcanic eruptions with a VSSI in excess of 1 TgS (Figs. 1a and S1; Table S2; Sigl et al., 2021); a volcanic event detection frequency slightly less than or comparable to prior reconstructions for the Common Era (Plummer et al., 2012; Sigl et al., 2015). Of these events, 22 are classified as bipolar, seven are only present in the Greenland records, and one was solely identified in the Antarctic records (Table S2). A distinct cluster of events can be identified between 12,980–12,870 a BP$_{\text{GICC05}}$ with four major bipolar volcanic signals identified in this relatively short

Table 1

(a) Cumulative volcanic sulphate deposition in Greenland (D_{GL}) and Antarctica (D_{AN}) for major eruptions around the new radiocarbon date of the LSE (Reinig et al., 2021) in comparison to the major eruptions of Okmok, Alaska and Tambora and Krakatau, both Indonesia. Ice-core ages are on the GICC05 chronology (Rasmussen et al., 2006) (BP 1950) and are based on previous volcanic synchronisation (Svensson et al., 2020; Buizert et al., 2018; Seierstad et al., 2014). Interhemispheric asymmetry ratio ($D_{GL}/(D_{GL} + D_{AN})$) of atmospheric sulphate burden and estimated stratospheric sulphur infection calculated following Toohey and Sigl (2017). [a] Based on age-transfer functions in Adolphi et al. (2018). [b] The source and age of this eruption have been revised by McConnell et al. (2020). [c] Estimates based on data from the same four cores used in the current work and processed with the same methodology. [d] Estimates previously published in Toohey and Sigl (2017) and used data from a broader network of ice cores between 1 and 1900 CE. A complete list of all volcanic events is provided at https://doi.pangaea.de/10.1594/PANGAEA.930557. (b) Cumulative volcanic sulphate deposition in Greenland and Antarctica for major eruptions around the new dendrochronological date of the LSE compared to simulated cumulative total sulphate deposition in nearby grid-points using 15 and 100 $TgSO_2$ emissions scenarios for the LSE.

(a)

Eruption	GICC05 age (a BP)	Within ^{10}Be age constraints[a]	Greenland cum. volc. SO_4^{2-}(kg km^{-2}) [1σ]	Antarctica cum. volc. SO_4^{2-}(kg km^{-2}) [1σ]	Interhemispheric asymmetry ratio	Stratospheric sulphur injection (VSSI, TgS) [1σ]	Reference
V1	13023	yes	4 [±2]	2 [±1]	0.66	2 [±1]	this study
V2	13013	yes	4 [±3]	4 [±1]	0.49	3 [±1]	this study
V3	12994	yes	9 [±3]	3 [±1]	0.74	4 [±1]	this study
V4	12985	yes	6 [±3]	0	1.00	1 [±1]	this study
V5	12980	yes	227 [±64]	45 [±12]	0.83	91 [±25]	this study
V6	12946	no	45 [±13]	34 [±9]	0.57	27 [±6]	this study
V7	12914	no	26 [±7]	14 [±4]	0.65	13 [±3]	this study
V8	12871	no	279 [±78]	63 [±16]	0.82	114 [±31]	this study
Okmok	2002[b]	n/a	127 [±36]	17 [±4]	0.88	48 [±16]	this study[c]
Okmok	2002[b]	n/a	100 [±28]	15 [±4]	0.87	39 [±16]	Toohey and Sigl (2017)[d]
Tambora	134	n/a	44 [±28]	52 [±13]	0.46	32 [±7]	this study[c]
Tambora	134	n/a	38 [±28]	46 [±12]	0.46	28 [±5]	Toohey and Sigl (2017)[d]
Krakatau	67	n/a	17 [±5]	13 [±3]	0.57	10 [±2]	this study[c]
Krakatau	67	n/a	18 [±5]	10 [±3]	0.63	9 [±2]	Toohey and Sigl (2017)[d]

(b)

Model/Eruption	GICC05 age (a BP)	GISP2	NGRIP	WD	EDML	Greenland	Antarctica	Interhemispheric asymmetry ratio
		Cumulative ice core SO_4 deposition (kg km^{-2})						
LSE 100 Tg SO_2 model	n/a	258	354	58	47	306	53	0.85
LSE 15 Tg SO_2 model	n/a	35	40	7	4	38	6	0.87
V3 in ice cores	12994	16 [±3]	3 [±3]	4 [±1]	3 [±1]	9	3	0.74
V5 in ice cores	12980	347 [±39]	107 [±13]	100 [±11]	31 [±4]	227	45	0.83

period (V5-8 on Fig. 2a). This cluster also was identified by Svensson et al. (2020) in their volcanic synchronisation of Greenland and Antarctica for the last glacial period and all were postulated to be from low-latitude eruptions. The interhemispheric asymmetry ratios reported here, however, show greater NH sulphate loading, for the first and last events (i.e. V5 and V8) compared to the two central events (i.e. V6 and V7; Table 1a), thus suggesting more northerly volcanic sources. The greater sulphate loading in the Northern Hemisphere also is reflected in the reconstructed SAOD between 30 and 90°N for these events and the global radiative forcing is greatest for the V5 and V8 volcanic events (Fig. S2a; Table S3). These inferences are consistent with the interhemispheric asymmetry ratios for the three well-characterised explosive eruptions of Okmok, Tambora and Krakatau (Table 1a). The sulphate emitted by the Okmok and Tambora eruptions had significant impacts on global climate, lowering temperatures regionally by up to 3 °C for several years following the events (Oppenheimer, 2003; McConnell et al., 2020). Comparing VSSI values shows that, per eruption, the atmospheric sulphate loading for the V5 and V8 events was more than double that for either the Okmok or Tambora eruptions (Table 1a), suggesting that these events likely had an impact on global temperatures.

The overall volcanic forcing for the 110-year cluster between 12,980–12,870 a BP_{GICC05} is significant when compared to three well-known volcanically active periods during the Common Era; 1783–1890 CE, 1171–1286 CE and 536–641 CE (Fig. S2b; Table S4). These periods are similar in length and associated with notable cool periods, e.g. the Little Ice Age and Late Antique Little Ice Age, commonly attributed to volcanic effects on atmosphere, sea-ice and ocean heat content (Sigl et al., 2015; Büntgen et al., 2020). Comparing the volcanic reconstruction for these three intervals from Sigl et al. (2015) and Toohey and Sigl (2017) to the time period encompassing V5 to V8 shows that the cumulative VSSI was between ~1.6 and 2.4 fold greater and global SAOD and radiative forcing was 1.3–1.4 times greater prior to the YD inception (Table S4). The volcanic forcing prior to the YD was also relatively more extreme in the NH, with cumulative NH sulphate loading and NH SAOD both about 1.8–2 times greater than during the Common Era periods (Table S4), and driven by the proposed source of the V5 and V8 events in this hemisphere.

Overall, this analysis shows there could have been a volcanic influence on the inception of the YD, due to this distinct cluster of events and the V8 eruption is the most likely event to have had a singular influence, as previously suggested by Baldini et al. (2018), as it occurred 25 years prior to the YD inception. However, it is unlikely to be the sole mechanism as both the GI-1a/GS-1 transition, ~100 years in the Greenland record (Steffensen et al., 2008), and the entire YD cooling, ~1300 years, are too long to be explained exclusively by volcanic forcing. The volcanism could, however, have triggered longer term positive feedbacks in the climate system (such as changes in the AMOC) leading to prolonged cooling, as previously suggested for the YD and other periods of cooling, such

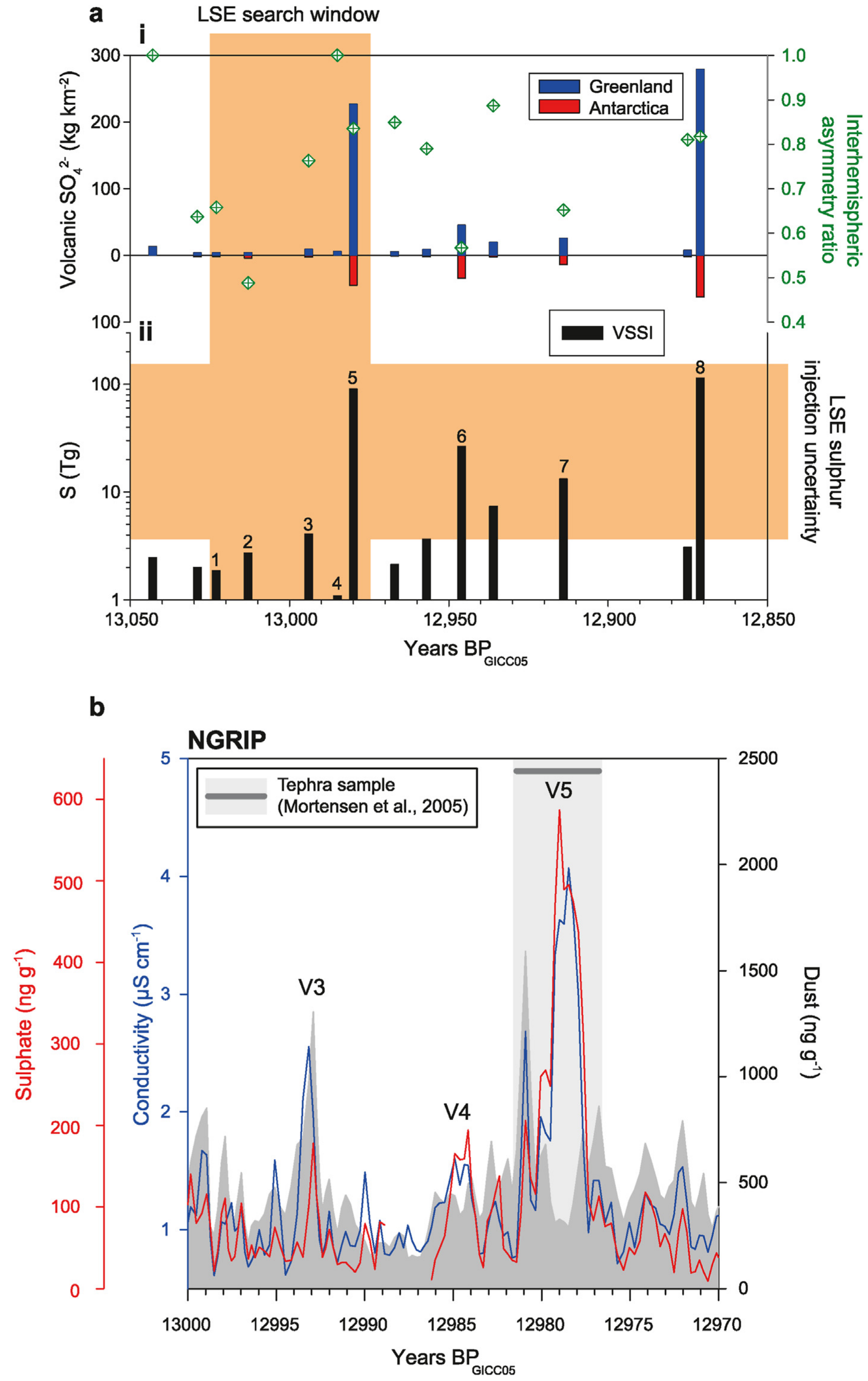

Fig. 2. (a) (i): Cumulative (i.e. event integrated) sulphate deposition in Greenland (D_{GL}; from GISP2 (Mayewski et al., 1997) and NGRIP (Bigler et al., 2011)) and Antarctica (D_{AN}; from WD (Cole-Dai et al., 2021) and EDML (Severi et al., 2007)) between 13,050 and 12,850 a BP (GICC05 chronology) and interhemispheric asymmetry ratio ($D_{GL}/(D_{GL} + D_{AN})$; (ii) reconstructed stratospheric sulphur injection from volcanic eruptions. All ice cores are synchronised (Svensson et al., 2020; Buizert et al., 2018; Seierstad et al., 2014) on the GICC05 chronology (Rasmussen et al., 2006) and only eruptions > 1TgS are shown. Orange bars denote the LSE search windows based on age and estimated sulphur injection. (b) Continuous sulphate, conductivity and dust records from the NGRIP ice core between 13,000 and 12,970 a BP$_{GICC05}$ (Ruth et al., 2003; Mortensen et al., 2005; Bigler et al., 2011). Grey bar denotes time range of tephra sample taken by Mortensen et al. (2005). Adapted from Reinig et al. (2021).

as those during the last glacial period (e.g. Zielinski et al., 1997; Robock et al., 2009; Baldini et al., 2015, 2018). In line, independent marine sediment Pa/Th data show that the YD occurred during a sustained reduction of the Atlantic Meridional Overturning Circulation (AMOC; McManus et al., 2004). The volcanic forcing may have acted as a trigger for the subsequent cooling during a period when the AMOC was more sensitive to external disturbance than during the Common Era; a hypothesis that could be tested

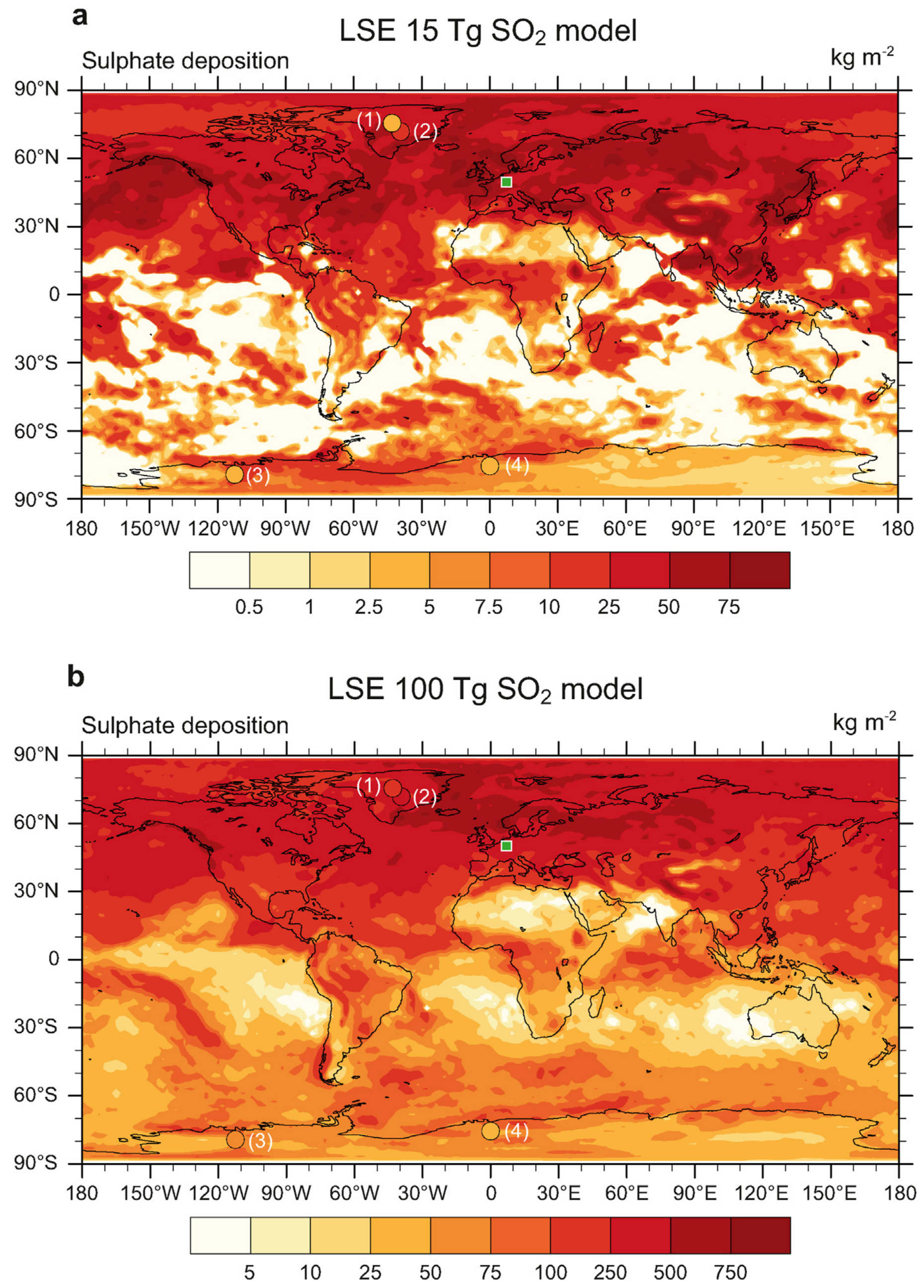

Fig. 3. Simulated sulphate deposition for (a) mid (15 Tg) and (b) high (100 Tg) sulphur emission scenarios for a NH mid-latitude Laacher See-type eruption. Circles represent the location of the ice cores in this study and the magnitude of simulated sulphate deposition at those locations: (1) NGRIP (2) GISP2 (3) WD (4) EDML. The green squares show the location of the LSE eruptive centre. Note the difference in colour scales between the panels.

with dedicated model experiments.

3.2. Tracing the Laacher See eruption

The distinct cluster of bipolar volcanic events identified within our reconstruction occurred around the prior and recently proposed ages for the LSE. Based on the prior age for the LSE (~12,880 ± 40 a BP) and their assumption that ~83 Mt SO_2 was emitted, Baldini et al. (2018) suggested that the V8 event represents sulphate deposition from the LSE. However, the new age does not support this proposition. Using the new LSE age and uncertainties in the Greenland ice-core chronology during GI-1a of −12/+21 years, based on comparison to U/Th dating from Adolphi et al. (2018), we propose that the search window for the LSE in the Greenland cores can be revised to between 13,025 and 12,975 a BP_{GICC05} (Figs. 2a and S3). Five of the volcanic events in our reconstruction occurred during this period, V1–V5, and could be candidates for the LSE (Fig. 2a). The VSSI of the V1, V2 and V4 events are less than the estimated sulphur emissions for the LSE, therefore, it is unlikely that these signals represent deposition from that event. The VSSI for both V3 and V5 fall within the range of sulphur dioxide emission estimates for the LSE (Fig. 2a). Comparing the spatial distribution of sulphate deposition, the VSSI and interhemispheric asymmetry ratios for these events to the simulated LSE-type eruption scenarios shows that V5 has strong similarities to the high-sulphur emission scenario while the V3 event is comparable to the mid-emission scenario (Table 1b; Fig. 3). Therefore, based on the age and emission parameters, both are plausible candidates for the volcanic imprint of the LSE.

The V5 event was proposed as a potential candidate for the LSE by Brauer et al. (1999). This was challenged by Mortensen et al. (2005) because they isolated tephra shards from the NGRIP ice core associated with the V5 sulphate peak similar in composition to the products of the Hekla volcano in Iceland (Fig. 2b). Closer inspection of the high temporal resolution sulphate concentrations from NGRIP, however, reveals two peaks in sulphate concentrations which could indicate that the V5 sulphate concentration signal represents sulphate deposition from two volcanic eruptions closely spaced in time (Fig. 2b). The older sulphate peak has a coeval peak in insoluble particle concentrations, which may be indicative of tephra presence (e.g. McConnell et al., 2020; Abbott et al., 2021), while a particle peak is not associated with the younger, and larger, sulphate peak (Fig. 2b). As the prior tephra sampling resolution covered both sulphate peaks, the stratigraphic relationship between the sulphate and tephra deposition is unclear but could be resolved with more detailed tephra investigations. Therefore, the tephra evidence of Mortensen et al. (2005) does not definitively rule out V5 as a plausible candidate for the LSE. Focussed tephra investigations using higher resolution and higher volume sampling may yet uncover LSE deposits in the Greenland ice cores. However, it is acknowledged that such investigations may never be successful as to date no tephra from continental European volcanic sources has been identified definitively in these records (Abbott and Davies, 2012; Cook, 2015; Plunkett et al., 2020, 2021).

4. Conclusions

Our 400-year volcanic reconstruction just prior to the inception of the YD identified 30 volcanic eruptions, including a distinct cluster of four major bipolar events between 12,980 and 12,870 a BP_{GICC05}. The overall volcanic forcing from this cluster was greater than during well-known volcanically active periods of the Common Era associated with distinct climatic cooling. This reconstruction can now be used in model investigations of the potential causes of the YD inception. Moreover, our results suggest that the magnitude and persistence of volcanic forcing directly preceding large scale climatic cooling need to be considered when exploring the mechanisms triggering abrupt cooling events during times of metastable AMOC conditions. Using a new age for the LSE we conclude that two volcanic eruptions, dated 12,994 ± 140 and 12,980 ± 140 a BP_{GICC05} respectively, may be plausible candidates for an imprint of this eruption in the Greenland ice cores, however no unambiguous evidence for a LSE imprint in Greenland exists to date. This could be explored further through focused tephra investigations, improved constraints on sulphur dioxide emissions from proximal LSE deposits, and sulphur isotope analysis on the Greenland ice to constrain atmospheric transport pathways for the sulphate (e.g. Burke et al., 2019).

Author contributions

All authors contributed towards this manuscript. PMA wrote the manuscript with MSi. MSi devised the study. UN, CT and FRi provided modelling results. JRM, MSe, HF, AS and MSi were involved in the ice core data collection and synchronisation. MT produced the radiative forcing dataset. FRe contributed towards the analysis of LSE candidates. All authors provided comments on the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

PA and MSi received funding from the European Research Council under the European Union's Horizon 2020 research and innovation programme (grant agreement no. 820047). UN and CT are supported by the Deutsche Forschungsgemeinschaft (DFG) Research Unit FOR2820 VolImpact (grant agreement no. 398006378). This work used resources of the Deutsches Klimarechenzentrum (DKRZ) granted by its Scientific Steering Committee (WLA) under project ID bb1093. FRi received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 817564). JRM received support from the U.S. National Science Foundation (grant No. 1925417). The University of Bern gratefully acknowledges the long-term financial support of ice-core studies by the Swiss National Science Foundation. We thank two anonymous reviewers for their comments that have helped to improve the manuscript.

Appendix ASupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2021.107260.

References

Abbott, P.M., Davies, S.M., 2012. Volcanism and the Greenland ice-cores: the tephra record. Earth Sci. Rev. 115 (3), 173–191.

Abbott, P.M., Plunkett, G., Corona, C., Chellman, N.J., McConnell, J.R., Pilcher, J.R., Stoffel, M., Sigl, M., 2021. Cryptotephra from the Icelandic Veiðivötn 1477 CE eruption in a Greenland ice core: confirming the dating of volcanic events in the 1450s CE and assessing the eruption's climatic impact. Clim. Past 17, 565–585.

Adolphi, F., Bronk Ramsey, C., Erhardt, T., Edwards, R.L., Cheng, H., Turney, C.S.M., Cooper, A., Svensson, A., Rasmussen, S.O., Fischer, H., Muscheler, R., 2018. Connecting the Greenland ice-core and U/Th timescales via cosmogenic radionuclides: testing the synchroneity of Dansgaard-Oeschger events. Clim. Past 14, 1755–1781.

Baldini, J.U.L., Brown, R.J., Mawdsley, N., 2018. Evaluating the link between the sulfur-rich Laacher See volcanic eruption and the Younger Dryas climate anomaly. Clim. Past 14, 969–990.

Baldini, J.U.L., Bramall, N., McElwaine, J.N., 2015. Was millennial scale climate change during the Last Glacial triggered by explosive volcanism? Sci. Rep. 5, 17442.

Berger, W.H., 1990. The Younger Dryas cold spell — a quest for causes. Global Planet. Change 89, 219–237.

Bigler, M., Svensson, A., Kettner, E., Vallelonga, P., Nielsen, M.E., Steffensen, J.P., 2011. Optimization of high-resolution continuous flow analysis for transient climate signals in ice cores. Environ. Sci. Technol. 45, 4483–4489.

Bigler, M., Svensson, A., Steffensen, J.P., Kaufmann, P., 2007. A new continuous high-resolution detection system for sulphate in ice cores. Ann. Glaciol. 45, 178–182.

Brauer, A., Endres, C., Negendank, J.F.W., 1999. Lateglacial calendar year chronology based on annually laminated sediments from Lake Meerfelder Maar, Germany. Quat. Int. 61, 17–25.

Broecker, W.S., Denton, G.H., Edwards, R.L., Cheng, H., Alley, R.B., Putman, A.E., 2010. Putting the Younger Dryas cold event into context. Quat. Sci. Rev. 29, 1078–1081.

Buizert, C., Sigl, M., Severi, M., Markle, B.R., Wettstein, J.J., McConnell, J.R., Pedro, J.B., Sodemann, H., Goto-Azuma, K., Kawamura, K., Fujita, S., Motoyama, H., Hirabayashi, M., Uemura, R., Stenni, B., Parrenin, F., He, F., Fudge, T.J., Steig, E., 2018. Abrupt ice age shifts in southern westerlies and antarctic climate forced from the north. Nature 563, 543–549.

Büntgen, U., Arseneault, D., Boucher, É., Churakova, O.V., Gennaretti, F., Crivellaro, A., Hughes, M.K., Kirdyanov, A.V., Klippel, L., Krusic, P.J., Linderholm, H.W., Ljungqvist, F.C., Ludescher, J., McCormick, M., Myglan, V.S., Nicolussi, K., Piermattei, A., Oppenheimer, C., Reinig, F., Sigl, M., Vaganov, E.A., Esper, J., 2020. Prominent role of volcanism in Common Era climate variability and human history. Dendrochronologia 64, 125757.

Cheng, H., Zhang, H., Spötl, C., Baker, J., Sinha, A., Li, H., Bartolomé, M., Moreno, A., Kathayat, G., Zhao, J., Dong, X., Li, Y., Ning, Y., Jia, X., Zong, B., Brahim, Y.A., Pérez-Mejias, C., Cai, Y., Novello, V.F., Cruz, F.W., Severinghaus, J.P., An, Z., Edwards, R.L., 2020. Timing and structure of the Younger Dryas event and its underlying climate dynamics. Proc. Natl. Acad. Sci. Unit. States Am. 117, 23408–23417.

Church, J.A., White, N.J., Arblaster, J.M., 2005. Significant decadal-scale impact of volcanic eruptions on sea level and ocean heat content. Nature 438, 74–77.

Cole-Dai, J., Ferris, D.G., Kennedy, J.A., Sigl, M., McConnell, J.R., Fudge, T.J., Geng, L., Maselli, O., Taylor, K.C., Souney, J.M., 2021. Comprehensive record of volcanic eruptions in the Holocene (11,000 years) from the WAIS Divide, Antarctica ice core. Journal of Geophysical Research – Atmospheres, e2020JD032855.

Cook, E., 2015. Tracing and Constraining Cryptotephra Deposits in the Greenland Ice Core Records between GS-5.1 and the Early Holocene. PhD. Swansea University, Swansea.

Firestone, R.B., West, A., Kennett, J.P., Becker, L., Bunch, T.E., Revay, Z.S., Schultz, P.H., Belgya, T., Kennett, D.J., Erlandson, J.M., Dickenson, O.J., Goodyear, A.C., Harris, R.S., Howard, G.A., Kloosterman, J.B., Lechler, P., Mayewski, P.A., Montgomery, J., Poreda, R., Darrah, T., Hee, S.S.Q., Smitha, A.R., Stich, A., Topping, W., Wittke, J.H., Wolbach, W.S., 2007. Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal extinctions and the Younger Dryas cooling. Proc. Natl. Acad. Sci. Unit. States Am. 104, 16016–16021.

Fischer, H., Wagenbach, D., Kipfstuhl, J., 1998. Sulfate and nitrate firn concentrations on the Greenland ice sheet: 2. Temporal anthropogenic deposition changes. J. Geophys. Res. 103, 21935–21942.

Gao, C.C., Oman, L., Robock, A., Stenchikov, G.L., 2007. Atmospheric volcanic loading derived from bipolar ice cores: accounting for the spatial distribution of volcanic deposition. J. Geophys. Res. Atmos. 112.

Giorgetta, M.A., Manzini, E., Roeckner, E., Esch, M., Bengtson, L., 2006. Climatology and forcing of the quasi-biennial oscillation in the MAECHAM5 model. J. Clim. 19, 3882–3901.

Global Volcanism Program, 2013. Volcanoes of the World, 4.10.1 (29 Jun 2021). In: Venzke, E. (Ed.), Smithsonian Institution. Downloaded 09 Jul 2021. https://doi.org/10.5479/si.GVP.VOTW4-2013.

Hansen, J., Sato, M., Ruedy, R., Nazarenko, L., Lacis, A., Schmidt, G.A., Russell, G., Aleinov, I., Bauer, M., Bauer, S., Bell, N., Cairns, B., Canuto, V., Chandler, M., Cheng, Y., Genio, A. Del, Faluvegi, G., Fleming, E., Friend, A., Hall, T., Jackman, C., Kelley, M., Kiang, N., Koch, D., Lean, J., Lerner, J., Lo, K., Menon, S., Miller, R., Minnis, P., Novakov, T., Oinas, V., Perlwitz, J., Perlwitz, J., Rind, D., Romanou, A., Shindell, D., Stone, P., Sun, S., Tausnev, N., Thresher, D., Wielicki, B., Wong, T., Yao, M., Zhang, S., 2005. Efficacy of climate forcings. J. Geophys. Res. 110 (D18), D18104.

Kennett, D.J., Kennett, J.P., West, A., Mercer, C., Hee, S.S.Q., Bement, L., Bunch, T.E., Sellers, M., Wolbach, W.S., 2009. Nanodiamonds in the younger Dryas boundary sediment layer. Science 323, 94-94.

Lauterbach, S., Brauer, A., Andersen, N., Danielopol, D.L., Dulski, P., Hüls, M., Milecka, K., Namiotko, T., Obremska, M., von Graffenstein, U., 2011. Environmental responses to Lateglacial climatic fluctuations recorded in the sediments of pre-Alpine Lake Mondsee (northeastern Alps). DECLAKES Participants J. Quat. Sci. 26, 253–267.

Mangerud, J., 2021. The discovery of the Younger Dryas, and comments on the current meaning and usage of the term. Boreas 50, 1–5.

Mangerud, J., Gulliksen, S., Larsen, E., 2010. ^{14}-C dated fluctuations of the western flank of the Scandinavian Ice Sheet 45-25 kyr BP compared with Bølling-Younger Dryas fluctuations and Dansgaard-Oeschger events in Greenland. Boreas 39, 328–342.

Marshall, L., Johnson, J.S., Mann, G.W., Lee, L., Dhomse, S.S., Regayre, L., Yoshioka, M., Carslaw, K.S., Schmidt, A., 2019. Exploring how eruption source parameters affect volcanic radiative forcing using statistical emulation. J. Geophys. Res. 124, 964–985.

Mayewski, P.A., Meeker, L.D., Twickler, M.S., Whitlow, S., Yang, Q.Z., Lyons, W.B., Prentice, M., 1997. Major features and forcing of high-latitude northern hemisphere atmospheric circulation using a 110,000-year-long glaciochemical series. J Geophys Res-Oceans 102, 26345–26366.

McConnell, J.R., Burke, A., Dunbar, N.W., Kohler, P., Thomas, J.L., Arienzo, M.M., Chellman, N.J., Maselli, O.J., Sigl, M., Adkins, J.F., Baggenstos, D., Burkhart, J.F., Brook, E.J., Buizert, C., Cole-Dai, J., Fudge, T.J., Knorr, G., Graf, H.F., Grieman, M.M., Iverson, N., McGwire, K.C., Mulvaney, R., Paris, G., Rhodes, R.H., Saltzman, E.S., Severinghaus, J.P., Steffensen, J.P., Taylor, K.C., Winckler, G., 2017. Synchronous volcanic eruptions and abrupt climate change similar to 17.7 ka plausibly linked by stratospheric ozone depletion. Proc. Natl. Acad. Sci. Unit. States Am. 114, 10035–10040.

McConnell, J.R., Sigl, M., Plunkett, G., Burke, A., Kim, W., Raible, C.C., Wilson, A.I., Manning, J.G., Ludlow, F.M., Chellman, N.J., Innes, H.M., Yang, Z., Larsen, J.F., Schaefer, J.R., Kipfstuhl, S., Mojtabavi, S., Wilhelms, F., Opel, T., Meyer, H., Steffensen, J.P., 2020. Extreme climate after massive eruption of Alaska's Okmok volcano in 43 BCE and effects on the late Roman Republic and Ptolemaic Kingdom. Proc. Natl. Acad. Sci. Unit. States Am. 117, 15443–15449.

McManus, J.F., Francois, R., Gherardi, J.-M., Kegwin, L.D., Brown-Leger, S., 2004. Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. Nature 428, 834–837.

Miller, G.H., Geirsdottir, A., Zhong, Y., Larsen, D.J., Otto-Bliesner, B.L., Holland, M.M., Bailey, D.A., Refsnider, K.A., Lehman, S.J., Southon, J.R., Anderson, C., Björnsson, H., Thordarson, T., 2012. Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks. Geophys. Res. Lett. 39, L02708.

Mortensen, A.K., Bigler, M., Grönvold, K., Steffensen, J.P., Johnsen, S.J., 2005. Volcanic ash layers from the Last Glacial Termination in the NGRIP ice core. J. Quat. Sci. 20, 209–219.

Newhall, C.G., Self, S., 1982. The volcanic explosivity index (VEI) an estimate of explosive magnitude for historical volcanism. J. Geophys. Res. 87 (C2), 1231–1238.

Niemeier, U., Riede, F., Timmreck, C., 2021. Simulation of ash clouds after a Laacher See-type eruption. Clim. Past 17, 633–652.

Niemeier, U., Timmreck, C., Graf, H.-F., Kinne, S., Rast, S., Self, S., 2009. Initial fate of fine ash and sulfur from large volcanic eruptions. Atmos. Chem. Phys. 9, 9043–9057.

Nye, H., Condron, A., 2021. Assessing the statistical uniqueness of the Younger Dryas: a robust multivariate analysis. Clim. Past 17, 1409–1421.

Oppenheimer, C., 2003. Climatic, environmental and human consequences of the largest known historical eruption: Tambora volcano (Indonesia) 1815. Prog. Phys. Geogr. 27, 230–259.

Petaev, M.I., Huang, S., Jacobsen, S.B., Zindler, A., 2013. Large Pt anomaly in the Greenland ice core points to a cataclysm at the onset of the Younger Dryas. Proc. Natl. Acad. Sci. Unit. States Am. 110, 12917–12920.

Plummer, C.T., Curran, M.A.J., van Ommen, T.D., Rasmussen, S.O., Moy, A.D., Vance, T.R., Clausen, H.B., Vinther, B.M., Mayewski, P.A., 2012. An independently dated 2000-yr volcanic record from Law Dome, East Antarctica, including a new perspective on the dating of the 1450s CE eruption of Kuwae, Vanuatu. Clim. Past 8, 1929–1940.

Plunkett, G., Sigl, M., Schwaiger, H., Tomlinson, E., Toohey, M., McConnell, J.R., Pilcher, J.R., Hasegawa, T., Siebe, C., 2021. No evidence for tephra in Greenland from the historic eruption of Vesuvius in 79 CE: implications for geochronology and paleoclimatology. Clim. Past Discuss.

Plunkett, G., Sigl, M., Pilcher, J.R., McConnell, J.R., Chellman, N., Steffensen, J.P., Büntgen, U., 2020. Smoking guns and volcanic ash: the importance of sparse tephras in Greenland ice cores. Polar Res. 39.

Rahmstorf, S., 2002. Ocean circulation and climate during the past 120,000 years. Nature 419, 207–214.

Rasmussen, S.O., Andersen, K.K., Svensson, A.M., Steffensen, J.P., Vinther, B.M., Clausen, H.B., Siggaard-Andersen, M.L., Johnsen, S.J., Larsen, L.B., Dahl-Jensen, D., Bigler, M., Rothlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M.E., Ruth, U., 2006. A new Greenland ice core chronology for the last glacial termination. J. Geophys. Res. Atmos. 111.

Rasmussen, S.O., Bigler, M., Blockley, S.P., Blunier, T., Buchardt, S.L., Clausen, H.B., Cvijanovic, I., Dahl-Jensen, D., Johnsen, S.J., Fischer, H., Gkinis, V., Guillevic, M., Hoek, W.Z., Lowe, J.J., Pedro, J.B., Popp, T., Seierstad, I.K., Steffensen, J.P., Svensson, A.M., Vallelonga, P., Vinther, B.M., Walker, M.J., Wheatley, J.J., Winstrup, M., 2014. A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. Quat. Sci. Rev. 106, 14–28.

Reinig, F., Wacker, L., Jöris, O., Oppenheimer, C., Guidobaldi, G., Nievergelt, D., Adolphi, F., Cherubini, P., Engels, S., Esper, J., Land, A., Lane, C., Pfanz, H., Remmele, S., Sigl, M., Sookdeo, A., Büntgen, U., 2021. Precise dating for the laacher see eruption synchronizes the younger Dryas. Nature 595, 66–69.

Renssen, H., Mairesse, A., Goosse, H., Mathiot, P., Heiri, O., Roche, D.M., Nisancioglu, K.H., Valdes, P.J., 2015. Multiple causes of the Younger Dryas cold period. Nat. Geosci. 8, 946–949.

Robock, A., 2000. Volcanic eruptions and climate. Rev. Geophys. 38, 191–219.

Robock, A., Ammann, C.M., Oman, L., Shindell, D., Levis, S., Stenchikov, G., 2009. Did the Toba volcanic eruption of ~74 ka B.P. produce widespread glaciation? J. Geophys. Res. 114, D10107.

Ruth, U., Wagenbach, D., Steffensen, J.P., Bigler, M., 2003. Continuous record of microparticle concentration and size distribution in the central Greenland NGRIP ice core during the last glacial period. J. Geophys. Res. C Oceans Atmos. 4098.

Schleussner, C.F., Feulner, G., 2013. A volcanically triggered regime shift in the subpolar North Atlantic Ocean as a possible origin of the Little Ice Age. Clim. Past 9, 1321–1330.

Schminke, H.-U., Park, C., Harms, E., 1999. Evolution and environmental impacts of the eruption of laacher See volcano (Germany) 12,900 a BP. Quat. Int. 61, 61–72.

Seierstad, I.K., Abbott, P.M., Bigler, M., Blunier, T., Bourne, A.J., Brook, E., Buchardt, S.L., Buizert, C., Clausen, H.B., Cook, E., Dahl-Jensen, D., Davies, S.M., Guillevic, M., Johnsen, S.J., Pedersen, D.S., Popp, T.J., Rasmussen, S.O., Severinghaus, J.P., Svensson, A., Vinther, B.M., 2014. Consistently dated records from the Greenland GRIP, GISP2 and NGRIP ice cores for the past 104 ka reveal regional millennial-scale delta O-18 gradients with possible Heinrich event imprint. Quat. Sci. Rev. 106, 29–46.

Severi, M., Becagli, S., Castellano, E., Morganti, A., Traversi, R., Udisti, R., Ruth, U., Fischer, H., Huybrechts, P., Wolff, E., Parrenin, F., Kaufmann, P., Lambert, F., Steffensen, J.P., 2007. Synchronisation of the EDML and EDC ice cores for the last 52 kyr by volcanic signature matching. Clim. Past 3, 367–374.

Severi, M., Becagli, S., Traversi, R., Udisti, R., 2015. Recovering paleo-records from antarctic ice-cores by coupling a continuous melting device and fast ion chromatography. Anal. Chem. 87, 11441–11447.

Sigl, M., Fudge, T.J., Winstrup, M., Cole-Dai, J., Ferris, D., McConnell, J.R., Taylor, K.C., Welten, K.C., Woodruff, T.E., Adolphi, F., Bisiaux, M., Brook, E.J., Buizert, C., Caffee, M.W., Dunbar, N.W., Edwards, R., Geng, L., Iverson, N., Koffman, B., Layman, L., Maselli, O.J., McGwire, K., Muscheler, R., Nishiizumi, K., Pasteris, D.R., Rhodes, R.H., Sowers, T.A., 2016. The WAIS Divide deep ice core WD2014 chronology - Part 2: annual-layer counting (0-31 ka BP). Clim. Past 12, 769–786.

Sigl, Michael, McConnell, Joseph, R, SeveriMirko, Fischer, 2021. Reconstructed volcanic stratospheric sulfur injections and volcanic sulfate deposition over Greenland and Antarctica for the Bølling-Allerød/Younger Dryas transition (13.20-12.80 ka BP). PANGAEA. Hubertus. https://doi.org/10.1594/PANGAEA.

930557.

Sigl, M., McConnell, J.R., Layman, L., Maselli, O., McGwire, K., Pasteris, D., Dahl-Jensen, D., Steffensen, J.P., Vinther, B., Edwards, R., Mulvaney, R., Kipfstuhl, S., 2013. A new bipolar ice core record of volcanism from WAIS Divide and NEEM and implications for climate forcing of the last 2000 years. J. Geophys. Res. 118 (3), 1151–1169.

Sigl, M., McConnell, J.R., Toohey, M., Curran, M., Das, S.B., Edwards, R., Isaksson, E., Kawamura, K., Kipfstuhl, S., Kruger, K., Layman, L., Maselli, O.J., Motizuki, Y., Motoyama, H., Pasteris, D.R., Severi, M., 2014. Insights from Antarctica on volcanic forcing during the Common Era. Nat. Clim. Change 4, 693–697.

Sigl, M., Winstrup, M., McConnell, J.R., Welten, K.C., Plunkett, G., Ludlow, F., Büntgen, U., Caffee, M., Chellman, N., Dahl-Jensen, D., Fischer, H., Kipfstuhl, S., Kostick, C., Maselli, O.J., Mekhaldi, F., Mulvaney, R., Muscheler, R., Pasteris, D.R., Pilcher, J.R., Salzer, M., Schupbach, S., Steffensen, J.P., Vinther, B.M., Woodruff, T.E., 2015. Timing and climate forcing of volcanic eruptions for the past 2,500 years. Nature 523, 543–549.

Steffensen, J.P., Andersen, K.K., Bigler, M., Clausen, H.B., Dahl-Jensen, D., Fischer, H., Goto-Azuma, K., Hansson, M., Johnsen, S.J., Jouzel, J., Masson-Delmotte, V., Popp, T., Rasmussen, S.O., Röthlisberger, R., Ruth, U., Stauffer, B., Siggard-Andersen, M.-L., Sveinbjörnsdóttir, Á., Svensson, A., White, J.W.C., 2008. High-resolution Greenland ice core data show abrupt climate change happens in few years. Science 321, 680–684.

Stier, P., Feichter, J., Kinne, S., Kloster, S., Vignati, E., Wilson, J., Ganzeveld, L., Tegen, I., Werner, M., Balkanski, Y., Schulz, M., Boucher, O., Minikin, A., Petzold, A., 2005. The aerosol-climate model ECHAM5-HAM. Atmos. Chem. Phys. 5, 1125–1156.

Svensson, A., Dahl-Jensen, D., Steffensen, J.P., Blunier, T., Rasmussen, S.O., Vinther, B.M., Vallelonga, P., Capron, E., Gkinis, V., Cook, E., Kjær, H.A., Muscheler, R., Kipfstuhl, S., Wilhelms, F., Stocker, T.F., Fischer, H., Adolphi, F., Erhardt, T., Sigl, M., Landais, A., Parrenin, F., Buizert, C., McConnell, J.R., Severi, M., Mulvaney, R., Bigler, M., 2020. Bipolar volcanic synchronization of abrupt climate change in Greenland and Antarctic ice cores during the last glacial period. Clim. Past 16, 1565–1580.

Sweatman, M.B., 2021. The Younger Dryas impact hypothesis: review of the impact evidence. Earth Sci. Rev. 218, 103677.

Textor, C., Sachs, P.M., Graf, H.-F., Hansteen, T.H., 2003. The 12 900 Years BP Laacher See Eruption: Estimation of Volatile Yields and Simulation of Their Fate in the Plume, vol. 213. Geological Society of London Special Publications, pp. 307–328.

Timmreck, C., 2012. Modeling the climatic effects of large explosive volcanic eruptions. WIREs Climate Change 3, 545–564.

Toohey, M., Krüger, K., Schmidt, H., Timmreck, C., Sigl, M., Stoffel, M., Wilson, R., 2019. Disproportionately strong climate forcing from extratropical explosive volcanic eruptions. Nat. Geosci. 12, 100–107.

Toohey, M., Krüger, K., Sigl, M., Stordal, F., Svensen, H., 2016a. Climatic and societal impacts of a volcanic double event at the dawn of the Middle Ages. Climatic Change 136, 401–412.

Toohey, M., Sigl, M., 2017. Volcanic stratospheric sulfur injections and aerosol optical depth from 500 BCE to 1900 CE. Earth Syst. Sci. Data 9, 809–831.

Toohey, M., Stevens, B., Schmidt, H., Timmreck, C., 2016b. Easy Volcanic Aerosol (EVA v1.0): an idealised forcing generator for climate simulations. Geosci. Model Dev. (GMD) 9, 4049–4070.

von Grafenstein, U., Erlenkeuser, H., Brauer, A., Jouzel, J., Johnsen, S.J., 1999. A mid-European decadal isotope-climate record from 15,500 to 5000 Years B.P. Science 284, 1654–1657.

Zhong, Y., Miller, G.H., Otto-Bliesner, B.L., Holland, M.M., Bailey, D.A., Schneider, D.P., Geirsdottir, A., 2011. Centennial-scale climate change from decadally-paced explosive volcanism: a coupled sea ice-ocean mechanism. Clim. Dynam. 37, 2373–2387.

Zielinski, G.A., Mayewski, P.A., Meeker, L.D., Grönvold, K., Germani, M.S., Whitlow, S., Twickler, M.S., Taylor, K., 1997. Volcanic aerosol records and tephrochronology of the Summit, Greenland, ice cores. J. Geophys. Res. 102 (26), 625-626,640.

Zielinski, G.A., Mayewski, P.A., Meeker, L.D., Whitlow, S., Twickler, M.S., 1996. A 110,000-yr record of explosive volcanism from the GISP2 (Greenland) ice core. Quat. Res. 45, 109–118.